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FOREWORD

In the past, water resources in Ireland have been managed in a rather piecemeal fashion. People often dealt separately with water quality and water 'quantity', and with water abstractions and discharges. People who dealt with surface water didn't have much to do with ground water, and vice versa. In recent times, this tendency has been reversed to some extent, and we hope this will continue.

One of the earliest items on many hydrology or hydrogeology courses is the Hydrological Cycle, which emphasises that all water - in the air, on the surface or underground - is intimately interlinked. So the interlinking of surface water and groundwater is the theme of this year's IAH seminar, our 19th, and we have invited a range of speakers to address the topic.

There were several reasons for our choice. One stimulus was last year's International Congress in Las Vegas, which, although intriguingly entitled 'Gambling with Ground Water', was sub-titled 'Surface Water and Ground Water Interactions'. Another was the upcoming European Union Framework Directive on Water; this has been several years in the drafting, and when it finally reaches the statute book will probably be the subject of one of these seminars. In the meantime, we know that it will strongly emphasise the need to integrate the evaluation and management of surface water and groundwater resources. Thirdly, there are several initiatives already under way in Ireland which seek to bring surface water and groundwater management together; these include the Water Quality Management Plands and the more recent Catchment Monitoring and Management Systems, both of which will be presented to us at this seminar.

We often mention that because groundwater is 'out of sight' it is often 'out of mind'. With today's theme in mind, we could also say that the connections between surface water and groundwater are also often taken for granted. Of course, some of them are obvious, for instance where a spring emerges from a rock face, or a stream disappears into a cave or swallow-hole. But mostly the connections are less obvious and very difficult to measure, as where groundwater seeps into or out of a river along many kilometres of channel. So this is a good opportunity to spend some time considering the various ways and environments in which surface water and groundwater interact.

We especially welcome Pat Leahy, Chief Geologist at the United States Geological Survey, which as an organisation has always been exemplary in embracing both surface and ground water resources. Pat spoke at last year's Las Vegas Congress, as did Bruce Misstear and Catherine Coxon, two of our Irish contributors.

From Britain, where there has been a healthy degree of water resources integration at least since the Water Resources Act of 1964, we welcome David Burgess (Environment Agency) and Peter Rippon (Mott MacDonald).

The Irish Group of IAH welcomes you to this seminar and encourages you to participate fully in the formal and informal discussions over the two days.

Geoff Wright,
President, IAH Irish Group

Paper No. 1. *Keynote: Lecture:*

Groundwater and Surface Water Relationships in the USA.

Dr. P. Patrick Leahy, United States Geological Survey.

GROUND WATER- AND SURFACE-WATER RELATIONSHIPS IN THE USA

P. Patrick Leahy , Chief Geologist, U.S. Geological Survey
R. K. Kotra, Geochemist, U.S. Geological Survey

ABSTRACT

Hydrogeologists are focusing more attention on the interaction of ground-water and surface-water systems. Similarly, geologists are committing more effort to mapping and analyzing surficial geologic deposits of all types especially as they relate to water-resource issues. A natural synergy between these efforts is developing that will greatly improve our ability to understand the hydraulic processes that dominate the interaction between ground-water and surface-water systems. These processes vary with hydrogeologic setting. For example, natural processes that dominate the interaction in coastal plain settings are very different from those that dominate fractured rock settings. In addition, human influences that affect this interaction must be identified to fully characterize the integrated behavior of ground water and surface water systems. Understanding these processes and interactions in turn will allow managers and the public to comprehend and evaluate the potential consequences (including biologic) of proposed management strategies to use these resources in a more efficient and effective manner.

INTRODUCTION

The science of hydrogeology has evolved rapidly during the past 150 years, since Henry Darcy (1856) developed a fundamental law based on a series of laboratory experiments that describes the flow of water through porous media. Darcy's law has become the basis for modeling and is the cornerstone for the development and evolution of the science of hydrogeology. However, hydrogeology by its very name involves more than simply physical laws. Because ground water occurs in a geologic environment, the description of the geologic materials that behave as aquifers and confining units has always been one of the fundamental underpinnings of hydrogeology. This observation is increasingly important in the study of the interaction of ground-water and surface-water systems. An improved understanding of these systems is becoming increasingly important because of their significance in defining the sustainability of water supplies, water-quality considerations, addressing biological issues such as critical habitat conservation and endangered species, and adjudicating water rights disputes.

As the world's demands on its water resources and concerns about the environment increase, the importance of viewing ground water and surface water as a single resource is becoming increasingly evident. The interaction of ground water and surface water is currently a significant concern in many investigations conducted by the U.S. Geological Survey (USGS) (Winter et al., 1998). For example, contaminated aquifers discharging into streams can cause long-term contamination of rivers, streams and estuaries. Conversely, streams can be a source of contamination to shallow aquifers. Surface water is hydraulically connected to ground water. However, since the interactions are difficult to observe and measure, they have been overlooked in water management considerations and policy. Both natural processes and human activities affect the interactions of ground water and surface water.

The focus of this report is on the present understanding of these processes and activities in selected settings in the United States (Winter et al., 1998). The interaction of ground water and surface water depends on the physiographic and climatic setting of the landscape. In various types of settings, interactions between ground water and surface water share some common features. Examples of recent USGS investigations in four types of settings (mountainous, riverine, coastal, and karst) are briefly described. In addition, three example studies highlighting the importance of defining the geologic framework to better define ground-water and surface-water interaction are also described.

NATURAL PROCESSES OF GROUND-WATER AND SURFACE-WATER INTERACTION

The continuous movement of water above, on, and below the surface of the Earth is described by the hydrologic cycle. Surface water occurs as streams, lakes, wetlands, bays and oceans, as well as in the solid forms -- snow and ice. The water below the surface is ground water and includes soil water. The hydrologic cycle is typically shown in a simplified manner with major transfers of water between the atmosphere, the continents and the oceans. However, for a more a complete understanding of the processes and improved water resource management, the hydrologic cycle must be examined at a wide range of scales -- spatial and temporal. The concept that ground water and surface water can interact at many points throughout the landscape is useful to illustrate the ideas and many facets of their interaction (Winter et al., 1998).

Streams, lakes, and wetlands can receive ground water inflow through their bed, have outflow through their bed, or have inflow and outflow occur at different locations resulting in either a net gain or loss in total flux. In a drainage basin, the chemistry of input water, such as precipitation, type of aquifer material present, and the contact time of water with the material control water chemistry. Many processes including oxidation, reduction, sorption, ion exchange, and microbiological processes during the contact can influence the ultimate chemical composition of the water and the biological and geological characteristics of the basin. The chemical interactions of ground water and surface water must be considered together where surface and subsurface flow systems interact. The movement of water between ground water and surface water provides a major pathway for chemical communication between terrestrial and aquatic systems. The transfer of nutrients, oxygen, and other constituents affects biogeochemical processes and ultimately affects the biological and chemical characteristics of aquatic systems downstream.

MOUNTAINOUS SETTINGS

The rugged nature of mountainous terrain makes it difficult to determine interactions of ground water and surface water. Only a few detailed hydrogeologic investigations of these interactions have been conducted. A field and modeling study of the Mirror Lake area in the White Mountains of New Hampshire showed that the sizes of ground-water flow systems contributing to surface-water bodies were considerably larger than their topographically defined watersheds. Much of the ground water in the fractured bedrock that discharges to Mirror Lake passes beneath the local flow system associated with Norris Brook. A more extensive deep ground-water flow system that discharges to the Pemigewasset River passes beneath flow systems associated with both Norris Brook and Mirror Lake. Understanding the role of the fractured rock aquifer system is critical to defining the interaction of ground water and surface water in these settings. A description of recent studies defining the fabric of fractured bedrock is included later in this paper.

In terms of water quality, the Chalk Creek in Colorado provides a notable example of the interaction of ground water and surface water. In addition to surface drainage from mines, contaminants were brought to the stream by ground-water inflow. The ground water had been contaminated by past mining activities and is a present day source of contamination to the stream. The nonpoint ground-water source of contamination will likely be much more difficult to clean up than the point source of contamination from the mine adit.

RIVERINE SETTINGS

The interaction of ground water and surface water in river valleys is affected by the interaction of local and regional ground water systems with the rivers, by flooding, and by evapotranspiration. The interaction of ground water with streams varies in complexity because they range in size from small streams near headwaters areas where the valleys are eroding rapidly and there is little sediment in the stream bed, to large rivers flowing in large valleys where alluvial processes have deposited thick sequences of sediment. Streams also intersect ground-water flow systems of greatly different scales. Depending upon the geology of an area, it is common that the ground-water flow in an area does not follow the surface-water drainage basin.

The Straight River, which runs through a sand plain in central Minnesota, is typical of a small stream that does not have a flood plain and derives most of its water from ground-water inflow. The water-table contours near the river bend sharply upstream, demonstrating that ground water moves directly into the river. It is estimated from baseflow studies that, on an annual basis, ground water accounts for more than 90 percent of the water in the river. Similar situations are commonly found in the Atlantic Coastal Plain. For example, more than 90 percent of the flow in Beaverdam Creek in southern Delaware consists of ground-water inflow.

A study of the lower Missouri River Valley illustrates the complexity of ground-water flow and its interaction with streams in large alluvial valleys. Configuration of the water table in this area shows that ground water flows into the river at right angles in some reaches, and it flows parallel to the river in some others. Patterns of water-table fluctuations with respect to proximity to the river were also observed.

COASTAL SETTINGS

In coastal settings the interaction of ground water and surface water is affected by discharge of ground water from regional flow systems, local flow systems associated with scarps and terraces, evapotranspiration, and tidal flooding. The Great Dismal Swamp in Virginia and North Carolina provides an example of the interaction of ground water and wetlands near a coastal scarp. The Suffolk Scarp borders the west side of Great Dismal Swamp. Water table wells and deeper wells placed across the scarp indicated a downward component of ground-water flow in the upland and an upward component of ground-water flow in the lowland at the edge of the swamp. However, at the edge of the swamp the direction of flow changed several times between spring and fall (in 1982) because transpiration of ground water lowered the water table below the water level of the deeper aquifer.

Nutrient movement from agricultural fields has been documented for the Rhode River watershed in Maryland. Applied fertilizer accounts for 69 per cent of nitrogen and 93 per cent of phosphorus input to this watershed. Most of the nitrogen that is not removed by harvested crops is transported in ground water and is taken up by the trees in riparian forests and wetlands or is denitrified to nitrogen gas in ground water before it reaches streams. However, most of the phosphorus not removed by harvested crops is attached to soil particles and is transported only during heavy precipitation when sediment from fields is transported into streams and is deposited in wetlands and subtidal mudflats at the head of the Rhode River estuary. Whether phosphorus is released to the water column or retained in sediments depends partly on whether sediments are exposed to oxygen. Thus, the uptake of nutrients and their storage in riparian forests, wetlands, and subtidal mudflats in the watershed has helped maintain relatively good water quality in the Rhode River estuary.

KARST SETTINGS

Surface-water and ground-water flow patterns are complex in karst terrain. Ground-water recharge is very efficient in this type of terrain because precipitation readily infiltrates rock openings. In karst terrain where limestones and dolomites are exposed at the land surface, numerous solution cavities along vertical joints and sinkholes provide an efficient link between the land surface and the water table. Such terrain is an excellent illustration of the high vulnerability of ground water to contamination by human activities at the land surface.

Lake Barco is one of many lakes occupying depressions in northern Florida. A study of the interaction of Lake Barco with ground water indicated that shallow ground water flows into the northern and northeastern parts of the lake, and lake water seeps out to shallow ground water in the western and southern parts. However, ground-water flow is downward beneath most of Lake Barco and provides recharge to the regional ground-water flow system. Studies also indicated significant differences in the chemistry of shallow ground water flowing into the lake, Lake Barco water, shallow ground water down gradient from the lake, and deeper ground water beneath the lake.

HUMAN ACTIVITIES AND THE INTERACTION OF GROUND WATER AND SURFACE WATER

Human activities affect the distribution, quantity, and quality of water resources. A large array of human activities affects the interaction of ground water and surface water. In addition, the impacts of human activities encompass a wide range of spatial and temporal scales and include agricultural, urban, and industrial development, drainage of the land surface, and modification of river valleys.

Agriculture has been one of the principal modifying forces in many areas of the United States. Tillage practices have been adjusted to maximize retention of water in soils and to minimize erosion (and runoff). Two activities related to agriculture that are of particular importance to the interaction of ground water and surface water are irrigation and the application of chemicals to cropland.

The state of Nebraska ranks second in the United States with respect to the area of irrigated acreage and the quantity of water used for irrigation. Extensive supply systems have been developed to tap surface water as well as ground water. Significant rises and declines in ground-water levels are observed. Ground-water levels rise in some areas irrigated with surface water and decrease in some areas irrigated with ground water. Rises in ground-water levels near streams result in increased ground-water inflow to gaining streams or decreased flow from the stream to ground water for losing streams. In some areas, a losing stream can become a gaining stream after irrigation. Whether ground water or surface water is used to irrigate land, water managers now recognize that development of either resource could affect the other.

Application of pesticides and fertilizers to cropland can result often in significant additions of contaminants to water resources. Nitrate contamination of ground water and surface water is widespread in the United States. High concentrations of nitrate can contribute to excessive growth of aquatic plants, depletion of oxygen, fishkills, and general degradation of aquatic habitats. A study of Waquoit Bay, Massachusetts, tied the decline of eelgrass beds since 1950 to a progressive increase in nitrate input due to expansion of domestic septic-field developments in the drainage basin. Loss of eelgrass is a concern because it stabilizes sediment and provides ideal habitat for juvenile fish and other fauna in coastal bays and estuaries.

A study of the sources of atrazine, a widely used herbicide detected in the Cedar River and its associated aquifer in Iowa, indicated that ground water was the major source of atrazine in the river during base-flow conditions. During periods of high streamflow, surface water containing high concentrations of atrazine moved into the bank sediments and alluvial aquifer, then slowly discharged back to the river as the river level declined.

Point sources of contamination to surface-water bodies are an anticipated side effect of urban and industrial development. Contaminants in the surface water can affect ground-water quality especially where streams normally seep to ground water, or ground water withdrawals induce seepage from the stream, or floods cause stream water to become bank storage. Point sources of contamination to ground water can be associated with accidental spills, septic tanks, storage tanks, landfills, and industrial lagoons. Contaminant plumes transported by ground water often discharge into surface-water bodies.

In natural settings with a shallow water table or a ponded surface, drainage of the land is a prerequisite for agricultural and urban development. The effects of drainage can include modification of the areal distribution of ground-water recharge and discharge, changes in baseflow to streams, and impacts on ecosystems.

The increase of water levels in reservoirs induces the surface water to move into bank storage. When water levels in reservoirs are lowered, this bank storage returns to the reservoir. Depending on the size of the reservoir and the magnitude of fluctuation of the water level in the reservoir, the amount of water involved in bank storage can be large. A study of bank storage associated with Hungry Horse Reservoir in

Montana, a part of the Columbia River system, indicated that the amount of water that would return to the reservoir from bank storage after water levels are lowered is large. This discharge from bank storage needs to be considered in the reservoir management plan for the Columbia River system.

In low-lying areas where the water table is close to the land surface, such as in flood plains, direct transpiration from ground water can reduce ground-water discharge to surface water and can even cause surface water to recharge ground water. This process has attracted particular attention in arid areas, where transpiration by vegetation on flood plains of western rivers can have a significant effect on stream flows. A study of transpiration along a reach of the Gila River, upstream from San Carlos Reservoir, Arizona was carried out over a 10-year period, including removal of vegetation from the flood plain. The average effect of vegetation removal over the entire study reach was that the Gila River changed from a continually losing river for most years before clearing to a gaining stream during some months for most years following clearing. The invasive salt cedar, which commonly lines the banks of many western streams and rivers, may play a significant role in this effect.

GEOLOGIC STUDIES IN SUPPORT OF UNDERSTANDING GROUND- AND SURFACE-WATER INTERACTION

MIDDLE RIO GRANDE VALLEY, NEW MEXICO

Studies over the last few years by the USGS, the State of New Mexico, and cities and counties in the Albuquerque area have aimed to improve quantitative understanding of the hydrogeologic framework of the Rio Grande rift basins (Bartolino, 1997). Sediments deposited in these rift basins over the last 15 million years are the principal aquifers that provide more than 80 percent of the water needed by the growing population of the Santa Fe-Albuquerque areas. Of major interest is the long-term sustainability of the ground-water system of the Albuquerque area. The quantity and quality of this ground-water resource will have a direct influence on the growth of this area. An important part of this study is to develop an understanding of the interaction of the ground-water system with the Rio Grande River and its tributaries. Defining the hydraulic properties of the ground-water system is an important part of this study. The hydraulic properties of the aquifers are strongly influenced by the sediment grain size and sorting, and these properties reflect the interaction of fault-tectonic events and sedimentation patterns of tributary and through-flowing rivers. The continuity of these aquifers is also affected by slip on post-depositional faults and, in some cases, by rock alteration caused by reactions with ground water moving along and near fault zones.

Detailed aeromagnetic surveys have been especially valuable in helping to define the patterns and offsets on numerous buried fault systems in the rift basins. These high-resolution surveys clearly show detailed fault offsets that displace the slightly magnetic sediments of the rift basins. Airborne electromagnetic surveys help to map in three dimensions the distribution of conductive, low permeability clay and silt units in the subsurface, and to distinguish them from the higher permeability gravel and sand deposits laid down through time by the trunk streams of the basins. Coupled with detailed geologic mapping, the information from the geophysical surveys is being used to develop a geologic model for the basin which will be a key component in a revised ground-water flow model for the Albuquerque basin. The objective is to provide the information used to make water management decisions by local governments for long-range planning.

BEDROCK REGIONAL AQUIFER SYSTEMATICS STUDY (BRASS)

A new effort at the USGS has begun that will attempt to totally integrate the day-to-day work of field geologists and hydrologists. Interdisciplinary teams of scientists from the USGS are working together in several pilot projects to determine ways to improve models of the flow and chemical evolution of ground water in regions underlain by fractured bedrock. The goal is to maximize the resources, techniques, and talents of the field geologists and hydrologists to answer a series of critical questions in a given watershed. What is the relative influence on ground-water flow and storage, in a given volume of bedrock and regolith, of primary porosity (interstitial) versus secondary porosity (planar structures)? Of all the various types of secondary porosity, which are most influential: bedding planes, compositional contacts, cleavage, foliation, faults, or joints and fractures? How do these relative influences vary in different structural or tectonic regimes? What is the relative chemical influence on ground water of the bulk composition and primary mineralogy of bedrock lithologies and regolith versus the secondary mineralizations of veins and fracture coatings? Within the study watersheds in New Hampshire, Pennsylvania, and South Dakota, activities by hydrologists and geologists involve the continuous transfer of data between two disciplines as part of an iterative process to refine the hydrogeologic model. The geologists will map the distribution of lithologies, sample them for petrographic and geochemical analysis, map and make extensive measurements of all structural elements and note evidence for ground-water flow through them. They would map seeps, springs, and wetlands, incorporate geophysical data, and define the tectonic history of the area. The hydrologists would gather streamflow, rain gage, and well data, conduct seepage runs, measure stream temperature and conductance, sample streams for water chemistry, conduct aquifer tests, conduct borehole and surface geophysical surveys, and model ground-water flow. A critical element of this new project will be the transfer of information between hydrologists and geologists *when* it is collected, not years later. This will allow continuous redesign and modification of project plans that, for example, would allow hydrologists to place stream gages at significant geologic contacts identified by geologists, and to obtain geologic explanations for anomalous chemical compositions of water.

In the summer of 1998, USGS scientists mapped the bedrock geology of two 71/2-Minute quadrangles in southern New Hampshire as part of the BRASS effort. The primary objective centered on evaluating the influence of geologic structures (particularly fractures) on the distribution of bedrock ground-water well yields. Analysis of the distribution of lithologies, and brittle fracture parameters such as spacing, aperture, frequency, and orientation, were coupled with results from spatial analysis of domestic well yields. This analysis showed very distinct trends with different orientations for the different mapped rock units. Comparison of the geological data with these spatial analysis patterns showed a direct correlation between mapped tectonically controlled fracture domains present in each of the rock units and the directional trend of ground-water flow.

In addition to their work in southern New Hampshire, detailed geologic mapping and brittle fracture analysis was conducted within the Hubbard Brook watershed at the Mirror Lake site in central New Hampshire. This work included the subdivision of the complex crystalline rocks into twelve different lithologic units, the identification of two major fault zones, which may provide constraints upon bedrock ground-water flow paths and stream discharge, and the acquisition of outcrop-scale fracture-orientation, spacing, and aperture data. This work supports the growing conclusion that precise geologic boundary constraints are essential towards developing effective ground-water models of fractured bedrock and accompanying surface waters.

REGIONAL COALITIONS THAT ADDRESS CRITICAL WATER NEEDS

The central Great Lakes region, with a large and growing population, has an acute need for geologic maps to better define the three-dimensional framework of regional aquifers and confining units. The need to properly characterize and model these ground-water aquifers, which supply much of the drinking water in the region, is recognized by the State Geological Surveys of Indiana, Illinois, Michigan and Ohio, as an issue that crosses traditional political boundaries. Ground water from aquifers in shallow glacial materials is a critical resource, fulfilling the domestic water needs of 50 percent of the residents of Illinois and Indiana, while Michigan and Ohio rank first and fifth, respectively, in total number of domestic water wells. It is also clear that to tackle this large problem, resources must be pooled and leveraged; to that end the USGS has joined four state geological surveys in a long-range planning process that describes the roles and responsibilities of each organization, including mechanisms to determine priorities. Because the critical third dimension of the glacial cover cannot be mapped by conventional methods, it must be explored using expensive drilling and geophysical techniques.

The central Great Lakes states are facing numerous economic and environmental decisions that are directly related to a clear understanding of the fragile and complex glacial deposits including their interaction with surface waters. Understanding the connections between surface and ground water in areas where the aquifers and confining units are not clearly defined is presently impossible. This is another example where the iterative interaction between geologists and hydrologists is necessary to construct meaningful ground-water flow models.

Many of the problems facing the Great Lakes states arise from the fact that the glacial deposits have multiple and often conflicting uses. These sediments are the foundation of some of the richest farmland in the United States and contain sand and gravel deposits, which are acutely needed for sustaining industrial and private infrastructure. Rapid development and growth in this region is forcing regulatory and zoning agencies to make difficult decisions on competing land uses. Better information provided in user-friendly three-dimensional geologic map databases will allow these governing bodies to better understand the full consequences of their actions. Only when geologists and hydrologists present their interpretations of the glacial sediments and their complex ground-water system in a unified manner will the full impact of land-use decisions on both ground- and surface-water resources be appreciated.

SUMMARY

Ground water and surface water are inextricably linked. Natural processes, human activities, and the geologic framework are all critical factors that are needed to adequately understand the magnitude of the interactions of ground water and surface water. These factors not only influence the quantity and quality of ground-water resources but also have a profound effect on habitat issues and water management.

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Paper No. 2.

Groundwater Resource Management in England & Wales: A Quest for Sustainable Development.

Dr. David Burgess, UK Environmental Agency.

Groundwater Resource Management in England & Wales : a Quest for Sustainable Development.

David Burgess (Environment Agency, Peterborough, England)

Abstract:

The management of groundwater resources in England & Wales was initially based only on measures of the renewable resource. This has been extended to include the need to preserve the springs, river flows surface water levels dependent on groundwater discharges as a key objective of a sustainable management of groundwater resources. The impacts of all new groundwater pumping proposals on the surface water environment are now evaluated using a number of techniques some of which are under further development. The sustainable management of groundwater catchments also includes the control of pumping from existing groundwater sources to meet agreed environmental targets. This approach is illustrated by examples of groundwater catchments managed to augment surface flows, prevent saline intrusion and preserve the integrity of wetland conservation sites

Introduction

Groundwater pumping provides about a third of the public water supplies of England and Wales. The total annual quantity of groundwater abstracted amounts to over 2,300 million m^3 per year. In recent years there has been increasing concern over the impact of groundwater pumping on rivers, springs and wetlands. To accommodate these concerns, the concept of the sustainable management of groundwater resources has evolved as striking a balance between the needs of groundwater users and the long term needs of the water environment.

The Environment Agency controls the abstraction of groundwater by issuing abstraction licences under the Water Resources Act 1991. This, together with the predecessor Water Resources Act 1963, requires the licensing authority to assess the impact of all new pumping proposals on both existing water rights and river flows. This concern for river flows has now been extended to include all aspects of the water environment such as springs, seepages and wetlands. The Environment Act 1995, not only set up the Environment Agency but made it responsible for ensuring the sustainable development of land, air and water.

This paper examines how the concept of sustainable development is increasingly being applied to the management of groundwater resources. It examines first how groundwater resource limits are estimated, the methods used for assessing the impact of new groundwater abstraction proposals on surface waters and the management of groundwater pumping to meet environmental targets.

Defining Groundwater Resource Availability

The rational planning and management of a renewable resource such as groundwater requires measures that state both the current and potential availability of individual aquifer units or groundwater catchments. Within England and Wales, such measures have usually been developed for two purposes. Firstly, as a means of limiting the issue of groundwater abstraction licences to levels that prevent environmental damage or derogation of water rights. Secondly, to produce a measure of groundwater resource availability for water resource planning purposes that is analogous to the yield calculations used for surface reservoirs.

Ideally, groundwater resource estimates are best based on regional numerical models constructed to simulate groundwater flow for the whole catchment or aquifer unit.(e.g. Rushton *et al.* 1989). Such models are necessary to provide an accurate assessment of groundwater yield and in forecasting how different pumping patterns are likely to affect groundwater levels and groundwater discharges. The Agency has a ten year programme for deriving such models for all the major aquifer units of England & Wales. In the interim there remains the need to evaluate groundwater resources at the catchment scale both using the results from existing groundwater models where available, and employing less accurate, simple estimates for those units where groundwater models are not available.

Simple estimates of the renewable resource of a groundwater catchment are usually based on the assumption of steady state or dynamic equilibrium for which the long term recharge to groundwater equals the long term groundwater discharge. In the UK, the first estimates of groundwater resources were derived from the infiltration over a notional recharge area, the infiltration being derived from the long term rainfall minus the actual evaporation with some adjustment for direct surface runoff (e.g. Day 1964). Estimates based on groundwater discharge employed baseflow separation of hydrographs from long term gauging stations (e.g. Ineson & Downing 1965).

Both these methods have limitations. For instance estimates of recharge are reliant on soil moisture accounting techniques which include assumptions about the extent and initial status of soil moisture storage. These assumptions can only be tested at a limited number of sites within England and Wales where regular measurements of soil moisture have been made (Ragab *et al.* 1997). Equally the estimation of groundwater discharge is dependent on the arbitrary methods of baseflow separation from river hydrographs (Gustard *et al.* 1992). The method also requires a flow record free of upstream artificial influences such as sewage treatment works or industrial effluents as well as pumping from surface and groundwater. This restriction severely limits the successful use of baseflow separation techniques in many of the highly developed groundwater catchments of southern England.

Both techniques require some knowledge of the water table in order to define the groundwater catchment that is receiving recharge or contributing to groundwater discharge. The seasonal fluctuation of water tables can make the definition of steady state recharge areas and groundwater catchment boundaries difficult. For example, some Chalk groundwater catchment areas are known to seasonally fluctuate by over 30% (e.g. Gypsy Race, East Yorkshire in Foster & Milton (1976)).

Although such methods define the long term renewable resource, this should not be taken as equating to the sustainable groundwater resource. Allowing an aquifer to be pumped up to the renewable rate will result in widespread lowering of groundwater levels and reductions in spring and river flows as groundwater storage is seasonally depleted. This would result in the derogation of water rights and environmental damage associated with a depletion of springs and flows to wetland conservation sites. It would also result in a reduction of downstream river flows with consequent negative effects on fisheries, river ecology and the yield of water supply intakes (Sophocleous 1997). In coastal areas pumping up to the renewable resource limit results in reverse groundwater table gradients and widespread water quality changes.

Therefore in order for estimates of groundwater resource to be considered sustainable, estimates of the renewable resource must be adjusted downwards by amounts that protect both the existing groundwater users and the environmental features dependent on groundwater. An example of this approach is that taken in planning the groundwater resources for the relatively dry, East Anglian region of England (National River Authority 1994). Over this region and for each groundwater unit the following simple accounting procedure was adopted to estimate the sustainable resource:

(i) The renewable resource was calculated from long term estimates of infiltration, baseflow separation or from groundwater models, where available. The renewable resource was then adjusted to allow for prolonged storage changes during periods of unreliable recharge such as experienced during 1989 to 1991. The extent of this adjustment is currently undergoing further research and development (Environment Agency 1997)

(ii) The amount of groundwater discharge required to maintain both the quality, ecological status and the reliability of river intakes was subtracted from the above renewable resource. The amount of groundwater discharge required to meet low river flows was taken as the 95 percentile from a flow duration curve calculated at a river gauging station nearest to the outfall of the catchment. Where a gauging station did not exist or where records were of insufficient length, the 95% flow was estimated from regression equations based on catchment characteristics (Gustard *et al.* 1992) For aquifers bounding coastal areas a groundwater flow of 0.5 l/s/km flow front was used to estimate the discharge required to prevent the movement inland of salt water.

(iii) The renewable resource is reduced further by the net effect of current abstraction licences to give the sustainable resource as available for further abstraction. The net effect is calculated from a series of rules on how pumping from current groundwater sources depletes river flows and how this is offset by the return of effluents discharged to the rivers for the groundwater catchment in question.

The above procedure has provided a simple and effective method of indicating resource availability. It has also provided an important tool for the control of groundwater abstraction licences or permits. Tables and maps have been drawn up that indicate those groundwater units where existing authorised abstraction amounts exceeds the available resource and groundwater is no longer considered to be available for further abstraction. They also show those groundwater units where resources are still available and where applications for new groundwater licences may be considered.

Methods for Assessing the Local Impact of Groundwater Pumping

It is the policy of the Agency that all new proposals for significant groundwater pumping must be accompanied by a report detailing the likely effect on surrounding groundwater users, springs, rivers and wetlands. Detailed guidance on this procedure and the test pumping of new boreholes is given in the Agency's Water Resources Licensing manual (Environment Agency 1998).

Evaluating and forecasting the likely impact of groundwater pumping on springs and river flows is a requirement for most proposals received for unconfined groundwater units. The methods used range from analytical solutions for the first look at a proposal through to the use of calibrated numerical models when abstraction proposals are likely to produce a significant impact on the water environment.

The main analytical techniques used are based on equations as adapted by Jenkins (1970). In common with other analytical techniques, these equations include a number of restrictive assumptions, the most notable being that the river and borehole fully penetrate the aquifer, the river is the only source of recharge and that the aquifer is isotropic and homogenous. Nevertheless, the techniques provide quick and useful "first pass" estimates of stream depletion used for designing test pumping and as a basis for deciding the need for further investigations. The techniques provide a useful insight into both the time lag between the start of pumping and depletion of river flow as well as the persistence of stream depletion after groundwater pumping has stopped. This can be particularly useful in evaluating the effect of seasonal pumping cycles on river flows associated with spray irrigation licence applications (Wallace *et al.* 1990).

Such analytical techniques can be readily adapted for easy use within spreadsheet computer programs for ease of use by licensing hydrogeologists. Even so the over simplification and idealisation of such simple analytical models should limit their use to the preliminary screening of groundwater proposals and to the design of the duration and observations for test pumping. For most of the aquifers of south east England, where the rivers run on extensive flood plain deposits, the assumptions of a fully penetrating river and isotropic conditions within the analytical solutions could be considered an over simplification and unrealistic.

It is for these reasons that computer programs that use simplified, strip numerical models are also to be included within future methods of evaluation (Sophocleous *et al.* 1995). A long term goal is that such site specific models should be accommodated within calibrated regional numerical models to assess the impact of new groundwater pumping proposals at both the local and catchment scale.

Managing Groundwater Pumping to meet Environmental Targets

While the local impact of individual proposals to pump groundwater are evaluated on a site by site basis, catchment wide development of groundwater resources requires a more integrated and considered approach. The management of groundwater pumping to meet environmental targets such as surface water flows or prevent deterioration in quality remains a key objective for catchment wide schemes for the sustainable development of groundwater resources.

(i) Seasonal Groundwater pumping to augment River flows.

The seasonal pumping of groundwater into rivers to augment lower flows is now a well established pattern of development for many of the aquifers in England & Wales. The effectiveness and efficiency of this type of pumping depends on the lag and attenuation between the start of pumping and depletion of flows already mentioned above. A full account of the theory and methods used for this type of development are given in Downing (1986).

The conventional use of seasonal river augmentation pumping is to increase the yield and reliability of downstream river water supply intakes. A good example of this type of scheme is the Shropshire groundwater scheme on the River Severn, England. The River Severn provides water to several water supply intakes between Shrewsbury and Bristol. These flows are supplemented during most summers by releasing water stored in reservoirs in the headwaters of the river in Wales. However, in exceptionally dry summers such as 1976, 1989 and 1995 the storage in the reservoirs is insufficient to meet both the demands of the river intake and to allow sufficient flow to preserve the rivers environment. Instead, groundwater is pumped into the Severn from the underlying Triassic sandstone aquifer in north Shropshire. Full development of the scheme will provide a downstream yield of 225 Ml/d from up to 70 boreholes pumping into the River Severn for 100 days in exceptionally dry years (Downing 1986).

Increasingly seasonal groundwater pumping is used to augment flows in rivers where traditional direct borehole supplies have depleted river flows to environmentally unacceptable levels. A good example of this type of scheme is that within the Lodes-Granta catchment to the north-east of Cambridge, England. This is an area of some 608 km^2 largely underlain by the mainly unconfined, chalk aquifer. The catchment lies in one of the driest areas of the UK with a mean annual effective rainfall of 140 mm. and frequent summer droughts. As a result local springs and rivers are heavily dependent on groundwater discharges to maintain summer flows into a number of internationally important wetland and spring conservation sites. The underlying Chalk aquifer is also a major source of public water supply. Increased demand of up to 55 Ml/d from 14 sources throughout the 1980s resulted in concern for the integrity of the wetlands and summer flows. The options to resolve this potential conflict were explored using a numerical model (Rushton & Fawthrop 1991) to select a pattern of pumping that met all the local environmental targets for maintaining spring flows and wetlands. This resulted in a scheme that included 6 new boreholes to seasonally pump water to 12 springheads via nearly 40 km of pipeline, finished in 1994. The maximum output of the scheme is 20 Ml/d but has resulted in the groundwater pumping allowed for public supply to be raised to 80 Ml/day.

(ii) Managing Groundwater pumping to Control Saline Intrusion

Saline intrusion has occurred at a limited number of locations in England where Chalk and Triassic sandstone aquifers are over pumped near coastlines and estuaries (Downing 1986). For these aquifers setting the sustainable rate of abstraction requires a knowledge of the rate of recharge, amounts of groundwater pumped and the groundwater flow within the aquifer to prevent or limit the extent of saline intrusion.

Traditionally the sustainable rate of pumping has been set against long term values of groundwater recharge and discharge. However for the north Lincolnshire Chalk aquifer, a more dynamic approach has been adopted. Historically this aquifer has provided a source of relatively cheap water to meet the public water supply and industrial demands of south Humberside. As a result of over pumping in the 1950's a saline intrusion of over 2.5km occurred inland around Grimsby (Gray 1964). The licences to pump groundwater pre-date the rational control and assessment required by the 1963 Water Resource Act. Consequently, the permitted rate of groundwater abstraction still remains at 193 Ml/d, which is about 85% of the long term recharge.

Groundwater investigations over the last 20 years were aimed at the development and calibration of a reliable numerical model for the aquifer unit. This model was originally developed to assess the strategic options for managing the aquifer. However, following the significant groundwater droughts of 1989/92 and 1995/96 its use was extended to include the operational control of groundwater pumping in conjunction with surface water storage. To achieve this, the recharge and groundwater pumping are regularly updated within the model on a 3 monthly basis. The model is then used to forecast the movement of saline water for different combinations of likely recharge and abstraction amounts. The results from these runs are then discussed with the groundwater users to decide the groundwater pumping rates that can be achieved without increased salt concentrations. In this way any shortfall in groundwater source outputs is forecast, agreed and the deficit made up from planned pumping of surface water transfers and storage. As a result during the drought of 1989 to 1992 groundwater pumping from the Chalk aquifer was kept at between 110 Ml/d and 135 Ml/d but with no significant rise in chloride concentrations as measured at key monitoring boreholes (Spink & Watling 1995).

(iii) Relocating Groundwater Pumping Away from Wetland Conservation Sites

The discharge of groundwater to the surface is characterised by either poor land drainage, seepages, springs and ultimately an effluent or gaining river flows. Even in the densely populated, agricultural landscapes that cover the aquifers of England & Wales, some of these features have survived in an isolated, semi-natural or natural state. The ecological value of such wetland sites has been increasingly recognised with many being conserved and protected under National (Wild Life & Countryside Act 1981) and European legislation (EC Habitats & Species Directive (92/43/EC)).

The dispersed nature of these features matched against the widespread demand in borehole sources for both rural water supplies and spray irrigation has resulted in a rising number of cases where groundwater pumping is perceived or has been shown to reduce flows or water levels to neighboring wetlands. For new groundwater pumping proposals likely to affect wetland conservation sites it is common for the sources to either be relocated away from the wetland, or for conditions to limit the effects of pumping to be included within the abstraction licence or the application for a licence to be refused.

Research on the vulnerability of East Anglian wetland conservation sites to groundwater pumping proposals has resulted in a hydrological classification of different wetland types (Lloyd *et al.* 1993) and guidance on impact assessment (Williams *et al.* 1995).

However, evaluating the effects of existing groundwater abstraction licences on neighboring wetlands requires both a detailed hydrogeological investigation to quantify changes in flows or water levels and ecological surveys to evaluate the conservation significance of the changes. These investigations often involve detailed field work both in terms of vegetation surveys and accurate piezometry. Where an adverse effect of groundwater pumping is evident, the Agency has taken steps either to reduce the pumping rate or relocate the borehole source away from the affected wetland (National Rivers Authority 1993).

A good example of this approach is provided at the Redgrave & Lopham Fen in the headwaters of the River Waveney in East Anglia. The Fen is an internationally recognised conservation site, covers nearly 125 hectares and is the largest fen of its type in lowland England. In the late 1950s two public water supply boreholes were drilled into the underlying Chalk aquifer immediately adjacent to the Fen. These supply up to 3.6 Ml/d to surrounding towns and villages. As a result of this pumping the perennial upward and lateral movement of Chalk groundwater was replaced by seasonal downward movement of water from the Fen with summer groundwater heads being 1 metre below Fen level. Test pumping and radial flow modeling suggested that some 26% of the pumped groundwater was at the expense of seepage and spring flow into the Fen. These hydrogeological changes were matched to a deterioration of the flora and fauna at the site (Harding 1993). Following discussions with the water company and English Nature the decision was taken to relocate the groundwater pumping to a borehole 3.5km east of the site and downstream of the Fen. The replacement boreholes have now been drilled and test pumped and will pump groundwater into public water supply during the summer of 1999. The total cost of the replacement supply is in the order of £3.2m and includes the cost of the investigations, source works, pipeline and restoration work on the Fen.

Conclusions

The increasing diversity and sophistication of how groundwater pumping is managed at the catchment scale to meet environmental targets, illustrates well how the concept of sustainable groundwater resource development has evolved in England & Wales. Initial, far sighted legal obligations to consider the effects of groundwater pumping on surface water features such as rivers have now been replaced by a widespread public concern to maintain water levels and flows to preserve the health and ecology of the whole of the water environment. The outcome is that ground and surface water are increasingly planned as a combined resource.

The evaluation of groundwater resources no longer requires one fixed measure of the so called "safe yield" of an aquifer unit, but a range of possible options for future development. In the future, climatic change may result in revisions to groundwater resource estimates. However, of far greater importance is the change in the value that society puts on the different components of groundwater discharge and their importance to preserving the water environment. Thirty years ago wetlands were seen as a challenge to the land drainage engineer. Wetlands are now seen as a necessary part of a sustainable catchment management plan for local communities that value the biological diversity within them.

To adapt to these changing needs , the groundwater managers of the future will have to employ all the skills of numerical computer modeling to be able to evaluate and forecast the options for sustainable groundwater development. They will also require good communication and education skills to be able to gain the necessary consensus as to which of the available options is the one best suited to the environmental and social needs of the groundwater catchment in question.

Acknowledgments

The methods and results described in the paper owe a lot to my colleagues too numerous to mention. However the opinions and views given are those of the author only and are not necessarily those of the Environment Agency.

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Paper No. 3.

Integrated Surface Water and Groundwater Modelling.

Peter Rippon, Mott MacDonald Ltd.

INTEGRATED SURFACE WATER AND GROUNDWATER MODELLING

PETER RIPPON (HYDROGEOLOGIST, MOTT MACDONALD)

ABSTRACT

Groundwater models are now widely used in water resources management in England. Most aquifers are closely linked with river systems to which they contribute baseflows from seepages and springs. As a result, major groundwater abstractions almost inevitably affect river flows. To assess with confidence the effect of utilising groundwater resources, an aquifer and river system has to be linked within an integrated model which can simulate varying hydrogeological conditions throughout the catchment.

In the early 1990's, Mott MacDonald developed an integrated catchment management model (ICMM) for water resources assessments. Details of ICMM, an indication of the methods of model calibration and examples of the application of the model in assessing water resources issues are provided. The integrated modelling approach maximises the use of readily available hydrological and hydrogeological data. It provides the water resources planner with a sound framework and support for decision making.

INTRODUCTION

The integrated catchment management model (ICMM) developed by Mott MacDonald is based on a multi-layered finite difference aquifer model with calculation of seepages from the aquifer to the river (or leakage if the river is perched) and routing of river flows through the catchment. The model has now been applied in more than ten catchment and aquifer studies. Most of these studies have been located in south east England, the driest part of the country, where there is heavy reliance on groundwater resources. Studies include an investigation of the catchment of the River Darent in Kent. The Darent was identified in the early 1990's as the river worst affected by overabstraction in drought periods, in the country. Many of the models are of the Chalk aquifer, with the Lower Greensand also forming an additional important source of groundwater in some catchments such as the Darent. The Sherwood Sandstone, and thick overlying deposits of Boulder Clay and sands & gravels, was modelled for the Wyre catchment study in north west England.

Most of the catchment models have been developed either for the Environment Agency or water companies. However, groundwater models, generally of more limited areas, have also been produced for private abstractors and quarrying companies. Because of the more limited size, these tend not to be fully integrated with river systems but are capable of accurately simulating spring flows.

The size of model areas has varied considerably. Many of the models are of single river catchments, some with two or three tributaries, ranging in size from 100 to 1000 km^2. However, a recent commission for Three Valleys Water is for a regional model which extends over nearly 4 000 km^2 to the north of London and into East Anglia. This covers all the main river systems in the water company resources area, as well as the upper catchments of several other rivers. The intention is that the model will form the basis for improved management of groundwater resources from the Chalk aquifer, particularly in drought conditions. Insights into the aquifer system, gained from regional model results, could be used in the development of sub-models of critical catchments or sub-catchments within the resources area which require more detailed study. The regional model and any sub-models would be linked through common aquifer geometry and simulated groundwater flows at the sub-model boundaries.

OUTLINE OF THE MODEL

The model, used for simulation is based on the integrated finite difference method (IFDM). The IFDM approach involves the conversion of differential equations describing groundwater flow into water balance equations of the polygons of a model grid network. Polygons can be varied in size, shape and orientation to fit local details and physical characteristics of the modelled system.

A further basic feature of the model is the resolution of three-dimensional groundwater flow into horizontal and vertical components. As the horizontal dimensions of the aquifer system are large in comparison with its thickness, it is reasonable to assume that all flow within a permeable layer is horizontal. Transfer of water between aquifers is assumed to be vertical and is represented by a leakage mechanism across an aquitard or interface separating the aquifers.

River elements are incorporated between adjacent groundwater polygons. At each of these elements a volume difference between water entering and leaving the element is balanced by a loss or gain to the aquifer system. A leakage mechanism is introduced where the river flows across alluvium. The volume transfer between the river and the aquifer system is fully integrated within the catchment model.

Recharge to the aquifer system is evaluated separately using either a modified version of the Stanford watershed model or the Penman Grindley method of calculation. The Stanford watershed model is a lumped parameter model simulating flow through the root zone and unsaturated zone to the aquifer system, and also direct overland flows and interflow to the river. Penman Grindley is widely used to assess soil moisture balances and percolation through the root zone.

Input data for recharge calculation include daily rainfall and weekly potential evapotranspiration. Through calibration of the Stanford model at gauging stations, recharge can be evaluated for each gauged subcatchment. For the integrated catchment management model, the recharge evaluated by the Stanford model is distributed across each subcatchment, taking into account such factors as surface geology and rainfall distribution. The accuracy of percolation data produced by the Penman Grindley method can be assessed approximately by undertaking annual water balances for the catchment.

CALIBRATION OF ICMM

The integrated catchment management model is calibrated mainly by variation of input parameters describing aquifer and river properties until a reasonable match is obtained between model results and observed historical river flows and groundwater levels. Once an acceptable match between simulated and observed data has been achieved, the model can be used to predict the effects of catchment management practices.

The success of a model is dependent upon the accuracy of model calibration. Calibration is normally carried out against three criteria: river flows at permanent gauging sites, river flow accretion profiles and groundwater piezometry. The level of accuracy of calibration is dependent upon the data availability and the objectives of the model. Normally, however, calibrations are accepted when the flow balances at gauging stations are within 5% of observed, and the correct seasonal variations in river flows and groundwater levels have been achieved.

The correct long term volume balance at the gauging stations is often achieved fairly quickly. However, simulating the correct seasonal variations in both groundwater levels and river flows is more problematical. For example, it is often possible to simulate winter peaks and summer low flows in a Chalk fed river system by adopting a very low specific yield value for Chalk (<0.5%). However groundwater level fluctuations are correspondingly over simulated. This problem has been resolved by adopting a non-linear transmissivity distribution, simulating very high transmissivities at the end of winter and extremely low transmissivities at the end of droughts. A non-linear transmissivity distribution can be incorporated using one of two methods: by using depth-dependent permeability with the highest permeability positioned within the normal range of groundwater fluctuations; or by dividing the Chalk into two layers, a 'fissure layer' with very high permeability overlying a 'rock' layer with low permeability. The latter method was used in a model of the Thetford area in East Anglia and is being adopted in the regional model for Three Valleys Water.

Generally model transient simulations are undertaken for a historical period of ten to twenty-five years using monthly timesteps. However, timesteps of shorter duration are possible. Timesteps of five days duration have been used to simulate periods of long term test pumping and also to simulate variations in levels in lakes fed by groundwater in the River Darent project.

Examples of the accuracy of model calibration are given in Figures 1 to 5, taken from the River Darent project. A reasonable simulation of river flows was obtained at the main gauging station for the catchment model (Figure 1) and very accurate simulation obtained from a sub-model of the main Chalk valley (Figure 2). Some reasonable simulations of flow profiles along the river and accurate simulations of lake levels were also produced (Figure 3 and 4) using the sub-model. Variations in groundwater levels in observation boreholes are often subject to localised groundwater conditions. Nonetheless, reasonably accurate simulations were possible for many boreholes as evidenced by Figure 5. The overall difference in level, present throughout the hydrographs in Figure 5, results from a slight difference in location between the observation borehole and the centre of the corresponding model grid cell.

WATER RESOURCES MANAGEMENT

Once calibrated, models can be used to assess water resources issues such as:

- the impact of historical groundwater abstractions on river flows, particularly during droughts, and the level of naturalised flows without any abstraction;
- the impact of groundwater abstractions if increased to the full licensed rates, and any proposed changes in groundwater abstraction licences;
- management of groundwater abstraction to minimise the impact on river flows;
- the effectiveness of channel lining or flow augmentation from river support boreholes in improving low flows during droughts;
- the likely extent of dewatering necessary in areas where quarrying is required below the water table, and the impact of quarrying on water resources and abstractors;

- the impact of landfill on groundwater levels and groundwater capture zones;
- Potential impacts of climate change or changes in land use.

Models and sub-models have also been used to assess the impacts of abstraction and droughts on spring flows and lakes fed by groundwater. All these assessments are best undertaken in an assessment of the resource system as a whole, as provided by the application of an integrated surface water and groundwater model.

RIVER DARENT

Following the development and calibration of the Darent catchment model in the early 1990's, the model was used to:

- assist in setting up acceptable minimum target flows for the river;
- determine at which groundwater pumping stations a reduction in abstraction would be most efficient in terms of restoring flows to the river;
- assess the efficiency of a proposed river support boreholes scheme.

Target flows were determined using a combination of environmental surveys and analysis of naturalised flows produced by model simulation. A series of model runs were used to assess the impact of abstraction from different pumping stations in the Lower Greensand and the Chalk. Contrary to previous opinion, modelling indicated that a major reduction in abstraction from the Lower Greensand in the upper catchment would be more beneficial than an equivalent reduction from the Chalk along the mid and lower reaches of the river. Simulations were also undertaken to determine an approximate spacing along the river for river support boreholes. As a result, an action plan has been implemented by the Environment Agency and Thames Water Utilities (the largest single abstractor in the catchment), combining major reductions in abstraction from the Lower Greensand, reduction in Chalk abstraction and implementation of a river support scheme.

The various components of the action plan were implemented in the years 1994 to 1997. The response time for improvements in river flow as a result of reduction in Lower Greensand abstraction should be up to two years. With the natural variation in flows occurring in the river, no clear evidence of an improvement would be expected as yet. Nonetheless, flows in the upper catchment appeared to be higher in a drought in 1997 than in similar drought years in the early 1990's. Trials in 1996, using up to five river support boreholes, indicated considerable improvements in flow in the middle reaches of the catchment.

A further phase of modelling, undertaken in 1997, was used to develop a sub-model of the mid catchment Chalk reaches of the river. The sub-model is being used, amongst other things, to assess in detail the impact of pumping on fishing lakes and any requirements for support of lake levels in drought periods. The catchment model and sub-model have now been transferred to the Environment Agency and training provided in their use.

THETFORD AREA OF EAST ANGLIA

Modelling was undertaken for Cambridge Water Company which is developing new abstraction sites in the Chalk to the east of Cambridge. A major issue in this area is the impact of abstraction on the Thetford meres, a number of shallow groundwater fed lakes with considerable conservation interest. The meres dry out naturally during drought periods.

Initial modelling indicated that there was unlikely to be any significant impact on the meres as a result of long term abstraction. A steep gradient in the water table between the abstraction sites and the meres indicated a partial barrier to groundwater flow.

Trial pumping in 1994, over a three month period in the autumn, prior to the onset of aquifer recharge, indicated no drawdown in the meres area. Further modelling, updated to include the test period, gave additional confidence in the original conclusion that pumping would have little if any impact on the meres.

FYLDE AQUIFER

Modelling highlighted the importance of percolation through thick, saturated Drift deposits overlying the Sherwood sandstone aquifer, rather than inflow to the aquifer from adjoining formations. Increasing abstraction was found to produce increased percolation which could then lead to leakage from rivers and a low lying SSSI wetland. Modelling confirmed a need for careful management of the resources in the aquifer. ICMM was transferred to the Client (the Environment Agency) for regular updating and use in water resources management.

Model results were used successfully to support the Environment Agency in a public hearing concerning the Agency's refusal to grant permission for a new abstraction licence in the Preston area.

DISCUSSION

The above examples briefly indicate the use of ICMM in water resources management. In many cases, models are best developed in stages. An initial modelling exercise is quite likely to lead to a need for further data collection in certain areas. The modelling, however, assists greatly in identifying these areas and the extent of the investigations required. Once calibrated, models can be used with confidence to predict the impacts of droughts and abstractions or other developments on the aquifer.

Most catchment models have been calibrated using substantial quantities of hydrological and hydrogeological data. However, where few data are available, models can still be used as part of a useful initial appraisal. They can be helpful in assessing critical areas for further investigation or data collection and also whether particular resource management proposals are worth pursuing. For example, a very approximate model was used for an area in East Anglia to assess a possible range of impacts on spring flows in moving an abstraction from one source to another nearby. Approximate models have also been used to assess the likely extent of quarry dewatering and possible impacts on stream flows and existing groundwater abstractions in the quarry area.

Figure 1
Simulation of Flows at Hawley

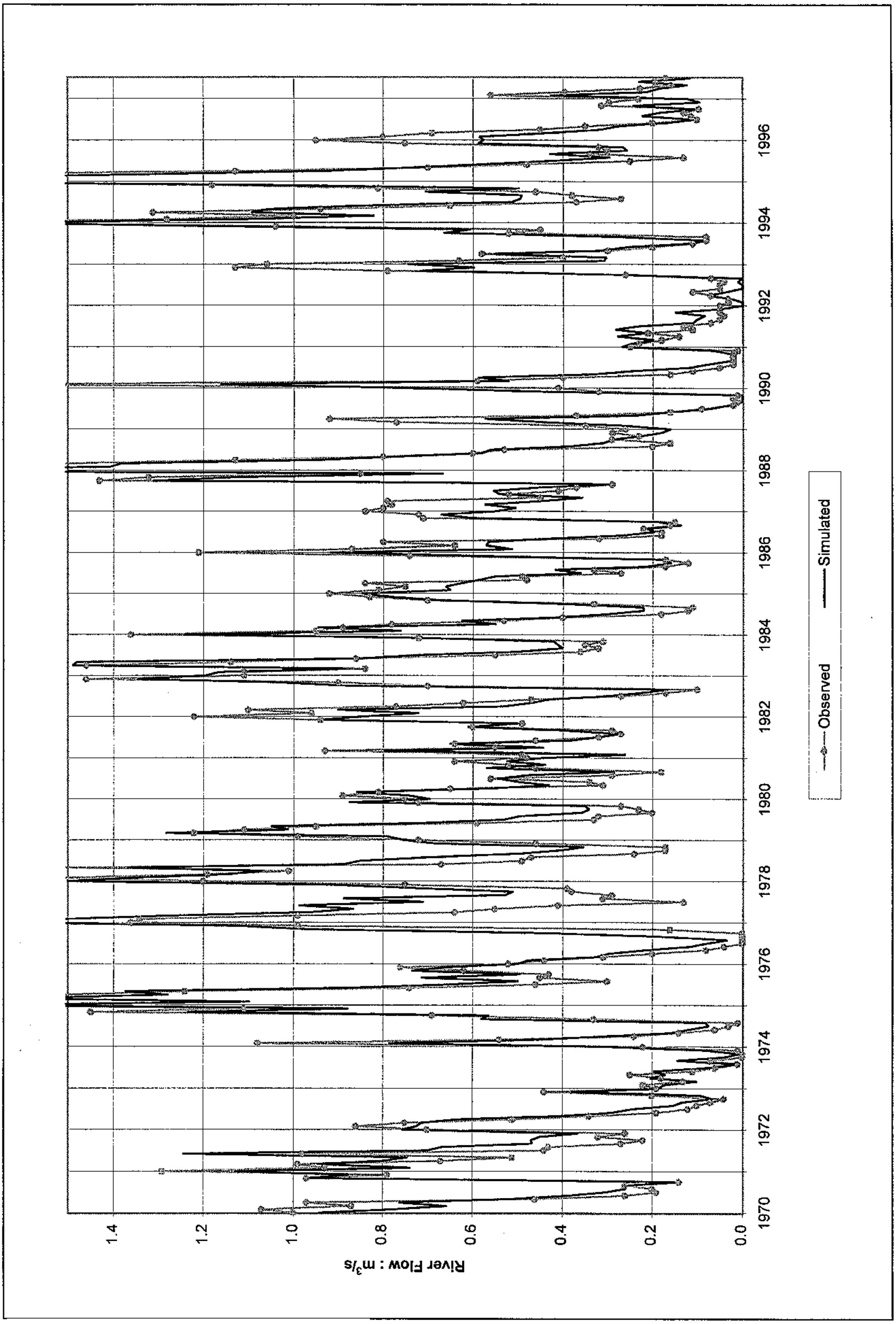

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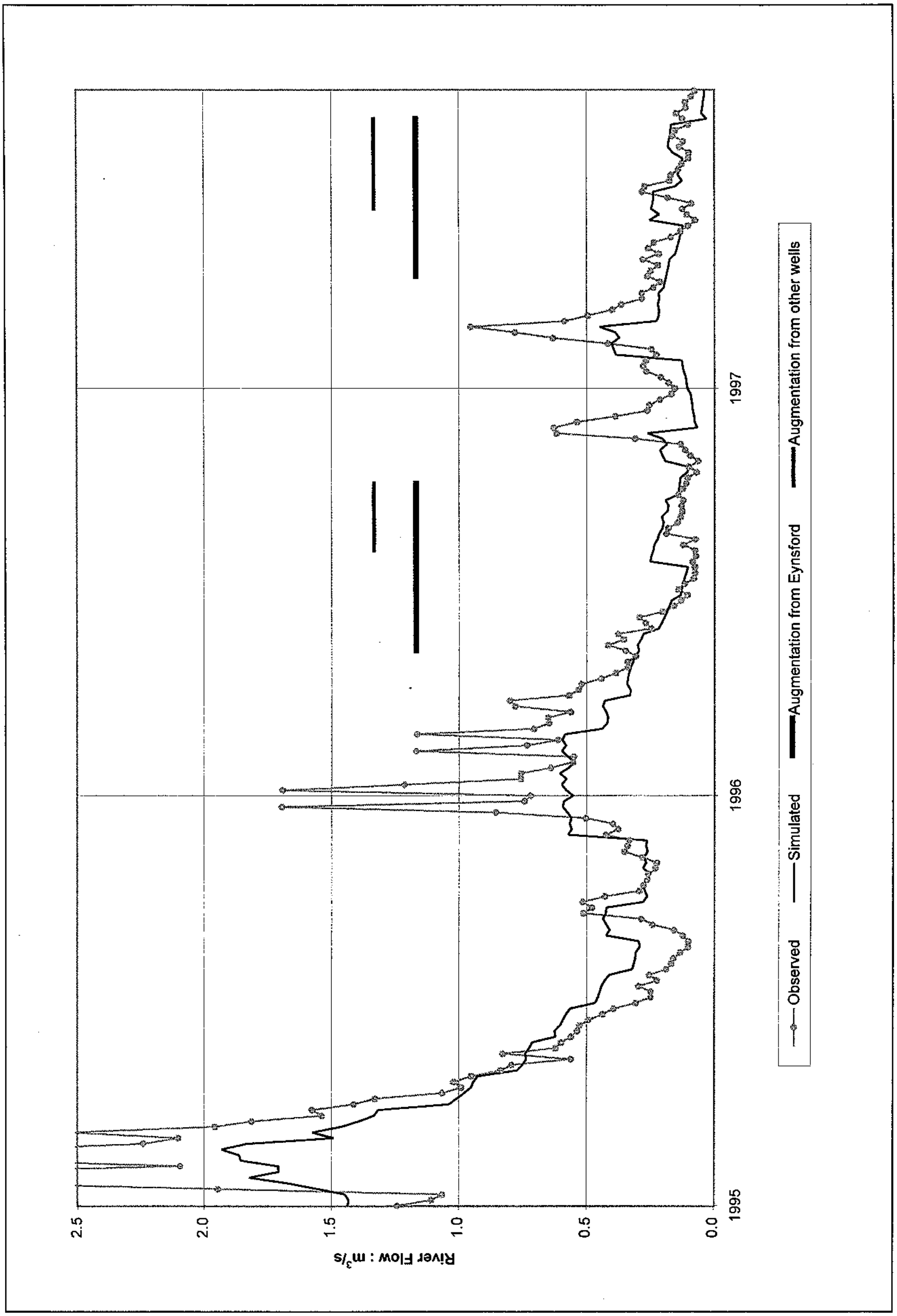
Figure 2

Simulation of Flows at Hawley with a 5 day Timestep



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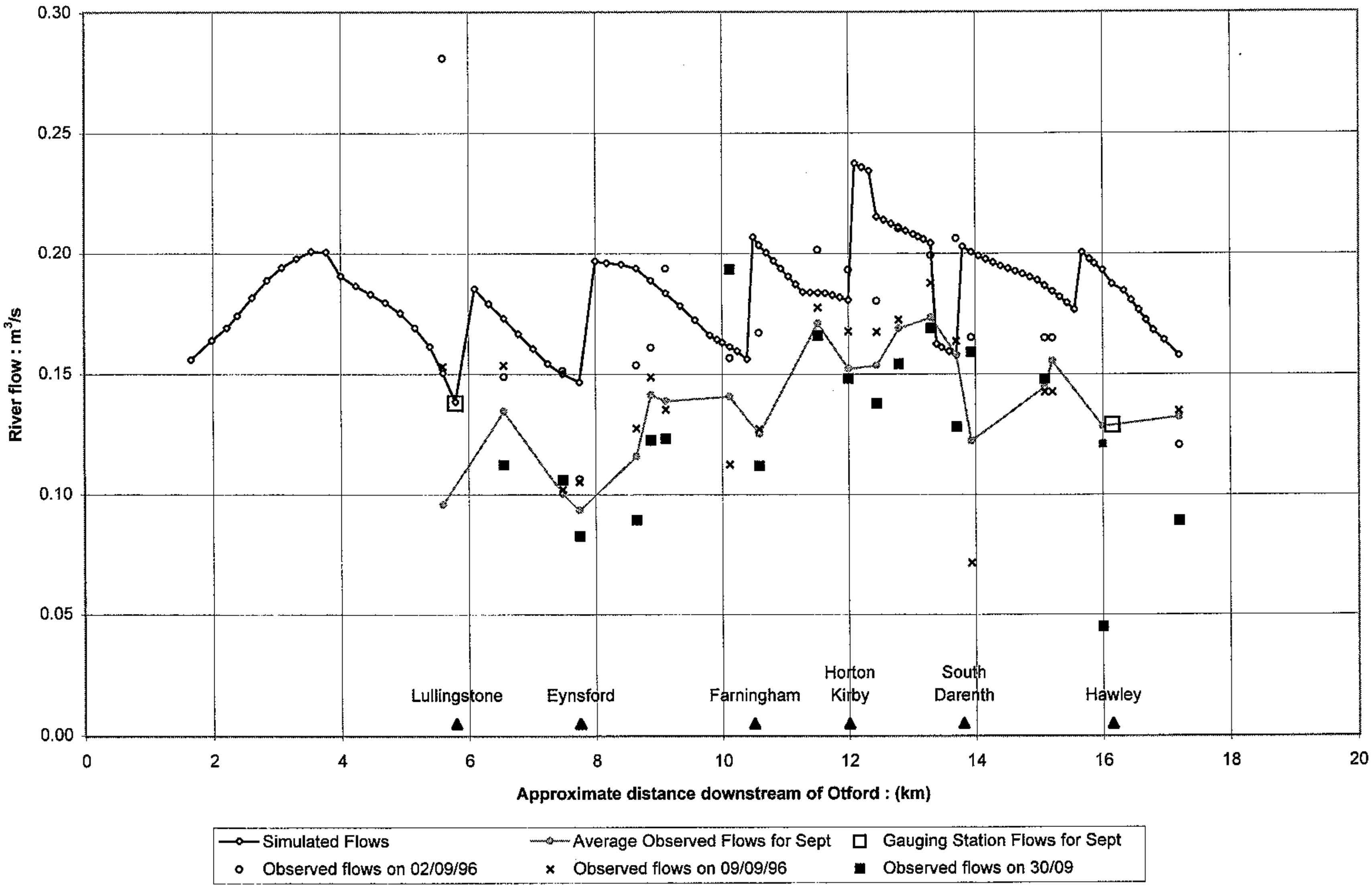
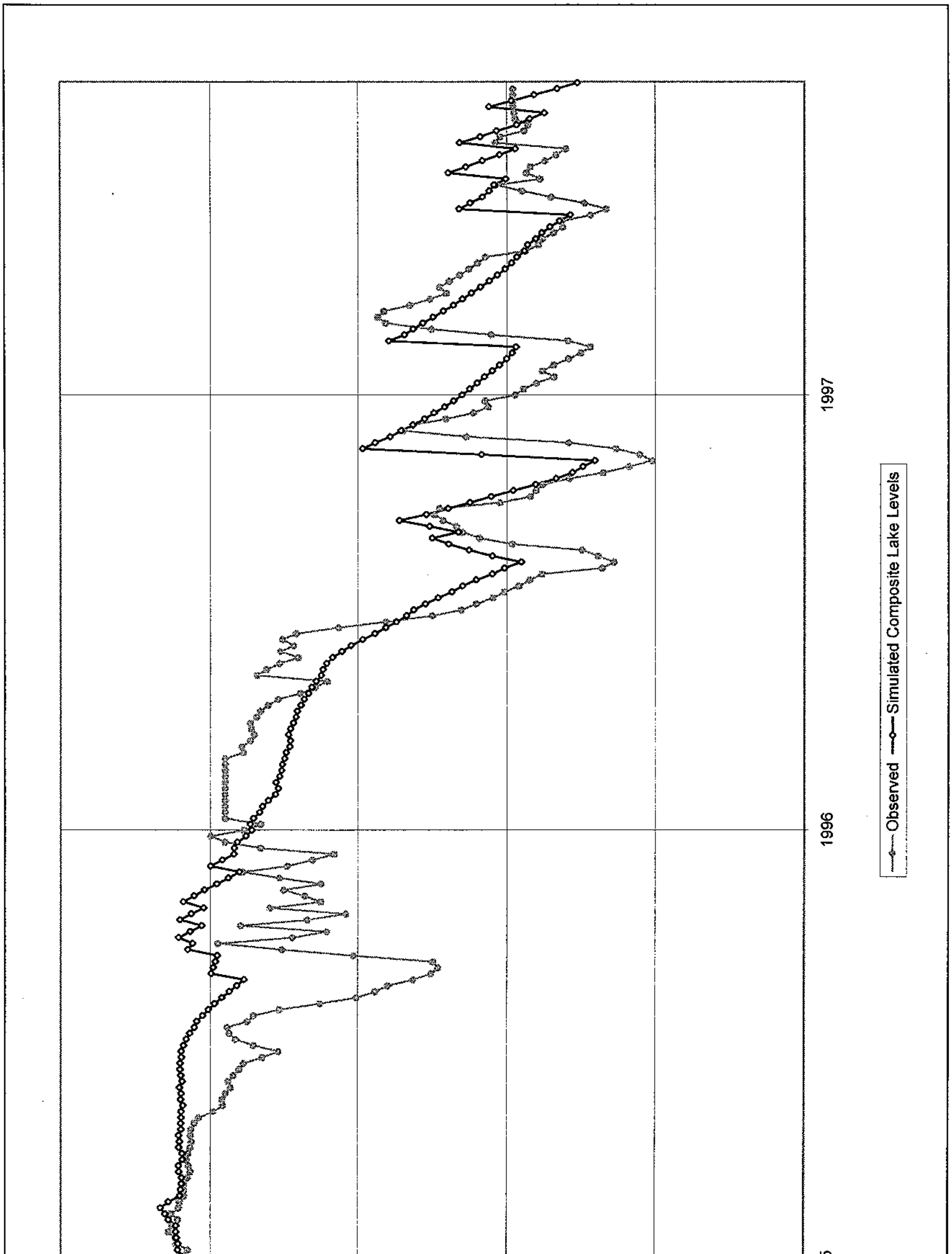


Figure 3
Simulation of Flow Profile for September 1996

Figure 4

Simulation of Lake Levels at Horton Kirby



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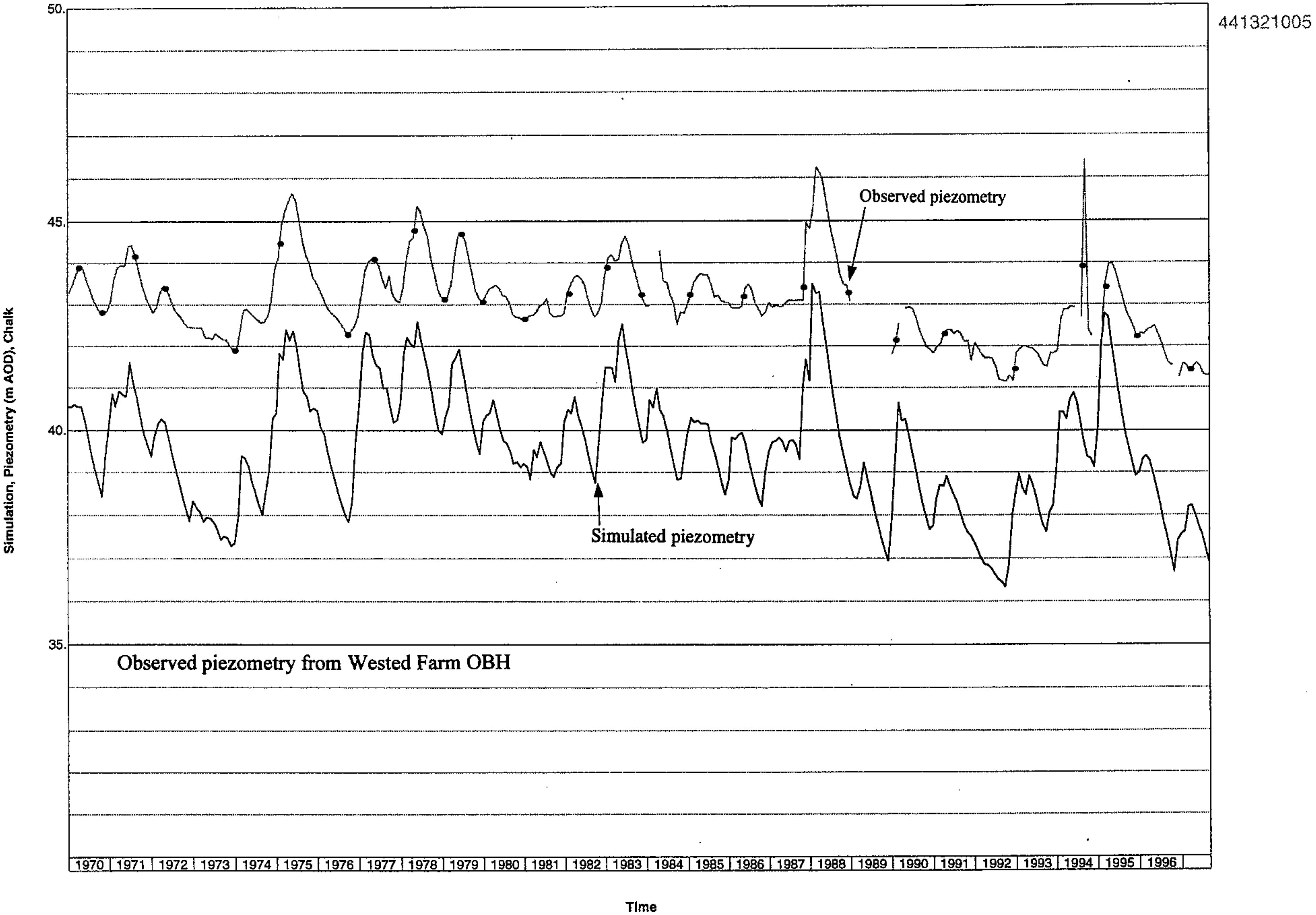

Figure 5

Simulated and Observed Chalk Groundwater Levels, Darent Interfluve

Paper No. 4.

*Nitrates in County Offaly.

Des Page & Jack Keyes, Offaly County Council.

*This paper was not available at the time of print and is therefore not bound in these proceedings. The paper was distributed separately during the seminar.

Paper No. 5.

Groundwater & Surface Water: Exploiting a Combined Resource.

Bruce Misstear, Trinity College Dublin.

GROUNDWATER AND SURFACE WATER: EXPLOITING A COMBINED RESOURCE

Bruce D. Misstear
Department of Civil, Structural & Environmental Engineering, Trinity College Dublin

ABSTRACT

This paper reviews the various types of scheme available for the combined use of groundwater and surface water. The schemes considered include bankside wells, artificial recharge involving aquifer storage and recovery (ASR), artificial recharge by small dams, infiltration galleries in riverbeds or along riverbanks, and river augmentation from groundwater. Of these, bankside wells (which may involve infiltration galleries) are probably of most relevance to Ireland, and the paper ends with a discussion of the key issues for the planning and design of such schemes.

INTRODUCTION

Exploiting groundwater and surface water resources as a combined resource may be achieved through many different types of scheme, including:

- bankside wells;
- artificial groundwater recharge;
- infiltration galleries;
- river augmentation.

Some of these, such as artificial recharge and river augmentation, come under the heading of conjunctive use schemes. The conjunctive use of surface water and groundwater can be defined as 'the management of surface (water) and groundwater resources in a coordinated operation to the end that the total yield of such a system over a period of years exceeds the sum of the yields of the separate components of the system resulting from an uncoordinated operation' (Coe, 1990). There are therefore potential benefits in terms of total yield, reliability of supply and cost.

The various types of combined use scheme are described below, with examples from different parts of the world. The main objective of the paper is to highlight the key issues in the planning of each type of scheme.

BANKSIDE WELLS

Bankside well schemes involve the abstraction of (mainly) river water via wells located close to the riverbank. Two major examples are described below, the Káraný scheme in the Czech Republic and the Spey scheme in Scotland

The Káraný waterworks is located near the confluence of the Labe (Elbe) and Jizera rivers, about 25 km northeast of Prague (Figure 1). The raw water supply is obtained from a series of wellfields constructed in Quaternary alluvium. The scheme was constructed in two phases. The first phase was designed by the famous – at least to hydrogeologists - G. A. Thiem, and involved some 684 wells located along a 20 km reach of the Jizera river (Clark *et al.*, 1992 and Knezék and Kubala, 1994). The wells are sited between 50 m and 200 m from the river, and are up to 15 m deep.

The second scheme at Káraný was added between 1965 and 1968, partly in response to a decline in river water owing to both agricultural and industrial pollution. This second scheme includes an artificial recharge component. Raw water is taken from a river intake, pumped to a pretreatment plant and then recharged to the alluvial aquifer via infiltration basins (Figure 2). There are 15 infiltration basins, each approximately 30 m in width and 200 m long. The infiltration water is treated with algicide where necessary. The scheme is designed to provide a 30-day underground retention time, and the recharged water is abstracted by a series of shallow wells and deeper Ranney wells. The total yield of the Káraný scheme is about 180,000 m^3/d.

An aquifer protection policy has been introduced to protect the wellfield against pollution. Under this policy, the Jizera catchment is classified into a number of protection zones, ranging from an inner zone surrounding the infiltration basins, in which no developments are permitted, to an outer zone covering the whole catchment and in which, for example, there are restrictions on effluent discharges. Of concern, however, are the sources of pollution that pre-date the protection policy – such as the former military base at Milovice, which is located within the Jizera catchment, about 10 km northeast of the Káraný waterworks.

The Spey bankside wellfield was developed in the early 1990s to supply the Lower Moray region and Banff coastal area of northeast Scotland. The scheme was designed by Mott MacDonald for the Grampian Regional Council. The wellfield is located along a 3 km stretch of the left bank of the Spey, upstream of Fochabers (see Figure 3). The wellfield comprises 36 wells (including 4 standby) and has a maximum design yield of 27,000 m^3/d. This represents only about 3 % of the 1 in 50 year low flow in the river (Watt *et al.*, 1986). The wells abstract from an alluvial sand and gravel aquifer, up to 15 m thick, that overlies Old Red Sandstone bedrock. The current wellfield abstraction is about 15,000 m^3/d (Jones *et al.*, 1997).

A major reason for choosing a bankside well scheme rather than a direct river intake was that water pumped via the alluvium was found to have significantly reduced colour levels compared to river water. Investigations showed this colour removal to be associated with microbial action in the gravels (Watt *et al.*, 1986). An understanding of the colour removal process was important in selecting the optimum distance of the wellfield from the river. Increasing the distance would increase the opportunity for the colour removal processes to take place. However, the impacts of the wellfield on agriculture also would increase, as the water level drawdown during pumping would increase away from the river, thus potentially reducing the capillary contribution of groundwater to the root zone. A further factor that needed to be considered was the impact on fish of noise levels from borehole pumps located close to the river. After detailed investigations of these and other factors, the wells were located about 50 m from the river.

Measures to protect the Spey scheme from pollution include:

- purchase of land and the introduction of restrictions on farming practices close to the wellfield;
- installation of a pollution monitor in the river about 8 km upstream of the wellfield;
- incorporation of a backflushing system in the wellfield design.

The objective of the backflushing system is to reduce the risk of pollution from the river entering the aquifer. It would operate once pollution has been detected in the river by the pollution monitor located upstream of the wellfield. After pollution has been detected, the well pumps would be shutdown, and the backflushing system would operate by the release of water from a 9,000 m^3 capacity raw water reservoir back to the wellfield, and down into the wells. This would raise groundwater levels, such that the pollutants do not enter, or at least are flushed out of, the aquifer. The system was tested successfully during lengthy trials in 1996 (Jones *et al.*, 1997).

Some recent modelling work by the University of Aberdeen has delineated potential groundwater protection zones around the wellfield (Chen *et al.*, 1997). The model packages MODFLOW and

MODPATH were used for this analysis. The model simulations show that river water accounts for 69% and 74% of the total abstraction under current and design yields respectively. These results confirm that the main pollution threat to the wellfield is from the River Spey. The results also confirm that there is a need to control land-based sources of pollution: the capture zone analysis shows that the area in which farming practices have been imposed is conservative.

The author is not aware of any major bankside well schemes in Ireland. However, there are a number of cases where wells located in alluvial or fluvio-glacial deposits take part of their supply from the nearby river. In addition, there are several small water supply schemes involving infiltration galleries along river valleys, as noted later in this paper.

ARTIFICIAL RECHARGE

The infiltration basins included in the Káraný waterworks are an example of one type of artificial recharge scheme. Other types are:

- aquifer storage and recovery;
- groundwater recharge dams.

AQUIFER STORAGE AND RECOVERY

Aquifer storage and recovery (ASR) may be defined as 'the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed' (Pyne, 1995). ASR schemes normally involve recharge of surface water to the aquifer in winter when river flows are high, and re-abstraction of the water from the aquifer in summer when river flows are low. Dual purpose abstraction-recharge wells are often used.

The main development of the ASR concept has taken place in the USA, where there are currently 27 operational schemes (Jones *et al.*, 1998). Many of these schemes are constructed in sand and gravel aquifers. One such scheme is in the Las Vegas valley in Nevada. Here, intensive groundwater abstractions in the last 50 years have lead to declines in groundwater level of up to 60 m (Johnson *et al.*, 1998). An ASR scheme was implemented in 1988, whereby treated surface water from Lake Mead is recharged into the alluvial aquifer from October to May. The wells are then pumped mainly during the peak demand summer period. The permitting system is such that the recharge water is effectively 'banked' for future abstraction.

One major ASR scheme has been implemented in Britain. This is the Enfield-Haringey and Lea Valley scheme in north London, which is operated by Thames Water (O'Shea *et al.*, 1995). This makes use of the available storage in the Chalk aquifer and the overlying 'Basal Sands' aquifer resulting from long-term groundwater abstractions in the region. An interesting feature of this scheme is that the re-abstracted water in the Enfield-Haringey area is used to augment flows in the New River, before being re-treated and put into supply.

Owing to several dry summers in the 1990s, and consequent pressures on resources, several other UK water companies are now investigating the feasibility of ASR schemes. In the Anglian area, recent field trials have highlighted the problem that cost-effective development of ASR in the major Chalk aquifer is partly inhibited by diffusion exchange processes between the matrix and the fissures, which lead to a decline in the quality of the recharge water (Cook and Moncaster, 1998). As well as quality changes in the recharge water, other important issues in considering ASR are:

- injection rates;
- recovery rates;

- aquifer properties, including available storage;
- clogging of the wells.

The British Geological Survey has recently carried out a review of the ASR potential in England and Wales (Jones *et al.*, 1998). Perhaps of most relevance to Ireland, the review concludes that Carboniferous Limestone is generally unsuitable for ASR. Reasons given include the unpredictable nature of the aquifer properties and the unpredictable well yields. A further issue in Ireland is that many of the aquifers may be effectively 'full' during the winter months, when natural groundwater recharge is rejected.

RECHARGE DAMS

Small dams are often used in arid zones to enhance the groundwater recharge from surface flows. In Oman, for example, 15 such dams have been constructed since the early 1980s (Al Muqbali and Schmid, 1995). These dams are designed to hold back a proportion of the flood flow that would otherwise be lost to the sea or to the salt pans in the desert interior. They therefore provide a degree of flood protection as well as groundwater recharge. The water stored behind the dam is released slowly for infiltration into the wadi channel downstream of the dam. The dams are generally constructed as earth embankments with over-toppable spillway sections. Important issues in the planning of such schemes are:

- the potential additional resource that will be provided by the dam;
- impacts on water users further along the wadi system;
- hydrological uncertainties in arid regions, and their implications for design (e.g. peak flood for spillway design);
- evaporation losses;
- sedimentation and hence maintenance of the reservoir;
- infiltration capacity of the wadi gravel aquifer;
- available groundwater storage in the wadi gravel aquifer;
- availability of local materials for dam construction.

With respect of the first issue, various consultancy studies in Oman have indicated that the additional resource provided by these dams is often relatively small (these studies are summarised in Mohsin *et al.*, 1995).

INFILTRATION GALLERIES

Infiltration galleries are horizontal wells that collect water over almost their entire lengths. They are particularly suited to exploiting thin aquifers in river beds or along river banks. There are several small water supply schemes in Ireland based on infiltration galleries. An infiltration gallery along the Upper Dinin river north of Castlecomer, for example, reportedly supplies about 900 m^3/d to a regional water supply scheme (Misstear *et al.*, 1980). Daly (1988, 1989) has reviewed the suitability of infiltration galleries for Irish hydrogeological conditions. Daly pointed out that most of the water abstracted has a groundwater origin. However, infiltration galleries can also be used to abstract mainly river water as part of a bankside well scheme where the aquifer is unsuitable for conventional wells. When designing and operating an infiltration gallery, important issues include:

- vulnerability of shallow infiltration galleries to pollution, and hence the need for appropriate source protection measures;
- clogging of the horizontal screen owing to low water entry velocities, and hence the need for regular maintenance.

A special type of infiltration gallery developed in the arid regions of Southwest Asia and the Middle East is the falaj (plural aflaj, Arabic) or qanat (Persian). Whereas a conventional infiltration gallery drains to a sump, from where the water is pumped into supply, the falaj system supplies water to the point of demand entirely by gravity. Many of the aflaj in Oman are hundreds of years old and have underground sections many kilometres in length; they thus represent remarkable historical examples of surface water and groundwater exploitation.

RIVER AUGMENTATION

There are several schemes involving the augmentation of river water from groundwater in Britain, but none in Ireland that the author is aware of. Some of the British schemes are proper conjunctive use schemes in which groundwater is used to regulate river flows in dry periods so that surface water abstractions downstream can be maintained. The rivers Severn (in Shropshire), Fylde (in Lancashire) and Lambourn (in Berkshire) all have examples of this type of conjunctive use scheme (Shaw, 1994, Downing, 1998).

A second type of scheme involves the use of groundwater to augment low river flows in dry periods with the primary aim of maintaining (or restoring) the environmental quality of the river. The river Darent in Kent has been the subject of detailed investigations into this type of river augmentation (Rippon and Wyness, 1994, Rippon, 1999).

DISCUSSION

The main types of scheme for the combined use of groundwater and surface water have been reviewed in this paper. Perhaps of most relevance to Ireland is the potential for bankside well schemes, using either conventional vertical wells or infiltration galleries, depending on the hydrogeology. Key issues in the planning of such schemes are:

1. The thickness, lateral extent, permeability and storage characteristics of the river alluvium.
2. The extent of hydraulic connection between the aquifer and the river, taking into account the hydraulic gradients at different times of year, and the presence or absence of low permeability stream bed deposits.
3. The impact of aquifer abstractions on river flows, especially during periods of low flow.
4. The impact of aquifer abstractions on riparian agriculture.
5. The comparative quality of the groundwater and river water, and the impacts on quality of pumping from a bankside wellfield.
6. The degree of 'pretreatment' resulting from the flow of the river water through the alluvial aquifer.
7. Potential sources of pollution to the wellfield, including pollution from the river and from land-based activities.
8. The need for a protection scheme covering the risks to both surface water and groundwater.
9. The need for a monitoring programme of both surface water and groundwater.
10. A maintenance programme for the wells; this is especially important where infiltration galleries are being considered.

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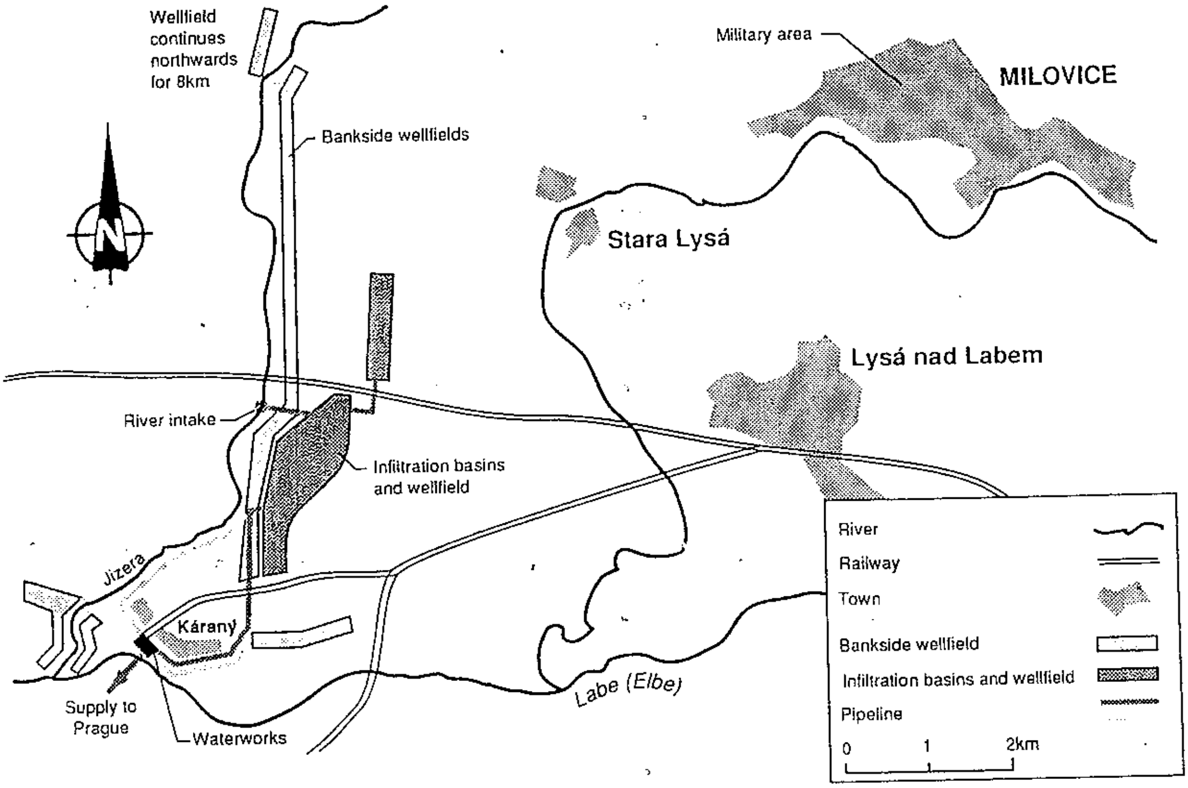


Figure 1 Location of the Kárany bankside wellfields, Czech Republic

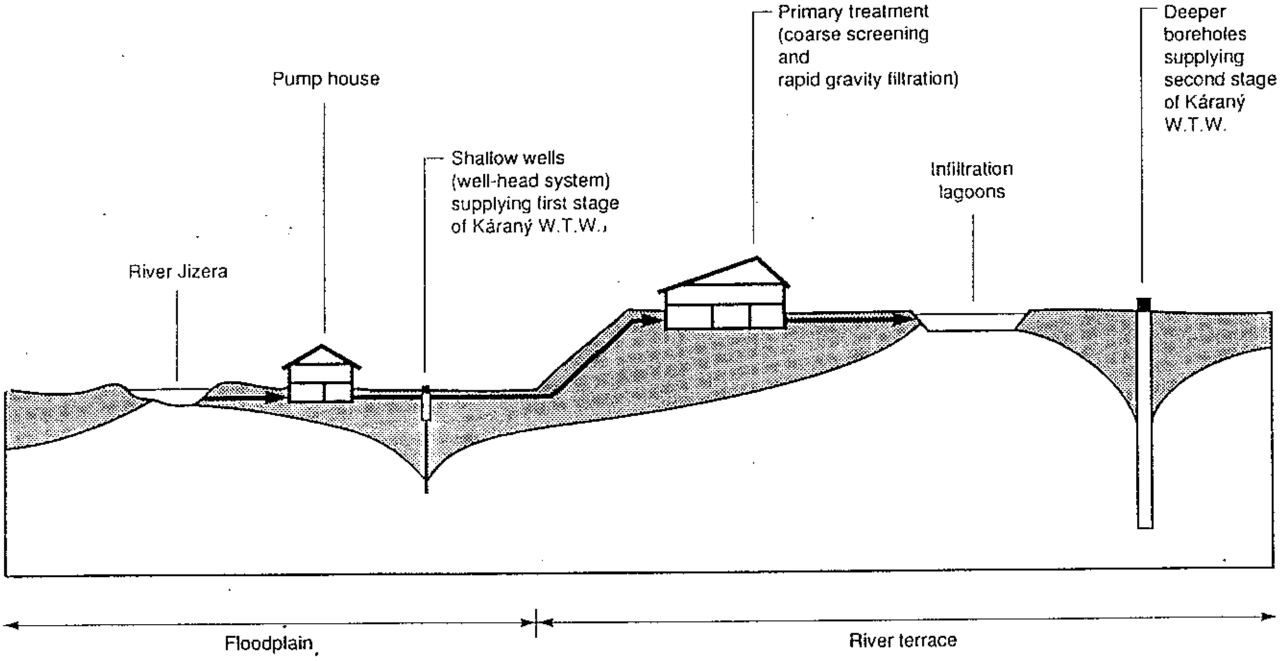


Figure 2 Schematic section showing the bankside wells and infiltration basins at Kárany (From Clark *et al.*, 1992)

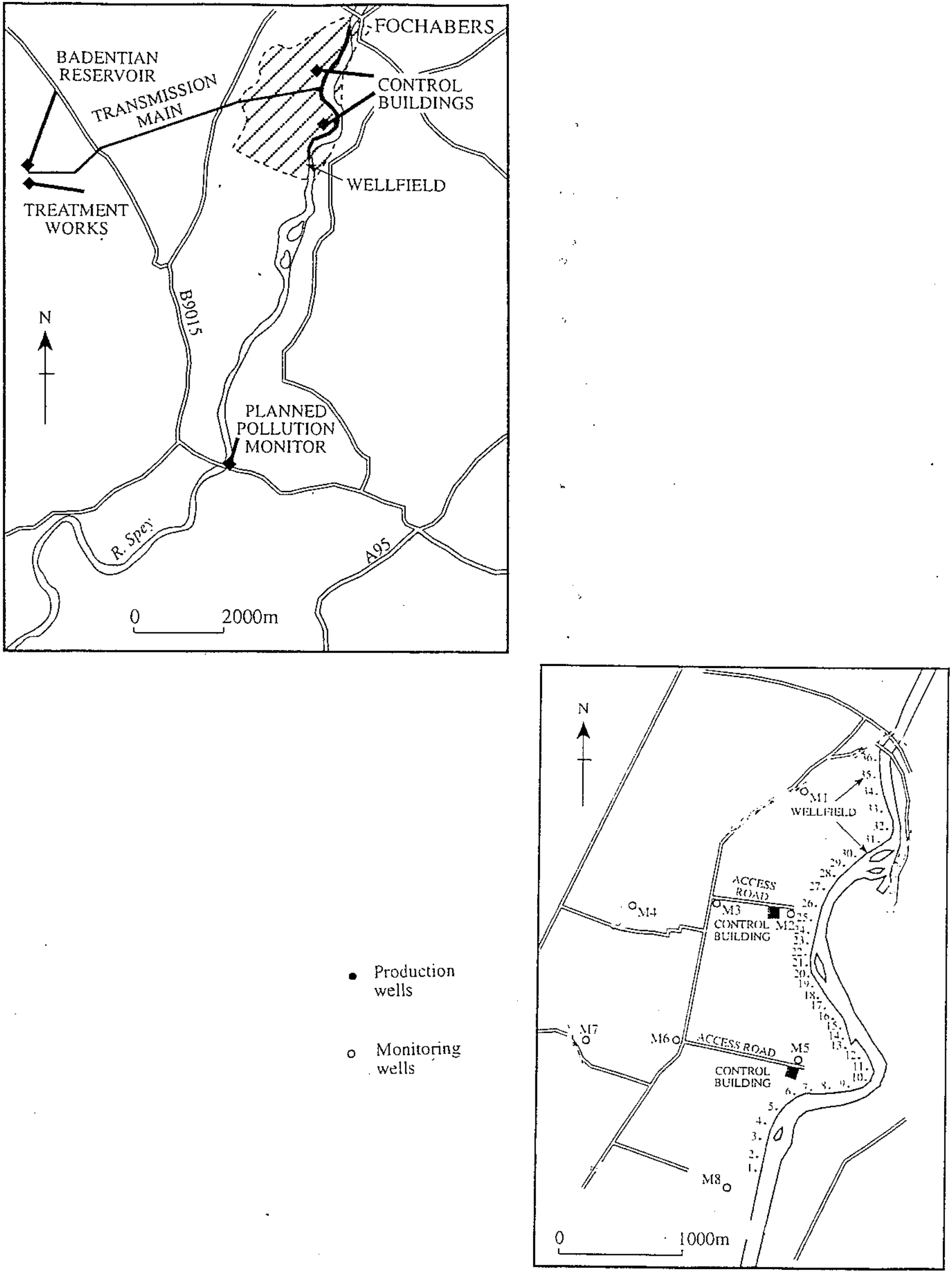


Figure 3 The Spey bankside wellfield, Scotland
(Adapted from Chen *et al.*, 1997 and Mott MacDonald)

Paper No. 6.

Water Quality Management Planning.

Andy Fanning, Environmental Protection Agency.

Water Quality Management Planning (Past, Present and Future)

Andy Fanning & Dr. Matthew Crowe
Environmental Management and Planning Division, Environmental Protection Agency

ABSTRACT

To date, water quality management planning has been restricted to the management of surface water; groundwater protection being addressed separately through the preparation of groundwater protection schemes. While these methodologies have different approaches they do share the same general objectives.

Recent developments in national policy show a definite move towards the revitalisation of water resource management. The draft EU Water Framework Directive, if adopted, will have major implications for water quality management planning in Ireland as its overall objective is to establish a framework for the protection and improvement of surface waters, estuaries, coastal waters and groundwater with the aim of achieving "good water status".

The number of technical tools available to water resource managers has increased significantly since the early 1980s. While not all of these tools are applicable to both groundwater and surface water management the majority of them do have this dual role.

Taking into account the changes in legislation, policy frameworks and developments in technology, any revised or new plan will have a different focus from existing ones. If new plans are to be closely linked to the requirements of the draft Water Framework Directive, they would be required to achieve some level of integration of groundwater and surface water management. This integration will have to be addressed in the updating of the methodology for the preparation of water quality management plans.

INTRODUCTION

Water quality management planning was introduced to Ireland with the enactment of the Local Government (Water Pollution) Act in 1977. Generally speaking, water quality management planning in Ireland to date has been restricted to the management of surface waters with groundwater protection being addressed through the preparation of groundwater protection schemes. This paper is based in part on a publication by the Agency dealing with water quality management planning entitled "Water Quality Management Planning in Ireland" which is presently in press.

In looking at the future management of waters in Ireland, an examination of the existing management systems is necessary. To date, the management of groundwaters and surface waters has been carried out in very different manners. This paper gives the background to surface water management to together with a brief resume of groundwater protection schemes and assesses the potential for a unified approach to water management in the future.

FRAMEWORK FOR WATER QUALITY MANAGEMENT PLANS AND GROUNDWATER PROTECTION SCHEMES

Section 15 of the Local Government (Water Pollution) Act, 1977 provides for the creation of water quality management plans in the Republic of Ireland. The creation of the plans under the Act is a reserved function of the elected representatives making up the local authority itself and cannot be delegated to any official of the authority.

The main provision of Section 15 is that plans shall:

"contain such objectives for the prevention and abatement of pollution of the waters the subject of the plan and such other provisions as appear to the local authority to be necessary."

A plan cannot contain any requirement that is inconsistent with quality standards for waters or effluents made by the Minister under Section 26 of the Act. Local authorities also have a statutory duty to have regard to water quality management plans when considering any application for a discharge licence under the Local Government (Water Pollution) Act, 1977. The EPA is similarly required to have regard to water quality management plans when assessing IPC and waste licence applications. This includes licensing by the EPA of direct discharges to aquifers by sanitary authorities under the recent Protection of Groundwater Regulations, 1999 (S.I. 41 of 1999).

The overall objective of a water quality management plan is to ensure an acceptable standard of water for specific uses at the time and place where it is needed. To achieve this objective a plan must ensure that the quality of a catchment's waters is maintained in a satisfactory condition and - where necessary - improved, thereby safeguarding public health and catering for water abstraction and fisheries maintenance, as well as relevant water-based amenities and recreational requirements. It should be noted that the definition of "waters" within the Local Government (Water Pollution) Act, 1977 includes both surface waters and aquifers (or part of either). This allows for the inclusion of groundwaters in any revised or new water quality management plan.

The objectives of Groundwater Protection Schemes are very similar to those of (surface) water quality management planning . One description of the aim of Groundwater Protection Schemes is :

" to maintain the quality and quantity of groundwater and in some cases improve it, by applying a risk assessment based approach to groundwater protection and sustainable development."(DoeLG/EPA/GSI, 1999)

Groundwater protection schemes do not have a statutory basis but due to their direct relevance to the protection of water supplies they have an operational importance which promotes their implementation. They may in the future be utilised within or in conjunction with development plans to assess the environmental suitability of certain land uses in defined locations.

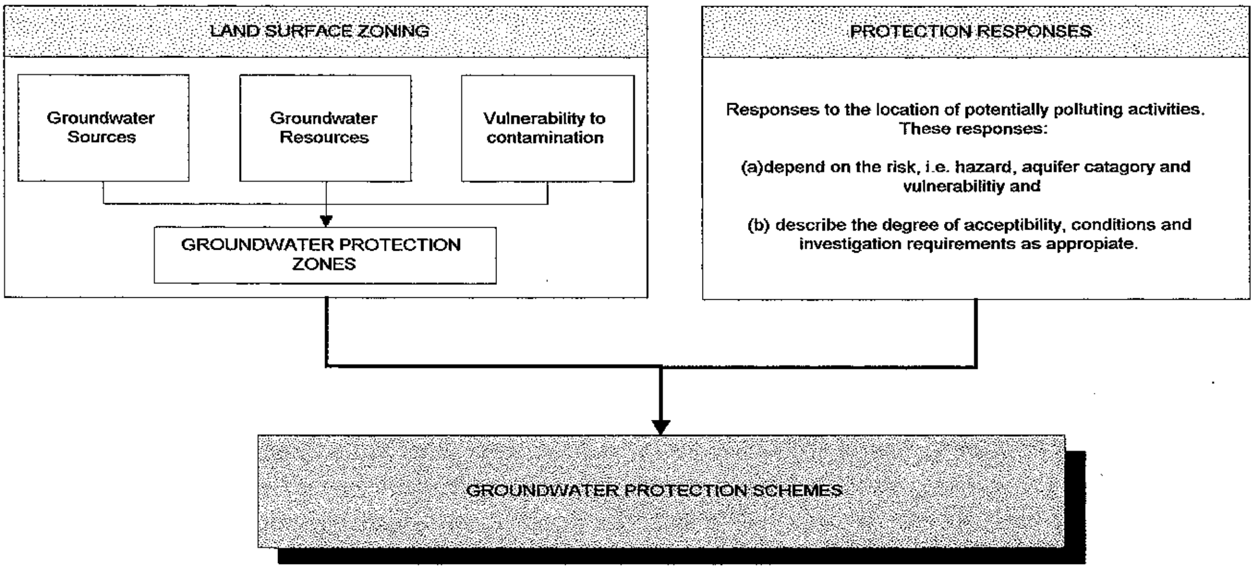
EXISTING METHODOLOGIES FOR THE PREPARATION OF GROUNDWATER PROTECTION SCHEMES AND WATER QUALITY MANAGEMENT PLANS

One of the most notable aspects of groundwater protection and surface water management to date has been the widely different methods used to achieve similar objectives. Both have as their basic objective the maintenance of water resources. In relation to groundwaters this has been a protectionist approach with groundwater protection responses being related to the risk of contamination. Typically, restoration of contaminated groundwaters is considered outside the scope of the scheme. The management of surface waters and especially catchments has been based on both the protection of the resource and mitigation of existing pollution.

The method for formulating groundwater protection schemes has been revised by GSI/EPA/DoELG and will be published in May 1999. In brief, the methodology brings together land surface zoning and groundwater protection responses. Using a risk assessment based approach, the methodology provides a framework to assist in decision making on the location and nature of developments with a view to protecting groundwater.

The two main components to a groundwater protection scheme are land surface zoning and protection response for potentially polluting activities. A diagram of the scheme is shown in Figure 1.

Figure 1: Components of Groundwater Protection Schemes



The land surface zoning aspect is based on a series of maps covering bedrock and subsoil geology, depth to bedrock and well locations. These maps are integrated to form aquifer maps and vulnerability maps. The resulting final map is a groundwater protection zone (resource) map which can form the basis for land use planning. It delineates land area in terms of groundwater vulnerability to pollution and their groundwater potential.

Groundwater protection responses indicate the acceptability of specific land uses such as landfills, on-site systems for single houses and landspreading of organic waste within an area or sets out particular measures to be taken in relation to these uses.

Water quality management plans in Ireland have predominantly been prepared using a methodology formulated by An Foras Forbartha (McCumiskey 1982). The method was based on the concepts of environmental quality objectives and environmental quality standards (EQO/EQS) and waste assimilative capacity (WAC).

The underlying philosophy of the waste assimilative capacity concept is that a surface waterbody has the potential to process pollutants up to some defined limit without causing harm to the environment or significant degradation of water quality.

In Irish water quality management planning, waste assimilative capacity was defined as the available BOD capacity at a certain point based on the background concentration at ninety five percentile flow. The WAC was defined as:-

$$WAC = (BOD_{max} - BOD_{back}) * 95\%ile\ flow * 86.4\ kg\ BOD/day$$

BOD_{max} = Maximum permitted concentration ($4mgl^{-1}$)
BOD_{back} = Background or upstream BOD
95%ile flow = Flow equalled or exceeded 95 % of the time

The most notable sources of EQO/EQS used in the preparation of water quality management plans are European Community use-related water quality Directives and Memorandum No.1, Water Quality Guidelines prepared for the Minister for the Environment in 1978. Specific EQS were recommended in relation to a number of parameters.

A fourteen step procedure was proposed An Foras Forbartha for preparing a water quality management plan (See Table 1).

Table 1: Procedure for the preparation of Water Quality Management Planning

1	Identify existing and future beneficial water uses to be protected.
2	Compile all available data on water quality and water resources within the catchment.
3	Examine the data in (ii) above and determine the characteristic elements which mainly determine water quality at selected control sections along the main river channel and its tributaries.
4	Select the receiving water standards deemed necessary to support the various beneficial uses. In doing this reference should be made to data and information from various international sources including the EPA (US), EEC directives and Memorandum No.1 and the general water quality conditions pertaining in the catchment.
5	Compute estimates of the Waste Assimilative Capacity (WAC) of the river and tributaries at key locations
6	Compute population projections for the catchment (20 years).
7	Compute estimates of the existing generated waste water loads
8	Compute projections of the generated waste water loads for the period covered by the plan.
9	Identify all existing and future abstractions.
10	Estimate the water quality conditions likely to arise at key locations in the catchment as a result of existing and projected waste water loads. Identify level of waste load reduction required.
11	Review all possible options in relation to the treatment of existing and projected waste loads prior to discharge and determine the reserve capacity of the river at the selected key locations in relating to these options.
12	Select the appropriate treatment options for existing waste discharges (public and private) so that the receiving water standards can be met and a suitable reserve capacity for future developments maintained.
13	Determine the main priorities for capital investment in both public and private waste water treatment facilities.
14	Outline the general procedures that should be adopted for the laying down of effluent emission standards for future waste water discharges.

OPERATION AND IMPLEMENTATION

Both groundwater protection schemes and water quality management plans have been in existence since the mid 1980's.

Groundwater protection schemes based on a scheme developed by the Geological Survey of Ireland in the early 1980s have been used for a number of years by a number of local authorities (Offaly, Wexford, North Cork, Galway and Louth). This scheme has been revised and has recently been used to prepare a number of groundwater protection schemes including those for counties Limerick, Waterford, Tipperary, Meath, Wicklow and Offaly.

While no systematic revision of the method of preparation of water quality management plans has yet been made, fifteen water quality management plans have been adopted since 1977(Figure 2). In addition, a number of other draft plans and cross border strategies being prepared. As the development of these plans/strategies has taken place in parallel with a number of technical advances, some significant changes have occurred in the water quality management process(see section: Advances In Techniques And Technology)

Eleven of the water quality management plans were formulated by either the Water Resources Division of AFF or by its successor, the Environmental Research Unit. The plan for the Suir catchment was the first adopted in September 1984. Other plans prepared by the AFF adopted in the 1980's were the Barrow, Slaney and Nore catchments and Cavan County. The plans for the upper and lower Shannon were adopted in 1991 and 1992 respectively. The final plan to be adopted based on AFF/ERU drafting was the Liffey plan in 1997.

How successful has water quality management planning been? The main purpose of water quality management planning is to ensure that the quality of waters covered by the plan is maintained so that existing and future beneficial uses are protected. On a national level, there has been a marked reduction in the length of seriously polluted channel from at least 6% in 1971 (original surveys covered only 2,700km and are not directly comparable with the more recent extended surveys) to 1% in 1994. However, the relative success of water quality management planning is called into question by the continuing deterioration in the quality of freshwaters (EPA, 1996). Long term trends based on some 2,900 km of river channel, which have been surveyed periodically since 1971, have shown a continuing decline in the length of unpolluted water channel from 84% in 1971 to just 57% in 1994 with the most striking trends being a five-fold increase in the extent of slight pollution and a three-fold increase in moderate pollution. These trends have been found to a lesser extent within a much wider baseline of 12,700 km of channel that has been surveyed since 1987.

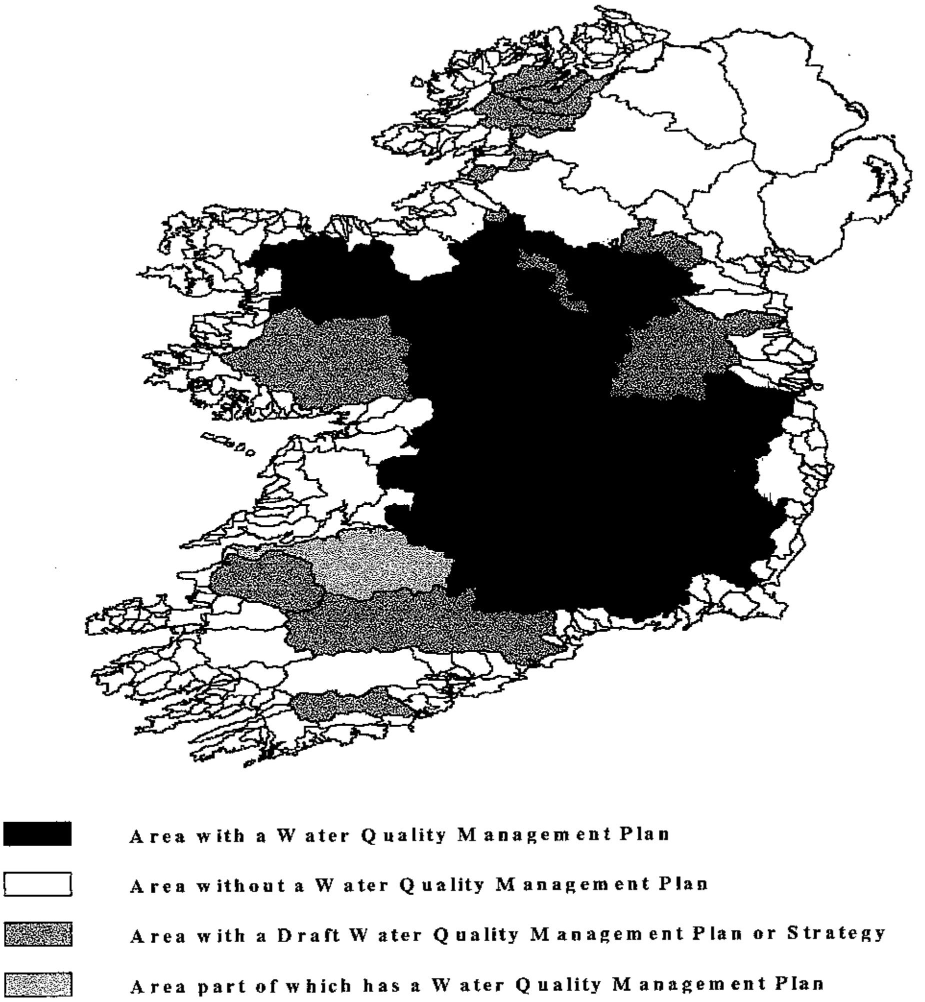
It should be noted that diffuse sources of pollution were outside the scope of the methodology as were ecological aspects of the riverine habitat. The scope of the plans was restricted due to information gaps and the lack of available data at the time the plans were formulated. In addition, the control of point-source industrial and domestic discharges was considered a priority at that time. Today, eutrophication is acknowledged as one of the main environmental problems. It is evident that future plans will have to address this issue.

An associated technique for the management of surface waters is the catchment monitoring and management programme. While plans, draft plans and strategies share many similarities, catchment monitoring and management programmes differ in their emphasis and basic methodology. While they cannot be considered as replacements for water quality management plans, they do provide information which can be used in the creation and implementation of plans.

address some of the aspects of diffuse pollution especially that of run-off and its effect on surface water quality. The programmes operate under the supervision of catchment co-ordinators who liaise with both catchment steering committees and an operational management group made up of representatives from all of the major stakeholders in the catchment.

The Lough Derg and Lough Ree Monitoring and Management System was the first of these programmes to commence operation in 1997. There are similar programmes being implemented for the Suir, Boyne and Liffey river catchments and Lough Leane near Killarney. While there are no proposals to initiate any other such projects in the short term, this approach may be extended to other important river and lake catchments over the period of the next National Development Plan, 2000 to 2006.

Figure 2: Distribution of Water Quality Management Planning in Ireland



CHANGES IN THE REGULATORY AND POLICY FRAMEWORK

Recent developments in national policy show a definite move towards the revitalisation of water quality management planning. In 1997, the Department of the Environment and Local Governments published a policy document entitled "Sustainable Development, A Strategy for Ireland". Key strategic actions in relation to water resources within this document included the development of an updated methodology for the preparation of water quality management plans and its use in the review of all existing plans over the next 5 to 10 years. Their revised objectives will most likely require compliance with the interim quality standards contained in "Managing Irelands Rivers and Lakes - A Catchment based Strategy Against Eutrophication" (Department of the Environment and Local Government, 1997). The reviewed plans will also have to comply with the provisions of the Local Government (Water Pollution) Act, 1977 (Water Quality Standards for Phosphorus) Regulations, 1998 (S.I. 258 of 1998).

The national monitoring programmes for lakes, rivers, estuarine and groundwater are presently being prepared by the EPA in consultation with other organisations. These programmes will provide information for the review of water quality management plans and the formulation of river basin management plans and should be analysed to show they satisfy the information requirements of these plans. This analysis will be carried out before the revised programmes are adopted.

A draft EU Water Framework Directive has been proposed by the European Commission. The draft Directive, when adopted, will have major implications for water quality management planning in Ireland. It is expected that the draft Directive will form the framework for future catchment management systems. It should be noted that implementation of the draft Directive will likely require new legislation and the Commission is currently developing implementation guidelines for the draft directive.

Its overall objective is to establish a framework for the protection and improvement of surface waters, estuaries, coastal waters and groundwater with the aim of achieving "good water status". "Good water status" is defined within a classification system contained within the draft directive (Annex V). The classification system takes account of biological, physico-chemical and hydromorphological characteristics depending on the type of waterbody.

Member states will be required to identify individual river basins and assign them to "river basin districts". A river basin district is defined as

" an area of land and sea, made up of one or more neighbouring river basins, together with their associated groundwater and coastal waters. "

These river basin districts will be the primary administrative units for the purposes of water management. As such, it is evident that basin plans must deal with both groundwaters and surface waters. How integrated the approach will be is questionable at present. The draft Directive suggests that river basin management plans can be supplemented by the production of more detailed programmes and management plans to deal with specific aspects of water management including catchment, estuarine and coastal management plans. This provision within the draft Directive could allow for the integration of groundwater and surface water management plans.

A competent authority must be designated for each river basin district to ensure the application of the requirements of the draft Directive. Each competent authority must publish a river basin management plan for each river basin district. The Commission suggests that this can be achieved through the co-ordination of administrative efforts rather than by the imposition of a single agency or authority. However, it is likely this will depend upon the traditions of the relevant member states. It is not yet clear how river basin districts will be administered in Ireland.

In Ireland, the existing catchment sizes are relatively small and it is likely that many will be amalgamated together to produce river basin districts which are of a suitable size for reporting purposes to the Commission.

ADVANCES IN TECHNIQUES AND TECHNOLOGY

The tools available to the water quality management practitioner and the developer of groundwater protection schemes have increased significantly since the early 1980s. This includes development in both the approaches taken to dealing with these issues and technical tools. There have also been developments in associated regulatory systems. While not all of these tools are applicable to both groundwater and surface water management the majority of them do serve both fields of water management

Environmental management tools include the development of environmental management systems and the emergence of nutrient management planning as a control technique for diffuse pollution. Other relevance management tools include risk assessment, environmental indicators and management practices for riparian zones. The application of a systems approach to water management would lead towards dealing with groundwater and surface waters in an integrated fashion to prevent trans media movement of pollution.

Data compilation and analysis tools include the emergence of geographical information system technology, advances in modelling of aqueous systems, satellite and remote sensing, better data handling and logging of collected data through computerised systems. If groundwater and surface water management are to be integrated is appears likely that a geographical information system approach will be used. Geographical information systems have been used in the preparation of groundwater protection schemes and recent draft plans and are being used by the catchment monitoring and management programmes. The compilation and integration of the available datasets should therefore be possible and may allow for the testing of various integrated approaches to groundwater and surface water management.

The wider range of techniques and tools available to the water quality management planning practitioner have had and will continue to have significant impact on the making and implementation of plans. The improved quality and codification of data with improved graphical representation of information can play an important part in making information more accessible to policy makers, practitioners and the public in general.

ASSESSMENT OF THE POTENTIAL FOR AN INTEGRATED APPROACH

To date, no serious attempt has been made to integrate the management of groundwater and surface water resources. While the methodologies for the preparation of groundwater protection schemes and water quality management plans are different they do share some common problems such as nutrient enrichment. The development of any integrated system should initially be directed towards addressing these common problems.

While groundwater protection responses have been developed with solely groundwater in mind the revaluation of these responses could offer a combined response to potential contamination of both water regimes. In addition to bedrock geology, depth to bedrock, subsoils, aquifer type and well yield data, other datasets would be needed if an integrated protection scheme were to be evolved. These additional datasets would include:

- topographical information;
- vegetation maps;

- soils maps; and
- distances from waterbodies.

Some work has been carried out on the determination of run-off potential and risk-based mapping of land for potential for surface water pollution. The combination of a risk-based map for surface water pollution potential and a groundwater vulnerability map can be considered a logical step in the assessment of an integrated approach to water management.

It must also be considered that differences do exist between the two regimes and that some problems are specific to each. Groundwaters do not maintain diverse ecological systems as rivers and estuaries do (with the exception of fens). The protection of groundwater resources can therefore be seen as maintenance of flow and protection of the resource from contamination. The protection of surface waters has a wider scope including ecosystem maintenance or restoration in addition to chemical water quality and flow maintenance.

An attempt to find common ground between the approaches may be initially directed to heavily karstified areas where surface water/groundwater interaction is high and any protective measures will have a direct benefit to both water regimes.

SOME CONCLUSIONS

Taking into account the changes in legislation, policy frameworks and developments in technical tools and in the plans themselves, any revised or new water quality management plan will have a different focus from existing ones. Some conclusions that can be drawn in relation to their future are that:

- Future plans will have to address eutrophication and diffuse sources of pollution;

- If new plans are to be closely linked to the requirements of the draft Water Framework Directive, their scope will have to expand to reflect the wide definition of waters within the draft. This would require some level of integration of groundwater and surface water management;

- Another important difference between existing and future plans will relate to how they are implemented. Future plans will be more dynamic and will require an assessment of progress and frequent auditing of targets and goals;

- Future plans will have to deal not only with existing problems but must also be flexible enough to assess pressures building on catchments and to either remove or alleviate these pressures; and

- Integrated groundwater and surface water is not presently being practised in Ireland. Any future methodology for water quality management planning will have to address this shortcoming and provide a framework for this integration.

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Paper No. 7.

*Catchment Moniroting & Management Systems.

Ciaran O'Keefe, Dr. Colin Byrne, & Ray Earle,
The Three Rivers Project.

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*An abstract only was available for this paper at the time of going to print. This full paper was distributed separately during the seminar.

CATCHMENT MONITORING & MANAGEMENT SYSTEMS

Colin Byrne[1], Ciaran O'Keefe[2], & Ray Earle[3].

[1]Tipperary South Riding County Council
[2]M.C. O'Sullivan & Co. Ltd., Ashurst, Mount Merrion Avenue, Blackrock, County Dublin.
[3]Kildare County Council & Meath County Council

ABSTRACT

There is currently a series of catchment-based water quality monitoring and management systems being developed throughout Ireland sponsored by the Department of the Environment & Local Government. Several other systems are expected to start in 2000. Implementation of these systems is a response to the increasing level of eutrophication of surface waters due, principally, to phosphorus. Catchment scale programmes are now recognised as the most appropriate units to manage water quality. The catchment approach is the basis of the national strategy against eutrophication and is a key concept in the draft E.U. Water Framework Directive currently being debated at European level.

The main objectives of the catchment systems are to **(1)** gather all available environmental information relevant to surface water and groundwater quality and to integrate it within a Geographical Information System (GIS). **(2)** Enhance the existing water quality monitoring network where necessary. **(3)** Estimate pollution loads according to industrial, municipal, and land-use activities. **(4)** Implement pollution control strategies, on a pilot sub-catchment basis, by promoting Best Management Practices (BMPs), and increasing public awareness of the problems and issues involved.

To date the focus of catchment studies has been on phosphorus loss to surface waters. Groundwaters have been considered less vulnerable to phosphorus contamination and, therefore, have not been considered in as much detail. Also, monitoring of groundwater quality is less well established than for surface waters. However, because of the importance of groundwater in its own right, the importance of groundwater discharge to surface water and the recognition that point source contamination of boreholes is significant there is now a greater emphasis on groundwater. This will, undoubtedly, increase as groundwater monitoring becomes more established and as catchment studies evolve. In the course of the *Three Rivers Project* (Boyne, Liffey, & Suir rivers), consideration is being given to available Groundwater Protection Schemes. The pilot sub-catchment programme will involve the assessment of groundwater vulnerability, point source pollution from septic tanks, farmyards, etc. Implementation of pollution control measures will be directed at protecting both surface waters and groundwaters. Progress in the *Three Rivers Project* to date will be outlined in the accompanying paper.

Paper No. 8.

Influent Rivers: A Pollution Threat to Spring Water Supplies.

Steve Hobbs & Andrew Moag, Aspinwall & Co.

INFLUENT RIVERS – A POLLUTION THREAT TO SPRING WATER SUPPLIES ?

S L Hobbs
Aspinwall & Company, 5 Chiltern Close, Cardiff Industrial Park, Cardiff CF4 5DL

ABSTRACT

A number of influent rivers cross the southern outcrop of the Carboniferous Limestone in South Wales. They lose a proportion of their flow to groundwater via both discrete sinks and leaky river beds. These influent rivers represent a pollution risk to local springs. The degree of risk is dependent upon many factors that include pollutant type, proximity and volume of influent flow. These factors are considered in an assessment of the Schwyll Spring public water supply that is near Bridgend in South Wales.

INTRODUCTION

Schwyll Spring is located near the town of Bridgend in South Wales. The discharge from the 13 individual springs at this location used to flow into the adjacent River Ewenny (Knox, 1933) until 1872 when the water was first used for supply (Jones 1985). Early in the twentieth century a shaft was dug to the south east of the springs to prevent the influx of poor quality river water to the springs during high water. This shaft encountered a natural chamber that has subsequently been entered by cave divers and which continues for over 440 m upstream (and is still open) with several routes going off the main passage.

Welsh Water has a licence to abstract up to 7955 Ml/year from Schwyll Spring. Water quality is generally good except following heavy rainfall when the water can run turbid and the spring is taken out of supply.

PHYSICAL SETTING

REGIONAL SETTING

Bridgend is located close to the South Wales coastline in a relatively flat area with low hills. To the north the land climbs associated with the western end of the South Wales valleys and the Brecon Beacons beyond. In simple terms the geology of South Wales comprises a broad east west orientated syncline with Carboniferous Coal Measures strata forming the core some 25 km in width. A relatively narrow band of Carboniferous Limestone surrounds this core with Devonian Old Red Sandstone outcropping around this. Triassic and Jurrasic deposits, dominated by mudstones, overly the limestone and sandstone in places along the coast.

LOCAL SETTING

Schwyll spring is located at about 5 metres above Ordnance Datum (m AOD) on the south side of the River Ewenny (Figure 1). The latter flows south west for 1 km before becoming tributary to the Ogmore River which discharges into the Bristol Channel some 3 km to the south west of the spring. To the south the land rises steeply to Ogmore Down and Beacon Down which have a plateau surface at about 80 m AOD. The surface of this plateau is dissected by several dry valleys on its north west and north east sides. The plateau is cut by the River Alun, a small north west flowing watercourse within a steep sided valley. This river is tributary to the Ewenny upstream of the spring. To the west of the spring, on the far side of the Ewenny and Ogmore Rivers lies the sand dune system of Merthyr-mawr Warren. To the north and north east the land rises gently towards the town of Bridgend and the M4 motorway (Figure 1).

The geology in the vicinity of Schwyll Spring comprises Dinantian Carboniferous Limestone (on the southern side of the South Wales coal field syncline) which is overlain in places by drift deposits including wind blown sand, head and alluvium adjacent to the river. The limestone dips at 5 to 15° to the south and is by cut by several faults, one of which, the Rhiw Fault, is probably partly responsible for the location of the spring. Some 1 km to the north and 3 km to the south and east the limestone is overlain by Lower Lias limestones and mudstones and Triassic mudstones. The latter include the conglomeratic marginal facies which can be in hydraulic continuity with the limestone.

Within the Ogmore catchment the rivers Ogmore, Ewenny and Alun all flow across the limestone outcrop along part of their length. In such areas loss of river water to groundwater takes place, perhaps the most striking local example of which is at Merthyr Mawr. Sinks on the bank of the river take water that flows through a series of passages, some of which are intersected by shallow potholes, before the water rises and flows back into the river some 700 m downstream. At other locations, such as on the south side of Bridgend, loss of river water by diffuse bed seepage is more common (Welsh Water Authority, undated). In dry weather sections of the Afon Alun are completely lost to groundwater.

SPRING CATCHMENT

CATCHMENT AREA

The Carboniferous Limestone in the UK has a low primary porosity and permeability. However, preferential dissolution of carbonate rocks along bedding planes, fractures and joints increases the porosity and can increase the permeability by many orders of magnitude. Spatial variations in dissolution can produce a heterogeneous aquifer in which the permeability at two locations a short distance apart can vary substantially. The location and nature of these preferential flow routes is of great importance in establishing the catchment of a spring in such an aquifer.

As a starting point to determine the approximate spring catchment a simple water balance was calculated. This utilised the estimated spring discharge and the effective rainfall in the area to determine the outcrop necessary to support the spring. This calculation was at best an estimate as there is no continuous measurement of discharge at the spring and only occasional "spot " measurements. These indicated an annual average discharge of the order of 12 300 Ml/year (Hobbs, 1993). With an effective rainfall in the area of some 540 mm/year this is equivalent to a catchment of some 23 km^2. Based on the available outcrop area, the area calculated above and the estimated area for other abstractions in the locality a conjectural catchment area has been formulated (Figure 2).

WATER TRACING

The above calculation indicates an approximate catchment area for Schwyll Spring but does not allow an estimate of its extent. A number of attempts have been made to trace sinking streams and influent rivers to the spring (Knox, 1933, Aldous, 1986, 1988, Dixon et al 1986, Williams & Brown, 1989). These attempts confirmed that the spring is recharged by dispersed rainfall over the outcrop of the limestone in addition to that from a small number of stream sinks and from rivers influent to the Carboniferous Limestone. A summary of the traces is presented on Figure 1.

Of most interest here are the traces attempted from the River Ogmore, River Ewenny, River Alun and the Merthyr Mawr sinks. Each of these will be considered briefly (see Hobbs, 1993 for more details).

River Ogmore traces – these were undertaken from two different sections of the Ogmore using bacteriophage. They proved a positive connection with Schwyll Spring, albeit with sporadic tracer breakthrough. The traces confirm that the Ogmore is influent where it crosses the Carboniferous Limestone.

River Ewenny Traces – a series of traces were undertaken at different times with both fluorescent dye and bacteriophage. Both tracers were injected into a sink in the bed of the Ewenny, however, only the bacteriophage traces were positive at Schwyll Spring. A further bacteriophage trace was completed some 4 km downstream of the above sink. The tracer was injected to the river and was detected at the spring, albeit sporadically with low recovery.

River Alun Traces – bacteriophage injected into the river were not detected at Schwyll. However, both fluorescent dye and phages injected to the Tymaen sinkhole adjacent to the lower stretch of the river, 0.5 km east of Schwyll proved positive.

Merthyr Mawr Trace – both fluorescent dye and bacteriophage traces were positive to the downstream risings on the Ogmore. Only the bacteriophages were also positively traced to Schwyll Spring.

The above traces indicate that influent river water comprises a component of the water discharged from Schwyll Spring. However, the results of the tracing are very variable with low recoveries suggesting that dilution is high and that there is not a direct open conduit (passage) link between the influent water courses and Schwyll.

INFLUENT RIVERS

The work outlined above indicates that some of the water rising at Schwyll Spring comprises influent river water. However, the tracing work was unable to estimate the proportion of the spring discharge that comprises influent river water. Two further means of estimating this have been examined, flow gauging and spring chemistry.

FLOW GAUGING

Although there are four permanent gauging stations in the River Ogmore catchment only two are in the study area (Figure 1) and neither of these are suitably located to determine the river loss to groundwater. A number of "spot" gauging exercises have been undertaken but these are largely random and discontinuous in nature. A total of 15 sites have been monitored since 1965 but only on one occasion is the data suitable for examining river losses. A survey of 5 points on the River Ogmore carried out on 11 August 1986 indicates that 20 % of the 135 Ml/d river flow entered the ground between Pen y Cae bridge over the M4 motorway and the Swing Bridge in Bridgend town (Figure 1). This is some six times the estimated discharge from Schwyll Spring ! In contrast Glamorgan River Authority (1971) reported a 4 Ml/d loss from the River Ogmore in the Bridgend area.

WATER CHEMISTRY

A brief examination of the water quality at Schwyll Spring was made to determine if any clear indication of river water recharge could be gleaned. However, excepting the turbidity pulses, there was insufficient information to allow an estimate of the importance of river water recharge. This may be because river water is a very small contributor, or it may be that travel times are sufficiently slow that any difference between groundwater and river water chemistry is masked before the water resurges at Schwyll.

DISCUSSION

Of the traces to Schwyll Spring only those from the Tymaen sink, 0.5 km away, were particularly successful, and even then the maximum tracer recovery was only 20 %. The remainder of the traces indicate that connections exist between the influent rivers and Schwyll Spring although there is not a direct open conduit (passage) link between the influent rivers and the spring.

The assessment of water chemistry is of little assistance in estimating the proportion of influent river water appearing at Schwyll whilst the spot gauging indicates widely differing volumes. The large variations could be partly caused by seasonal and spatial variations. The gauging carried out in 1986 was completed in summer when groundwater levels were likely to have been low such that river leakage would have been high. At such times diffuse seepage is maximised in addition to that which can enter stream sinks as concentrated recharge. The water lost to ground may have reappeared further downstream or at one of the other springs which are present in the area in addition to Schwyll.

In addition to the tracer tests, gauging and water analysis the potential catchment area has been assessed based on "first principles". The approximate spring discharge is known, the effective rainfall in the area is known as is the available outcrop area. These simple calculations indicate that there is a substantial amount of aquifer available to support spring flow and few other know discharge points (Figure 2). The latter does, however, have to be treated with caution. Substantial submarine springs are known to exist in the Bristol Channel, that from the Great Spring which was intersected when boring the Severn Railway Tunnel encountered a flow estimated as 27 000 Ml/year.

The data indicates that river water from the Ogmore catchment does enter the ground at a number of locations. Some of these result in recharge to the Carboniferous Limestone with flow eventually reaching Schwyll Spring. However, the route to the spring is neither direct nor particularly rapid. The results do not indicate a well developed conduit system from the sinks to the spring.

POTENTIAL FOR POLLUTION

Even though the results of the above investigations do not allow the exact proportion of influent river water to be determined the data do have implications for pollution prevention at the spring. The potential impact of influent river water upon Schwyll Spring is difficult to predict as it will be dependent upon a number of factors as follows:

- Antecedent conditions including rainfall, groundwater levels and river discharge;
- The type of pollutant, especially whether they float, sink, remain in suspension or are dissolved;
- The location within the catchment where the pollutant is lost; and,
- The nature of the connection between the point of loss and the spring.

The importance of antecedent conditions is that they influence the amount of water that may move from surface to groundwater. With low groundwater levels, and especially if river levels are high (following a summer thunderstorm for example), then the amount of influent water may be expected to be greater than when groundwater levels are high and river flow is moderate. River discharge *per se* is also important. High discharges mean that there is a greater volume of water available for dilution should a pollutant be lost to a river. However, the converse can also be true if the pollutant is natural such as suspended sediment (see below).

The type of pollutant is critical. Where the loss is to river and is a light non aqueous phase liquid (LNAPL), such as diesel for example, then the pollution potential to groundwater is reduced provided that there is sufficient water in the river to separate the river surface from groundwater. The diesel would float and only that part moving into solution would enter the groundwater system. Furthermore, if the pollution spill occurred in the upper reaches of the catchment this gives the relevant authorities time to deploy downstream booms etc to reduce movement of floating free product. This is clearly not the case where river levels are low or where the majority of the river water sinks at a discrete point. At such a time even the floating material will be lost to groundwater. Where dense non aqueous phase liquids (DNAPL) are lost to a river these will sink and may take time to move downstream (depending upon river discharge). This allows the relevant authority time to mitigate, although this is more complex to carry out successfully than with LNAPL's.

The greatest risk to groundwater from influent rivers is from pollutants that move into solution. These can travel at the same speed as the river water and can become dispersed such that the opportunities for mitigation are fewer. However, through the process of dispersion the impact can be reduced. Pollutants can also move in suspension and cause a problem, although flow must be turbulent to support these particles and in terms of groundwater pollution is only of relevance to those systems with solutionally enlarged flow paths.

The location of a pollutant loss within a catchment is an important influence upon the potential impact. Losses in the upper reaches of a catchment mean that a significant period of time may elapse before the pollutant reaches an influent point lower in the catchment. This may allow time for the relevant authorities to undertake mitigating action. Longer travel times / distances also provide additional dilution, dispersion and attenuation as the pollutant plume moves downstream.

The nature of the connection between the point of influence and the spring is a major control on the type of incident that may occur at the spring. Losses close to the spring, or those with open, high velocity, well defined flow paths can result in relatively short duration high peak impacts. Those where the losses are more distant and the flow paths less direct can result in a pollutant plume of longer duration but with a peak of less concentration.

Potential pollutants maybe either natural or "man made". The most common natural pollutant, and one that regularly affects Scwyll is turbidity. This is probably caused by suspended sediment laden runoff entering a discrete stream sinkhole following rainstorms. The elevated turbidity pulses, which results in the spring being taken out of supply, suggest a rapid and "open" connection between the sink and the spring.

At Schwyll the main potential sources of spring contamination are:

- Tymaen sink – a discrete sinking stream which has been traced to Schwyll;
- Merthyr Mawr sinks - discrete stream sinks on the bank of the River Ogmore which have been traced (albeit with sporadic break though) to Schwyll; and,
- Influent sections of the rivers Ewenny, Alun and Ogmore.

Of these, Tymaen sink is probably partly responsible for the turbidity pulses at Schwyll. If they became a significant problem then it maybe that management options (eg. stream diversion) could be examined to control the entry of turbid water to the sink. Although Tymaen sink is very close to Schwyll such that dilution and dispersion of any man induced pollutant would be limited, the stream is small and from a rural area. It therefore represents a relatively low risk from such pollutants.

The traces from Merthyr Mawr sinks were not strongly positive such that any pollutant is unlikely to move rapidly or with little dilution to Schwyll. This therefore represents a relatively low pollution risk.

The influent rivers probably represent a higher risk to Schwyll than the discrete sources. In theory the whole catchment upstream of the influent sections of river could contribute to the spring. Within this catchment are many industrial discharges that may cause pollution if a leak occurs or if there is a failure in their systems that result in an unauthorised effluent discharge. The information collected as part of this investigation better allows the Environment Agency to assess planning applications for new developments within the catchment area for Schwyll Spring. It is also of great assistance in assessing applications for industrial discharge consents and renewals of existing consents within the catchment.

In addition to the risk of pollution from industrial discharges there is also the potential for contaminants from road accidents to enter rivers in the catchment. This is particularly so in the vicinity of the motorway which passes some 5.5 km to the north of the spring (Figure 1). One such accident that occurred in 1985 resulted in a significant loss of oil to the River Ewenny. However, a large proportion of this oil was trapped by booms placed across the river by Welsh Water and there was no detectable increase in oil concentrations at Schwyll.

As well as providing information to the Regulatory Authority to help protect Schwyll Spring it also provides information to help the Water Company to manage the supply. The water company have long been aware of the problem of turbidity at the spring and have constructed storage tanks to accommodate periods when the spring is taken out of supply due to high turbidity. Better knowledge regarding areas where rivers are influent and the likely volume of influent water can also help with water management if a pollution incident does occur. If the water company are aware that a pollution incident has taken place they can take precautions to ensure that any breakout at the spring is identified and the spring is taken out of supply if this represents a hazard to health. It also allows them time to fill the on site tanks if they are empty and to source replacement water supplies if the pollution incident is significant and likely to take the spring out of supply for some time.

ACKNOWLEDGEMENTS

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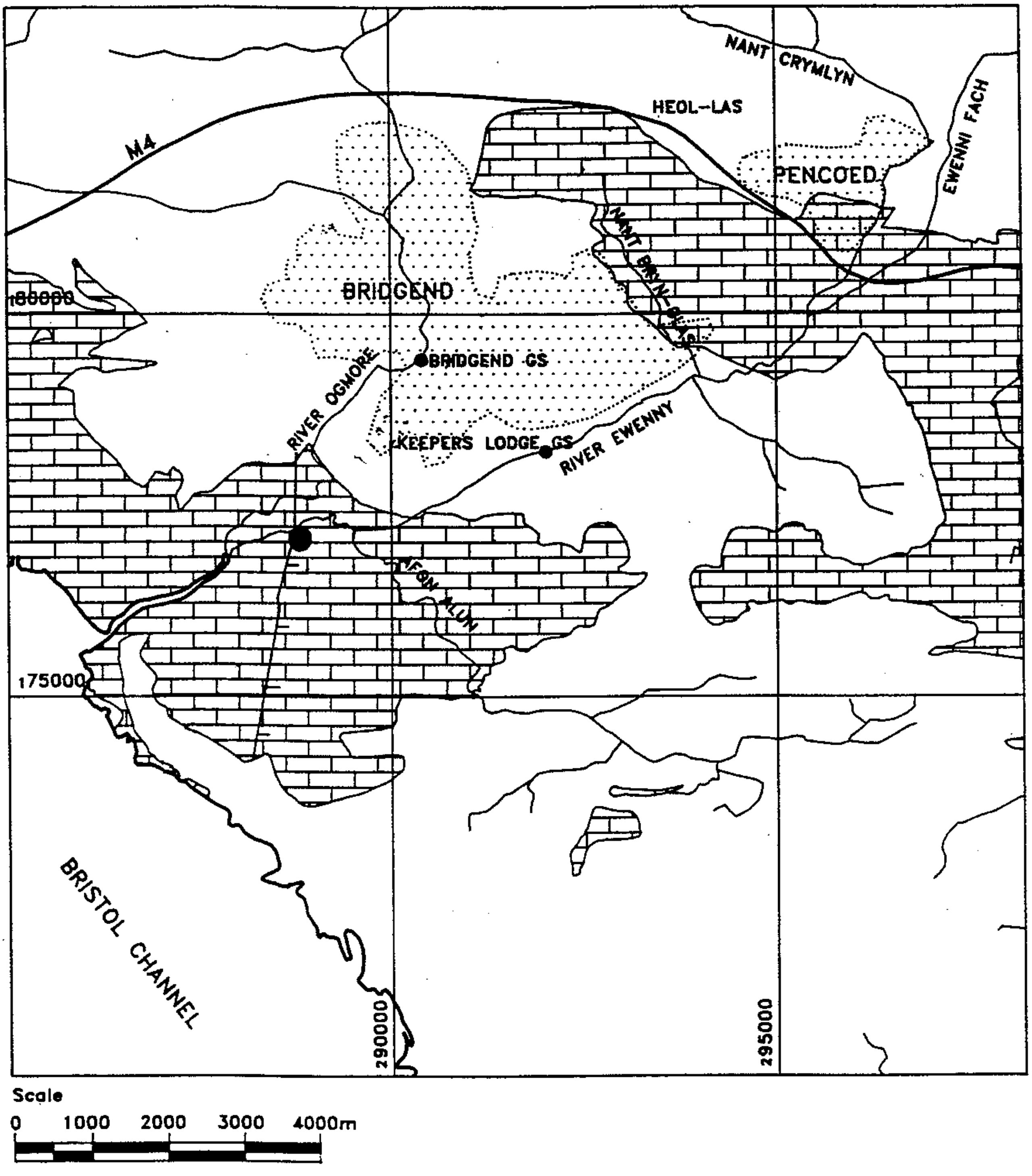

FIGURE 1

STUDY AREA AND OUTLINE SOLID GEOLOGY

KEY

▦	Carboniferous Limestone/Marginal Facies outcrop (including drift covered outcrop)
░	Built up Areas
•	Permanent Gauging Stations
●	Schwyll Spring
〰	Major Rivers
—	Line of M4
⊢	Rhiw Fault (tick indicates side of downthrow)

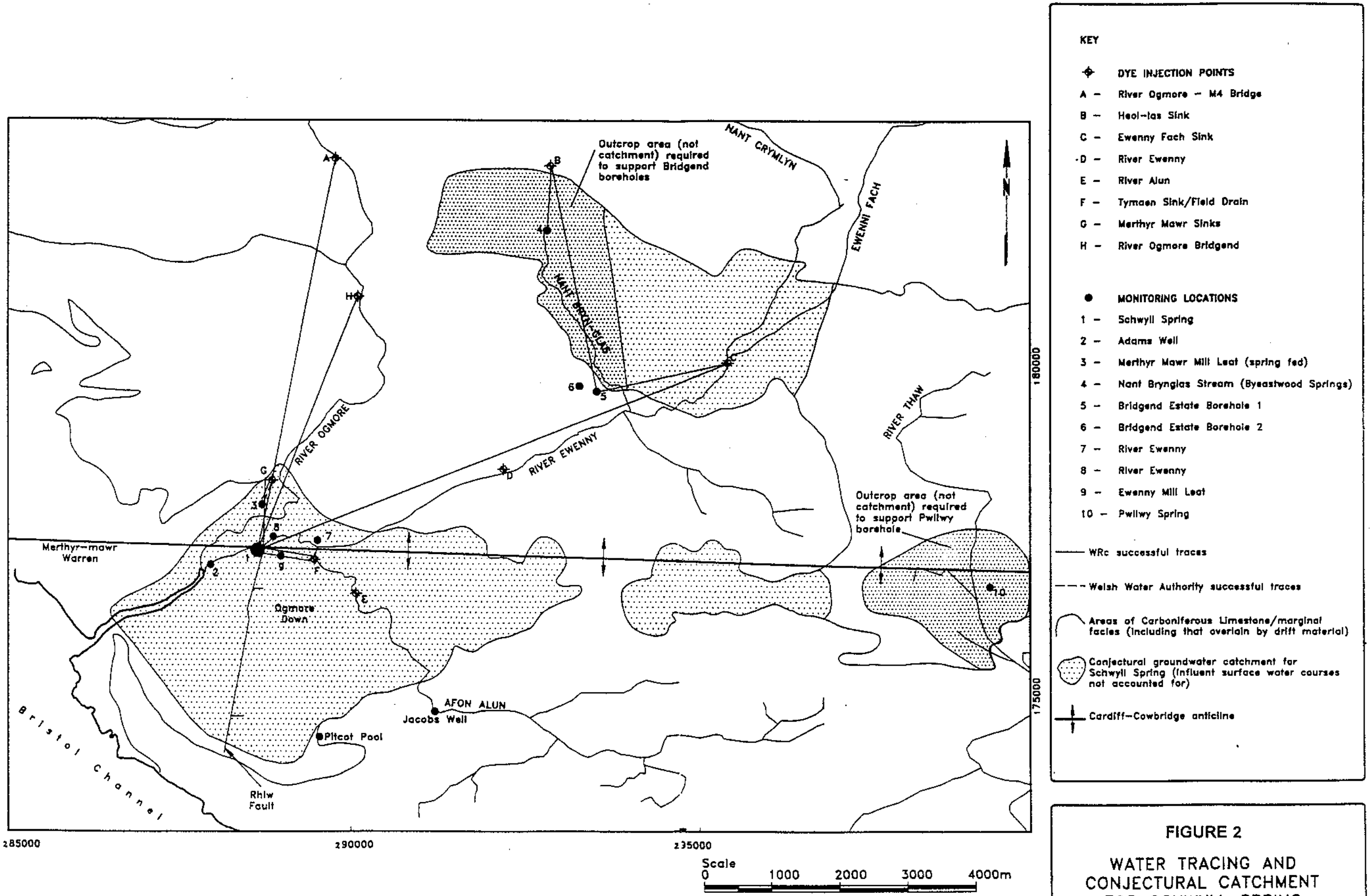

FIGURE 2

WATER TRACING AND CONJECTURAL CATCHMENT FOR SCHWYLL SPRING

Paper No. 9.

Drainage, Runoff, and Vulnerability Maps.

Monica Lee, Geological Survey of Ireland & Trinity College Dublin.

THE USE OF DRAINAGE AND RUNOFF IN GROUNDWATER VULNERABILITY MAPPING

Monica Lee[1, 2], Bruce D. Misstear[1], Paul M. Johnston[1] and Donal Daly[2].
[1] Department of Civil, Structural and Environmental Engineering, Trinity College, Dublin 2.
[2] Geological Survey of Ireland, Beggars Bush, Haddington Road, Dublin 4.

Abstract: *The assessment of groundwater vulnerability in Ireland is based mainly on the properties of the subsoil. Research is being carried out to determine the usefulness of secondary indicators of groundwater vulnerability. These secondary indicators include groundwater recharge, natural drainage density, artificial drainage density and the application of the Flood Studies Report to derive a relative scale of runoff. The results to date indicate that all of these characteristics are useful in assessing groundwater vulnerability, although different characteristics are applicable at different mapping scales (ranging from a field, or local scale to a regional scale). The research aims to establish a systematic approach for incorporating these secondary indicators in a vulnerability assessment programme.*

INTRODUCTION

The vulnerability of an aquifer to pollution depends on many factors, including the properties of the topsoil and the subsoil, the presence of an unsaturated zone, and the type of recharge. In the national groundwater protection scheme in Ireland, the properties of the subsoil are the primary means of classifying groundwater vulnerability (Department of Environment and Local Government et al., 1999 and Misstear et al, 1998). The topsoil is not included in the vulnerability classification because many of the potential contaminants (septic tank effluent, for instance) may enter the ground below the topsoil. (However, the topsoil is considered as part of the risk management component of the groundwater protection scheme where appropriate). The unsaturated zone of Irish bedrock aquifers is also not relied upon for the attenuation of contaminants, since the vast majority of these aquifers are characterised by fissure flow. Where bedrock with well-developed karst features occurs at or near the ground surface, the type of recharge (point or diffuse) becomes significant in assessing groundwater vulnerability.

The main properties of the subsoil that determine groundwater vulnerability are its permeability (classed as high, moderate or low) and thickness. On Irish Quaternary geology maps, subsoil is divided into the following categories: (i) till (or 'boulder clay'), (ii) sand and gravel, (iii) alluvium, including lake sediments, (iv) peat and (v) bedrock outcrop or subcrop (<1 m). Glacial tills are the most widespread subsoil units here in Ireland, and are therefore of most importance for assessing groundwater vulnerability. The tills are currently subdivided on the maps according to their dominant clast petrography which is not wholly relevant to subsoil permeability. The subsoil permeability is primarily related to the particle size distribution although it is recognised that other factors, such as subsoil density and compactness, and the presence of preferential flow paths, have an influence on permeability. Many of the till units (as currently mapped) have a wide range of particle size distributions, and therefore exhibit a wide range of permeability values. An on-going research project aims to refine the field and laboratory methods used for measuring subsoil permeability and shall be referred to in this paper.

This paper describes a concurrent research project, which is examining the usefulness of secondary indicators for assessing groundwater vulnerability. These secondary indicators include: the groundwater recharge determined from either a soil moisture balance or baseflow estimation approach; the density of the natural surface water drainage; the density of the artificial drainage network; and the application of the Flood Studies Report catchment characteristics procedure (Natural Environmental Research Council, 1975) to the sites under study. These different facets of the research project are described in turn below. The research also includes the assessment of ecology as a secondary indicator of groundwater vulnerability, but is outside the scope of the present paper. Both this project, and the project on measuring subsoil permeability values referred to above, are being carried out by the Geological Survey of Ireland in conjunction with the Department of Civil, Structural and Environmental Engineering at Trinity College Dublin.

INVESTIGATION METHODS AND RESULTS

GROUNDWATER RECHARGE

For a given aquifer, it is assumed that groundwater recharge is an indirect measure of topsoil and subsoil permeability, and hence of groundwater vulnerability. In qualitative terms, a high recharge rate implies that water can move relatively easily through the topsoil and subsoil to the aquifer, and hence indicates high aquifer vulnerability. Similarly, a low recharge rate indicates low aquifer vulnerability. If these assumptions hold true, then variations in groundwater recharge across an area should relate, to some extent, to variations in subsoil permeability.

To test these assumptions, two catchments in south east Co. Meath, located between Trim and Dunshaughlin, were identified which have similar topsoil, topography and meteorological characteristics, but different subsoils. The first catchment contributes to a reach of the River Skate and is measured at Drumree gauging station. The second is a subcatchment of the River Clonymeath.

Average monthly rainfall, Penman potential evapotranspiration and average daily streamflow data were collated for the period 1979 to 1983 inclusive (the only period for which all three sets of data were available). Actual evapotranspiration was derived from the Penman potential evapotranspiration by a monthly soil moisture balance using the Danish Aslyng Scale (Aslyng, 1965), which previous studies have found to be suitable for Irish conditions (Connaughton, 1967; An Foras Forbartha and GSI, 1981). Potential recharge was then estimated from the simple water balance relationship:

$$G = P - AE - RO$$

where G is potential groundwater recharge, P is precipitation, AE is actual evapotranspiration and RO is surface runoff. The surface runoff was obtained from stream hydrographs, after deducting the baseflow. The results of the recharge analysis are given in Table 1, expressed as an annual recharge rate per unit catchment area. It can be seen that the recharge rate is higher for the Drumree catchment, which is consistent with the limestone-derived till in this area being more free-draining than the shale-derived till in the Clonymeath catchment. This assumption is further substantiated by the available particle size distribution data. As shown in Table 1, the samples representing the Clonymeath catchment have a higher average percentage of 'fines' than the Drumree catchment. The fines combine the 'silt' and 'clay' fraction of a particle size distribution, as measured in a laboratory, and a higher percentage is assumed to reduce the permeability of the material as these particles will block smaller pore spaces. There were four particle size distribution data points available for the Clonymeath catchment but none within the Drumree catchment. Therefore an average of the four closest data points to this catchment (between 0.5 km and 4.0 km from the catchment boundary which were also located within the limestone derived till) was taken.

For comparison, the average annual baseflow index (BFI) was derived for each catchment. In simple terms, the BFI is the ratio of baseflow volume to total flow volume (Institute of Hydrology, 1980), and hence provides a conceptual estimate of long-term recharge. The Drumree catchment shows a higher BFI, which is again consistent with the expected higher recharge through the subsoils in this catchment.

Table 1 Catchment characteristics and results for the Drumree and Clonymeath catchments.

Site	**Drumree**	**Clonymeath**
Size (km^2)	3.95	17.01
Bedrock	Muddy Limestone	Namurian Shale and Sandstone
Subsoil	90% Limestone derived till	68% Namurian derived till
Average % of fines	44	61
Pot. Recharge (mm/unit area/a)	286	226
BFI	0.59	0.37
Stream Density (km/km^2)	0.76	0.85

Finally, the natural (stream) drainage density for the two areas was also calculated. The Drumree catchment exhibits a lower stream density than the Clonymeath catchment. This once more suggests a higher recharge rate in the Drumree catchment. The analysis of drainage density is explained in more detail below.

NATURAL DRAINAGE DENSITY

The natural drainage density is influenced by the infiltration capacity of the land, as affected by permeability amongst other factors (Verstappen, 1983). For this project, it is assumed that there is a relationship between natural drainage density and groundwater recharge. In areas with a low recharge potential, there will be proportionally less infiltration and more runoff, and this will be reflected in the natural drainage density.

Natural drainage density was calculated as the total length of streams and rivers per unit area, and is referred to herein as stream density. The analysis was carried out for various topsoil units in the eastern half of Co. Meath. Topsoil was used as an indicator of the subsoil (detailed subsoil data were not available) because its texture is closely related to the mineral composition of the parent material, which constitutes the subsoil, or bedrock where subsoil is absent (Cruickshank, 1972). The eastern part of Co. Meath was chosen because this area is relatively flat, with little variation in its meteorology. Furthermore, the analysis was undertaken within specific catchments so that these results could be compared to available gauged flow data in the future.

The 49 soil categories identified in Meath (Finch et al., 1983) were simplified into five main groupings: excessively well drained, well drained, moderately well drained, poorly drained, and unclassified (mainly peat). The stream densities for the moderately well drained and the poorly drained categories were compared as this was the recharge distinction of interest.

The results of this analysis, shown in Figure 1, indicate that the stream densities are higher for the poorly drained soils, with the exception of catchment 2b for which the converse is true. On further analysis of catchment 2b, it appears that this area, situated on the coastline, was not suitable for this type of analysis because it is a low-lying area, probably influenced by a high water table, and may in fact be a groundwater discharge area. In areas such as this, the stream density would not reflect the recharge potential of the subsurface material.

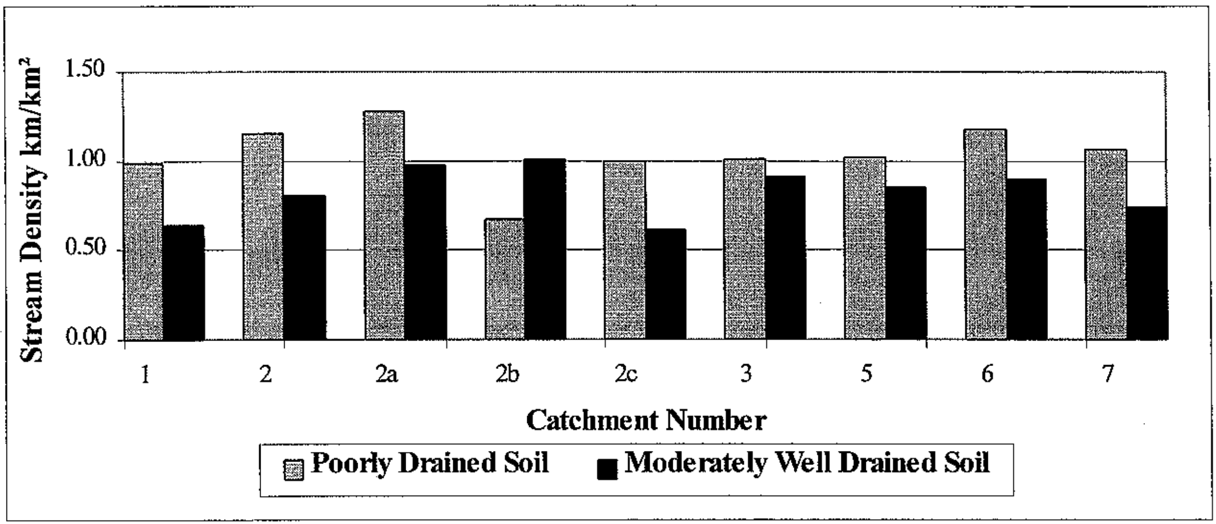

Figure 1 Stream density for soil types within eastern Co. Meath.

ARTIFICIAL DRAINAGE DENSITY

Artificial drainage channels are installed by landowners to compensate for poor natural drainage capacity. Again, it is assumed that the density of artificial drainage will be related to the infiltration potential of the topsoil and subsoil. Relationships between drainage capacity and the drain spacing have been formalised through equations such as Dupuit-Forcheimer and Glover-Dumm (Smedema and Rycroft, 1983). An assessment of artificial drainage density (length of drainage channel per unit area) within small catchments was undertaken for comparison with the soil and subsoil characteristics, and hence with the assumed recharge potential. The drains included in the analysis were the ditches that generally run along field boundaries.

Two sites of contrasting recharge potential were identified; 'Ballinamore', located in south eastern Co. Leitrim, and 'Rathdowney' in south western Co. Laois (see Table 2). As with the natural stream density analysis, a higher artificial drainage density would be expected in the areas with a lower recharge potential.

Table 2 Site characteristic information for Ballinamore and Rathdowney sites.

Site	**Subsoil Classification**	**Permeability (m/s)**	**Soil Type**	**Assumed Recharge Potential**
Ballinamore Site	CLAY	6.41×10^{-10}	Gley[1]	Low
Rathdowney Site	SILT	4.80×10^{-8}	Grey Brown Podzolic[2]	Moderate

[1] County Leitrim Resource Survey (An Foras Talúntais, 1973)

[2] National Soil Survey of Ireland; Soils of County Laois (Conry, 1987)

Also highlighted in Table 2 are the results of field work undertaken to determine the subsoil classification and permeability at these sites (Swartz, pers. comm., 1999). The subsoil classifications were determined from representative samples described according to BS5930: 1981, Code of Practice for Site Investigation. The permeability was estimated from slug tests carried out in piezometers installed at the sites.

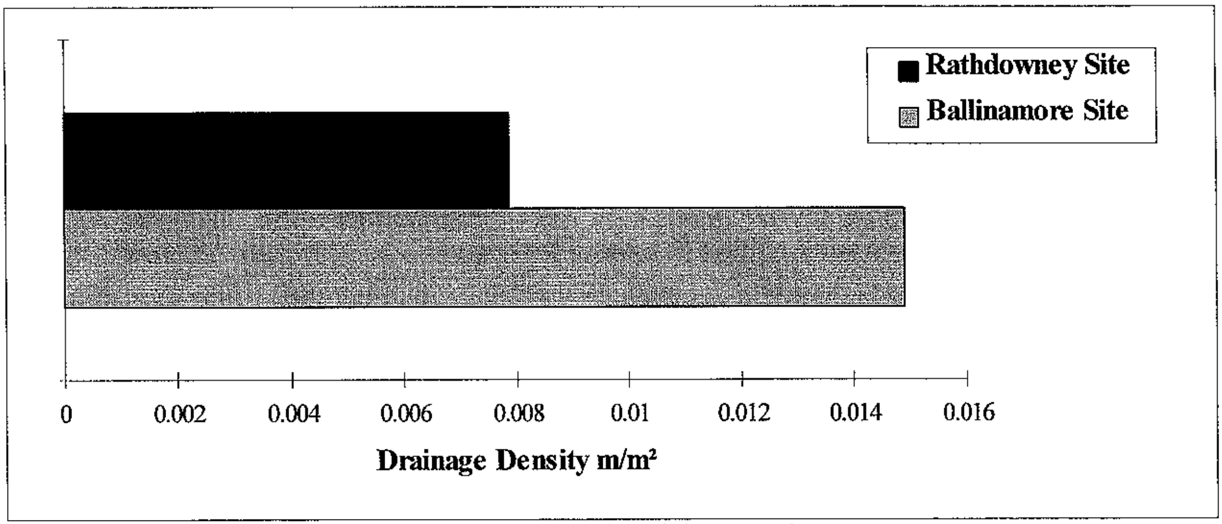

Figure 2 Drainage density for the Ballinamore and Rathdowney sites.

Figure 2 illustrates that the Ballinamore site (i.e. the site with the lower recharge potential) has approximately twice the drainage density of the Rathdowney site. Results indicating that there is a lower potential recharge at the Ballinamore site is further substantiated by the subsoil classification and the permeability results. In further investigations, it was found there was no significant difference between the two areas when comparing channel cross sections; this is thought to be a function of the excavation method. However, the comparison of field size did indicate that the Ballinamore site has a greater number of considerably smaller fields. This suggests that analysis of field size elsewhere could provide information on recharge potential - although it is recognised that land division in certain regions of Ireland is historically a function of inheritance, and therefore may not always be related to the physical characteristics of the land.

FLOOD STUDIES REPORT

For this research project, it was suggested that a design flood flow for a return period equal to the bank-full capacity of a river could be estimated using the Flood Studies Report procedures (Natural Environmental Research Council, 1975). The Flood Studies Report (FSR) is applicable to Ireland because the procedures were derived from statistical analysis of all available precipitation and streamflow data in the United Kingdom and the Republic of Ireland. The estimated bank-full capacity can therefore be assumed to be a runoff parameter and can be used as a hydrological response to compare different catchments - a larger bank-full design flood flow per unit area implies a greater runoff, less infiltration and hence less potential recharge. This hydrological response can also be used to further validate the drainage density analysis.

The FSR procedure of particular interest is the estimation of mean annual flood from catchment characteristics. This was developed to give preliminary flood estimates where no streamflow records exist and hence can be applied to any area of interest, such as those already discussed. Where the catchment is ungauged, the mean annual flood is estimated by using an appropriate regional equation which requires a measure of several catchment characteristics. These are measured on topographical maps and taken from maps compiled in the FSR. The mean annual flood can then be used to obtain the required design flood flow (i.e. bank-full capacity in this instance) from regional curves.

The catchment characteristics equation used for the research is as follows:

$$Q = 0.0172\ \mathrm{AREA}^{0.94}\ \mathrm{STMFRQ}^{0.27}\ \mathrm{S1085}^{0.16}\ \mathrm{SOIL}^{1.23}\ \mathrm{R_{SMD}}^{1.03}\ (1 + \mathrm{LAKE})^{-0.85} \qquad (1)$$

where Q is the mean annual flood, AREA is the site/catchment area (km^2), STMFRQ is stream frequency in junctions per km^2, S1085 is main stream slope between 10 % and 85 % of its length from the catchment discharge point (m/km), SOIL is an index determined from five soil types, R_{SMD} is a measure of the rainfall (mm) and LAKE is an index of lake area as a proportion of total area.

Further to this equation, modifications have been made which make this procedure more appropriate for smaller catchments, i.e. less than 20 km^2 (Wilson, 1990). The sites studied are significantly less than this (Drumree is 3.95 km^2 and Clonymeath is 17.01 km^2, Ballinamore and Rathdowney are both slightly smaller than 1 km^2) and hence two of these modified equations were also applied:

$$Q = 0.00066\ \mathrm{AREA}^{0.92}\ \mathrm{SAAR}^{1.22}\ \mathrm{SOIL}^{2.0} \qquad (2)$$

$$Q = 0.0288\ \mathrm{AREA}^{0.90}\ \mathrm{R_{SMD}}^{1.23}\ \mathrm{SOIL}^{1.77}\ \mathrm{STMFRQ}^{0.23} \qquad (3)$$

where SAAR is the mean annual rainfall (mm).

To date, the mean annual floods have been estimated for the Clonymeath, Drumree, Ballinamore and Rathdowney study areas. As shown in Figure 3a below, the Clonymeath and Drumree catchment results were compared to the averaged annual peak of the recorded streamflows using all available streamflow data (1978-1983 and 1979-1987 for Clonymeath and Drumree respectively), in order to establish whether these equations are an appropriate estimation. For the Clonymeath catchment, equation (1) gives the best estimate of mean annual flood although equation (2) is a better estimate for the Drumree catchment. At this stage, it is thought that because the Clonymeath catchment is approaching the 20 km^2 size, equation (1) might be more appropriate. The Drumree catchment, on the other hand, is considerably smaller than this threshold and hence the modified equations would be more suitable.

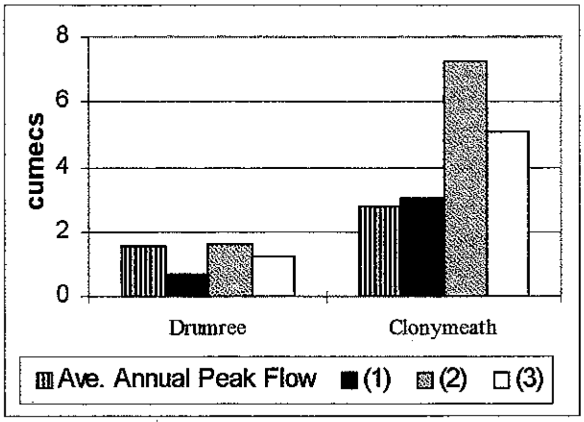

Figure 3a Streamflow and FSR equation results for Clonymeath and Drumree catchments.

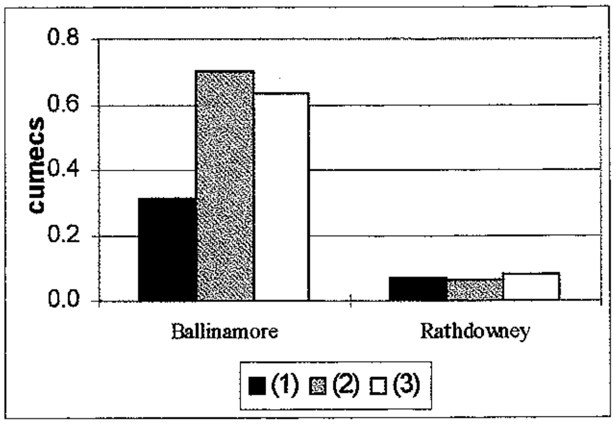

Figure 3b FSR equation results for Ballinamore and Rathdowney sites.

Comparisons of the equation results between the Ballinamore and Rathdowney sites are shown in Figure 3b. All three equations indicate that there is a higher estimated mean annual flood for the Ballinamore site which also has a higher artificial drainage density. Unfortunately, there are no actual streamflow data for these sites to use as a comparison.

DISCUSSION AND CONCLUSIONS

The results of the research project to date indicate that groundwater recharge, drainage density and FSR catchment characteristics equations are potentially useful as secondary indicators of groundwater vulnerability. Groundwater recharge estimates using a soil moisture balance or baseflow index are limited to catchments that have the necessary meteorological and streamflow data. A further limitation is that hydrometric catchment boundaries rarely coincide with geological boundaries, making the interpretation of results more problematic. The stream density and artificial drainage density indicators have the limitation that they cannot be applied to flat, low-lying areas with shallow water tables. The preliminary results of the FSR catchment characteristics procedures suggest that they can be used to validate other potential indicators. As this stage however, it is recognised that the FSR equations are not necessarily appropriate for very small areas (less than 1km^2), hence their applicability may only be in qualitative terms. This may limit their usefulness for this research.

The different approaches described in the paper are applicable at different scales. The soil water balance and baseflow index approaches can be applied at the catchment scale, although individual catchments could be amalgamated for regional analysis. The stream density assessments are also applicable at the catchment or regional scale. The artificial drainage density approach, on the other hand, is more suitable for the field to catchment scale. It is therefore concluded that assessments of drainage characteristics could usefully be incorporated into the present groundwater vulnerability mapping programmes at the field scale. In contrast, assessments of groundwater recharge and stream density are potentially useful to confirm the broad vulnerability classification at the regional scale of map production (1:50,000).

Finally, it should be emphasised that water balance and drainage characteristics can only be considered as *secondary* indicators of groundwater vulnerability. They are not intended for use as mapping tools on their own. Rather, any mapping methodology that incorporates these secondary indicators should also encompass other relevant data such as particle size distributions of the subsoil, standardised subsoil descriptions, permeability values, topographical observations such as geomorphology, elevation and slope and ecological indicators.

FURTHER RESEARCH

It is planned to carry out further research on the use of drainage and runoff as secondary indicators of groundwater vulnerability. This research will include:

1. Soil moisture water balance and stream baseflow assessments for an area of sand and gravel deposits with a high groundwater recharge potential, for comparison with the results from the relatively low permeability sites described in this paper.
2. Stream density analyses for (i) further sites with moderately well drained and poorly drained soil types, (ii) sites with excessively well drained and well drained soil types, and (iii) sites of various soil type where a correlation with streamflow data is possible.
3. Drainage density analysis in areas of uncertain recharge potential.
4. Completion and application of the FSR catchment characteristic procedure to the areas of further research, highlighted above.

As briefly mentioned in the introduction, other on-going research includes the assessment of ecology, and more specifically, vegetation indicators of groundwater vulnerability. This will be undertaken in conjuction with the further research outlined above.

Another potential area of research, which is outside the scope of the current programme, is the use of satellite imagery for mapping secondary indicators of groundwater vulnerability. The European CORINE (Co-ordination of Information on the Environment) land-use database (Cruickshank, 1997) had been identified for use in the present project, but the land-use categories are considered to be too broad for mapping groundwater vulnerability at the scale required. However, other remotely sensed data may prove useful in future vulnerability assessments.

ACKNOWLEDGEMENTS

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Paper No. 10.

Groundwater & Surface Water Relationships in Karst Terrain.

Dr. Catherine Coxon & Dr. David Drew, Trinity College Dublin.

GROUNDWATER AND SURFACE WATER RELATIONSHIPS IN KARST TERRAIN: SOME IRISH EXAMPLES

Catherine Coxon[1] **and David Drew**[2]

1. Department of Geology, Trinity College Dublin
2. Department of Geography, Trinity College Dublin

ABSTRACT

In karst areas, the linkages between groundwater and surface water are highly intricate. The occurrence of point recharge and of conduit flow through the karst aquifer can make the distinction between surface and groundwater an arbitrary one, and the high degree of interaction means that surface water quality and groundwater quality are closely interrelated. This situation is seen in the western limestone lowlands of Ireland, where rivers, lakes and turloughs provide line and point recharge to the aquifers, and equally groundwater discharge provides major inputs to surface waters. Surface water contaminants enter the aquifer via sinking streams, while rapid transfer through the aquifer by conduit flow means that groundwater contaminants may in turn be discharged into surface waters. Water resource management in such areas must take these close linkages into account; the delineation of groundwater source protection zones poses particular problems where extensive partially contributing areas are present.

INTRODUCTION

The importance and complexity of groundwater – surface water interactions is increasingly being recognised in all hydrogeological situations (Brahana *et al.*, 1998; Winter *et al.*, 1998). It is arguably in karst areas that this interaction reaches the greatest degree of intricacy, and where its practical significance to water resource managers is paramount. This may seem a surprising assertion, as a classic feature of karst environments is the absence of surface water, with virtually all excess precipitation being quickly converted to recharge and discharging primarily from springs. (In an Irish context, the Burren plateau with its water shortages springs to mind). However, many regions which are regarded as being at least partially karstic contain surface hydrological systems of rivers and lakes occurring on the limestone, and not just sinking streams originating on other adjacent rock types. Internationally, such areas would include much of central Florida, the karst of Puerto Rico and large areas of southern China, while in an Irish context, the extensive limestone lowland of south-east Mayo, Roscommon, east Galway and east Clare illustrates the phenomenon.

The existence of an efficient subterranean karst drainage network together with a surface drainage pattern often leads to complex interactions between the two hydrological systems. In areas with highly developed karst conduit drainage the effect is comparable to the simultaneous presence of both a surface and an underground fluvial system. The hydrological interaction results in a close interrelationship between surface water and groundwater quality. Contaminants usually associated with surface waters, which would not normally enter aquifers by diffuse recharge, may enter karst conduits from sinking streams. Equally, the rapid throughput and lack of attenuation in the karst aquifer mean that groundwater contaminants may emerge at springs and contaminate surface waters to a greater degree than in other aquifer types. In this paper, these interactions are illustrated using examples from the karstified lowland limestone of the west of Ireland, and the implications for water resource management are discussed.

THE STUDY AREA

The region and specific study areas described in this paper (Figure 1) consist of a lowland (5-50m above sea level) covering approximately 6000 km^2 in counties Galway, Clare and Mayo. The bedrock is Lower Carboniferous limestone. Over much of the area, it corresponds to the Burren Formation: a pure bioclastic calcarenite which contains no primary permeability, but is well-bedded and jointed so has extensive secondary permeability and is susceptible to karstification. Impure limestones of lower permeability are also found, particularly to the east of the area in Figure 1. In the south, the limestone occupies a lowland corridor between Upper Carboniferous shales and sandstones to the west and the Devonian sandstone of the Slieve Aughty mountains to the east. The region is blanketed in Quaternary deposits of very variable composition and thickness (Drew & Daly, 1993). The eastern part of the area in Figure 1 has glacial deposits several metres thick, and areas of basin peat. Although there are many local variations, generally the deposits are less than three metres thick in the centre and west of the area, and in places, rendzina soil directly overlies the pure limestone.

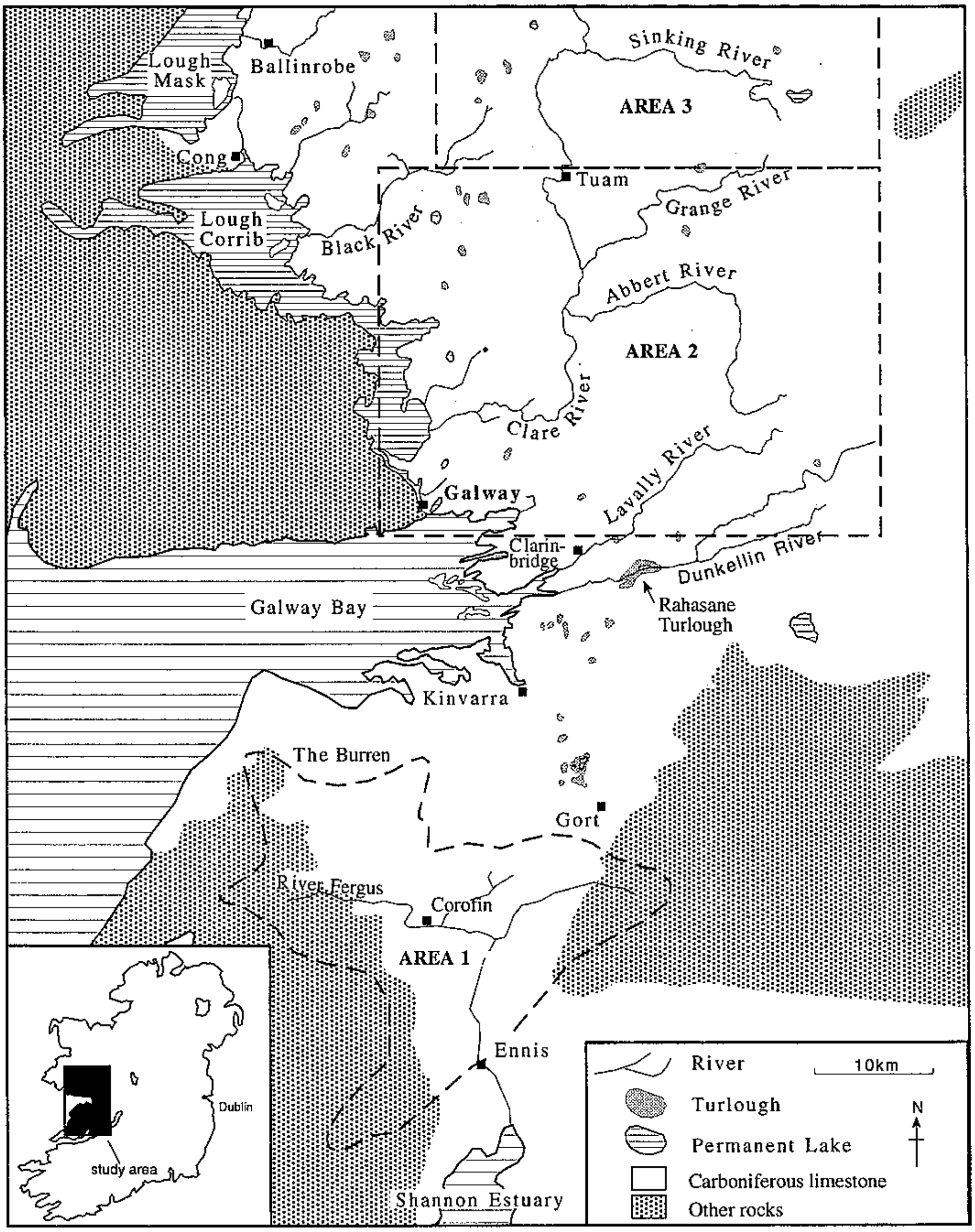

Figure 1. The location of the study area

THE HYDROLOGICAL SYSTEMS

INTERCHANGES OF WATER AND DIFFICULTIES IN CATCHMENT DELIMITATION

The bedrock and Quaternary geology influences both the surface water and groundwater hydrology. Over much of the area, where the pure limestone coincides with a thin Quaternary cover, the two hydrologic systems are completely intertwined. Arterial drainage has affected the area since the mid nineteenth century, linking lakes and turloughs and creating wholly new river systems. However, under low stage conditions groundwater flows revert to what was presumably their natural condition prior to drainage and the artificial channels cease to relate with groundwater and become dry.

Area 1, the Fergus catchment, is described at greater length elsewhere (Coxon, 1995; Coxon & Drew, 1998). The tortuous river course southwards across the lowland towards Ennis (Figure 2) includes some artificial stretches created by drainage engineers in the nineteenth century. However, a significant proportion of the river flow does not follow the whole of this above-ground course, but takes a series of short-cuts from swallow holes in the river bed and lake shores to springs which feed the river further down-catchment (see Figure 2.b). Underground velocities along these routes vary from c. 20 m/hr along west - east routes to c. 100-200 m/hr along north - south routes. These rapid velocities indicate a high degree of karstification, particularly given the low hydraulic gradients (of the order of 1m/km).

Further north, groundwater flow from east to west cuts across surface catchment boundaries (Drew, 1992; Drew & Daly, 1993). In Area 2 (Figure 3), water passes underground from the Abbert river (a tributary of the Clare river) out of the Clare surface catchment to springs at Aucloggeen which flow directly into Lough Corrib. In Area 3 to the north (shown in Figure 4), not only are there underground linkages within the Clare river catchment (with water passing from an influent reach of the Sinking River catchment to a spring feeding the main Clare river), but there is also an interbasin transfer of water to the headwaters of the Black river catchment. Again, these underground transfers are by rapid flow in karst conduits or solutionally widened fissures; for example, water sinking at Ballyglunin passes to Aucloggeen springs at a velocity of 200 m/hr.

The close linkages between surface water and groundwater mean that lake and river catchments in this area cannot be defined solely on the basis of surface topographic divides, but must take groundwater inputs and outputs into consideration. Equally, the catchment areas of springs cannot be defined by conventional hydrogeological means. The surface catchments of influent and sinking rivers contributing to spring flow must be taken into account. Karst groundwater flow may transfer water between surface catchments: a spring in one river catchment may receive water from a sinking stream in another catchment. Also, the catchment upstream of a swallow hole or influent reach may only contribute part of its flow to the spring, and the proportion of water passing to the spring may vary at different times of year and different water levels. This problem is illustrated below with reference to a number of case examples.

DELIMITATION OF SPRING CATCHMENT AREAS

Drumcliff springs

Tracing experiments enabled the catchment boundary of Drumcliff springs (S1 in Figure 2) to be defined with a reasonable degree of certainty. It covers an area of approximately 60 km^2 (area 1 in Figure 2.a). However, the area does not always drain solely to Drumcliff springs; at times of higher water levels, not all of the Ballygriffy river water sinks at SH1 but some passes overground to the River Fergus. Also at times of high water levels, some of the water sinking at SH1 passes to a small ephemeral spring located 250 metres to the south of Drumcliff springs. Thus Area 1 does not contribute all of its water to Drumcliff springs at all times.

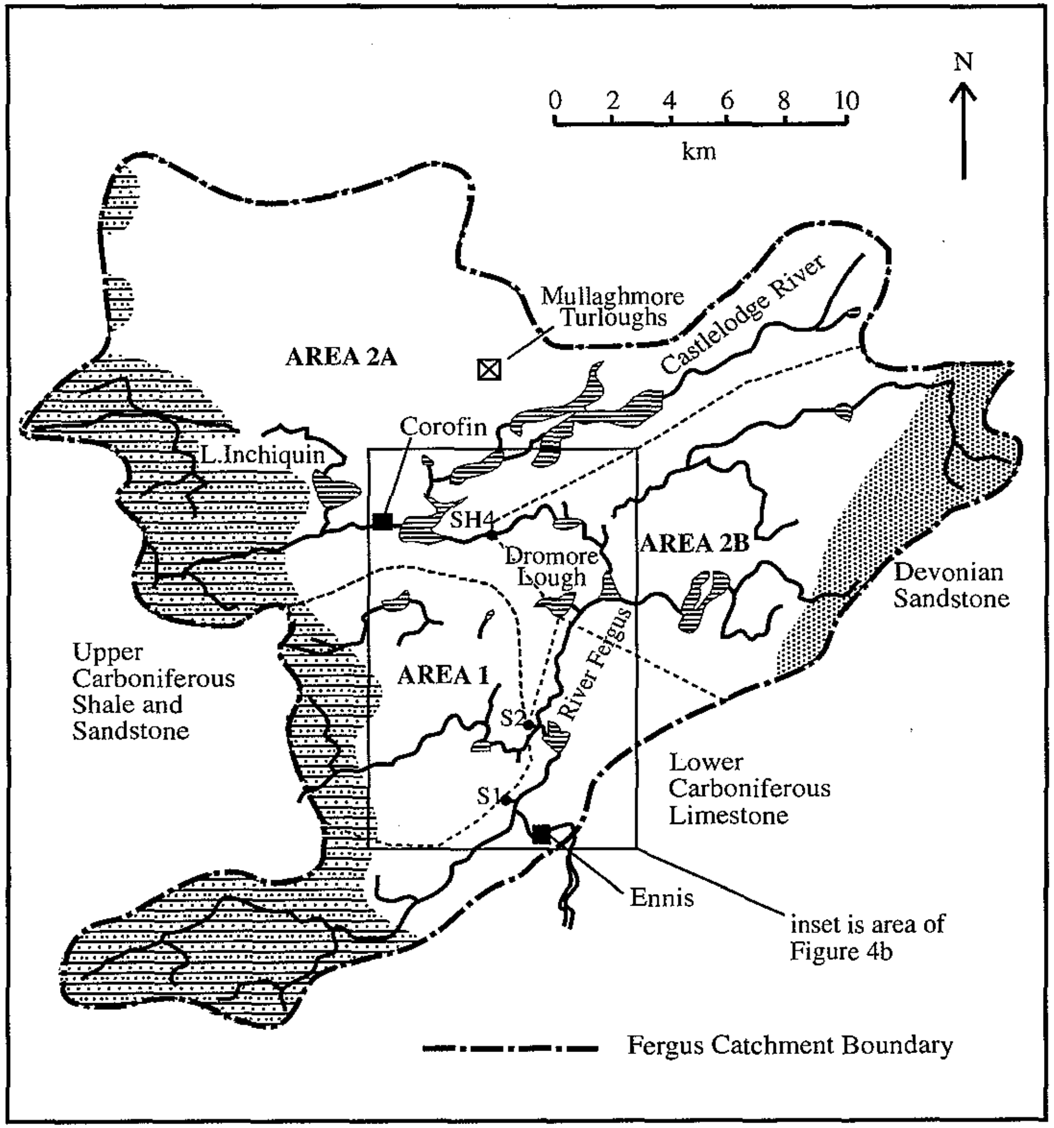

Figure 2a. The Fergus Catchment

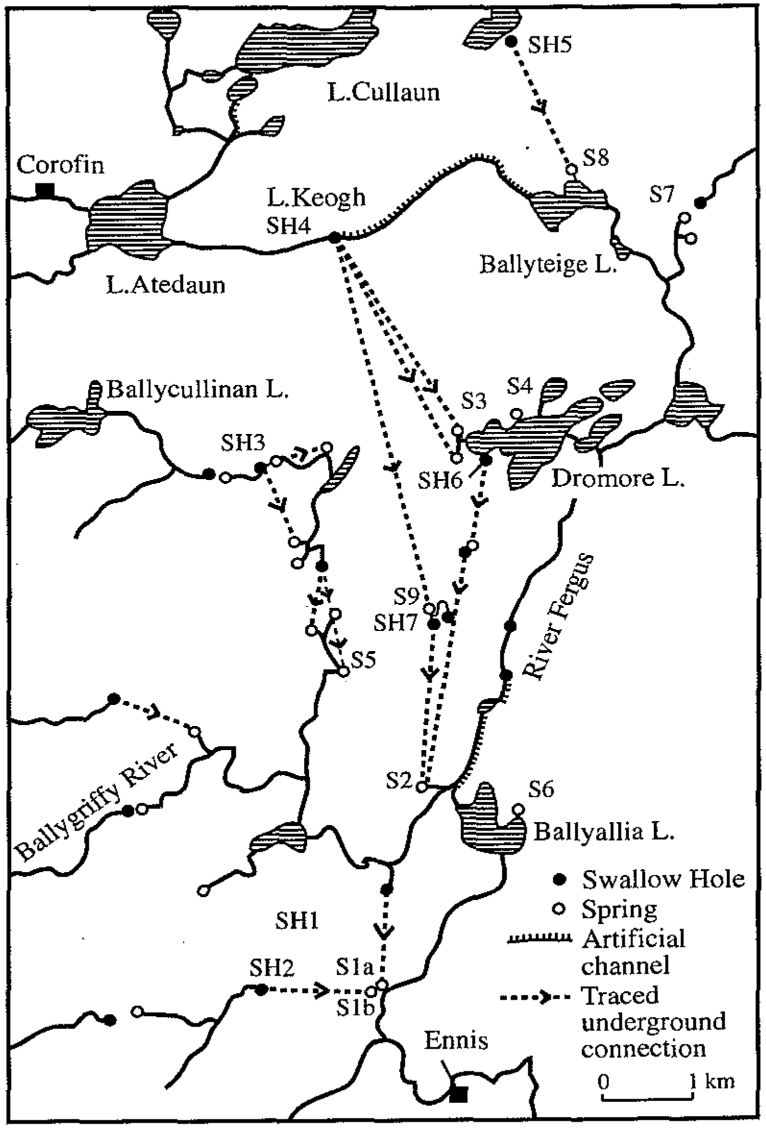

Figure 2b. Springs, swallow holes and underground connections

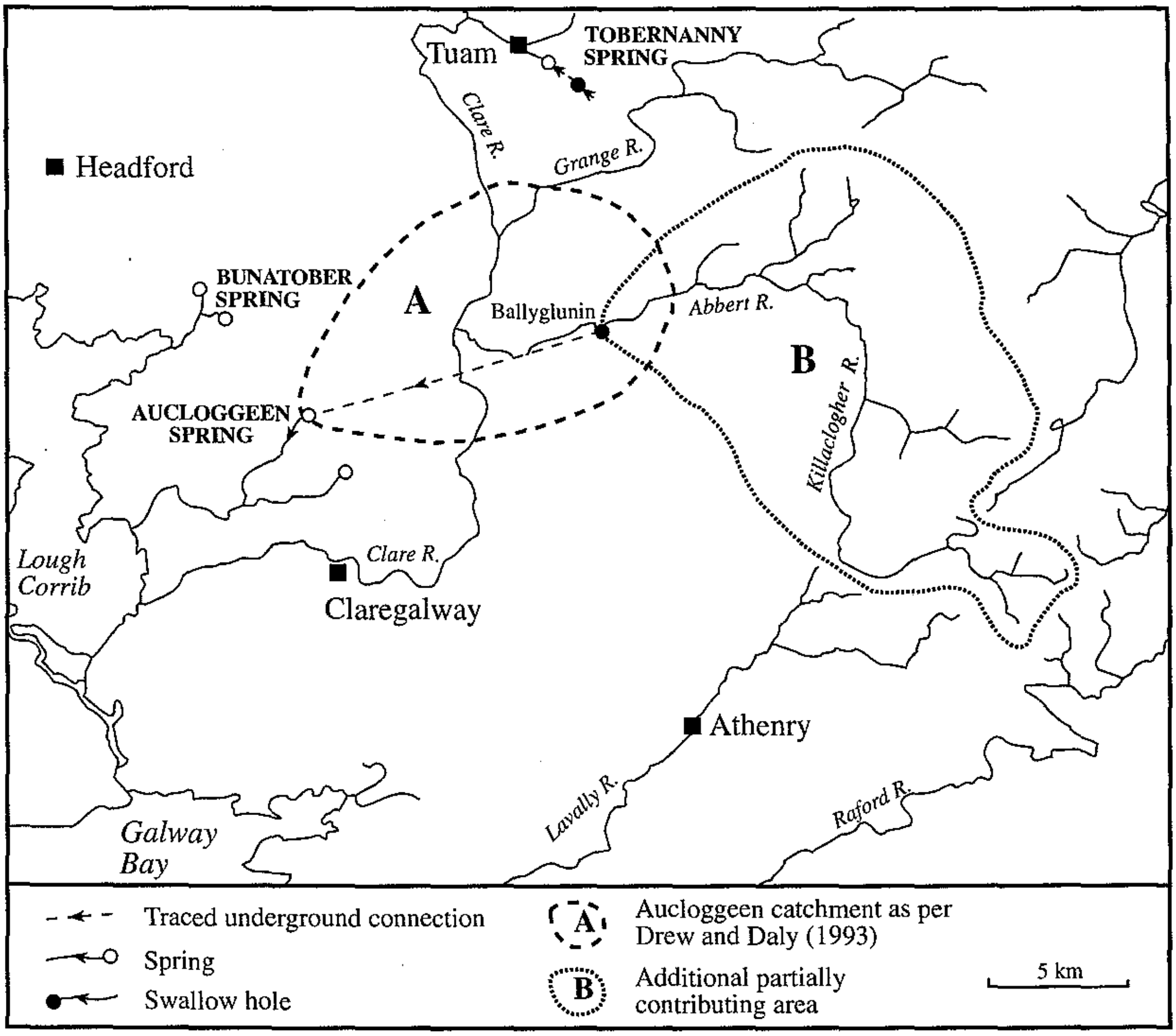

Figure 3. Aucloggeen spring catchment (Area 2 on Figure 1)

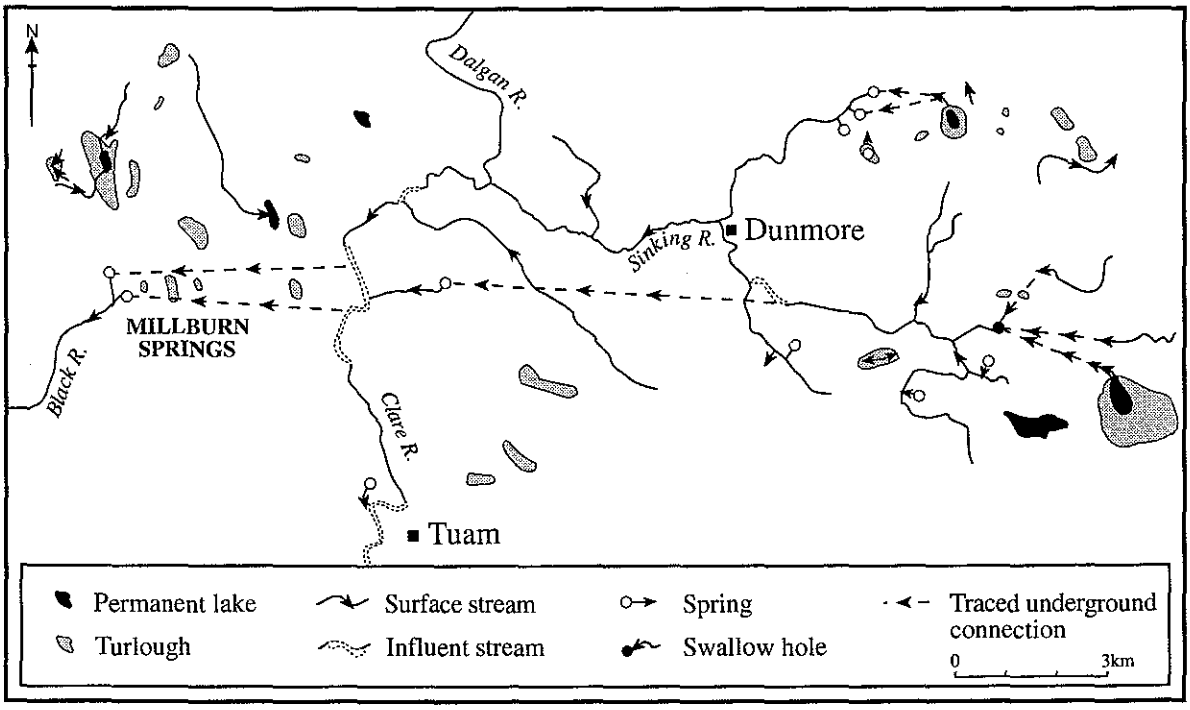

Figure 4. Part of Milburn spring's catchment (Area 3 on Figure 1)

Pouladower spring

This issue of catchment areas contributing only part of their flow to a spring is even more significant in the case of Pouladower spring (S2 in Figure 2). This spring is fed by Fergus river water sinking at SH4, 7 km to the north, which in turn is fed both by the Castlelodge river draining the lowland to the north, and by a large part of the Burren plateau (see Figure 2.a). Thus the catchment area of S2 is of the order of 250 km^2 (area 2A in Figure 2.a), yet the spring accounts for only part of the flow from this area, the remainder passing along an artificial surface channel to Ballyteige Lough. Furthermore, the channel between the River Fergus and Dromore Lough takes flow in either direction depending on relative water levels, and on occasions when water flows from the Fergus river into Dromore Lough, this means that a further 130 km^2 (area 2B in Figure 2.a) could contribute part of its flow to Pouladower via the swallow holes in Dromore Lough.

Aucloggeen spring

The catchment of Aucloggeen spring as delimited in Drew and Daly (1993) is shown as area A in Figure 3. This catchment boundary was based on a combination of tracing test results and a calculation of the recharge area required to generate the spring flow. However, the fact that Abbert river water leaking into Ballyglunin Cave passes to the springs means that the Abbert river catchment upstream of Ballyglunin (area B in Figure 3) can also be regarded as part of the Aucloggeen catchment. However, again this is a partially contributing area only; a varying proportion of the flow of the Abbert river continues on its surface course to join the Clare river.

Millburn springs

The springs at Millburn and Kilshanvy form the headwaters of the Black River, which flows south-west to Lough Corrib (Figure 1). Water sinking from the Clare River in the vicinity of Liskeevy Bridge has been traced to these springs (Figure 4). Thus the spring catchment includes a very extensive partially contributing area upstream of this point. Part of this area is shown in Figure 4: water from the Sinking River reaches this influent zone of the Clare river by both surface and underground routes. In addition, the catchment extends northwards to encompass the catchment of the Dalgan river, which joins with the Sinking River to form the Clare River. In total, approximately 400 km^2 drains to the influent reach feeding Millburn springs. As with the examples above, a varying amount of the river water sinks underground; in the summer, the river loses approximately 30% of its flow in this reach.

WATER QUALITY INTERACTIONS

INTRODUCTION

The distinctive nature of karst aquifers has important implications for both groundwater quality and surface water quality. Karst aquifers are particularly vulnerable to contamination due to a number of factors including the presence of an epikarstic zone and the existence of both conduit and diffuse flow within the aquifer, but a particularly critical factor is the occurrence of point recharge. Surface water contaminants (both natural and anthropogenic) many enter the aquifer via sinking streams, while the rapid transfer through the aquifer by conduit flow and the consequent lack of attenuation means that groundwater contaminants may in turn be discharged into surface waters.

The contaminants entering and passing through the karst aquifer may include substances not normally associated with groundwater contamination. For example, suspended sediment may not only cause problems of turbidity in water supplies but may also provide a method of entry for strongly sorbed materials which would otherwise remain within the soil zone. The interdependence of surface water quality and groundwater quality in the western Irish karst lowland is illustrated by a range of examples below.

INFLUENCE OF SURFACE WATERS ON GROUNDWATER QUALITY

Chemical quality of the groundwater in this region is generally good, and the problems that arise are often of natural rather than anthropogenic origin. For example, in a number of springs and boreholes in the lower Fergus catchment, iron concentrations, turbidity and colour are periodically above acceptable levels (Coxon & Drew, 1998). This appears to be due to high iron concentrations in swallow hole recharge waters derived from the shale and overlying blanket peat to the east of the area. Another groundwater source where similar problems have arisen is in Tobernanny spring, which provides the supply to the town of Tuam (Figure 3). This spring has severe discoloration and iron concentrations exceeding 5 mg/l under high water conditions (when peaty water sinking in a swallow hole contributes *c*.50% of spring outflow), but it is of potable quality under medium to low flows (when the swallow hole water contribution drops to 1% of spring outflow) (Drew, 1992).

Surface water inputs to groundwater may also carry contaminants of anthropogenic origin. Faecal microoganisms are the greatest water quality problem in this region (Aldwell *et al.*, 1988). This problem is by no means always related to surface water inputs, with microorganisms gaining entry in many instances by subsurface effluent disposal (from septic tank systems or pits holding animal wastes). However the entry of contaminated surface waters and their free passage along conduits and solutionally widened fissures undoubtedly aggravates the problem. For example, in the lower Fergus catchment, bacterial quality of untreated groundwaters is generally unsatisfactory, and problems are particularly acute in the springs (Coxon & Drew, 1998). It may be noted that while the public water supplies are chlorinated, private domestic and farm groundwater supplies in the area do not generally undergo any treatment.

INFLUENCE OF GROUNDWATER ON SURFACE WATER QUALITY

The water chemistry of lakes and turloughs, which influences their ecology, is highly dependent on the surface water-groundwater relationships. In the Gort – Kinvarra area (Figure 1), lakes fed in whole or part by allogenic water either by surface input or via karst conduits have inflows that are sediment rich, acidic and variable in temperature in comparison with lakes fed by shallow epikarst water or karst springs (Southern Water Global, 1998). Over much of the wider study area, turlough water originates as groundwater entering via springs or estavelles, and calcite deposition in the turloughs occurs following loss of carbon dioxide from the inflowing groundwater (Coxon, 1994). The trophic status of groundwater–fed lakes and turloughs is controlled by the nutrient content of the inflowing groundwater. Phosphorus concentrations in groundwater in this region and their input to surface water are discussed at greater length by Kilroy *et al.* (1999, this volume).

Another parameter more usually associated with surface waters than with groundwaters, which has given rise to problems in karst groundwater discharges, is suspended sediment. For example, under very high flow conditions Bunatober spring in Co. Galway (Figure 3) contains high concentrations of suspended silt, which appear to be derived from infilled karst depressions and caverns 5-8 km to the north. The spring supplies a salmon hatchery, and on one occasion the suspended sediment concentration of 5 mg/l caused a high mortality among the young fish. (Drew, 1992).

WATER RESOURCE MANAGEMENT ISSUES

GROUNDWATER MANAGEMENT

The management of groundwater resources and groundwater supplies in karst areas such as those described in this paper must take account of the close interaction with surface water. This is particularly the case with spring waters, since in many instances these are fed at least partly by point recharge from sinking streams, passing rapidly through the aquifer by conduit flow. Even where the point recharge forms a small proportion of the spring flow and so is relatively unimportant in quantitative terms, it may be of considerable concern in relation to groundwater quality. Conduit flow allows rapid contaminant transfer through the aquifer, with minimal opportunity for attenuation by adsorption, ion exchange, chemical breakdown or microbial die-off. For example, Aucloggeen springs (Figure 3), which provide a group-scheme water supply, are reached by water from the Abbert River within 48 hours, while at Drumcliff springs, which provide the water supply for the town of Ennis and its environs, there is a time-lag of only 7-9 hours between swallow hole SH1 and the springs (Figure 2.b). Short underground residence times mean that very little time is available for remedial action to avoid contamination of drinking water supplies, and an early warning system to enable shutdown of the supply may be required. Such a system (based on continuous monitoring of rainfall and groundwater levels) has now been put in place at the Bunatober salmon hatchery supply mentioned above. Thus managing such supplies is often more akin to management of surface water abstractions than of conventional groundwater sources.

Standard Irish procedures for groundwater source protection (Daly & Deakin, 1996) involve the designation of an inner source protection area (SI), bounded by a 100 day travel time within the saturated zone, and an outer source protection area (SO), with an outer limit corresponding to the boundary of the catchment or contributing area (with zones of varying intrinsic vulnerability being identified within these areas). In a karstic situation with underground residence times of hours or days along certain flow routes through the aquifer, the designation of a 100 day travel time limit is not feasible, and such karst spring supplies should be viewed as more comparable to surface water abstractions than to groundwater abstractions. However, the delimitation of the catchment area supplying the spring is clearly desirable, yet this too poses problems.

The issue of partially contributing areas has already been outlined with reference to four springs. In the case of Aucloggeen springs, the partially contributing catchment of the Abbert River, i.e. an area of *c.*160 km^2 (area B in Figure 3) needs to be taken into account in addition to the direct contributing area (area A in Figure 3). At Pouladower spring, an even more extensive area of *c.*380 km^2 (areas 2A and 2B in Figure 2.a) could potentially impact on the springs, although the spring flow accounts for only a small proportion of total recharge in this area. Clearly some modification of the standard protocols for source protection zonation is required in such instances. Vulnerable areas in the furthest reaches of the upper catchment pose less of a risk to the spring than areas of similar vulnerability close to the source, not only because of the greater distance involved, but also because only a proportion of the contaminated water will pass underground to the spring. Nevertheless, the fact that a pollution incident in these areas could impact on the springs means that they cannot be ignored in a protection plan.

SURFACE WATER MANAGEMENT

Where surface water bodies are fed largely or entirely by groundwater, both water levels and quality can only be managed on the basis of a proper understanding of the groundwater hydrology and quality. Turloughs are a particular case in point. The seasonal flooding and emptying of turloughs gives rise to distinctive flood-tolerant grassland communities. The freshwater invertebrates are also distinctive and many turloughs are important winter feeding areas for ducks, geese and waders. The greatest threat to turloughs is posed by drainage schemes. In a national survey of turloughs (Coxon, 1987), it was found that a third of sites no longer flood to any significant degree due to drainage schemes carried out from the mid-nineteenth century to the present day. Turloughs have been identified as priority habitats under the E.C. Habitats Directive (92/43/EEC) and 43 turloughs have been proposed as Special Areas of Conservation under this directive, including several sites in the Gort-Kinvarra area (Figure 1). However, extensive flooding in this area during the winter of 1994/95, beyond the normal turlough flooding limits, which rendered many houses uninhabitable, brought calls for a drainage scheme to prevent flooding of agricultural land and dwellings. This resulted in the commissioning of a detailed hydrological study of the area (Southern Water Global, 1998), but the conflict between the practical need for flood prevention and the need to maintain turlough sites of international ecological importance has yet to be resolved.

Although the primary threat to turlough ecosystems is from changes to their hydrological regime, changes to the quality of inflowing groundwater could also have an adverse effect. This issue has arisen in relation to turloughs in the Mullaghmore area, within the Burren National Park, where it was proposed to site a visitor centre.. Because of concerns that nutrients released into groundwater from a proposed effluent treatment plant might enter the turloughs and change their trophic status, detailed studies of hydrology and water chemistry were undertaken. If any effluent discharges are permitted in future developments, they are likely to be severely constrained and closely monitored.

CONCLUSIONS

To summarise, karst areas have a high degree of interconnection and interaction between surface and underground waters, with the magnitude and direction of water interchanges varying over time. Water resource management in such environments must take account of this. It should be borne in mind that alterations to surface water systems commonly provoke immediate changes in the groundwater system, both in terms of water quality and quantity, and vice-versa. Also, when managing karst spring catchments, a strategy must be devised to deal with partial contributing areas of sinking or influent streams.

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Paper No. 11.

The Contribution of Groundwater Phosphorus to Surface Water Eutrophication.

Garrett Kilroy, Trinity College Dublin.

THE CONTRIBUTION OF GROUNDWATER PHOSPHORUS TO SURFACE WATER EUTROPHICATION

G. Kilroy, C. Coxon, N. Allott and K. Rybaczuk

Trinity College Dublin

ABSTRACT

The increasing degree of eutrophication currently being experienced in Irish surface waters has serious implications for the water quality and amenity value of lakes and rivers. Transfer of phosphorus (P) from soils to surface waters is currently receiving considerable attention both internationally and within Ireland. Research on this topic has highlighted the lack of knowledge on the proportion of P reaching rivers and lakes from different routes, and the need to quantify inputs from aquifers. In Irish groundwater studies, P has been overlooked primarily because the maximum admissible concentration for drinking water (5000 $\mu g\ l^{-1}$ P_2O_5 *or 2200* $\mu g\ l^{-1}$ *P) is rarely approached except in areas of gross localised contamination. In surface waters, however, the concern with P is at much lower concentrations. Recent data presented here has shown that P is found in some Irish groundwaters at concentrations that induce eutrophication in surface waters. Inclusion of P in groundwater analytical studies may be warranted in areas in close proximity to sensitive surface water bodies, and in areas with a high degree of karstification.*

INTRODUCTION

Recent investigations have identified eutrophication as the primary threat to surface water quality in Ireland (Bowman *et al.*, 1996; McGarrigle, 1998). Eutrophication, the enrichment of waters by nutrients, results in a deterioration in water quality and amenity value through excessive growth of algae and higher plants. Phosphorus (P) is the key nutrient which generally limits the growth of plants in freshwater. This is because P is generally the nutrient in shortest supply in freshwater and thus changes in P will have a direct effect on plant biomass. Therefore, an understanding of phosphorus loadings from all sources is crucial. Figure 1 indicates various pathways of P movement from land to water. Many investigations have examined phosphorus losses from land through overland flow and drainage waters. However, the least known and often neglected sources of phosphorus is via groundwater discharge at springs and in river baseflow. The objectives of this paper are to outline the factors that determine P concentrations in groundwater, to examine the current levels of P in Irish groundwaters, and to discuss its relevance in groundwater investigations.

SURFACE WATER QUALITY IN IRELAND

In Ireland, although there has been a decrease in the extent of seriously polluted river channels in recent years, there are increasing levels of less severe pollution, associated with eutrophication (with 5-fold and 3-fold increases in the length of slightly polluted and moderately polluted channel respectively between 1971 and 1994). Nutrient enrichment of Irish lakes is also a serious concern, with a recent survey showing 18% of lakes to have a strong to very high level of eutrophication (Stapleton, 1996).

Phosphorus in surface waters may arise from diffuse (non-point sources), chiefly agricultural activities, and from point sources, chiefly waste discharges from municipal and industrial waste treatment plants.

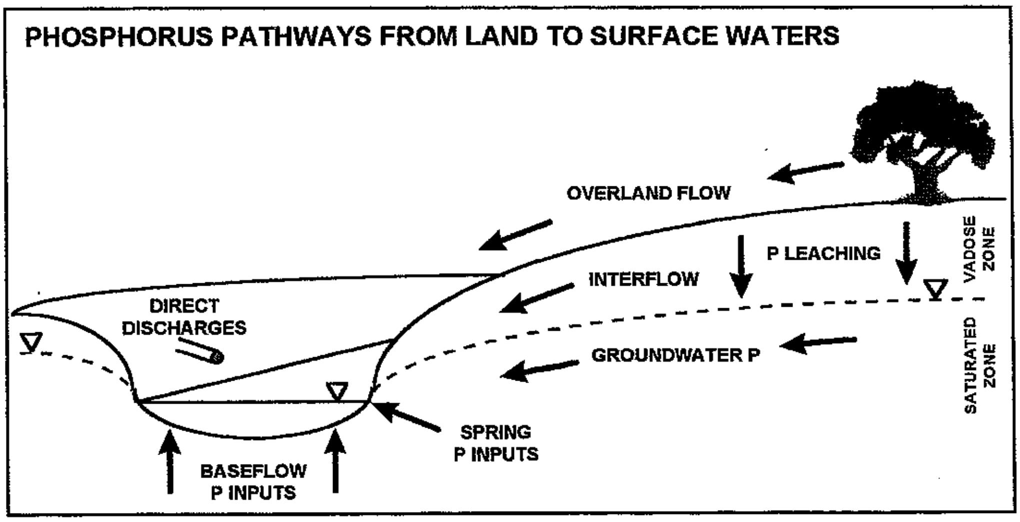

Figure 1 Phosphorus pathways from land to surface waters including groundwater inputs as spring and baseflow.

Due to both easier identification and control, considerable progress has been made to eliminate point source inputs of phosphorus. Legislation such as the Urban Wastewater Directive (91/271/EEC) is continuing to increase the degree of phosphorus removal from urban discharges through the upgrading of existing treatment plants and the provision of new plants. As a result, diffuse sources of P may be expected to be responsible for a larger share of water quality problems in the future. Agricultural sources of P include the landspreading of slurries and dirty water, application of inorganic fertilizers and manures, and farmyard runoff. Tunney (1990) estimated the P balance in Irish agriculture to be 77,296 tonnes of inputs and 31,255 tonnes of outputs. The surplus P either accumulates in the soil or is lost through transfers to aquatic ecosystems (Sharpley *et al.*, 1995).

CRITICAL LEVELS OF PHOSPHORUS

A number of fractions of P are commonly recognised in natural waters. Total P analysis is carried out on unfiltered, digested samples, whereas molybdate reactive P, or MRP (often referred to as orthophosphate-P) analysis is carried out on filtered, undigested samples. MRP is the most bioavailable component (i.e. most readily taken up and used in plant growth). However, total P is also important since it not only includes dissolved P, but also includes particulate P, which whilst been less bioavailable to plants can provide a long-term P source.

P has been a frequently neglected parameter in studies of groundwater chemistry. Except in very large quantities phosphorus does not pose a human health risk, and eutrophic conditions will not occur in groundwater because light is essential for algal growth. In Irish groundwater studies, P has been overlooked primarily because the maximum admissible concentration for drinking waters under Directive 80/778/EEC on the quality of water intended for human consumption (5000 $\mu g\ l^{-1}$ P_2O_5 or 2200 $\mu g\ l^{-1}$ P; Flanagan, 1992) is rarely approached except in areas of gross localised contamination. Indeed, the recently revised Directive on water intended for human consumption (98/83/EC) due to be implemented in 2003, does not contain any limit for P.

However, in surface waters the concern with phosphorus is at much lower concentrations. Total P concentrations in excess of only 20 $\mu g\ l^{-1}$ P may trigger eutrophication in some lakes (Champ, 1998). The flushing effect in rivers may provide them with greater protection to P loadings; however McGarrigle's (1998) study on national river data for the period 1991-1994 suggests that adverse impacts become apparent once unfiltered molybdate reactive phosphate levels exceed 30 $\mu g\ l^{-1}$. The recent regulations on water quality standards for phosphorus (S.I. No. 258 of 1998) set out a similar suite of target levels for rivers and lakes of varying trophic status in a national strategy to tackle surface water eutrophication.

Therefore, a dichotomy exists between regulatory levels required for groundwater P in terms of drinking water quality and the level of P required to induce eutrophic conditions in surface waters.

MOVEMENT OF PHOSPHORUS TO GROUNDWATER

Research into P losses from soil to water has concentrated on the overland flow pathway. This focus is not without legitimate reason. Phosphate is strongly adsorbed onto positively charged particles and can react with many cations, particularly calcium, aluminium and iron to produce relatively insoluble minerals (e.g. hydroxyapatite). Nonetheless, though strongly adsorbed onto soil, phosphate can show enhanced leaching to groundwater because in some circumstances the sorption capacity of the soil can be exceeded. The degree of saturation will be dependent on land use, soil type and phosphorus inputs (Breeuwsma & Reijerink, 1992). Other authors (e.g. Isenbeck-Schröter *et al.*, 1993) have emphasised precipitation of phosphate minerals as the key mechanism for limiting vertical distribution of P.

Leaching of P from soils has been identified in areas which have characteristics such as coarse textured soils (Eghball *et al.*, 1996), sandy soils with high permeability (e.g. Chen *et al.*, 1996), soils with low P sorption capacity (Breeuwsma *et al.*, 1995) and areas with shallow water tables (e.g. Grant *et al.*, 1996).

Increasing attention has been given to preferential flow as a mechanism for agricultural contaminants to reach groundwater. Movement through cracks in the soil, worm burrows and other macropores reduces the contact time between percolating water and soil and thus decreases the natural attenuation capability of the soil (Ryan, 1998). Several authors (e.g. Dils & Heathwaite, 1996) have suggested preferential flow as mechanism for P to bypass the soil's natural sorbing capacity.

Septic tank systems, whilst more indicative of point rather than diffuse sources, have provided some information on P migration rates. Robertson *et al.* (1998), in a review of phosphate mobility in septic tank plumes, report plume concentrations of 500-5000 $\mu g\ l^{-1}$ P and migration rates of one metre per annum in calcareous sand aquifers. Given the long-term use of septic tank systems and the minimum recommended set-back distance from surface water bodies of 10 metres (NSAI, 1991), even this highly retarded phosphate migration velocity may be of concern under certain circumstances.

PHOSPHORUS IN KARST SYSTEMS

Karst aquifers are extremely vulnerable to contamination due to a number of factors including the occurrence of point recharge, the presence of an epikarstic zone and the existence of both conduit and diffuse flow within the aquifer. Surface water contaminants (including phosphorus) may enter the aquifer via sinking streams, while the rapid transfer through the aquifer by conduit flow and the consequent lack of attenuation means that groundwater contaminants may in turn be discharged into surface waters.

Hardwick (1995) found elevated phosphate concentrations in cave recharge in Derbyshire that generally increased following applications of sewage sludge to the overlying field.

The threat by nutrients in silage effluent and artificial fertilisers has been identified in the Burren karst in western Ireland (Drew, 1996). The Burren is highly vulnerable to water pollution from this source because of its thin or absent soils and its highly karstified aquifers. Lowland karst areas where there is a close interaction between surface water and groundwater (Coxon & Drew, 1999, this volume) may also be vulnerable to P transfer via groundwater pathways.

PHOSPHORUS IN IRISH AQUIFERS

In order to examine phosphorus levels in a national context summary data from the Environmental Protection Agency's National Groundwater Quality Monitoring Program (NGQMP) were investigated. Mean orthophosphate-P levels in samples recovered between 1995 and 1997 from 189 sites were examined. The data are presented as a frequency distribution histogram in Figure 2. The data are positively skewed; 42% and 24% of the sites reported mean orthophosphate-P levels greater than 20 $\mu g\ l^{-1}$ and 30 $\mu g\ l^{-1}$ respectively. Whilst these concentrations are low from a drinking water point of view, they represent a potentially important input to susceptible lakes and rivers.

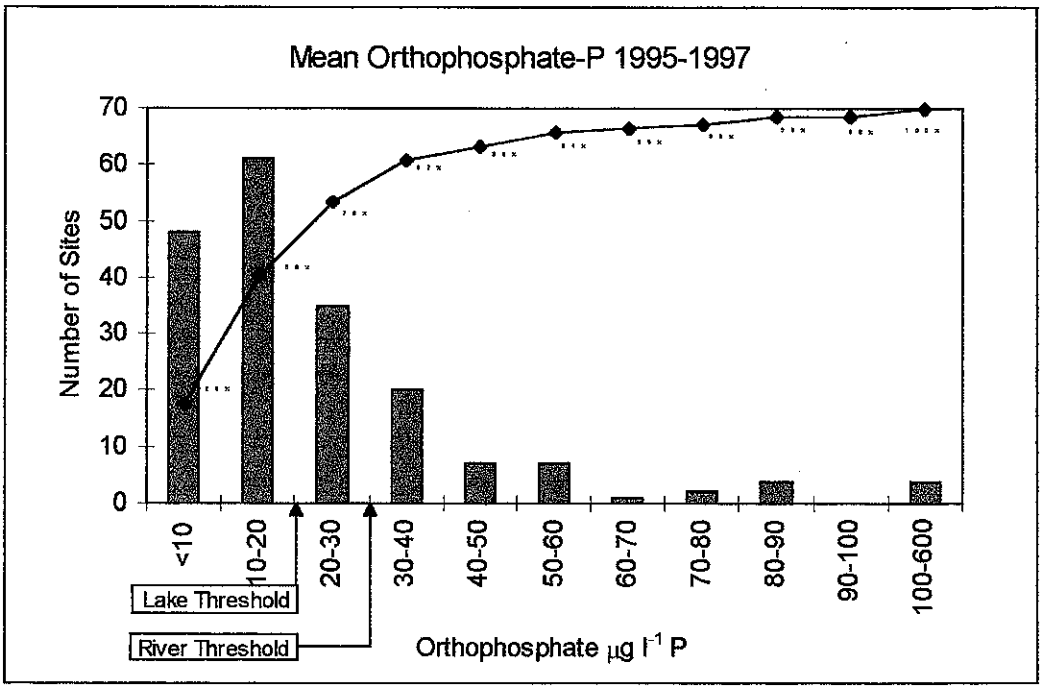

Figure 2. Irish national mean groundwater orthophosphate-P levels. Unpublished data from the EPA NGQMP. '%' denotes the cumulative percentage of sites counted for a given category. 42% and 24% of the sites have mean orthophosphate-P levels greater than the adopted eutrophication thresholds for lakes and rivers respectively.

As part of the authors' on-going research into phosphorus levels in Irish groundwater, sites in catchments in Co. Limerick (Deel and Maigue catchment), Co. Clare (Fergus catchment) and Co. Mayo (Robe catchment) were sampled between July and September 1998. A combination of boreholes, springs, dug wells and some associated surface water features were sampled. The samples were analysed for total P to ensure that both dissolved and particulate fractions were obtained. Table 1 lists summary statistics for the groundwater site types sampled during this period.

Table 1. Groundwater total P levels (μg l^{-1}) in Limerick, Clare & Mayo sites sampled between July and September 1998

Site Type	Mean	Median	Range	Std Dev	No. of Samples
Boreholes	132	23	<5 - 1814	349	78
Springs	32	27	<5 - 120	23	60
Dug Wells	23	14	<5 - 76	19	23

Greatest variability was apparent from boreholes, as indicated by the range and standard deviation of the data. Given the skewness of the borehole data, as reflected by the difference between the mean and median, the median may be a more accurate summary of borehole total P levels during this sampling period. Extreme total P values in these boreholes (one and two orders of magnitude greater than the level required for eutrophication) are of obvious concern. The spring and dug well data exhibited much lower variability and greater normality, perhaps indicating less susceptibility to point source inputs. It is unlikely that these extreme P borehole concentrations are indicative of diffuse contamination. It is more probable that they reflect gross localised contamination either directly at a poorly protected well-head, or through fissure flow to the borehole. However, more detailed site specific examination will be required to confirm this.

All the sites were revisited in February 1999 to examine seasonal variations in groundwater P. Figure 3 presents summer (July-September 1998) and winter data (February 1999) for all catchments as a frequency distribution histogram. Concentrations greater than 100 μg l^{-1} P were omitted from this analysis in order to focus on changes in diffuse inputs to groundwater.

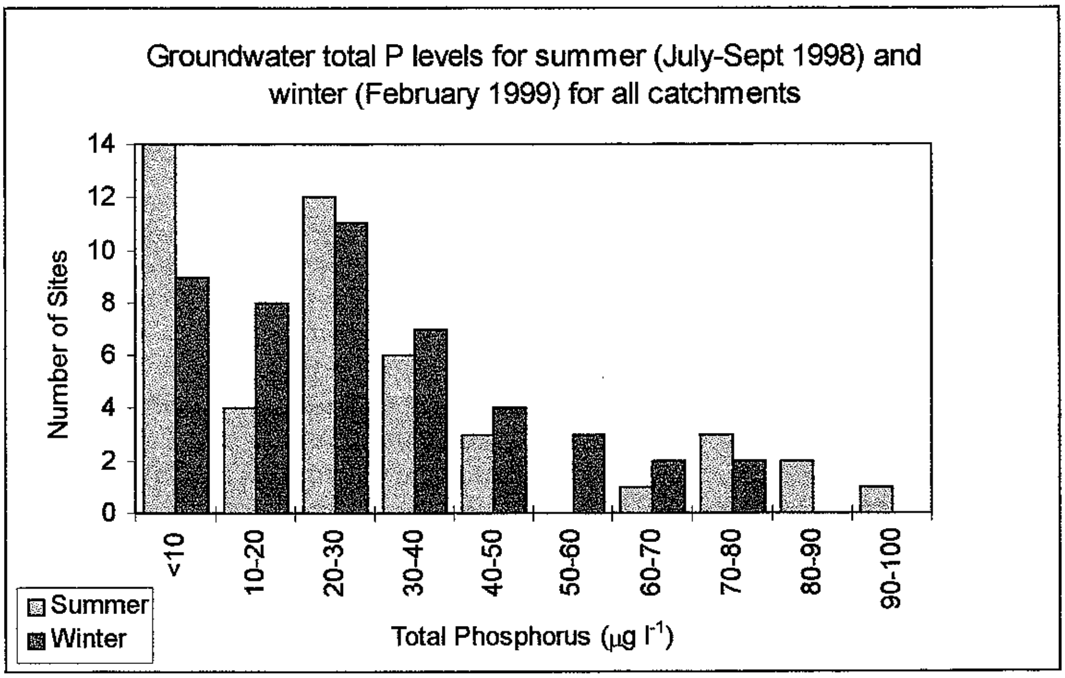

Figure 3 Groundwater total P levels in summer (light bars) and winter (dark bars). Sites with levels greater than 100 μg l^{-1} P were omitted to focus on diffuse groundwater P. Median values of 24 and 27μg l^{-1} P were obtained for summer and winter respectively.

Both summer and winter data exhibited skewed distributions. The median total P values for summer and winter were 24 and 27 μg l^{-1} P respectively. The overall distributions are similar, however, one would expect higher P in winter months due to greater recharge. It should be noted that the summer of 1998 was exceptionally wet and may have led to a smaller difference between winter and summer, thus direct comparisons in recharge terms may be difficult.

During the summer of 1998, 60% and 38% of these sites exhibited groundwater levels of total P greater than 20 $\mu g\ l^{-1}$ and 30 $\mu g\ l^{-1}$ respectively (the thresholds for lakes and rivers discussed above). These concentrations may be of concern in certain circumstances, particularly since these levels are present during the summer months when the risk of surface water eutrophication is greatest. One of the difficulties associated with examining diffuse inputs from groundwater to surface water is calculating loadings. It is hoped to carry out detailed hydrograph analysis and examination of river P data during periods of baseflow. These P concentrations during low flows will provide an indicative estimate of groundwater P loadings. However, potential point sources of P would need to eliminated before conclusions on baseflow inputs can be made.

CONTROLS OF PHOSPHORUS IN IRISH AQUIFERS

Some preliminary investigations were carried out on the Limerick sites to examine some of the hydrogeological factors controlling P in groundwater (Kilroy *et al.*, 1998). P levels from both the NGQMP and the authors' summer 1998 dataset were investigated in more detail using hydrogeological information from the Limerick Groundwater Protection Scheme and Geological Survey of Ireland (GSI) reports on groundwater source protection. Both datasets indicated several trends. Sites that were located on the more impervious gley soils were generally associated with lower groundwater P levels than sites on the more free draining brown earths and grey-brown podzolics. Increasing well depth, overburden thickness and unsaturated zone thickness resulted in lower P. Samples recovered from high and extreme vulnerability zones (as defined by the GSI Scheme) were generally above 20 $\mu g\ l^{-1}$ P. More detailed examination of hydrogeological and land-use parameters is required to better characterise situations which result in elevated groundwater P.

CONCLUSIONS

Current increasing instances of eutrophication has serious implications for the water quality and amenity value of Irish surface waters. P has long been a neglected parameter in groundwater studies. Conventional wisdom is that phosphorus is retained in the soil zone by adsorption and precipitation reactions, and has low mobility in groundwater; however, in some situations this may not provide complete attenuation. The data presented here has shown that P is found in some Irish groundwaters at concentrations that induce eutrophication in surface waters. However, further investigations are required to examine the extent to which this groundwater P is reaching surface water, and to characterise these situations where they exist. Inclusion of P in groundwater analytical studies may be warranted in areas in close proximity to sensitive surface water bodies, and in areas with a high degree of karstification. Hydrogeological contaminant studies need to consider the circumstances where groundwater-surface water interactions dictate a more important role to otherwise benign groundwater parameters like phosphorus.

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Paper No. 12.

Water Strategy for Kildare: The Consultants' Report.

Teri Hayes, K.T. Cullen & Co. Ltd.
Tommy Farrell, Nicholas O'Dwyer & Partners.

AN OVERVIEW OF WATER RESOURCES IN CO. KILDARE AND THEIR POSSIBLE EXPLOITATION INTO THE FUTURE.

***Note:** This paper gives an overview of some work completed as part of an unpublished consultants report "County Kildare Water Strategy Study".*

Mr. Tommy Farrell (Nicholas O'Dwyer Ltd.,)
& Ms. Teri Hayes (K.T. Cullen & Co. Ltd.).

ABSTRACT

The objective of the water strategy study is to develop a long term water supply strategy that will enable the demands of County Kildare to be met up to the design horizon of the year 2020. This entails formulating an effective policy to focus the direction of future investments. It is evident that, given trends of growth in the prevailing economic climate, particularly in the Greater Dublin Region, water is set to become an increasingly limited resource and prudent forward planning is imperative to avoid serious shortfalls in supply in the foreseeable future. A consultants report is being prepared for Kildare Co.Council by Nicholas O' Dwyer Ltd., and Patrick J. Tobin and Co. Ltd., K.T. Cullen & Co. Ltd and Professor Con Connane.

This paper briefly outlines the available surface water and groundwater resources in the county. The strategy when adopted will detail the management and proposed use of these combined resources.

INTRODUCTION

Based on the expected growth rates in the Kildare county as a whole and in particular in the greater Dublin region, future water resources are required. An overview of the existing water supply situation in County Kildare is presented in this paper. The existing sources (surface and groundwater) are discussed together with the procedure s undertaken for resource assessment.

Kildare is drained by the Liffey and Barrow rivers. The highest ground levels are on the eastern side of the county in the foothills of the Wicklow Mountains. The ground falls towards the Liffey Valley as the river flows westwards then north eastwards towards Dublin. A belt of undulating high ground extends westwards across the centre of the county and also from the Naas environs to the south of the county. The western regions are flat and relatively low lying, with the Barrow river controlling drainage in the southwest of the county.

EXISTING WATER SUPPLY SYSTEMS

At present, Kildare is heavily dependent on the River Liffey system for its water supply. The two major water sources are Ballymore Eustace Water Treatment and Leixlip Water Treatment Works which are shared with Dublin Corporation and Fingal County Council, account for approximately 80% of the water supply in the county.

The current total water demand in County Kildare amounts to approximately 52 MLD. The concentration of demand is heavily centred in the north east of the county around the major towns of Leixlip, Maynooth, Celbridge and Kilcock. The main centres of consumption in the central area are Kildare Town, Newbridge and Naas. There is relatively low demand along the western boundary of the county where only Athy and to a lesser extent Monasterevin and Rathangan, have significant consumption.

The remainder of the water currently in supply is acquired mainly from groundwater sources.
Existing County Council groundwater sources (29 in total) were assessed to determine their vulnerability and to supply information on aquifer yields. The parameters used in the vulnerability assessment consisted of geological control, well head protection, well construction, water quality data and proximity to contaminant sources such as roads, septic tanks etc. In summary the vulnerability assessment concluded that vulnerability ranged from four wells with extreme vulnerability to two wells with low vulnerability. Yields varied from 30 cubic metres per day to 1,137 cubic metres per day. The high vulnerability was found to be mainly due to poor well location in relation to contaminant sources and is not representative of the aquifers as a whole.

FUTURE DEMANDS

The assessment of the future demands of the area takes account of the high population growth rates being experienced. The growth trend is not evenly balanced across the county. The north east will experience the highest level of growth, followed by the central region, while the population in the remaining mainly rural areas are expected to remain relatively static. The current population is within the range of 139,000 and the design population for water provision in 2020 has been assessed in the range of 213,500 to 241,000. Taking into account other components of demand such as the institutional / commercial sector, industrial development, agricultural usage and losses, the total water required is anticipated to rise from the current 52 MLD to 93.7 MLD in 2020.

POTENTIAL SOURCES

Crucial to the advance planning of Kildare's water supply is the development of other major sources to alleviate the dependency on the River Liffey and to address a situation where demand will rise from 52 MLD to 93.7 MLD. In this Study, both surface water and groundwater resources were investigated to assess the potential for source development. Besides the requirement to find an additional 41.7 MLD during the period to 2020 to match demands, the potential sources need to be located within reasonable proximity of the main demand locations.

An assessment of the two major surface water in the region was undertaken, i.e. R. Barrow and the R. Liffey. Generally over 40 years of hydrometric data was considered together with an assessment of catchment interactions and an evaluation of current river water usage. The most viable new surface water source has been identified in the Study as the River Barrow which flows along the eastern boundary of the county from Monasterevin southwards past Athy. From the initial hydrological studies, the extraction potential is estimated as 0.5 m^3/s for a 50 year return period, corresponding to approximately 43MLD. Further localised gauging would be required to confirm these results. Prior to development a water rights order would need to be undertaken as governed by the Water Supplies Act 1942. Development of the River Shannon as a water supply for the greater Dublin region would be a major civil engineering project .

To evaluate potentially high yielding aquifers, existing yield information was compiled. Information was collated from the Geological Survey of Ireland well record and mineral exploration data, K.T. Cullen & Co. Ltd. in-house database and County Council data, A total of 391 data points were considered, However, data (in particular yield information) is sparse. Potential aquifer sources were identified from an assessment of overburden geology, bedrock geology and hydrogeological information.

In the groundwater investigations, the following bedrock and overburden aquifers were identified as potential sources,. Limited trial well drilling, pump testing and water analysis was undertaken to add to the existing yield and water quality data. More intensive field studies and geophysical investigations would be required prior to the design stage of any well field development.

(i) The Calp limestone in the north of the county around Longwood-Enfield and in the Edenderry area. Yields are quite variable , however yields of greater than 1 ML/d have been recorded at these locations. Groundwater from this aquifer is generally hard (300mg/l to 400 mg/l), with elevated iron and manganese common

(ii) The Allenwood Formation located around Monasterevin-Rathangan. Well fields in this formation in Portlaoise have yielded high quality water, between 2.35 ML/d and 4.4 ML/d. Known well yields in the area are 0.27-1.8 ML/d. Hard water is again common (300mg/l-400mg/l) with elevated iron and manganese noted in the Portlaoise well field.

(ii) The Rickardstown Formation around Naas is considered a lateral extension of the Waulsortian and Allenwood Formations. Wells developed at Osbournstown have been known to yield c. 1.0ML/d. Elevated Iron and manganese was again noted in the trial well sample.

(iii) The Blessington Gravels. Well records in the Blessington area have shown yields in the order of 0.5-0.6 ML/d. Gravel deposits can be over 30 metres thick but their distribution is quite variable.

(iv) The Naas .Gravels. The estimated yield from a dewatering project at Roberstown is 3.0 ML/d. Wells in the area are rare, with yield of 0.12- 1.0 ML/d recorded.

(v) The Curragh Gravels.- The Curragh is underlain by a great expanse of gravelly glacial deposits which extend extend beyond the Curragh to Nurney and Suncroft in the south, the Hill of Allen in the north and near Kilcullen in the east. Drilling undertaken as part of the Kildare By-pass project has shown these gravels extend to greater than 60 metres in the centre of a bedrock trough. Known single well yields range from 0.23 to 3.0 ML/d. The water is hard and generally unpolluted with a calcium and bicarbonate dominated chemistry which makes up some 80% of the mineralisation. The Curragh Aquifer clearly emerges as a groundwater resource of great potential. However any major water extraction development would require an extensive Environmental Impact Statement in view of the proximity of the highly sensitive Class I Habitat of Pollardstown Fen.

CONCLUSIONS

The River Liffey continues to be the major surface water resource for the Kildare and greater Dublin area. However, increased demand in the next two decades will require the development of new resources. This study has identified the River Barrow as a new water resource together with a number of groundwater resources.

A desk evaluation of the available yields and quality in the Kildare aquifers showed that baseline groundwater data is sparse. Quality and yield data is often not representative of the entire aquifer due to site specific pollution and yield requirements. Collating existing yield and quality data,, known geology and hydrogeology and the results of a limited trial well investigation, three bedrock aquifers and two overburden aquifers were identified as capable of sustainable development . More intensive field studies and geophysical investigations will be required prior to the location and design of any future well field development. Longterm pumptests and monitoring will be required to determine sustainable long term aquifer yield. Where groundwater extraction is planned to exceed 5ML/d an environmental impact assessment will need to be undertaken prior to development.

The Strategy Study has indicated that some surface water resources can be developed and that Co. Kilare has abundant undeveloped groundwater. It is clear that an integrated approach to the exploitation of both surface water and groundwater resources in the county is required to meet the current short fall and to provide for future development.

Paper No. 13.

Isotopes as a Measure of Surface Water Infiltration: A Case Study in Northern Ireland.

Ciara McConville, Doran & Partners.
Dr. R. Kalin, Queen's University Belfast.

RECHARGE IN THE ENLER RIVER CATCHMENT, CO. DOWN: A COMPARISON OF WATER BALANCE AND O-18 PROFILES IN THE UNSATURATED ZONE

Ms. C. McConville and Dr. R.M. Kalin
Environmental Engineering Research Centre
School of Civil Engineering,
The Queen's University of Belfast,
Belfast, N. Ireland, BT7 1NN.

ABSTRACT

A water balance study was of limited use for determining recharge rate and mechanisms in the Enler Catchment, N. Ireland. Here spatially limited data for the water balance resulted in varied calculation of the annual and monthly net infiltration rate. This paper outlines a method whereby high-resolution soil profiles (1-2 cm) were obtained from both laboratory sand columns and from field cores in the upper 2 m of the unsaturated zone using O-18 of water. These profiles show changes in isotopic composition that likely range from individual rainfall events to annually integrated cycles of rainfall. Recharge rates were calculated from stable isotope profiles for each of the 4 main soil types in the Enler catchment and summed over each area resulting in an average recharge of 66mm/a. The recharge figure found is comparable with previous findings. This type of data could provide valuable information about recharge rates and mechanisms and may facilitate better prediction of contaminant transport pathways in the vadose zone.

INTRODUCTION

The increasing importance of groundwater as a water source has focused attention on both the quantity and mechanisms of recharge and on the transport of potential contaminants through the unsaturated zone (Foster, *et al.* 1982; U.S. EPA, 1987). Progressive changes in farming practice in the UK since the 1960's have resulted in rising nitrate and pesticide concentrations in the water infiltrating through the unsaturated zone (Foster & Bath, 1982; Skinner, *et al.* 1997). Water balance studies have traditionally been used for resource evaluation (Keller, 1970), but in recent years have also been used to assess the impact of human activities on the water environment (Bhatt, 1997). As the hydrological cycle provides the mechanism for transport of contaminants in both the saturated and unsaturated zones, measurement of fluxes is crucial for pollution control. It is therefore important to understand recharge, in terms of groundwater resource evaluation and the impact of pollutants from the soil system. This paper explores the potential of using stable isotopes profiles in the unsaturated zone in temperate climates as an alternative to using the water balance method to determine the rate and mechanisms of infiltration.

Studies of natural variations in the $\delta^{18}O$ of soil water in the unsaturated zone of temperate climates has been used to estimate recharge mechanisms and rates in temperate climates (Thoma et al., 1979; Bath et al., 1982; Wellings & Cooper, 1983; Saxena & Dressie, 1983; Saxena, 1984; Darling & Bath, 1988; Geake & Foster, 1989). In these areas, with a marked seasonal temperature cycle, $\delta^{18}O$ of precipitation shows close correlation to air temperatures. This 'temperature effect' produces precipitation which is 'tagged' due to the temperature dependence. If piston flow is assumed (Zimmerman, 1967) recharge from successive seasons, or storm events can be identified from $\delta^{18}O$ profiles in the infiltrating water of the unsaturated zone. The temporal displacement of peaks either enriched (summer) in $\delta^{18}O$ or depleted (winter) in $\delta^{18}O$ can be used to estimate seasonal and annual recharge. If θ is the average volumetric soil moisture content between two summer peaks located at depths Z_A and Z_B, θ_f is the volumetric field capacity, and $Z_B - Z_A = \Delta Z$ is the annual displacement, then recharge (R) during the time period t_A to t_B can be expressed as:

$$R = (\theta - \theta_f) \times \Delta Z \qquad (1)$$

If the water table is deep, successive summer or winter tagged layers may be found, therefore, in theory, equation (1) can be used to estimate recharge. Where the infiltration rate is too fast to store annual cycles, isotope profiles may show individual rain events or monthly-integrated rainfall averages. If a history of the $\delta^{18}O$ in precipitation is known close to the study site then these isotopic variations in the unsaturated zone can potentially be translated into infiltration rates.

STUDY AREA

The area in this study is the catchment of the River Enler located 10 miles east of Belfast, N. Ireland (figure 1a). This 54.8 km^2 catchment is predominantly rural with approximately 10 % suburban development. The town of Comber is situated on the Enler River, at a point where it enters the tidal Strangford Lough. The river valley consists of a broad floodplain flanked on both sides by till covered bedrock hills.

The solid geology of the Enler Catchment is diverse. Much of the south-west and northern parts of the catchment are underlain by Lower Palaeozoic rocks, mainly greywacke, which is considered relatively impermeable except where fracture flow occurs. The central part of the catchment is underlain by the well-graded Triassic Sherwood sandstone; fine to medium grained (0.5 - 2 mm in diameter) with subordinate interbeds of mudstone and siltstone (Smith, *et al.* 1991). Where Tertiary dolerite sills intrude the Triassic Sandstone, the sills have resisted erosion and now cap the sandstone on Scrabo Hill. The glacial drift in the catchment consists of fluvio-glacial sands and gravel along the Enler valley, overlain in some parts by alluvial deposits. The remaining catchment is covered by glacial deposits that consist of sandstone fragments embedded in a matrix of silt and sub-glacial till, (with the exception where bedrock is close to the surface due to glacial erosion).

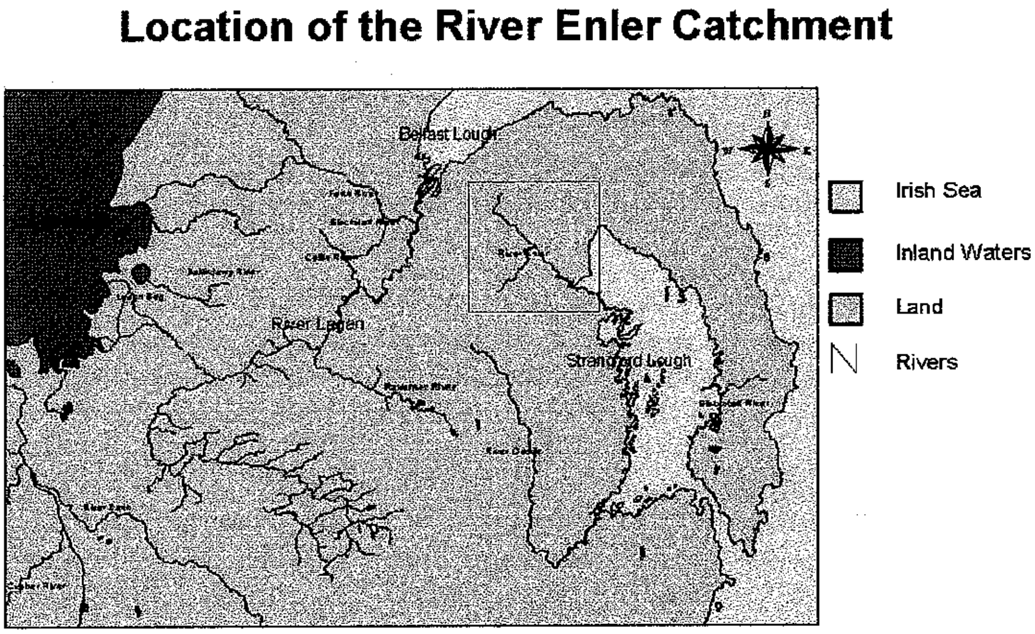

Figure 1A. Location of River Enler Catchment in North East Ireland

Soil types in the Enler Catchment (Figure 1b) range from free draining Brown Earths, which have little differentiation between horizons and provide excellent agricultural soil, to impeded drainage

Surface Water Gleys that exhibit varied hydraulic properties (Cruickshank, 1997). These soils have a variety of parent materials ranging from Triassic Sandstone till to sands. Figure 1b, which is after the HOST classification (DANI) for N. Ireland, shows the potential for wide ranging infiltration rates in the catchment. Land use in the Enler Catchment is predominantly agricultural, including arable pasture, dairy pasture, and rough pasture. Diffuse inputs of agricultural contaminants to groundwater are likely to occur, in this catchment, where arable land is found on the Triassic Sandstone unit (Clarke, *et al.* 1990). Fertiliser application on the catchment is extensive and has resulted in increasing nitrate levels in the River Enler ranging from 5 mg/l in 1987 to peak levels of up to 40 mg/l in 1997 (DoE, 1997). With the introduction of the EC Nitrate Directive (91/679), the Enler Catchment is likely to be designated a Nitrate Vulnerable Zone thus making determination of water transport increasingly important.

The Enler catchment overlies two aquifer systems. The upper drift aquifer consists of sand and gravel deposits up to 6 m thick underlain by sub-glacial till, and is contained in a glacial channel cut between the Triassic Sherwood Sandstone to the north and the Silurian Greywacke to the south. It was suggested by Foster (1969) that recharge to the sand and gravel aquifer from direct precipitation could amount to 4.5 Ml/d with additional recharge from streambed leakage. Robbins (1996) has suggested a recharge of 60mm/a over the catchment. The hydraulic conductivity of the aquifer in this area is around 102 m/d (Robins and Shearer, 1994). The lower main aquifer in the catchment, the Sherwood Sandstone, is considered an excellent source of groundwater (Kalin & Roberts, 1997; Gibbons & Kalin, 1997). The Sherwood Sandstone has a relatively high porosity of 24 %, a transmissivity of up to 250 m^2/d, and a storativity in the order of 10^{-3}. This aquifer has no known outcrop and, although it covers an extensive area outside of the catchment boundaries, it has been suggested that the only significant source of recharge to the aquifer is by induced leakage from the overlying Quaternary deposits in the Enler Catchment.

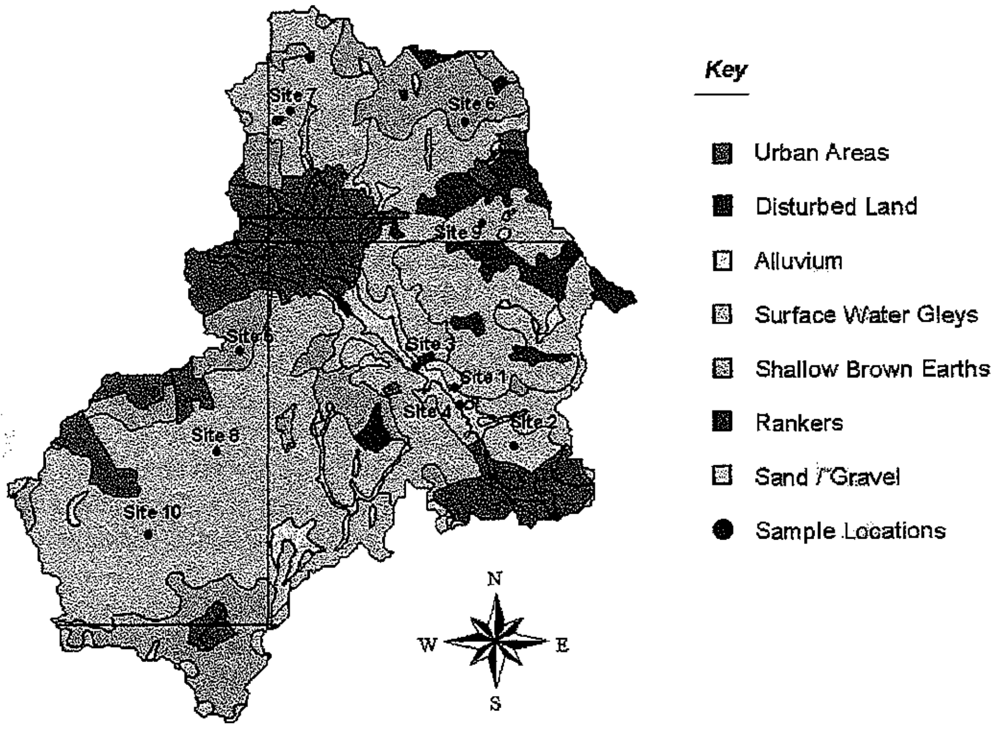

Figure 1b. HOST classification of soils in the Enler Catchment with sampling locations for stable isotope profiles in the unsaturated zone.

The lack of major surface water resources in this area suggests that much of the effective recharge contributes to groundwater recharge and has thus caused interest in utilisation of the groundwater resources for both public and private use since the 1930's. During the 1960's and 70's hydrogeological studies were carried out in this area by the Geological Survey of Northern Ireland. These studies revealed a highly productive aquifer system that could be easily exploited to complement the public water supply (Price & Foster, 1974; Bennett, 1976). Since the 1970's groundwater withdrawal in the area has been on the increase. Currently about 8,000 m^3/d is extracted from the Sherwood sandstone aquifer and 1,000 m^3/d from the sand and gravel for public supply, not including an undefined use by industry and agriculture (after Department of Agriculture for Northern Ireland).

WATER BALANCE OF THE ENLER CATCHMENT

The complexity of surface hydrology makes estimating recharge in the Enler Catchment using the water balance approach difficult. Not all components of the water balance can be measured accurately through time within a given catchment. Precipitation is quantifiable with proper instrumentation, however areal representation is a problem. Evapotranspiration (ET) can be estimated directly by physical means (Essery & Wilcock, 1990), or calculated from meteorological data (Ben-Asher, 1978). It is generally accepted that ET is the component most in error, with typical errors of 15-20%. Infiltration in the catchment is the residual of the water balance equation, and therefore subject to compounding of potential errors in the other terms. The general water balance equation as applied here to the Enler drainage system and is given by;

$$P = ET + Q + R \pm \Delta S \tag{2}$$

where P is precipitation, ET is evapotranspiration, Q is stream flow, R is net effective recharge and ΔS is the change in soil moisture over a given time period. All are expressed in mm over the catchment area.

The Belfast Climate Office measured precipitation on the Enler Catchment daily at four sites. Rain gauges are the standard Meteorological Office Mark II rain gauge (Met. Office, 1982). The Thiesson polygon method (Shaw, 1985) was applied using rainfall measurements from nearby gauges. Here, rainfall measurements were weighted by the fractions of the catchment area represented by each gauge, and then summed over the catchment area.

Of all the processes in the hydrological cycle, ET is the most difficult to quantify for this catchment, due to the complexity of processes involved and the variability of transpiration rates from heterogeneous vegetation. In this study ET was computer generated using the Penman-Monteith combination equation which modifies the original Penman equation (Penman, 1948) by introducing canopy and aerodynamic resistance terms (Allen et al., 1989). Meteorological observations of wind speed, relative humidity, wet and dry bulb temperature, and net daily radiation were measured by the Belfast Climate for the study area. These observations were then used to calculate ET and Soil Moisture Deficit (SMD). The River Enler is gauged daily by the Hydrometrics unit of the Dept. of Agriculture for Northern Ireland. The only gauging structure in the catchment is a flat-V weir at Comber. The river flow is measured in m^3/s and was subsequently converted into mm over the catchment area for the calculation of the water balance.

The results of the monthly net infiltration calculated from the water balance on the Enler Catchment, between the years 1987-96, are shown in figure 2. This graph indicates that the calculated monthly effective infiltration values show a cyclic pattern indicating that recharge is most likely occurring during the winter months and an increase in SMD occurring in the summer months. Assuming winter precipitation first makes up for the summer increase in SMD, this graph would suggest that overall, little or no recharge to the groundwater system occurs in this catchment. The annual recharge for the catchment was also calculated for this data and varies considerably between -60 and 90 mm over the catchment area. In some years the catchment experiences a 'negative' recharge value indicating a loss of water from the catchment. This again would suggest that overall little or no recharge contributes to the aquifer system below the Enler Catchment. This is in contrast to the findings of Foster (1969) who suggested a higher average infiltration of 128 mm per annum. The discrepancy in the infiltration values is difficult to explain particularly as the method used in previous studies were not referenced. However, this does indicate the uncertainties in using this approach to understand or predict water movement in the unsaturated zone.

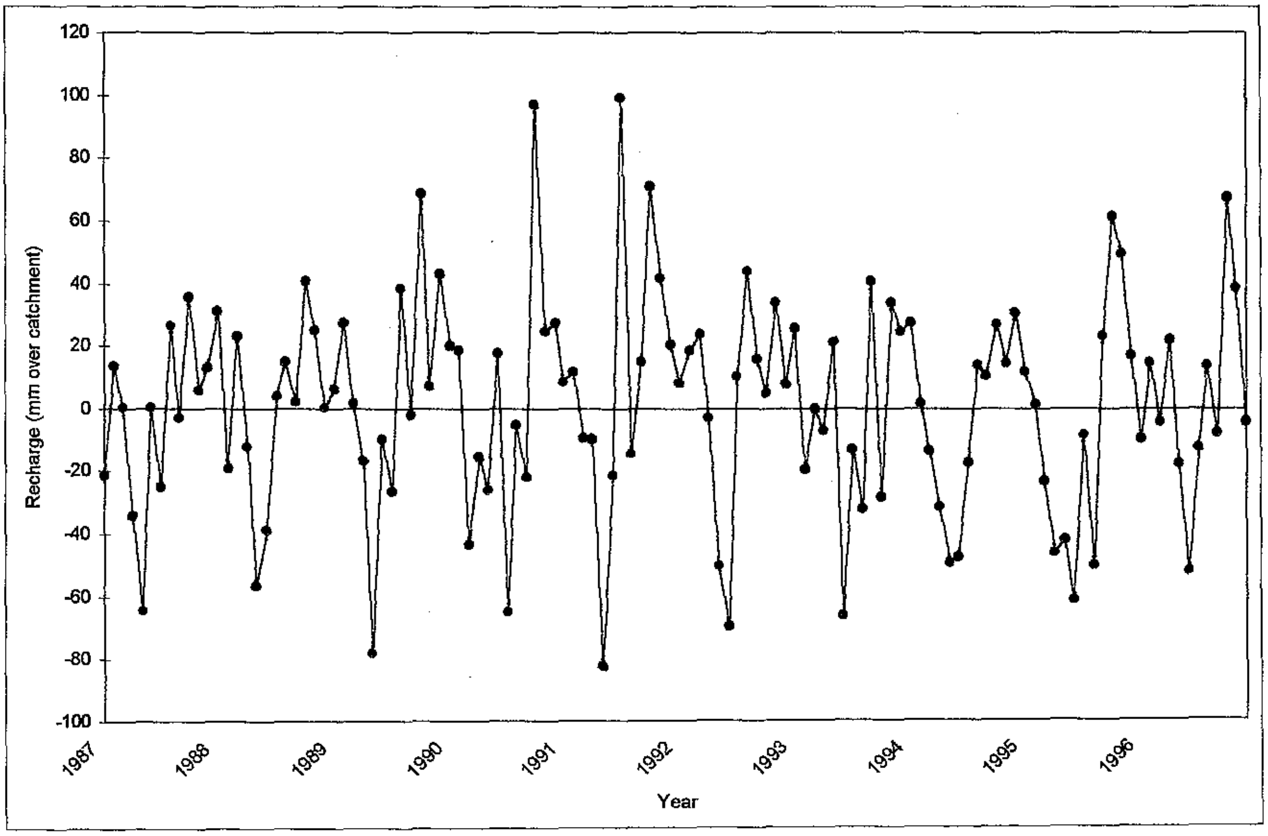

Figure 2. Graph showing the calculated net infiltration in the Enler Catchment over the period 1987-1996.

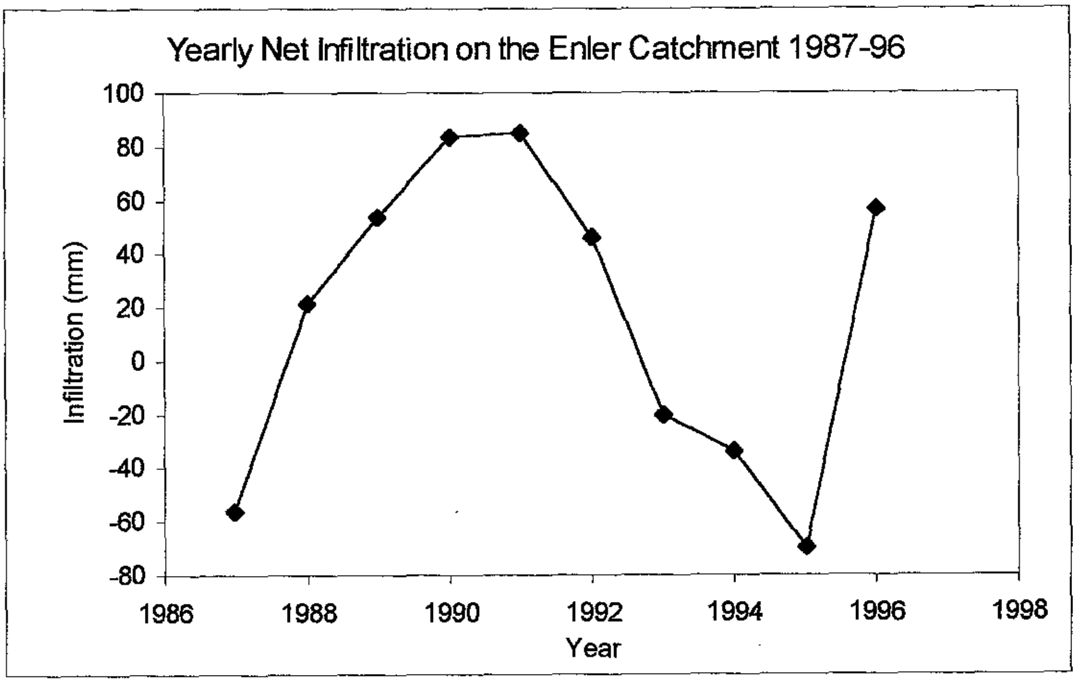

Figure 3. Net Infiltration to groundwater calculated on an annual basis from the Water Balance.

The use of the water balance technique for recharge evaluation is the standard approach used in Ireland. Figure 3 shows the overall 'net' annual infiltration on the Enler Catchment for the periods 1987 to 1996. It is interesting to note that a number of years during this period result in *no* recharge to the groundwater system. The errors involved in evaluation of each component of the water balance were high for this catchment, and error in the recharge may be up to 100% when considering propagation of the errors for each of the measured values. Also water balance calculations were insufficient to identify recharge mechanisms, and thus are of limited use when considering pathways for contaminant transport. Therefore it was decided to investigate the potential of using environmental isotopes in the unsaturated zone to enhance the knowledge of recharge mechanisms and infiltration rates in the study catchment as storm event vary in stable isotopic composition and there is a pronounced annual cycle of stable isotopes in Irish precipitation (40 years of data from IAEA precipitation network at Valentia).

EXPERIMENTAL METHODS

Isotopes have been used as tracers of water movement for over 40 years in both arid climates (Allison *et al.*, 1984) and temperate climates (Bath *et al.*, 1982). Water movement in the unsaturated zone was first investigated using stable isotope techniques in Germany (Zimmerman *et al.*, 1965, 1966) and a useful summary of isotope studies in the unsaturated zone is given by Fontes (1980, 1983). More recently investigations have focused on using isotopes to determine the recharge rate and identify recharge mechanisms (Dincer *et al.*, 1974; Saxena & Dressie, 1983; Saxena, 1987). Of all tracers, ^{3}H, ^{2}H, and ^{18}O most accurately simulate the movement of water in the unsaturated zone as these isotopes are bound within the water molecule itself, and are therefore most useful.

Stable oxygen isotope analysis of soil water was determined using the direct equilibration method developed at the Queen's University of Belfast (McConville *et al.*, 1999). Approximately 8 cm^3 of soil was placed into pre-weighed 10 ml pierceable screw top glass vacutainers. The vacutainers were weighed and placed on a specially designed vacuum line which removed air from the sample vials via capillary needles, and CO_2 was introduced (McConville *et al.*, 1999). The sample vials were transferred into a constant temperature water bath, specially designed at Queens University for use with a Gilson autosampler, and allowed to equilibrate with CO_2 for 12 hours at 25 °C (Epstein & Mayeda, 1953). The samples were automatically transferred into the mass spectrometer via the MultiPrep system (Micromass, 1998) which automatically pierced each sample vial and transferred an aliquot of CO_2 to a -80 °C cold trap, and then the dried CO_2 was transferred to the Prism III IRMS for analysis (Micromass, 1995). Using this method small soil samples can be accurately analysed for the δ^{18}O content providing high resolution profiles with acceptable accuracy's of $\pm$ 0.1 ‰. The results of δ^{18}O analysis of water are expressed permil (‰) relative to VSMOW.

The stable isotopic composition of rainfall varies from storm to storm and throughout the year. Thus, water travelling through the unsaturated zone will vary in isotopic composition. At each of the 10 sites in the catchment, approximately 15 cm of top soil was removed. Samples were obtained using a drive-in-sampler that consists of a specially constructed strengthened metal sample tube, 60 mm internal diameter, with side windows. The sample tubes were driven into the ground by a hydraulic jack hammer, which delivered 900 blows per minute, using a portable compressor unit. The sample tubes were then removed from the ground using a specially designed clam and jack system. Soil samples were then removed from the sample tube, via the side windows, in 20 mm increments and placed in a vacutainer for δ^{18}O analysis or bagged for water content. All samples were carefully handled and stored in order to minimise sample contamination or pore water evaporation. Larger soil samples were removed for particle-size distribution and permeability determination. The depth of coring was dependent on soil conditions but was usually up to 1.5 m to 2.0 m deep.

RESULTS AND DISCUSSION

A number of sites were sampled in each of the soil types outlined above so as to give a representative view of the recharge characteristics through soils with differing properties. The number of profiles taken in each classification was mainly dependent on its % area in the catchment. Ten sites were sampled in total. Four sites were chosen on the surface water gleys, as this class represents the largest area in the catchment, and then 2 each in the alluvium, sand and gravel, and brown earth soil types. An example of one $\delta^{18}O$ profile obtained at site 7, which corresponds to a surface water gley, is shown in Figure 4.

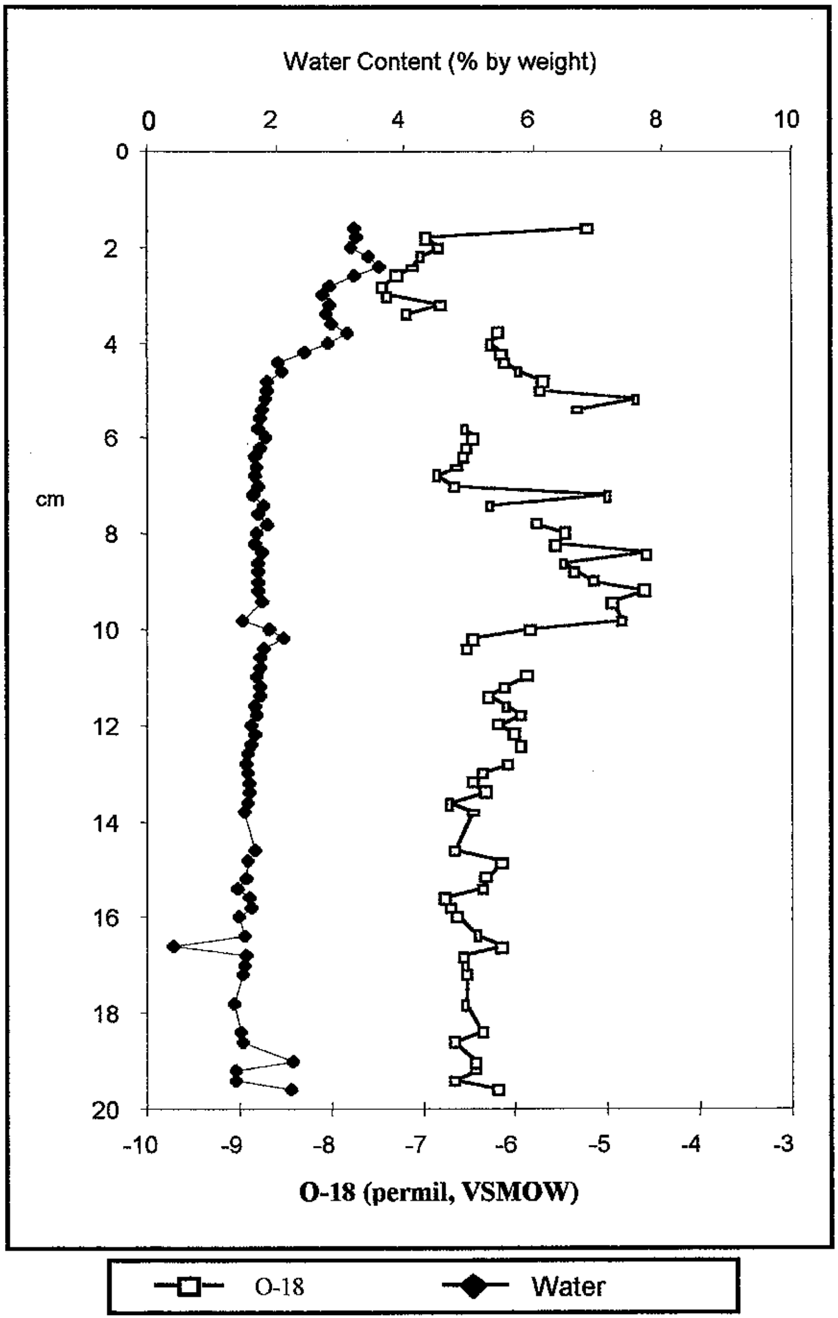

Figure 4. $\delta^{18}O$ and soil water content for Field site 7

The soil type for this site is documented as a surface water gley overlying a glacial till, which should exhibit slow drainage. The drill log obtained for the site did not show the presence of 'gley' at the top of the profile. It did however indicate a soft glacial till. Figure 4 shows the $\delta^{18}O$ and water content results for soil profiles obtained at this site. The water content profile shows a uniform water content of approximately 17% below 50cm depth, while above this the water content increases sharply to approximately 30%. This would be indicative of the soil profile found at this location with the higher water contents representing the gleyed topsoil and the uniform water content below this representing the uniform glacial till. The $\delta^{18}O$ profile for this site shows bands of isotopic activity. The upper 1m of the profile seems to exhibit a cyclic variation in the $\delta^{18}O$, with a range of over 2‰, while the below lm depth, the $\delta^{18}O$ is very uniform with an average of -6.4 ± 0.2‰. This difference in isotopic pattern may be partially explained from the drill log obtained at the site that clearly shows two distinct soil types with the interface corresponding to the depth at which the change in isotopic pattern occurs.

One suggestion may be that each soil type has different hydraulic conductivities. While the top soil band allows infiltration at a rate which facilitates the preserving of the isotopic signature in precipitation, the lower soil has a much slower permeability causing the isotopic signature to be lost due to diffusional re-distribution and mixing. In this case water movement may be more pronounced laterally along the soil boundary interface. Another suggestion is that the physical or chemical soil properties may influence the ability of the soil to store the $\delta^{18}O$ signature, in that different soil types may exhibit different $\delta^{18}O$ profiles even when the infiltration rate is similar. Although the uniform $\delta^{18}O$ of the lower part of the profile does not supply information on possible infiltration rates, the upper cyclic may contain vital information. The hypothesis suggested in this research is that the cyclic variation in the top 1m represents a seasonal isotopic signature with winter rainfall being depleted in $\delta^{18}O$ and summer rainfall being enriched. The isotopically depleted peaks at depths 30cm and 70 cm representing the winter rainfall of 1997/98 and 1996/97 respectively, and the enriched peaks at 50cm and 90cm representing the summer rainfall of 1997 and 1996 respectively. From this it can be assumed that in both years water in this profile has travelled 40cm each year. $\delta^{18}O$ results obtained from the precipitation collected at the Queen's University gauging station support this hypothesis. Average $\delta^{18}O$ in precipitation for winter 1997/98 and 1996/97 are −6.8‰ and −6.9‰ respectively, while for summer 1997 and 1996 it is −6.0‰ and −5.1‰ respectively. This correlates well with values found from the $\delta^{18}O$ profile of −7.1‰ and −6.7‰ for the winter of 1997/98 and 1996/97 respectively, and −5.7‰ and −5.1‰ for the summers of 1997 and 1996 respectively. Assuming a rate of water movement of 40cm per annum and using equation (1), the infiltration rate in the upper 1m of the profile can be calculated as 1.3×10^{-8} m/s. This value correlates reasonably well with the Guelph Permeameter measurement of 8×10^{-7} m/s obtained at this site. Assuming the minimum water content of the profile, approximately 11% (by weight) to be that of field capacity, the θ_f was calculated as 14% (by volume). This is much lower than that expected from a glacial till; however, the profile did contain some sand and substantial amounts of stones, which would reduce the field capacity. Therefore using equation (1), a recharge of approximately 22mm/a was calculated through this profile.

Using this method of interpretation, recharge rates calculated from the $\delta^{18}O$ profiles of the four main soil types are summarised in table 1. An average recharge rate was calculated for the entire Enler Catchment by proportioning the recharge rate of each soil type, found from $\delta^{18}O$ profiles, according to the percentage area covered by the that soil type. The table shows that although recharge rates are fast through the sand and gravel deposits of the Enler valley the area covered by these deposits is small and therefore the amount of recharge is low. Similarly, although it has been suggested previously that the glacial tills in the Enler Valley inhibit infiltration considerably (Robins & Shearer, 1994), and recharge in this study was found to be relatively small, the large percentage area of glacial till produced a substantial recharge amount through the glacial tills. The recharge in the Enler catchment was calculated by multiplying the recharge rate through each soil type, estimated from $\delta^{18}O$ profiles, by the proportion of area of catchment covered by that soil type (table 1). In this way average recharge in the study area was calculated as 66mm/annum. This value is supported by Robins & Shearer (1994), who quoted precipitation as ca. 900mm/a, potential evapotranspiration as 460mm/a, and if streamflow is taken as ca. 380mm/a (section 3.5.4) the remaining infiltration is 60mm/y.

Soil Type	% Area of Enler Catchment	Recharge (mm/a)	Contributing Recharge (mm/a)
Sands and Gravel	7.6	250	19
Alluvium	3.9	200	8
Brown earth on glacial till	16.9	60	10
Surface water gley on glacial till	54.8	22	12
Urban areas	16.8	100	17
Total recharge over the Enler Catchment			**66mm/annum**

Table 1. Summary of infiltration rates through soil types in the Enler Catchment and associated areas.

CONCLUSIONS

It has been shown that, although still widely used, the water balance method of calculating recharge to groundwater in the Enler catchment contains substantial uncertainty and did not give an indication of potential contaminant transport pathways. This paper outlines a method, using the stable isotope O-18 of water that has the potential to accurately describe both the quantity and mechanisms of water transport in the unsaturated zone. The isotopic method has been demonstrated to provide an excellent tool for the study of recharge mechanisms in temperate climates. The $\delta^{18}O$ profile obtained is shown to be strongly dependant on the rate of water movement through the profile. This research showed that the input of $\delta^{18}O$ in precipitation is held in the unsaturated zone of temperate climates under certain conditions, and can therefore be used as a useful indicator of water movement. Water Balance Techniques are simplistic and relatively inaccurate. In this research, a water balance calculated for the Enler Catchment showed a potential 100% error in the recharge variable, and also gave no indication of recharge mechanisms. Infiltration rates for different soil types estimated from $\delta^{18}O$ profiles in the study catchment, and summed according to the area of the relative soil type, giving an average infiltration rate of 66mm/year for the Enler Catchment. This value is consistent with previous estimates, and the $\delta^{18}O$ profiles can provide valuable information on recharge areas and mechanisms.

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