Understanding Geochemical Fluxes Between Groundwater and Surface Water: Scoping Report

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P2-260/5

UNDERSTANDING GEOCHEMICAL FLUXES BETWEEN GROUNDWATER AND SURFACE WATER: SCOPING REPORT

R&D Technical Report P2-260/5

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This scoping report identifies the current state of knowledge on surface water and groundwater interactions. It provides an overview of what information and tools are available and will assist in the evaluation of both internal and external future R&D projects needs.

Keywords
Groundwater, Surface Water, Quality, Quanitity, Base Flow Indices, Hyporheic Zone, Geochemical Flux, Water Framework Directive, River Basin District.

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GLOSSARY

Anthropogenic	Resulting from human activity.
Aquifer	A subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater.
Artificial water body	A body of surface water created by human activity.
Available groundwater resource	The long term annual average rate of overall recharge of the body of groundwater less the long term annual rate of flow required to achieve the ecological quality objectives for associated surface waters specified under Article 4 of the Water FD, to avoid any significant diminution in the ecological status of such waters and to avoid any significant damage to associated terrestrial ecosystems.
Base flow	The water that comes from groundwater discharging into the river.
Base Flow Index (BFI)	An estimate of the proportion of total river flow which derives from stored sources, for example aquifers but including also shallow superficial deposits.
Body of groundwater	A distinct volume of groundwater within an aquifer or aquifers.
Body of surface water	A discrete and significant element of surface water such as a lake, a reservoir, a stream, river or canal, part of a stream, river or canal, a transitional water or a stretch of coastal water.
Coastal water	Surface water on the landward side of a line every point of which is at a distance of one nautical mile on the seaward side from the nearest point of the baseline from which the breadth of territorial waters is measured, extending where appropriate up to the outer limit of transitional waters.
Combined approach	The control of discharges and emissions into surface waters according to the approach set out in Article 10 of the Water FD.
Competent Authority	An authority or authorities identified under Article 3(2) or 3(3) of the Water FD.
Cryptosporidium	A micro-organism which affects man, and many animal species including cattle and sheep. Causes the illness Cryptosporidiosis.
Diffuse source	A source of natural or man-made chemicals delivered to a receptor, such as a stream, surface water or groundwater; the source is distributed over an area, and may include run-off from fields, groundwater discharge, and urban run-off. Also referred to as a non-point source.
Direct discharge to groundwater	Discharge of pollutants into groundwater without percolation throughout the soil or subsoil.

Ecological status	An expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters, classified in accordance with Annex V.
Environmental objectives	The objectives set out in Article 4 of the Water FD.
Environmental quality standard	The concentration of a particular pollutant or group of pollutants in water, sediment or biota which should not be exceeded in order to protect human health and the environment.
Flux	The rate at which a substance is delivered to, or passes, a specified point (mass per unit time) and combines both flow rate and concentration. Flux = Water Quantity x Water Quality.
Geochemical Flux	The geochemical flux in groundwater and surface waters is the sum of the geochemical load carried through this sector of the hydrological cycle. Geochemical flux = Volume of water flow in Unit Time x Concentration of Geochemical Components in the water in the same unit time.
Good groundwater status	The status achieved by a groundwater body when both its quantitative status and its chemical status are at least "good".
Good quantitative status	The status defined in table 2.1.2 of Annex V.
Good surface water status	The status achieved by a surface water body when both its ecological status and its chemical status are at least "good".
Groundwater	All water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil.
Groundwater status	The general expression of the status of a body of groundwater, determined by the poorer of its quantitative status and its chemical status.
Hazardous substances	Substances or groups of substances that are toxic, persistent and liable to bio-accumulate; and other substances or groups of substances which give rise to an equivalent level of concern.
Hyporheic zone	The subsurface zone where shallow groundwater and stream water mix, i.e. bankside seepage zone.
Influent stream	One which flows above the water-table and contributes to it by natural leakage through the bed of the channel.
Inland water	All standing or flowing water on the surface of the land, and all groundwater on the landward side of the baseline from which the breadth of territorial waters is measured.
Lake	A body of standing inland surface water.
Load	Product of the concentration and streamflow, equivalent to the total amount of a constituent passing that point in the stream, at that time. Usually expressed as kilograms per time or pounds per time.

Non-point source	A source of natural or man-made chemicals delivered to a receptor, such as a stream, surface water or groundwater; the source is distributed over an area, and may include run-off from fields, groundwater discharge, and urban run-off. Also referred to as a diffuse source.
Point source	A source of natural or man-made chemicals that can be attributed to a single location, such as a pipe outflow.
Pollutant	Any substance liable to cause pollution, in particular those listed in Annex VIII of the Water FD.
Pollution	The direct or indirect introduction, as a result of human activity, of substances or heat into the air, water or land which may be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems, which result in damage to material property, or which impair or interfere with amenities and other legitimate uses of the environment.
Priority substances	Substances identified in accordance with Article 16(2) of the Water FD and listed in Annex X. Among these substances there are «priority hazardous substances» which means substances identified in accordance with Article 16(3) and (6) for which measures have to be taken in accordance with Article 16(1) and 16(8).
River	A body of inland water flowing for the most part on the surface of the land but which may flow underground for part of its course.
River basin	The area of land from which all surface run-off flows through a sequence of streams, rivers and, possibly, lakes into the sea at a single river mouth, estuary or delta.
River Basin District	The area of land and sea, made up of one or more neighbouring river basins together with their associated groundwaters and coastal waters, which is identified under Article 3(1) of the Water FD as the main unit for management of river basins.
Run-off	Overland flow to a stream that occurs when either (1) the precipitation rate exceeds the infiltration rate through the soil, (2) precipitation reaches soil that is already saturated, or (3) precipitation reaches a surface that is nearly impermeable, such as pavement or bedrock.
Sub-basin	The area of land from which all surface run-off flows through a series of streams, rivers and, possibly, lakes to a particular point in a water course (normally a lake or a river confluence).
Surface water	Inland waters, except groundwater; transitional waters and coastal waters, except in respect of chemical status for which it shall also include territorial waters.

Surface water status	The general expression of the status of a body of surface water, determined by the poorer of its ecological status and its chemical status.
Transitional waters	Bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters but which are substantially influenced by freshwater flows.
Water intended for human consumption	Has the same meaning as under Directive 80/778/EEC, as amended by Directive 98/83/EC.

LIST OF ACRONYMS

BFI	Base flow index.
BGS	British Geological Survey.
CAMS	Catchment Abstraction Management Strategies.
CEH	Centre for Ecology & Hydrology, includes the former Institute of Hydrology.
CHASM	Catchment Hydrology and Sustainable Management.
CSIRO	Commonwealth Scientific and Industrial Research Organisation. A scientific and industrial research organisation in Australia.
DEFRA	Department for Environment, Food and Rural Affairs.
DETR	Department of the Environment, Transport and the Regions.
EPSRC	Engineering and Physical Sciences Research Council, a UK Research Council.
GBASE	A geochemical baseline survey of the environment.
GIS	Geographical Information System.
HSPF	Hydrological Simulation Program – Fortran.
IGARF	Impact of Groundwater Abstractions on River Flows. Part of Agency Research programme.
LOCAR	Lowland Catchment Research. Part of the NERC thematic programme.
LOIS	Land-Ocean Interaction Study. A six year NERC project from 1992-1998.
MAFF	Ministry of Agriculture, Fisheries and Food.
MORECS	Met. Office Rainfall and Evaporation Calculation System. MORECS is the generic name for Met. Office services involving the routine calculation of soil moisture and evaporation for Great Britain.
MTBE	Methyl tertiary butyl ether. A petrol additive originally added to replace lead.
NERC	Natural Environment Research Council.
NERC URGENT	NERC study on Urban Regeneration and the Environment (URGENT).
NGWCLC	National Groundwater and Contaminated Land Centre (Environment Agency)
NICHE	National Infrastructure for Catchment Hydrology Experiments. A research organisation.
NICHE -CHASM	Another NICHE Consortium, which is extending the LOCAR programme to highland catchments, co-ordinator Prof. O'Connell of Newcastle University.
NICHE -LOCAR	Consortium co-ordinated by Prof. Wheater of Imperial College.

NRA	National Rivers Authority. One of the predecessors to the Environment Agency.
NVZ	Nitrate Vulnerable Zone.
NGWCLC	National Groundwater and Contaminated Land Centre.
POPPIE	Prediction of Pesticide Pollution in the Environment. A software package for the prediction of pesticide pollution in the environment from diffuse sources.
SERC	Science and Engineering Research Council. A UK Research Council.
SIMCAT	SIMulated CATchments modelling.
SSLRC	Soil Survey and Land Research Centre.
STWA	Severn Trent Water Authority.
UKWIR	United Kingdom Water Industry Research organisation.
USGS	United States Geological Survey.
WIMS	Water Information Management System. An Agency database of surface water quality and groundwater quality data.

EXECUTIVE SUMMARY

Legislative Drivers

Recognition of the central importance of interactions between groundwater and surface water in the formulation of water resource management and protection schemes has developed progressively during the past 25 years. The Council Directive of 4 May 1976 (76/646/EEC) on pollution caused by certain dangerous substances discharged into the aquatic environment and the daughter Directive of 17 December 1979 (80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances) take note of the dynamic interactions between activities which could result in the discharge of polluting substances and their impact on water resources. The linkage between the quality status of groundwater and surface water was further emphasised by a single article proposal by the European Commission for a Groundwater Action Programme in 1996. This programme had the objective of ensuring the - *protection and use of groundwater through integrated planning and sustainable management aiming at preventing further pollution, maintaining the quality of unpolluted groundwater, restoring, where appropriate, polluted groundwater*. This proposal broadened the emphasis on groundwater protection, which was already present in the Groundwater Directive (80/68/EEC), to include the restoration of polluted water.

Most recently, Directive 2000/60/EC of 22 December 2000, establishes a framework for community action in the field of water policy, "the Water Framework Directive" (Water FD). Article 2 of the Water FD provides new definitions of hydrological/hydrogeological units under which future management of natural water resources is to take place and which, amongst other functions, provide a framework for describing, understanding and controlling geochemical fluxes between surface water and groundwater. The Water FD requires that in future, water should be managed on the basis of "River Basin Districts", where the latter phrase has the meaning of a river basin together with its associated groundwater and coastal water, or a number of separate river catchments amalgamated for convenience into one geographical unit. Integrated management on this scale will require a sufficient understanding of the ways in which surface waters and groundwater interact to allow reliable estimates to be made of the balance of fluxes of water and potential contaminants through basins, so that both diffuse and point sources of pollution may be recognised and controlled.

Current UK Status

Historically, the management of water resources in England and Wales has focused on surface water and groundwater as separate entities. For many years it has been accepted that the water supplies for England and Wales are derived principally (67%) from surface water sources, with only about 33% taken directly from groundwater. It has also been widely believed (see, Department of Environment, 1978[1]) that because most groundwater supplies in the United Kingdom (UK) are abstracted from relatively deep, consolidated aquifers, they are well protected from surface source pollution, in contrast to the vulnerable shallow, and often unconsolidated, aquifers typical of parts of mainland Europe. A consequence of this received opinion has been that little attention has been given in the UK to the important role which aquifers play in modulating the overall quality of the freshwater resource.

[1] Department of the Environment. (1978). Co-operative programme of research on the behaviour of hazardous wastes in landfill sites. Final Report of Policy Review Committee. HMSO London. ISBN 0 11 751257 5

In reality, as development of both of these water resources increases, the use of one may affect the other. In many situations groundwater and surface water should be considered a single resource since rivers are effectively the 'outcrop' of groundwater at the surface. Contaminated aquifers that discharge to streams can cause long term contamination of surface water sources, and some influent streams may also be a source of contamination to aquifers. The Environment Agency (the Agency) believes there are good reasons to suspect that further improvements in water quality in some of our rivers will not be achieved until the groundwater - surface water geochemical flux is understood and the sources of groundwater contamination are dealt with.

In preparation for the increased management responsibility that implementation of the Directive will bring, the Agency have commissioned a scoping study to determine the state of knowledge on surface water and groundwater interactions. It assesses the extent to which sufficient information is available to describe and manage the situation in England and Wales, and identifies future R&D projects which may be required to satisfy deficiencies.

Aims and Methodology

The work programme was divided into four key tasks, the outputs of which are combined into this R&D Technical Report. The review was conducted via telecommunication with practitioners within the Agency, water utilities and companies, consultancies, research institutes and academic departments, in addition to conducting computer based literature searches. The four tasks or objectives comprised:

1. A literature review, to assess the state of technical knowledge concerning surface water and groundwater interactions, and to determine which factual databases are available in England and Wales;
2. Identification of ongoing and projected research projects which are relevant to the management of water resources at an integrated, basin-wide level;
3. To list and review tools for the management of integrated water resources which are already in use within the Agency;
4. To make recommendations for future research requirements for the Agency.

Conclusions

Conclusions and recommendations for future work are aimed at ensuring that new research initiatives compliment the current knowledge base, rather than re-inventing the wheel. The principal legislative driver is the Water Framework Directive (Water FD). The main requirements of the Water FD, directed at maintaining and improving the quality of water resources, would be satisfied by the ability to prepare reliable mass balances of the flux of water and its constituents in the terrestrial segment of the hydrological cycle and of the ways in which solute concentrations may vary in time and space.

A large amount of historic and current data relevant to the assessment and quantification of geochemical fluxes in the UK, already exists in reports and databases. Much of these data are held on a regional basis rather than in terms of the River Basin Districts defined in the Water FD. The review and comparison of water quality data between Regions and the re-evaluation of existing water quantity data can be used to develop a series of preliminary conceptual models of geochemical fluxes and of processes controlling surface and groundwater interactions on a catchment level. This valuable groundwork, which could be achieved at relatively low costs, will provide a baseline on which future research requirements should be based. Potential research topics arising as a result of this project, and to fulfil the UK's requirements in terms of the Water FD are discussed below:

- **Current status and water quality data collection network:** The quantitative movement of water in rivers and in aquifers is reasonably well understood, but the situation for quality issues is less encouraging. The scoping study suggests that the current level of information on surface water and groundwater quality may limit the extent to which confident statements may be made regarding geochemical fluxes. An initial R&D priority should look to revise the current surface water quality data network and align it to the current water quantity gauging network to gain optimum information on geochemical flux.
- **Using BFI to assess water flux:** The BFI (Base Flow Index) concept provides a means of assessing the proportion of flow in a river attributable to storage in the catchment above the gauge. Estimated non-naturalised BFIs for 1,400 river gauges in the UK can be used in conjunction with currently available hydrogeological/ geological information to provide a valuable indication of the probable flux characteristics of River Basin Districts as a precursor to undertaking more detailed assessments of geochemical flux.

Recommendations

Complete review of existing data

- **Flow and quantity:** Data on BFIs greatly exceed that for both groundwater and surface water quality. It would appear prudent therefore to address this inequality in availability before pursuing the wide scale quantification of geochemical fluxes. WRc suggest that new research is initially focused on a number of selected catchments to refine a working methodology and data requirements. The evaluation of this initial work would assist in prioritising subsequent catchment assessments. The LOCAR/ NICHE-CHASM programmes give the opportunity for large multidisciplinary projects to be organised. The value of an instrumented catchment is that it allows the identification and quantification of fluxes from initial precipitation, through groundwater flow, to the final discharge by a surface river from the mouth of the catchment. This work could also be used to extend the findings of Oakes and Keay (1990)[2] on the relationship between naturalised and measured flow BFIs and to determine more widely the magnitude of error that would be incurred if flux estimation were to proceed without taking account of effluent discharges.
- **Water quality data:** Following the selection of key catchments there would be a need to collate historic quantity and quality data for surface and groundwater. This data is probably best collated by individual Environment Agency Regions, as the Agency will be ultimately responsible for data interpretation. Collation is likely to be labour intensive, but should be centrally managed for consistency. It will be essential to make available sufficient time to contact all pertinent data sources. Some of these data may be old, but in the spirit of the Water FD, long-term monitoring and understanding of historic quantity trends are important.
- **Land use data:** In order to minimise costs it is recommended that the services of specialist organisations which provide land use data-sets should be engaged in the project. A variety of data files are maintained by governmental and non-governmental bodies.

[2] Oakes, D.B. & Keay, D., 1990. A Resource Model of the Great Ouse River system. CO 2504-M.

- **Data evaluation:** This would be undertaken using simple conceptual models of the water system dynamics of each catchment, generated from the data collated in the hydrological and hydrogeological reviews, and simple mass balance calculations would be undertaken through each catchment, using the BFI and water quality data, previously collected and collated. When the data sets are judged to have reached a sufficient level of reliability and comprehensiveness, it may be possible to employ or modify existing models which manipulate land use and environmental impact data. A good example is the POPPIE (the integrated software system for the Prediction Of Pesticide Pollution In the Environment) system, developed for the Agency by WRc, Soil Survey and Land Research Centre and Southern Science IT, which combines databases of soils, rivers, aquifers, land use, rainfall recharge and pesticide applications in a GIS. These databases could be readily applied to other problems (including water resources as well as water quality). The concepts applied in POPPIE have the potential to be used for water resource assessment and to assess the fate of other diffuse contaminants such as nitrate. The system could form a valuable part of a basin scale water and contaminant flux management tool.

New Work

- **Increase current understanding of the fate and behaviour of potential pollutants:** Anthropogenic and microbiological pollutants pose a significant and growing problem for water resources and processes in soils and aquifers are still not fully understood. Research is required to consolidate earlier studies and provide quantitative understanding of the fate and behaviour of these pollutants for use in environmental impact studies and to validate and develop catchment level conceptual models. Once the fate and impact of these potential pollutants on groundwater and ultimately surface water is better understood on a catchment level, this will provide a mechanism for prioritising remedial actions that will enable the Water FD targets to be met.
- **Quantification of transport pathways:** New initiatives are required to quantify the two most important transport pathways from precipitation to sea. Firstly the quantification of geochemical fluxes in precipitation events and subsequent run-off/ recharge events, and secondly the groundwater-surface water interactions in hyporheic zones. The hyporheic zone includes, but is not confined to the floodplain of a river system. The quantification of both flow and geochemical fluxes in these elements is difficult because they are both zones of geochemical activity and spatial variability. Further field-based research, backed by laboratory trials, should be developed to establish a sound scientific basis for evaluating the need for land remediation and land management strategies to control diffuse pollution sources.
- **Information exchange workshops:** Successful completion of the suggested programmes of work will involve many individuals and organisations, and will be expected to produce large volumes of new information and to generate new ideas and concepts. In order to maintain the maximum synergy between the participants it is suggested that the lessons learned during the intensive investigations of point and diffuse pollution sources during the 1970's should be applied and workshops held at intervals at which participants in the various programmes would be expected to present their findings and developing concepts in an open manner.

1 INTRODUCTION

1.1 Overall Objective

The overall objective of the project is:

- To undertake a scoping study which provides a sound basis for itemising the research needs surrounding groundwater - surface water interactions and identifies what work is already underway within England and Wales. The research needs should be prioritised and a short description of each with anticipated costs and timescales identified in a discrete programme for the Agency, which it can promote and implement as future R&D initiatives, with a particular focus on supporting the implementation of the Water Framework Directive (Water FD)[3].

1.2 Specific Objectives

The work programme is divided into four key tasks, the outputs of which are combined into this R&D Technical Report. The tasks or objectives comprise:-

1. Literature review, to assess the state of technical knowledge concerning surface water and groundwater interactions, and to determine which factual databases are available in England and Wales.

2. Identification of ongoing and projected research projects which are relevant to the management of water resources at an integrated, basin-wide level.

3. To list and review tools for the management of integrated water resources which are already in use within the Environment Agency (Agency). The tools are expected to include models of various types, the use of remote telemetry to sense the quality and quantity status of waters and the use of GIS based systems.

4. To make recommendations for future research requirements for the Agency.

1.3 Background

Recognition of the central importance of interactions between groundwater and surface water in the formulation of water resource management and protection schemes has developed progressively during the past 25 years. The Council Directive of 4 May 1976 (76/646/EEC) on pollution caused by certain dangerous substances discharged into the aquatic environment and the daughter Directive of 17 December 1979 (80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances) took note of the dynamic interactions between activities which could result in the discharge of polluting substances and their impact on water resources. The linkage between the quality status of

[3] Published in the Official Journal of the European Communities 22.12.2000. L 327/1-72.

groundwater and surface water was further emphasised by a single article proposal by the European Commission for a Groundwater Action Programme in 1996. This programme had the objective of ensuring the - *protection and use of groundwater through integrated planning and sustainable management aiming at preventing further pollution, maintaining the quality of unpolluted groundwater, restoring, where appropriate, polluted groundwater*. This proposal broadened the emphasis on groundwater protection, which was already present in the Groundwater Directive (80/68/EEC) to include the restoration of polluted water.

1.3.1 The Water Framework Directive (2000/60/EC)

Most recently, Directive 2000/60/EC of 22 December 2000, has established a framework for Community action in the field of water policy, referred to as "the Water Framework Directive" (Water FD). Article 2 of the Water FD provides new definitions of hydrological/hydrogeological units under which future management of natural water resources is to take place and which, amongst other functions, provide a framework for describing, understanding and controlling geochemical fluxes between surface water and groundwater. The relationships between the hydrological units are important to understanding the problems of flux management and critical definitions are reproduced below. Numbers in parenthesis refer to clauses in Article 2 of the Water FD.

- *"River basin" (13) means the area of land from which all surface run-off flows through a sequence of streams, rivers and, possibly, lakes into the sea at a single river mouth, estuary or delta.*

- *"River basin district" (15) means the area of land and sea, made up of one or more neighbouring river basins together with their associated groundwaters and coastal waters, which is identified under Article 3 (1) as the main unit for management of river basins.*

- *"Groundwater" (2) means all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil.* This definition is the same as that included in the Groundwater Directive and incorporated in Waste Management Regulation No. 15 (1994) and the Groundwater Regulations (1998).

- *"Aquifer" (11) means a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater.* This definition confirms that clays and similar sediments and strata with high porosity but very low permeability (hydraulic conductivity) are not to be treated as aquifers, but as aquicludes. Groundwater may be present in a body of rock/sediment which fails to meet the aquifer definition, but which may be capable of yielding small quantities of groundwater at a slow rate; such materials constitute aquitards.

- *"Body of groundwater" (12) means a distinct volume of groundwater within an aquifer or aquifers.*

In order to illustrate the mutual relationships between the hydrological concepts, a simple model for integrated water resource management is described in Section 1.3.2. A single conceptual region is used, with the surface water and groundwater elements described separately for clarity.

1.3.2 Simple model of integrated water resource management

The largest unit for which it will be necessary to manage water on an integrated scale under the provisions of the Water FD is to be the "River Basin District" (RBD), that is a major river catchment with its associated groundwater and coastal water, or a number of separate river catchments amalgamated for convenience into one geographical unit. An example of a UK RBD is the Thames catchment, which is an amalgamation of several smaller "River Basins".

Figure 1.1 provides a diagrammatic example of a River Basin District comprised of a single river basin with associated groundwater. The major river catchment boundary, is defined, for practical purposes, at the downstream end by the lowest gauging point. Beyond the limits of the major river catchment boundary are areas in which groundwater and minor streams discharge directly to coastal waters. The major river catchment may then be further divided into main tributary basins (River basins) and side stream catchments (2^{nd} to N^{th} order catchments) each defined at the downstream point by a gauge.

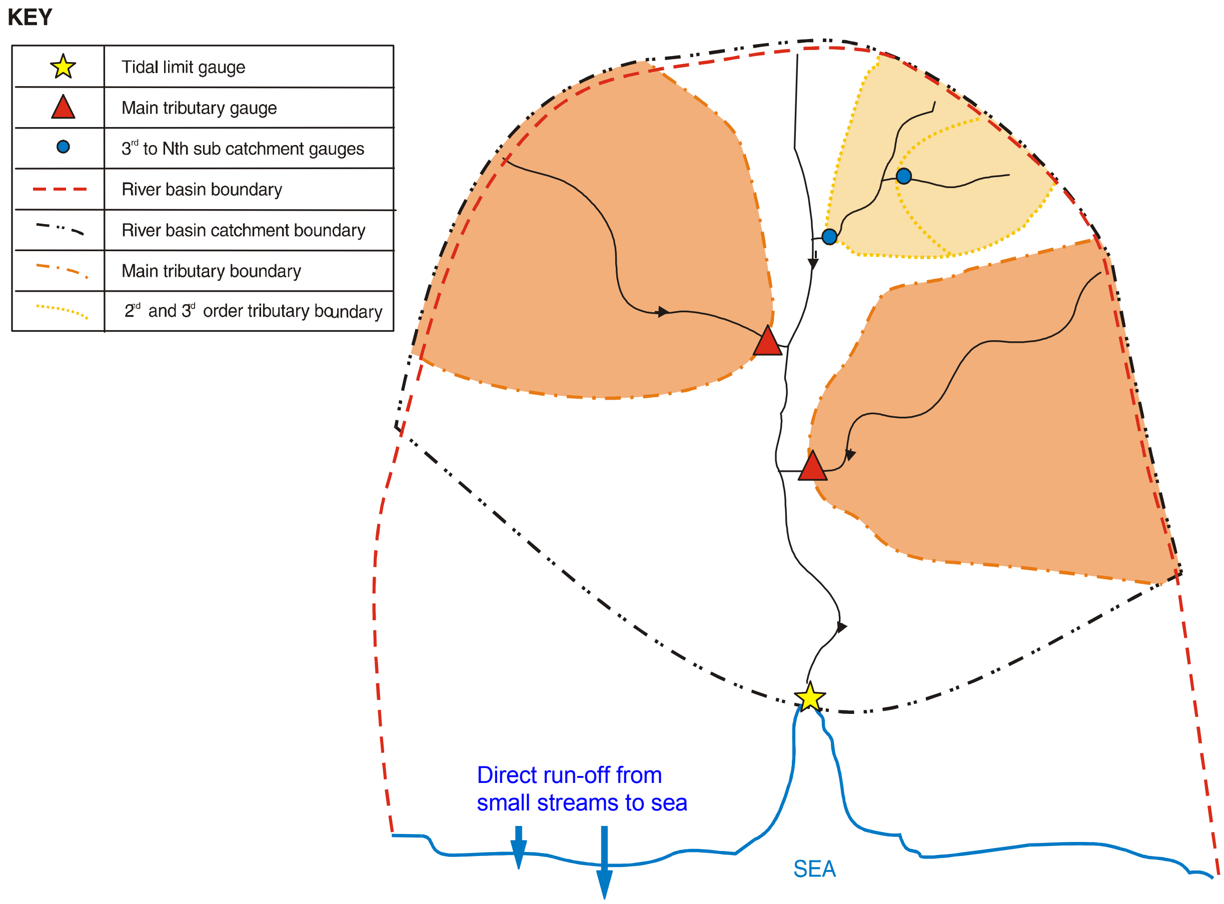


Figure 1.1 Schematic sub-division of a River Basin District into lower order surface water catchments

In Figure 1.2 the same region is shown, but divided on the basis of hydrogeological features. Geologically, the region comprises a plunging synclinal structure, with aquifer materials overlying aquicludes. In the southeastern part of the syncline, aquifer materials pass laterally into an aquitard. As a result, the western part of the area is composed of an **aquiclude** and there is no groundwater. The river basin draining from the west is supported almost entirely by surface run-off (no base flow) and along the coastal fringe surface water discharges directly to the sea via small streams. Within the central and much of the eastern area aquifers are present, with discharge as discrete springs and diffuse base flow to the surface water systems. A major groundwater divide splits the aquifers into two groundwater bodies. One of the bodies of groundwater is assumed to be under threat from extraction and/or pollution by anthropogenic activity, and is "at risk". The risk may fall into four categories:-

- Aquifers sustaining high abstraction rates, or with the potential so to do (mainly Major Aquifers as defined in PPPG[4]);
- Aquifers where the overall abstraction, particularly from large numbers of minor sources, does, or could, derogate base flows to streams or to wetlands;
- Areas of aquifer on which activities take place which individually or collectively pose a significant pollution load;
- Wetlands which are dependent on groundwater or where the base flow component of streamflow is an essential ecosystem support.

Groundwater bodies "at risk" will require formal monitoring with the results being subjected to trend analysis, with appropriate management measures and reporting procedures instigated. It will be essential to understand the geochemical interchanges between such bodies and surface waters. The second body is not at risk and detailed surveillance will not be needed, although operational controls will need to be in place. The concept of *body of groundwater* requires that the water be present in an aquifer and the need arises to define more precisely what constitutes a usable aquifer, than the loosely defined criteria reproduced in Section 1.3.1. A possible approach to reaching a workable definition, based on the storage, yield and quality characteristics of the system has been proposed by the UK Water Framework Directive Technical Advisory Group and is reproduced as Figure 1.3.

Finally, the southeastern part of the district in Figure 1.2 comprises aquitard materials, which contains groundwater, but not in the context of a groundwater body.

[4] PPPG – Policy and Practice for the Protection of Groundwater, Second Edition 1998

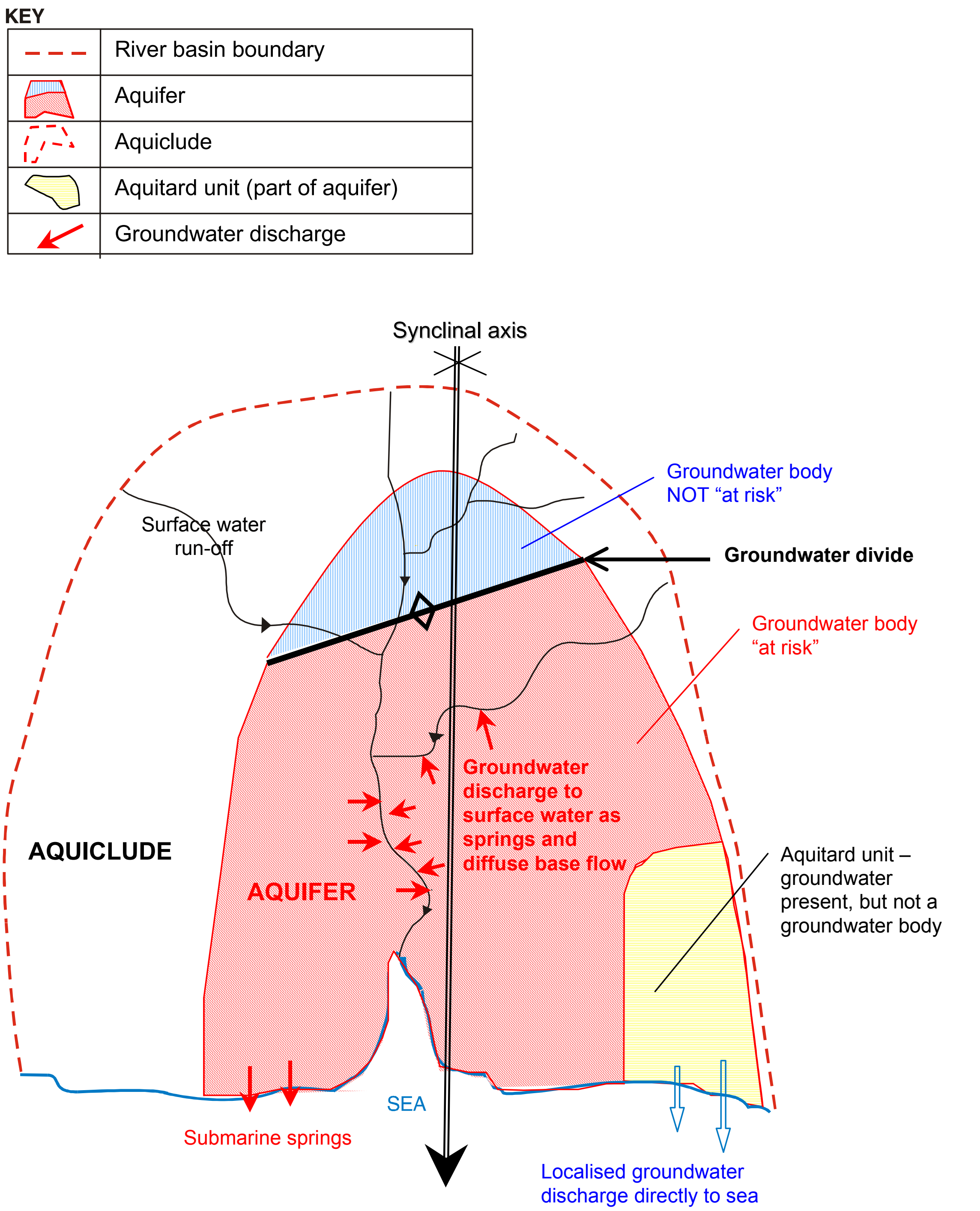
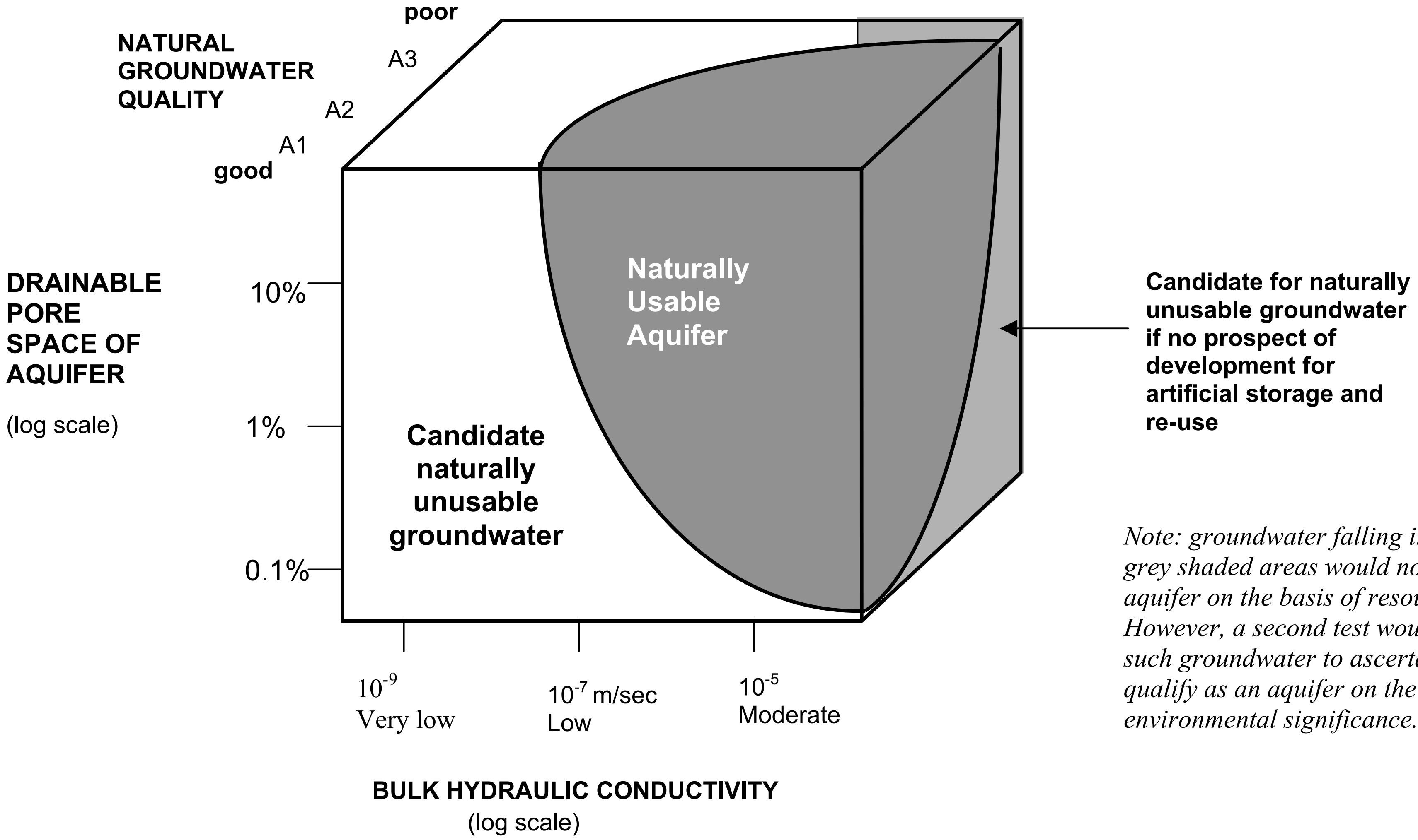


Figure 1.2 Schematic sub-division of a River Basin Catchment into Aquifer, Aquitard and Aquiclude units and Groundwater Bodies



Note: groundwater falling in the white and light grey shaded areas would not qualify as an aquifer on the basis of resource-use potential. However, a second test would be required for such groundwater to ascertain whether it would qualify as an aquifer on the basis of its environmental significance.

Figure 1.3 Identification of aquifers by hydrogeological properties

The geochemical flux through the system represents the sum of all the groundwater and surface water flows through each of the sub-catchments (both surface water and groundwater) with the associated transport of dissolved and suspended materials. The principal component of the model is a mass-balance, such that the flux (concentration multiplied by volume of flow) of materials through the surface and groundwater segments of the catchment can be fully accounted, taking into account additions to and removals from storage, and reactions which may transform or immobilise the substances. The "Source – Pathway – Receptor" risk assessment protocol may be adapted as a model for flux assessments. A simplified assessment module is shown in Figure 1.4.

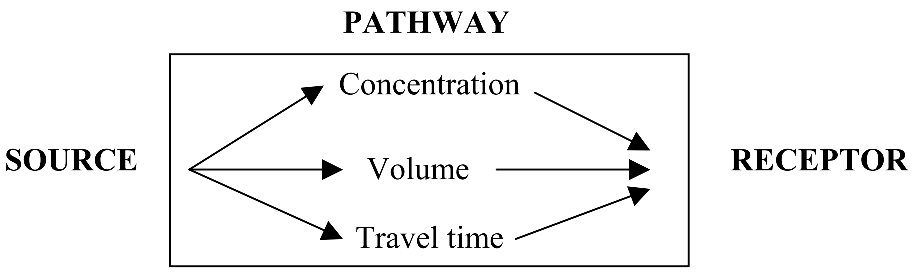


Figure 1.4 Schematic of modular assessment unit

In the simplest form of the model, the pathway considers only concentration and volume and derives a flux at the receptor (for example the most downstream gauge on a river). In this case, the contributions from each element identified upstream, for example, fluxes from tributary streams, from springs/base flow seepage, from effluent sources, are assumed to reach the receptor without delay and without undergoing any attenuation. Even in this simple case, it is apparent that the overall "Source – Pathway – Receptor" triad is composed of a series of identical sub-units, in which the receptor for one unit acts as the source term for a subsequent unit.

The many processes which may operate to change the flow rate and modify the dissolved or suspended load passing through a catchment unit are shown schematically in Figure 1.5. Integrated management on this scale will require a sufficient understanding of the ways in which surface water and groundwater interact to allow reliable estimates to be made of the balance of fluxes of water and potential contaminants through basins, so that both diffuse and point sources of pollution may be recognised and controlled.

This improved knowledge of the scientific issues of groundwater and surface water interactions is necessary to underpin and support the Agency in its regulatory role in implementing legislation, in particular the Nitrates Directive, the Integrated Pollution Prevention and Control (IPPC) Directive, the Habitats Directive as well as the Water FD, by providing the fundamental scientific understanding for integrated water management.

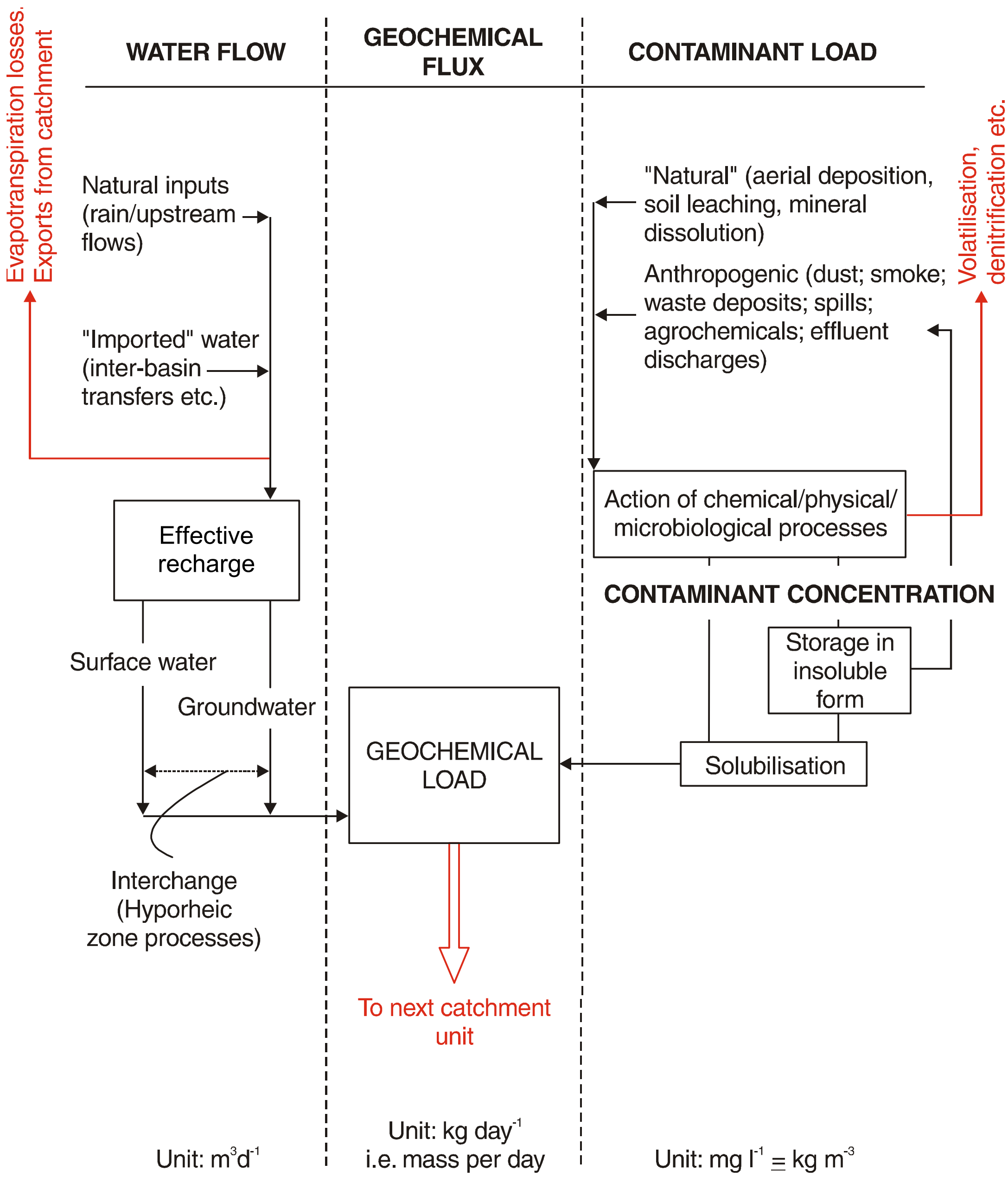


Figure 1.5 Schematic of geochemical fluxes

1.3.3 Background to current baseline understanding of surface water - groundwater geochemical fluxes in the UK

Historically, the management of water resources in England and Wales has focused on surface water and groundwater as separate entities. For many years it has been accepted that the water supplies for England and Wales are derived principally (67%) from surface water sources (river intakes and impoundments), with only about 33 percent taken directly from groundwater. It has also been widely believed (see, for example, Department of the

Environment, 1978[5]) that because most groundwater supplies in the United Kingdom are abstracted from relatively deep, consolidated aquifers, they are well protected from surface source pollution, in contrast to the vulnerable shallow, and often unconsolidated aquifers typical of parts of mainland Europe. A consequence of this received opinion has been that little attention has been given in the United Kingdom to the important role which aquifers play in modulating the overall quality of the freshwater resource.

In reality, as development of both of these water resources increases, the use of one may affect the other. In many situations groundwater and surface water should be considered a single resource since rivers are effectively the 'outcrop' of groundwater at the surface. Contaminated aquifers that discharge to streams can cause long term ("diffuse") contamination of surface water sources, and some influent streams may also be a source of contamination to aquifers. The Agency believes there are good reasons to suspect that further improvements in water quality in some of our rivers will not be achieved until the groundwater - surface water geochemical flux is understood and the sources of groundwater contamination are dealt with.

1.4 Methodology and Report Structure

In order to gather information and catalogue the relevant information which already exists, a literature review was conducted, which included a search of computer databases and information available on-line. A number of contacts within the academic, regulatory and research fields were identified and contacted (see Appendix A), either in person, by telephone or by e-mail. A summary of this review is given in Section 2, with further details included in Appendix B. The key references obtained during the literature search are classified by author and by category in Appendix C.

To obtain a summary of the existing projects and new initiatives underway in the UK a review was carried out, again via personal contacts, and is detailed in Section 3. A review of catchment management tools currently available in this field was also carried out and is detailed in Section 4.

A questionnaire was developed to facilitate collection and collation of information relevant to all aspects of the study from the Agency Regions and Water Utilities (see Appendix B.1). Section 5 then explains integrated catchment management and the requirements of the Water Framework Directive and introduces conceptual models of geochemical fluxes. Following the information obtained in the reviews, the extent to which geochemical fluxes can be adequately described in the UK situation, including some worked examples, is determined in Section 6.

The conclusions and recommendations reached, with particular emphasis on future research needs, are given in Section 7, including priorities, timescales and indicative costs.

[5] Department of the Environment. (1978). Co-operative programme of research on the behaviour of hazardous wastes in landfill sites. Final Report of the Policy Review Committee. 169 pp. HMSO London. ISBN 0 11 751257 5

2 LITERATURE REVIEW

2.1 Specific Objective of Task

The key aim of this task has been to accurately catalogue bodies of relevant information which already exist about how groundwater and surface water interact, with respect to quality and quantity issues, and about the processes involved, particularly in terms of flow regimes and contaminant fluxes between the two. Much of the knowledge in the UK about how groundwater and surface water interact and about the processes involved is dispersed and in many cases has not yet been collated and combined effectively. This review concentrates principally on identifying and listing relevant published work, and the existence of databases, which together could form the basis for collaborative research in future projects.

2.2 Section Structure

Section 2.3 details the methodologies adopted to gather information from on-line literature searches and the various key organisations contacted, either by telephone, e-mail or in person, with Section 2.4 summarising the information gained from these contacts and data sources. Section 2.5 provides a summary of key historic and current studies and databases identified by the review.

2.3 Review Methodology

The literature review has been aimed at identifying references pertinent to quality and quantity inter-relationships between groundwater and surface water fluxes.

A major problem with the literature review of this subject is that, historically, research in the field has been severely compartmentalised. Research and researchers have focused on either surface water or groundwater in isolation. Similarly groundwater quantity (resources) and groundwater quality were (and in some cases still are) treated as separate subjects. The references uncovered in this review therefore tend to fall within these separate categories, although, where possible, information has been collated on interactions between these two water bodies.

For the purposes of collating the results of the literature survey, the references have therefore been sub-divided into the following seven categories:

- Surface water quantity;
- Groundwater quantity;
- Surface water quality;
- Groundwater quality;
- Surface water/groundwater quantity;
- Surface water/groundwater quality; and
- Surface water/groundwater quantity and quality.

However, this classification has been recognised as restrictive and artificial and by the middle 1980's 'Catchment Studies' were in hand, in which integrated groundwater-surface water flux interactions were studied. An early study in the UK, funded by the National Rivers Authority (NRA) (one of the predecessors to the Agency), was the Granta Catchment Study (1984-1994) (Pesticides in Major Aquifers, Clark *et al*, 1995, NRA R&D Report 17). These integrated studies were the pre-cursors of NERC research now being initiated under the Lowland Catchment Research (LOCAR) thematic programme and the related NICHE-LOCAR and NICHE-CHASM Programmes (see List of Acronyms and Section 3.4.2 for more details).

As part of the review, the world-wide scientific literature was scrutinised by an STN International (Scientific and Technical Information Network) 'on-line' computer search using the search strategies and keyword search tools described in Appendix B.2.1. This search allowed for a wide range of scientific journals, periodicals, conference proceedings, reviews and reports to be assessed. A search of the "Current Contents" CD-ROM of Agricultural, Biological and Environmental Sciences journals was also completed (see Appendix B.2.3), using a number of key words and phrases as listed in Appendix B.2.2. These key words and phrases were also used to search a number of groundwater related organisations with information available on-line, as listed in Appendix B.2.4 and detailed in Appendix B.3.

In addition to the computer based literature searches, direct contact was made with active workers in relevant fields, from whom a list of key personnel were identified, with contact either in person, by telephone or by e-mail. These included a number of contacts within the academic and research fields, along with contacts in the Environment Agency and Water Utilities, who were able to provide an extensive range of key references to relevant studies, in addition to information on existing projects and new initiatives (see Section 3). A list of contacts is given in Appendix A.

Regional Environment Agency Officers were also approached to ascertain how the various Regions collect and collate data pertaining to both ground and surface waters. The objective of this exercise was to determine what databases are available and whether a similar methodology for dealing with data for both water quality and quantity is practised across the Regions.

The information gathering exercise from the Agency and the Water Utilities was facilitated by the development of a questionnaire, presented in Appendix B.1.

The references recorded from these various searches have been restricted to those assessed as important in the development of understanding of the interaction or quantification of groundwater and surface water fluxes.

2.4 Summary of Information by Activity

2.4.1 Data presentation

The important references and published works identified in all activities of the review have been collated and are presented as the "Literature Review Database" in Appendix C. In this Appendix, each reference has been assigned to one of the seven categories identified in Section 2.3. An additional column "status" gives the nature of the reference, i.e. report, journal article, database, model, conference proceedings or existing project. In order to facilitate searching this database, two versions have been produced:

- Appendix C.1 - the references are given in alphabetical order by author, to facilitate searching for a particular reference. All references quoted within the main text of this report can be identified by consulting this Appendix.

- Appendix C.2 - the references have been sub-divided according to the category (i.e. groundwater quality) and then sorted by status (i.e. report). This allows references in a particular category, to be reviewed.

In both Appendix C.1 and C.2, key references have been identified in **bolded text**. The content of particularly useful references, shown in *shaded italicised text*, have been summarised within Section 2.5 (UK Information Status Summary).

Details obtained from organisations with information available on-line is summarised in Appendix B.3.

The references obtained from the STN on-line search and CD ROM search (described in Appendix B.2.1 to B.2.3) are included in Appendix D, which includes abstracts for selected papers (see Appendix D.3). The UK references have been collated separately for clarity. The most pertinent of these references are included, for completeness, in the Literature Review Database (Appendix C).

2.4.2 Background

During the decade between the Water Resources Act (1963) and the Water Act (1973), both Groundwater and Surface Water Year Books were published under the direction of the Water Resources Board. After 1974 they were published by the Water Data Unit (Department of the Environment). During the same period of time (mid 1960's to 1980) workers at the Water Resources Board, the Water Research Centre (now WRc), the Institute of Hydrology and in the Water Data Unit developed methods for estimating the groundwater contribution to river flows by the analysis of hydrographs (base flow separation), building on earlier studies by workers such as Ineson and Downing (1964). The results are contained in publications by the Institute of Hydrology – Flood Studies Report, 1993, originally published by NERC in 1975, in 5 volumes; Low flow studies, 1980; and publications by the Water Resources Board (in particular WRB reports Nos. 15 and 16), with significant use of base flow separation to analyse surface water - groundwater interactions in WRB 1974 "Combined use of surface and groundwater in the Ely Ouse and Nar catchments" by C Wright.

Before the early 1970s, water quality concerns were directed principally at the compliance of water in supply with drinking water standards and the collection and collation of raw water quality information was not systematic. A possible exception, which could prove of value if it is ultimately the intention that flux balances should include estuarine and marine waters, was the detailed study of the quality of the Thames estuary by the Department of Scientific and Industrial Research (1964).

Significant understanding of the interdependent nature of groundwater and surface water flows and of modelling techniques to simulate the systems for management purposes was developed in the UK through the 1970's. Basin-scale development of river regulation by groundwater schemes (for example: the Lambourn scheme on the Chalk (Owen *et al*, 1978) and the Shropshire scheme on the Triassic Sandstone, STWA, 1977) and the conjunctive use studies of the Fylde region of Lancashire (Seymour *et al*, 1998), fully recognised the concept of interactions between surface and groundwater. The success of these schemes was dependent on the understanding of the relationship and continuum between surface and groundwater. The initial schemes considered water quality in relatively simplistic terms, but by the mid 1980's studies were in hand which provided useful information on the ways in which variations in geology and land drainage practices influence the nutrient load entering streams from agricultural activity (diffuse source), for example work on the tributary streams feeding the catchment of the Lee to the north of Harlow (Hill 1984, WRc Technical Report TR 203).

There has been a great deal of work in the last two decades on the impact of land use and industrial practices on groundwater and on surface water, but it is recognised that the relationship between the quality of groundwater and the quality of interrelated surface water is not well documented. A difficulty is that different chemical parameters affecting groundwater quality can have very differing impacts on surface water. For example, the degradation and retardation of inorganic species such as chloride, nutrients such as nitrate and organics such as pesticides will be totally different.

2.4.3 Regulator contacts - Environment Agency

The response to the questionnaire (Appendix B.1) sent to the Agency Regions illustrates a common approach to the current collation, storage and presentation of data. The following generalised points have arisen from the responses received:

- Surface water quality and groundwater quality data is held on WIMS (Water Information Management System), a national Oracle database system. All Regions are expecting to receive geochemical processing and presentation software (AquaChem) to complement the raw data. It is noted that Area offices also retain individual excel spreadsheet files and occasionally paper copies.

- Groundwater level data and surface flow gauging is stored on Hydrolog 2 across all Regions, which facilitates easy data access, a point raised in several Regions. In addition North West Region noted the use of Gaugeman. The Agency also has Hydrolog 3 which some Regions use to store aquifer parameters.

- The time period of recorded data within Hydrolog for groundwater levels goes back to the 1960s and 1970s. Within WIMS, sparse data is stored from the 1950's until the 1970's, from this point on data are readily available.

- Aquifer properties are not digitised and stored as a specific database. Typically values are available in paper format, from hydrogeological papers and individual reports, or obtained as required from relevant pumping tests. In addition, reference is made to the British Geological Survey (BGS) publication 'Aquifer Properties Manual' and the accompanying CD-ROM.

- Surface water flow gauging points do not generally correspond with surface water quality points. Within some Regions the correlation was far higher, for example within Anglian Region and the Dales Area of North East Region. Similarly, chemical sampling points rarely correspond to biological ones. For example, in the Agency's General Quality

Assessment scheme (GCA) (a method for classifying the water quality of river and canals, described in more detail in Section 2.5.2), the biological and chemical sites are not always coincident. However, they are subject to the same water quality, and as far as possible are not separated by tributaries, discharges, weirs or other potential influences on water quality.

- Many groundwater level boreholes are not monitored for groundwater quality. There appears to be no formal monitoring programme for routinely linking groundwater level and groundwater quality data, as quality data is preferred from pumped boreholes, whilst levels are favoured from static observation boreholes.

- Other than the National Abstraction Licence Database (NALD), the Regions were largely unaware of any other databases held by the water utility companies or other major industrial users.

With regard to Regional studies focusing on groundwater and surface water interaction, a number of studies were identified and these are described in Appendix B.1.1.

2.4.4 Industry contacts -Water Utilities

Discussions with water utilities and supply only companies (list of contacts in Appendix A.4) confirm that the routine collection and archiving of raw water quality data has generally declined since privatisation in 1989. This trend will need to be reversed by the requirements of the Water FD. The principal concern of the companies currently is compliance of water in the distribution systems with the Drinking Water Regulations, so large databases of treated water quality are maintained and exploited. Monitoring raw water quality at river intakes for parameters which impact on treatment (turbidity, pH, DO etc.) is routinely frequent, but more extensive analyses (for example, ion balance suites) are less frequent. In the case of groundwater, frequent (less than a week between samples) monitoring is unlikely, unless specific problems are recognised (nitrate, solvents, *Cryptosporidium,* for example). Differences are apparent between the level at which different companies maintain their raw water quality databases, but few provide even partial analyses on a monthly basis and in some cases complete water characterisation may be achieved only by a number of partial analyses over a year or longer. Generally, data less than ten years old are held on computer files and may be accessed relatively easily, but older data may be in redundant computer file formats, on fiches or punched cards.

With regard to existing projects and current initiatives being undertaken by the water utility companies, projects are primarily focused on supply sustainability and river augmentation. In addition, further projects have been initiated in response to time limited abstraction licensing and on the direct impact of abstraction on surface waters.

Current projects for all utility companies approached, are directed mainly towards quantity issues. Few current or proposed projects are focused on looking at water quality issues, either in isolation or combined with surface / groundwater quantity projects. For more details of the individual discussion points see Appendix B.1.2.

2.4.5 On-line searches

The extensive search of a number of on-line databases (as detailed in Appendix B.2 and B.3), gave rise to around five hundred overseas and UK references. These were then critically reviewed and reduced to key overseas (No. = 78) and UK (No. = 29) references, which are listed in Appendix D.1 and D.2 respectively, with abstracts given (where available) in Appendix D.3. A number of the pertinent UK and overseas references have also been added to the Literature Review Database (Appendix C).

The search of the computerised databases reviewed the more recent of the publications in this field. The results, both from UK and overseas, therefore reflects the current, (rather than historic) research, the focus of which appears to be on the floodplain and hyporheic zones of a catchment. The research is multidisciplinary but there is a strong focus on environmental and ecological aspects. This may be an artefact of the data search and how it is set up but is likely also to reflect to some extent a real trend.

During the search of groundwater related organisations with information on-line, detailed in Appendix B.3, a number of key papers were also identified. These are summarised below.

United States Geological Survey (USGS)

The USGS has produced a major overview of surface water/ groundwater interactions in the publication “USGS Circular 1139 – Ground Water and Surface Water A Single Resource”, by Winter *et al*, 1998. A summary of this paper is included in Appendix D.3.

Another important study in this field, identified during the search, is “Water Resources Investigations Report 98-4059 – Groundwater Discharge and Base Flow Nitrate Loads of Nontidal Streams, and their Relation to a Hydrogeomorphic Classification of the Chesapeake Bay Watershed, Middle Atlantic Coast” by Bachman *et al.* The abstract to this paper is also given in Appendix D.3.

United States Environmental Protection Agency (US EPA)

Two main reports were identified:

- *EPA/542/R-00/00 Proceedings of the Groundwater-surface water Interactions Workshop– July 2000*;

  The EPA’s Office of Solid Waste and Emergency Response (OSWER) sponsored this workshop, which was planned jointly by the Ecological Risk Assessment Forum and the Ground Water Forum. The overall goal was to provide an opportunity for individuals from various scientific and technical backgrounds to discuss the importance of the ground-water/surface-water transition zone and help regulators better understand environmental issues relating to the connections between groundwater and surface water. A detailed summary of the results of this workshop are presented in Appendix D.3

- *Biological Indicators of Groundwater- Surface water Interactions. September 1998.*

  Hyporheic organisms provide an indicator of the impact of contaminated groundwater discharge. If polluted groundwater is flowing into surface water, it is reasonable to predict that organisms within the hyporheic zone will show the effects of pollution before organisms dwelling within the water column. As a result, changes in hyporheic organisms and communities can serve as early indicators of pollutants entering surface water through groundwater discharge. However, researchers have characterised very few hyporheic organisms to date. The paper concludes that sufficient research has not yet been performed and standards have not yet been set, to determine if biological indicator methods can be effectively applied in the assessment of groundwater and surface water interaction and pollutant loading to the hyporheic zone.

2.5 UK Information Status Summary

2.5.1 Surface water quantity

Many of the earlier studies cited, considered groundwater as completely separate from surface water, and were mainly concerned with water resources, and in particular the development of aquifers to meet increasing demands. The Water Resources Board (WRB) undertook numerous studies in the late 1960's and early 1970's for regional planning purposes (Water Supplies in South East England, WRB 1996; Water Resources in the North, WRB 1970; Water Supplies in Wales and the Midlands, WRB 1971) often in co-operation with the River Authorities and engineering consultants. In these studies base flow support to river flows was recognised as being important, but groundwater development was considered as most suitable for local needs. The main source for future supplies in these reports was invariably the construction or enlargement of reservoirs.

During the same time (1960-70s), the establishment of a comprehensive network of river gauging points (hydrometric schemes) under Section 15 of the Water Resources Act 1963 provided the basis for critical work by Natural Environment Research Council (NERC) institutes, which culminated in the Flood Studies Report (1975 – five volumes) and the Low Flow Studies (Institute of Hydrology, 1980). The latter provides the method for estimation of Base Flow Indices (BFIs) which forms an essential basis of mass balance basin flux assessments. BFIs are explained in detail in Section 2.5.5.

The main database identified in connection with surface water quantity is the National River Flow Archive Database, described below.

National River Flow Archive Database

The National River Flow Archive (NRFA) is principally a database of daily mean river flow values from a network of over 1,300 gauging stations in the UK. Responsibility for these stations rests principally with the Agency in England and Wales, the Scottish Environment Protection Agency and in Northern Ireland, the Rivers Agency. Data from these, and other, measuring authorities now constitute a database exceeding 35,000 station-years of daily river flow data. Monthly peak flows are archived to provide a guide to overall flow variability but their precision can vary widely. In addition, monthly catchment rainfall data (mostly derived from data provided by the Met. Office) are routinely archived. Annual tables of daily flow data for around 200 gauging stations throughout the UK are published and are available for downloading from the web-site at http://www.nerc-wallingford.ac.uk/ih/nrfa/index.htm. A map is provided to assist in locating the gauging stations for which data can be accessed;

clicking on the appropriate region will bring up a list of stations for the selected measuring authority.

The NRFA is held at CEH Wallingford and, along with the National Groundwater Archive, is a major component of the National Water Archive. The database exists to provide not only a central database and retrieval service but also an extra level of hydrological validation.

Summary flow statistics for around 1,400 gauging stations, along with a comprehensive set of gauging station and catchment descriptions, is provided in the "Hydrometric Register and Statistics 1991-95", the third such five-year volume in the Hydrological data UK series. See Section 2.5.5 for more details.

2.5.2 Surface water quality

The quality of surface waters became an issue during the 1980's, driven in particular by EC Directives. The quality of surface waters was initially viewed as being unrelated to that of contributing groundwater. Considerable efforts went into studies of nitrate and pesticides in rivers, closely followed by investigations of effluents, farm wastes, oils and more esoteric chemicals such as endocrine disrupters. Some links to groundwater contamination levels were made, particularly with regard to diffuse pollutants e.g. Oakes *et al* (1981), Hill, 1984, Cable *et al* (1993).

The Agency's Water Information Management System (WIMS) database of surface water and groundwater quality is currently being upgraded, and now incorporates Regional databases.

General Quality Assessment scheme (GQA)

The Agency's method for classifying the water quality of rivers and canals is known as the GQA scheme. It is designed to provide an accurate and consistent assessment of the state of water quality and changes in state over time. The scheme includes the chemical GQA and the biological GQA.

The chemical GQA describes quality in terms of chemical measurements which detect the most common types of pollution. It allocates one of six grades (A to F) to each stretch of river, using the same, strictly defined procedures, throughout England and Wales. On average, sampling is carried out 12 times a year, at intervals of six kilometres.

The biological scheme is based on the macro-invertebrate communities of rivers and canals. These are small animals which can be seen with the naked eye and include mayflies, caddis-flies, worms, snails and shrimps. A consistent discipline is adopted across the country for sampling and analysis, including systems for auditing and controlling the quality of the data. Two biological samples are collected, one in spring and one in autumn.

Each biological site corresponds to a stretch of river also characterised by a chemical site. Although these sites are not always coincident, they are subject to the same water quality, and as far as possible are not separated by tributaries, discharges, weirs or other potential influences on water quality.

2.5.3 Groundwater quantity

Regional groundwater development received attention from the early 1970's onwards, starting with investigations such as the Shropshire Groundwater Scheme, the Great Ouse Groundwater Scheme, the London Basin artificial recharge scheme and the Fylde conjunctive use scheme. In these investigations the impact of groundwater development on surface water flows was recognised, but the thrust of investigations was on groundwater development.

The main databases in this field are the National Groundwater Level Archive and the National Well Record Archive, both are described briefly below.

The National Groundwater Level Archive

Each Environment Agency Region has an extensive archive of groundwater level data which has been collected by the Agency. A subset of this data is passed to BGS at Wallingford, who maintain the National Groundwater Level Archive. This archive includes water level data for around 170 representative wells and boreholes in the United Kingdom; the average length of record is around 24 years. The selection of wells was based on hydrogeological units identified in an investigation of the groundwater resources of the UK (Monkhouse and Richards, 1982); one site was chosen for each aquifer present in each unit.

This archive is supplemented by historical water level data (up to 1974 generally) for approximately 3,000 additional monitoring sites.

The data are stored on a computer database and water level records may be made available in various forms as specified by users. Retrievals are available for all of the sites listed in the Register of Selected Groundwater Observation Wells. Data may be obtained from http://www.nerc-wallingford.ac.uk/ih/nrfa/groundwater/index.htm.

National Well Record Archive (Well Master Database)

The British Geological Survey (BGS) also maintains the National Well Record Archive (NWRA) for England and Wales. Currently this archive includes hydrogeological details and reference information for over 100,000 shafts, boreholes and some springs - predominantly constructed or used for water supply or the monitoring of groundwater levels or quality. The archive is organised into paper files based upon the 10 kilometre squares of the National Grid. Each file includes a register, which details the accession number, the depth, the national grid reference and certain other details. This material is an essential component in the hydrogeological enquiry service operated by BGS and the register details are available in a digital format.

The archive is located at the Wallingford Office of BGS and all the non-confidential records are open to inspection by the general public.

2.5.4 Groundwater quality

Research into the quality of groundwater increased significantly during the 1980's, driven in particular by EC Directives. Considerable efforts went into the impact of sewage effluents, landfill leachates, nitrate and pesticides on groundwater, closely followed by investigations of the impacts of oils and more esoteric chemicals such as MTBE (methyl tertiary butyl ether). The impacts on surface waters received increasing attention in the 1990's particularly with regard to diffuse pollutants e.g. Clark and Oakes (1994), Oakes (1999), Clark *et al* (1995). Fluxes between groundwater and surface water were estimated, often using modelling procedures to allow surface water impacts to be calculated.

With the exception of localised, and often relatively short-term water quality databases derived from research or consultancy studies there are few significant compilations providing up to date information on raw water quality. Past national studies such as Monkhouse (1983) or Kendrick *et al* (1985) were restricted to limited lists of determinands.

Current upgrading of the Agency's WIMS database is taking place. This is a massive database, within which Regional databases are now incorporated. BGS take material out of WIMS for specific geological blocks, and along with their own data are producing a geochemical review for that block. This is being carried out in collaboration with the Agency under the Framework 5 BASELINE project (see also Section 3.4.7.2 on BGS).

2.5.5 Surface water and groundwater quantity

The importance of considering combined resources was recognised in the 1980's. Concepts such as river regulation, conjunctive use and artificial recharge were studied, in recognition of the fact that yields of combined sources were commonly greater than the sum of yields of sources operated independently. Regarding fluxes of water between aquifers and surface sources, a significant body of expertise and large quantities of data were assembled. The concept of *net gain*, the proportion of groundwater pumping into a river which increased river flow some distance downstream, was commonly used as a key indicator of the success of river regulation by groundwater. Complex systems such as the combined resources of the Great Ouse Basin (Oakes and Keay, 1990), and the Po Basin in northern Italy (Oakes, 1999) were increasingly subject to intensive studies to optimise yields and increase security of supplies. It became vitally important to correctly handle the interactions between aquifers and rivers.

The two main databases identified in this field are discussed below.

- **Hydrological Data UK series – the "Hydrometric Register and Statistics 1991-95"**

One of the most relevant databases identified in the literature search is in the Hydrological Data UK series, the "Hydrometric Register and Statistics 1991-95". This contains records of river flows and groundwater levels throughout the UK. For each of the 1,400 gauging stations the register gives details of the station number, river name, grid reference, catchment area, station type, period of record, mean flow, minimum flow, maximum flow, and 10 and 95 percentile flows. Derived parameters given include the mean annual run-off, and Base Flow Index. The latter is an invaluable parameter and is described in detail below.

Base Flow Index (BFI) is an estimate of the proportion of total river flow which derives from stored sources, for example aquifers but including also shallow superficial deposits. Base Flow Index (BFI) is calculated from the total river flow hydrograph by computation of the lower envelope to the flow hydrograph, with BFIs provided for all river gauges having at least a three year record of measurements. It is a valuable parameter for use in understanding and quantifying groundwater - surface water interactions.

The Register also gives an indication of the various types of abstractions from, and discharges to, a river which alter the natural flow regime. Base flow indices are calculated directly from measured river flows, and do not therefore relate to the natural condition. However, it may be shown that in most cases the BFI calculated from actual flows will not differ greatly from that for natural conditions. A comparison of actual and naturalised BFI's for catchments in the basin of the Great Ouse, calculated with the Great Ouse Resource Model (see below), is summarised in the best fit equation:

$$\text{BFI (actual flows)} = 0.89 * \text{BFI (naturalised flows)}, R^2 = 0.93$$

(where R is the Pearson correlation coefficient, and R^2 is the coefficient of determination (the proportion of variance in Y that is explained by the variance in X). R^2 is a measure of the goodness of fit - values close to 1 indicate a very good fit).

Under actual conditions, groundwater abstractions reduce base flow, with most of the abstracted water being returned to the river as effluent. The BFI under actual flow conditions will therefore generally be less than the equivalent BFI under naturalised conditions.

For the most downstream gauge on the River Thames at Kingston, for example, the BFI is given as 0.64 (or 64%), indicating that on average almost two thirds of the water flowing into the Thames estuary is derived from groundwater. The value will vary from year to year depending on the timing of rainfall recharge. For the Great Ouse at Denver, the BFI is 0.48 (48%), somewhat lower than for the Thames because of the greater percentage of clay cover in the catchment. For the River Conway in North Wales, the BFI at Cwm Llanerch is 0.28 (28%), indicating that there is relatively little storage in the catchment so flows are flashy.

- **Great Ouse Resource Model (Oakes, D and Keay, D, 1990)**

The Great Ouse Resource Model is a resource accounting model, having regard for all inputs (rainfall and effluent discharges) to, and outputs from (abstractions) the Great Ouse River system. Run-off was simulated as delayed rainfall onto impermeable soils, and recharge to aquifers through permeable soils was simulated with a lumped parameter model (see Section 4.6.2) which explicitly took account of groundwater abstractions. Effective recharge, and historic abstractions and effluent returns data were assembled for 58 sub-catchments, over a 16 year period. The model calculated the components of the water mass balance, including both the run-off and base flow, at each of the 392 river nodes across the basin. The model was able to accurately simulate total river flows at 8 key gauging stations. It was subsequently possible to test future surface water and groundwater development programs.

2.5.6 Surface water and groundwater quantity and quality

Few studies combining surface and groundwater interactions were reported before the early 1990s, an exception being a study by Birtles (1977) which related the levels of conservative parameters in the Severn at Tewkesbury to contributions from run-off, base flows and effluent discharges (see below for more details).

In the 1990's issues of water quality made it imperative to include quality assessments in whole basin studies. In order to be able to investigate water quality changes at the basin level it is essential to first have a clear understanding of the quantities of water in lakes, rivers and aquifers. The inclusion of quality was therefore a natural extension to the preceding water resource studies. Combined studies of resources and associated qualities have been completed for the River Gipping (Clark and Oakes, 1994), and for the River Po in northern Italy (Mainstone *et al*, 1997). Other similar studies are currently underway. These will provide invaluable information on the relationships between catchment base flows and surface water/groundwater chemical fluxes.

Of relevance also is the POPPIE (Prediction Of Pesticide Pollution In the Environment) system, developed for the Agency, which provides the means of combining data sets to give predictions of the environmental risk posed by pesticides (see below).

- **River water quality models based on stream hydrograph components (Birtles, 1977)**

Computer models were constructed to facilitate the dynamic simulation of water quality fluctuations in the River Severn near Tewkesbury. The approach was based on an analysis of total river flow into discrete components - direct run-off, base flow from the Triassic Sandstone, base flow from superficial deposits and effluent returns. The effluent return component was estimated to be a steady 3 cumecs. Base flows were separated from the remaining river flows using a lumped parameter model (see Section 4.6.2), and the residual was equated to the run-off component. The concentrations of conservative determinands in the river were then used to estimate the concentrations in the separate flow components. It was assumed that chemical concentrations in effluents and in base flows were constant through time. For run-off, the concentrations were assumed to be proportional to the run-off rate. Good agreement between measured and predicted flows and chemical concentrations were obtained. The method provides a useful way of separating run-off and base flow components in terms of both quantity and quality.

- **POPPIE - Prediction of Pesticide Pollution in the Environment (Oakes *et al*, 1995)**

To help in its monitoring and strategic planning functions, the Environment Agency has developed an integrated system for the prediction of pesticide pollution in the environment (POPPIE). The POPPIE software combines the functions of a Geographic Information System (GIS), database, risk assessment prediction and water quality planning information tool. A consortium comprising WRc, the Soil Survey and Land Research Centre (SSLRC) and the Central Science Laboratory (CSL), an agency of the former Ministry of Agriculture, Fisheries and Food (MAFF), undertook Phase 1 of the study, commencing in December 1994. Phase 1 comprised a Technical Design Scoping Study and development of the risk assessment modelling components for POPPIE. Physical development of the system was completed by Southern Science and WRc in 1995.

The databases comprise all of those information and data relevant to the fate and behaviour of pesticides applied to crops, used in sheep dip and used for amenity weed control. The databases include land use, pesticide use, rainfall recharge (MORECS), river catchments, aquifers and soils. Data are located in a 2 km square grid covering England and Wales. Included in the soil data is the Base Flow Index for each soil type. This is similar in concept to BFI calculated for river gauging sites (see Section 2.5.5), but as applied to soils means the fraction of effective rainfall onto the soil which is temporarily stored in an aquifer before reaching a river. The soil BFI's can be used in combination to estimate a river BFI anywhere in England and Wales by identifying all soils within the catchment to the gauging site. This is a task which the POPPIE software undertakes. The models comprise river and aquifer flow and pesticide fate simulations. The concepts applied in POPPIE have the potential to be used for water resource assessment and the fate of other chemicals such as nitrate. The system could form a part of a basin scale water and contaminant flux management tool.

POPPIE was updated in 2000 for land and pesticide use and rainfall. The Agency have done some further validation of the models that were provided with POPPIE, and are continuing that testing especially with regard to groundwater. A cut-down ARCVIEW version has been created for distribution to Agency Regions. Some further investigation into other uses (e.g. nutrients) is in progress.

2.5.7 Historic water quality databases

Historic water quality is contained within the Agency's GQA scheme – a method for classifying the water quality of rivers and canals. It is designed to provide an accurate and consistent assessment of the state of water quality (chemical and biological) and changes in state over time, and is described in Section 2.5.2.

During the 1970's and 80's, a number of the Regional Water Authorities compiled extensive databases of the quality of raw, treated and 'in supply' water in their Areas. In the case of the Severn Trent Water Authority (STWA) the data were published as a series of annual reports during the late 1970's (Severn Trent Water, 1977). These reports contained minimum, maximum and mean concentrations of a limited range of determinands, including microbial indicators, for raw waters at boreholes, wells, springs and river intakes, of treated surface waters and groundwater, of waters in reservoirs and in the distribution system and of the quality of licensed effluent discharges to the rivers. The data sets also summarised mean abstraction and discharge rates. A summary of the data provisions of such a publication is provided in Appendix E.

These data sets (as summarised in Appendix E) remain valuable because they allow a view to be taken of the overall quality of water on a catchment or sub-catchment basis, but are insufficiently detailed for use in completing any but the most basic mass balance flux estimates because:

- The lists of determinands are short and, being over 20 years old, may not contain compounds now considered to be of prime environmental importance;

- There is poor correspondence between determinand lists for raw and treated waters and those reported for effluent discharges, with only ammoniacal nitrogen in common;

- The mobile, conservative species chloride is reported from raw groundwater and surface water, but not from effluents, contributing to difficulties in striking even simple mass balances;

- The summarised data do not provide information on seasonal variations in water quality;

- There are likely to have been significant improvements in effluent quality, and changes in volumes discharged since the late 1970's and none of the quality data can be used to estimate current fluxes;

In spite of these shortcomings, these data are employed in Section 6.4 and 6.5 to illustrate the problems of attempting a flux mass balance.

3 A REVIEW OF EXISTING PROJECTS AND NEW INITIATIVES

3.1 Specific Objective of Task

This task and that of the Literature Review are complimentary and provide the factual base from which decisions may be reached regarding how adequate the existing knowledge and databases would be in fulfilling the requirements of reliable assessment of geochemical fluxes through "River Basin Districts" (RBD). This section of the report has the objective of determining the extent of ongoing work and interest in future initiatives within the research and consultancy community.

The specific issues which have been addressed are:

- The identification of research institutes and consultancies with appropriate facilities and interested staff who are currently carrying out related studies, or who would be interested in so doing. The identification of such institutions and individuals provide a means of locating sources of information which may not yet have reached the public domain, as well as providing valuable additional inputs to the literature review;

- Sources and extent of funding for appropriate studies.

3.2 Section Structure

Section 3.3 provides information on the ways in which the gathering of information was carried out. Section 3.4 and 3.5 summarise respectively the preliminary findings regarding ongoing studies and potential future initiatives. Section 3.6 contains the UK information status summary. Details of the persons consulted are included in Appendix A with details of some of the research initiatives encountered included in Appendix F.

3.3 Review Methodology

The gathering of information has been undertaken by the use of telephone and e-mail communication to targeted consultees, with downloading from web sites of information relevant to specific research programmes initiatives.

The names and affiliation of the individual consultees who have contributed information are listed in Appendix A.

3.4 Existing Projects

3.4.1 Funding agencies

The major funding agencies which have been identified as potential supporters of studies of geochemical fluxes in groundwater and surface waters are:

- The Research Councils;
- The Environment Agency;
- The European Union;
- The Water Utilities.

3.4.2 Research councils

The UK Research Councils, namely the Science and Engineering Research Council (SERC) and the Engineering and Physical Sciences Research Council (EPSRC), appear to be offering no funding for research into geochemical fluxes. The National Environmental Research Council (NERC), however, through its funding of thematic programmes of research and funding of secondary degrees at academic institutions, is at the centre of encouraging research into geochemical fluxes in groundwater and surface water.

The research undertaken in academic institutions for secondary degrees is discussed below under the individual institutions approached for the present study. The NERC thematic programmes and related research initiatives, however, are so large and fundamental to the subject of geochemical fluxes that the most pertinent are summarised as separate entities.

The Land-Ocean Interaction Study (LOIS) was a six year project from 1992 to 1998. This study was initiated largely in response to European needs to quantify the chemical fluxes delivered to the North Sea by the neighbouring Community countries. The UK effort involved 11 Institutes and 27 Universities and concentrated on the UK east coast, mainly the Humber and its catchment. Details of LOIS can be obtained from the website at http://www.pml.ac.uk/lois/main.htm (see Appendix F.1).

The Lowland Catchment Research (LOCAR) is the NERC thematic programme most pertinent to the subject of geochemical fluxes through groundwater and surface water. Details of this major programme can be obtained from the NERC website at http://www.nerc.ac.uk/funding/thematics/locar. Extracts from this website are given in Appendix F.2.

LOCAR will undertake comprehensive programmes of integrated research relating to the input-storage-discharge continuum and in-stream, riparian and wetland habitats within groundwater dominated systems. A central function of LOCAR is to establish high quality instrumented field research facilities in three lowland catchments – the Pang/Lambourn (Chalk Aquifer) in Berkshire, the Tern (Sherwood Sandstone Aquifer) in Shropshire and the Frome/Piddle catchment (Cretaceous and Jurassic) in Dorset.

NERC has allocated a budget of £7.75 million to the LOCAR programme over 5 years. This budget is being supplemented by a Joint Infrastructure Fund (JIF) financed consortium within the NICHE (National Infrastructure for Catchment Hydrology Experiments) organisation. This NICHE-LOCAR consortium, co-ordinated by Prof. H.S. Wheater of Imperial College, will contribute a further £2 million for instrumentation of the three designated catchments. A second NICHE consortium, the NICHE-CHASM (Catchment Hydrology and Sustainable Management,), is extending the LOCAR programme to highland catchments. It is understood that NICHE-CHASM (see Appendix F.3 taken from http://www.ncl.ac.uk/chasm), co-ordinated by Prof. P.E. O'Connell of Newcastle University, will contribute £4 million to the instrumentation of four catchments, the Upper Severn, the Eden, the Feshie in Scotland and the Oona in Northern Ireland. It is further understood that NICHE will provide a further £4 million for research to be undertaken in the NICHE-CHASM catchments.

The instrumentation of the LOCAR catchments began in December 2000 and is expected to be complete in the year 2001. The catchments will then be open for use in research proposals from interested parties. It is understood that the proposals will be subject to approval by the LOCAR Steering Committee but it is not clear what organisations will be free to submit proposals or how funding will be arranged. Will funding be by the NERC LOCAR budget, for example, or will proposers be expected to raise their own operational budgets?

More details of these projects can be found in the following appendices:

- LOIS in Appendix F.1 (website at http://www.pml.ac.uk/lois/main.htm);

- LOCAR in Appendix F.2 (website at http://www.nerc.ac.uk/funding/thematics/locar);

- NICHE-CHASM in Appendix F.3 (website at http://www.ncl.ac.uk/chasm);

3.4.3 Environment Agency

Information on direct support by the Agency for relevant projects has been gathered, through this task and through the literature review, and information obtained directly from the Agency Regions is reported in Appendix B.1.1. A number of examples of collaborative research which has come to hand during the discussions with research units, however, are listed below and detailed in subsequent sections (Sections 3.4.6 to 3.4.8):

- BGS - Baseline Geochemistry, under the Framework V Project;
- Mott MacDonalds - Chalk Low Flow Studies.

Reports on specific catchments include:

- Birmingham University - River Tame flux studies;
- Cotswold water park – gravel pits- groundwater interactions (CEH).
- Cranfield and K. Rushton - Studies aimed at improving estimates of groundwater recharge;
- Environmental Simulations International (ESI) - modelling and induced recharge to bankside boreholes;
- IGARF (Impact of Groundwater Abstractions on River Flows) by ESI and IGARF-II by Newcastle University;

Details of proposed projects due to be funded by the Agency can be found in their R&D Programme and Business Plan, these include:

- Phase 2 of geochemical fluxes study - 2001/02;
- Monitoring R&D - 2001/02;
- Groundwater quality standards and characterisation - 2001/02;
- Water FD and diffuse pollution framework projects.

3.4.4 European Union

A number of European Union projects have been identified in connection with UK research organisations, including:

- FAMEST Project – studying how metals move through contaminated soil and are transported to groundwater. See Section 3.4.7.2 under BGS for more details;

- European Community Framework V Project (EVK1-CT1999-0006) – UK contribution comprises baseline studies of groundwater in 36 selected areas in England and Wales from 1999 to 2004, see Section 3.4.7.2 - BGS for more details;

- NICOLAS project on nitrogen cycling (Durham University).

3.4.5 UK Water Utilities

Funding by the water utilities and the water supply companies is principally driven by specific operational problems and is either through UK Water Industry Research (UKWIR), for example, studies related to risk assessment of *Cryptosporidium* by BGS for Portsmouth Water Company and by WRc to provide general guidance, or through individual companies responding to specific needs, for example Cambridge Water Company's Thetford Scheme by Mott Macdonalds and Royal Holloway College's[6] work with The Three Valleys Water company. Southern Water[7] has also co-operated with BGS in connection with the North Downs, South Downs and Wessex Basin Chalk studies. Further details of projects are given in Section 2.4.4 and Appendix B.1.2.

3.4.6 Research organisations; people and institutions

The research organisations approached for information on their present activities and future plans for work on groundwater and surface water fluxes are listed in Appendix A.2.

Aberdeen University

The Dept. of Geography and Environment represents Aberdeen University, in partnership with Dundee University, in working on the Feshie catchment in the Cairngorms as part of the NICHE-CHASM Consortium. The Feshie catchment is expected to be instrumented in the

[6] Professor John Mather
[7] Mike Packman

summer of 2001. Aberdeen have also been studying the extent to which groundwater governs the quality of surface water in upland rivers.

In another research project, the physical, chemical and ecological significance of the hyporheic zone is being investigated in a number of streams to ascertain; (a) spatial variation in groundwater inputs to stream channels, (b) the effects on streamwater chemistry and (c) the consequences for aquatic organisms. The dynamic nature of the hyporheic zone is also being examined, particularly with respect to the impact on salmonid embryo mortalities. Collaborative research initiatives have commenced with the CEH and the Freshwater Laboratory of the Scottish Executive which are seeking to establish the hydraulic controls on bioenergetics of salmonids at different life stages.

Birmingham University

The Department of Geography and Environmental Sciences represents Birmingham University on the NICHE-LOCAR consortium. It is understood that the JIF funding of NICHE-LOCAR will provide £4 million to instrument the three catchments and that the NERC LOCAR funding will be used to supply research grants and operational costs. The NERC funding will be available for any organisation eligible for normal NERC grants.

The same Department are co-operating with CEH (former Institute of Hydrology) in quantifying fluxes from groundwater to surface water in the Pang/Lambourn catchment. This study is purely on quantitative fluxes but under LOCAR could be modified to include geochemical fluxes.

The School of Earth Sciences is undertaking work on the Tame catchment funded by the Agency's National Groundwater and Contaminated Land Centre (NGWCLC). A PhD entitled 'Impacts of Contaminated Land and Groundwater upon Urban Surface Water Quality' is being undertaken. Negotiations are also underway with CSIRO in Australia for a thermal heat pulse seepage meter. The groundwater flux to the Swan River is being studied and this meter enables seepage to be quantified and enables one to quantify the most difficult measurement of base flow seepage to a river.

The Civil Engineering Dept. is studying fluxes in the Tame catchment under a NERC URGENT project (Appendix F.4).

Bristol University

The Geography Dept. is undertaking research into groundwater fluxes at Leighton on the Severn stemming from a NERC large grant 'Integrated Modelling of Floodplain Hydrology and Hydraulics'. Mass balance analyses were undertaken to quantify exchanges, collect data on surface water/groundwater fluxes during both in and out of bank flood events. The processes were modelled using a 2D Flood Event groundwater model. This work is largely quantitative in nature but has clear implications for the movement of contaminants or agricultural nutrients from terrestrial to aquatic ecosystems.

Cranfield (Silsoe College)

The Institute of Water and the Environment is working with a transect of piezometers across the River Flit near Shefford. This transect was put in by Mott Macdonald in a study for the

Environment Agency involving a conceptual model of the relationship between groundwater and surface water.

Work is underway by a PhD student on recharge estimates through soil water balances. Assistance is being given by Ken Rushton (formerly of Birmingham University's Department of Civil Engineering), who is also working for the NGWCLC on improving the traditional Penman/Grindley recharge estimates to take better account of soil characteristics.

A relevant PhD at Silsoe is the modelling of river-aquifer interactions in a major seasonal river and its floodplain (in Nigeria). This work is similar to much of the relevant hydrogeological work in UK with emphasis on groundwater flow and quality modelling, or upgrading existing methodologies and models. The greater part, even in those cases where quantity and quality are being considered together, is studies of geochemical fluxes within the groundwater body.

Dublin University (Trinity College)

Our contact at the Dept. of Civil Engineering was not aware of specific research on the subject in Eire. The most relevant recent project on groundwater-surface water interaction was a major project on the karst of South Galway (The South Galway Flood Study) by Southern Water Global for the Office of Public Works (OPW). The Project Leader was Denis Peach of the British Geological Survey.

Durham University

Durham (Civil Engineering Dept.) is a member of the NICHE-CHASM consortium with particular interest in the Eden catchment of Northern England. They have been particularly active in studying the geochemical flux relations between groundwater and surface water along floodplains. They are co-operating with Bristol University on studies on the Severn floodplain below Shrewsbury with a PhD being undertaken on the chemistry of the system.

University of East Anglia

The School of Environmental Sciences has been active in research into surface water-groundwater relations in karstic aquifers. Of particular relevance to the subject of this report is the work on the M25 drainage structures in the Three Valleys Water Company's area in the karstic Chalk aquifer and studies of recharge mechanisms in the karstic limestones of the Mendips. They have also been working on the influence of bank storage in river flood plains, in particular the modulating influence of the bank storage on the quality of surface waters. The role of bank storage and the geochemical/biological processes within the floodplain areas in determining the quality of geochemical fluxes to surface waters is thought to become a fundamental part of future research.

There is also a study in progress of the coastal carbonate aquifer of North Norfolk. This work combines an indirect catchment-scale water budget study with small-scale direct studies of the coastal zone in order to assess the relative significance of groundwater discharges in terms of flux and nutrient loading. The various discharge mechanisms will be described.

Exeter University

Exeter University is a partner in the NICHE-LOCAR consortium.

Lancaster University

Lancaster University (Dept. of Environmental Sciences) is a member of the NICHE-CHASM consortium with particular interest in the Eden catchment. The main work of the team is quantitative hydrology on the surface/subsurface interactions on hillslopes and the modelling of dynamic contributing areas. This has included tracing exercises aimed at this interaction at Calder Hollow near Sellafield (funded by NIREX).

Our contact has reservations about the IHACRES (Institute of Hydrology/Centre for Resource & Environmental Studies at Australian National University) model of base flow separation. He suggests that their model separates only fast and slow responses and this is not necessarily surface water/base flow, nor is it an old/new water separation as is sometimes suggested.

London University - Imperial College

Prof. Howard Wheater (Dept. of Civil & Environmental Engineering) is the co-ordinator of the NICHE-LOCAR Consortium which provides a JIF £2 million grant to support the NERC LOCAR funding. It is understood that the £2 million will be used to make up a total of £5 million for instrumentation of the three LOCAR catchments. The Environment Agency is providing cash in kind by providing their existing databases on the three catchments and is represented on the Steering Committee, as well as having funds set aside for getting involved.

Imperial College have worked on various unsaturated/saturated zone pollution transport problems including modelling developments with particular reference to contaminated land (See Sheffield University).

London University - Royal Holloway College

A PhD has been undertaken in the Three Valley Water Company's area on 'Impact of Low Groundwater Levels on Water Quality' studying the surface water-groundwater interaction from the point of view of turbidity and pesticides. It was also reported that relevant work is not being undertaken at Royal Holloway at present but that in the past there has been extensive work on the subject. Of particular relevance to any planned future work is the study carried out in the Essex Stour valley on the use of tritium for quantifying base flow additions to stream flow (Mather. J. and Smith, D.B. 1973).

London - University College

There is no active research work being carried out at UCL which is directly related to groundwater-surface water fluxes. Two recent PhDs however, have some relevance. One studied the distribution of contaminants in the seasonally unsaturated zone of the Chalk aquifer and noted the potential significance of this zone in controlling the quality of base flow to streams. The other studied the flux of Dissolved Organic Carbon (DOC) from surface run-off direct via swallow holes to the Lincolnshire Limestone aquifer.

Newcastle University

Prof. PE O'Connell is the Co-ordinator of the NICHE-CHASM Consortium. A range of work is being undertaken in the field including the LOCAR project (in the Eden Catchment), the Environment Agency IGARF-II project (Impact of Groundwater Abstractions on River Flows, see also Section 3.4.8.3 and Appendix B.3.2 Item 5) and work for NIREX on the natural groundwater discharge to streams in West Cumbria.

Oxford University

The Geography Department confirmed that no research relevant to this Report is currently being done in their Department.

Reading University

Mike Price, Director of the MSc Hydrogeology and Groundwater Quality course at Postgraduate Research Institute in Sedimentology, is not aware of any relevant research being undertaken at Reading.

Sheffield University

Prof. David Lerner has no detailed information on work being undertaken on surface water-groundwater geochemical fluxes in UK but refers to work on measuring groundwater fluxes by the research group at Tuebingen University, Germany.

It should be noted that work by Prof. Lerner's group related to contaminated land research, and indeed similar work by other universities, environmental consultants and government research organisations is pushing forward the science of quantifying geochemical fluxes in groundwater. This work includes the development and upgrading of contaminant transport models to take account of attenuation processes that will be particularly relevant in any work on groundwater – surface water geochemical flux interactions.

3.4.7 Government research centres

The research organisations approached for information on their present activities and future plans for work on groundwater and surface water fluxes are listed in Appendix A.2.

3.4.7.1 Centre for Ecology & Hydrology (CEH, includes former Institute of Hydrology)

The NERC LOCAR Thematic Programme (Appendix F.2) was identified as the main research initiative relevant to the topic of groundwater and surface water geochemical fluxes. CEH is on the LOCAR Steering Committee and is a Partner Organisation on NICHE-LOCAR and NICHE-CHASM. CEH will be particularly interested in the Lambourn Catchment where they are working and in the Upper Severn which acts as a continuation of their longstanding research programme on Plynlimmon.

The CEH is the National Geoscience Data Centre and holds databases that will be important in any work on the surface water- groundwater interaction. The National Well Record Archive is the overarching data set (see also Section 2.5.3). This is on the 'Well Master' database and is being progressively digitised; this is about 25% complete but the Environment Agency is helping to complete it early. The Well Master database links the following data sets:

1. Aquifer Properties Data Set
2. Family of Quality Data Sets

- Data from Archives
- Data from BGS Laboratories
- Baseline Geochemistry Data
- The Environment Agency monitoring data goes to the Agency's database on WIMS

3. Groundwater Level Data Set

Level data are collected by the Agency and are held regionally but in a consistent system - HYDROLOG. The Agency sends the British Geological Survey (BGS) the data for about 170 strategic boreholes for the National Groundwater Level Archive (see Section 2.5.3).

The National River Flow Archive also is held at CEH with over 1,300 gauging stations and 35,000 station years (see also Section 2.5.1). The responsibility for the National River Flow and Groundwater Level Archives was transferred from DETR (Department of the Environment, Transport and the Regions) to NERC. There are river flow records at CEH but no formal water quality databases.

CEH also hold GBASE, a geochemical baseline survey of the environment which includes both stream sediments and stream waters. This has been completed for Scotland, Wales, Northern England and Humberside. Work is in progress in East and Central England.

There is the Harmonised Monitoring Network tied to the National Water Quality Database (held by the Environment Agency). This has 200 tidal limit stations with up to 80 determinands measured regularly. This was intended to measure the pollution flux to the sea and there are 25 years of data in some cases. These data were transferred to the NRA and now are held by the Agency.

The Harmonised Monitoring Network is related to the LOIS NERC Thematic Programme (Appendix F.1) in which CEH played a major role and which focused on quantifying the geochemical flux from the Humber catchment to the North Sea.

The CEH is undertaking work in the Pang-Lambourn catchment on the surface-groundwater interactions. The Hydrochemical Processes Group have studied the ages of groundwaters, the hydrology and the surface water- groundwater interactions. Similar work is in progress in the Chichester area following the 1994 Chichester floods. The interest is into periods of high recharge related to nitrate and other nutrient fluxes with the identification of meteorological drivers to washing nutrient from permeable catchments. This work is relevant to the Habitats Directive with the potential impacts of surface water-groundwater interactions on flood plains or in gravel pit-groundwater interactions in places like the Cotswold water park on the Thames.

3.4.7.2 The British Geological Survey (BGS)

The British Geological Survey is on the LOCAR Steering Committee and will be important in ensuring that the catchment studies include a significant groundwater element.

The BGS groundwater databases (held by CEH) really relate only to groundwater levels. Groundwater quality data are held by the Agency on a regional basis except for a National archive of nitrate data held at the NGWCLC in response to the requirements of the Nitrate Vulnerable Zone (NVZ) work by the Agency.

BGS has been prominent in the past in hydrogeological research, particularly in the studies of the geochemistry of major aquifers in the UK and in nutrient transport through groundwater systems.

Recent work of specific relevance to the surface water-groundwater geochemical fluxes include FAMEST, a project part-funded by the European Union, which is studying how metals move through contaminated soils and are transported to groundwater. The study is in co-operation with organisations in France, the Netherlands and Switzerland and includes aquifers covering a range of hydrological and geochemical conditions. ICI are funding a project to "Assess Contaminant Transport in the Permo-Triassic Sandstone" in order to provide an understanding of water and contaminant migration in this major aquifer.

A large Environment Agency / BGS project on 'The Baseline Geochemistry – UK Groundwaters' is also underway. This Project forms the UK contribution to a European Community ***Framework V Project*** (EVK1-CT1999-0006) and comprises baseline studies of groundwater in 36 selected areas in England and Wales from 1999 to 2004. The outputs of this work will comprise a series of reference documents and data for each of the areas which will help to provide a national overview of baseline groundwater quality. The results will be widely disseminated through scientific and general interest publications, seminars and meetings. There is also a study at Bere Regis into groundwater- surface water fluxes of nitrates. This follows work on geochemical fluxes into the Rhone floodplain (*Hydrogeology Journal*. Oct 2000 Vol. 8 Number 5: 549-563).

An internally funded 'National Groundwater Survey' is aimed at a comprehensive description of the major British aquifers including characterisation of the physical and chemical properties and processes which govern groundwater flow and pollutant transport and attenuation in the saturated and unsaturated zones.

A project on assessing the risk of *Cryptosporidium* infection of 19 groundwater sources has recently been completed for Portsmouth Water plc. This involved the assessment of risk of rapid transport of infective agents in surface water by rapid recharge mechanisms through the karstic Chalk aquifer. A similar project funded by UKWIR reviewed past research on *Cryptosporidium* movement in groundwater systems with an emphasis on rapid recharge mechanisms from surface waters.

3.4.8 Environmental consultancies

Information was sought from a number of environmental consultancies (see Appendix A.5 for list of consultancies and contact names). A summary of the information and comments received is given below. The consultant's ideas for future research requirements are given at the end of each section.

3.4.8.1 Entec UK

Entec UK have undertaken several projects looking at water flow between groundwater and rivers, notably regional modelling projects in Anglian Region (around Redgrave Fen), in Midlands Region (West Midlands Permo-Triassic rivers) and in Thames Region (Upper Lee catchment rivers on the NE Chilterns Chalk/Drift escarpment). These projects mostly focused on achieving low flow alleviation objectives so simulation of recharge/run-off and of groundwater-surface water flow is a critical issue. Modelling reports including a great deal of work reviewing data, integrating it into conceptual models and then representing these numerically are all held by the Agency in those Regions. In addition, 'single issue' studies have been made on leakage losses from streams, due to abstractions or in association with river transfer schemes, in many areas. These have included such techniques as tracer testing studies and spot flow gaugings.

With reference to geochemical studies, Entec UK have done a lot of work on nitrate fluxes/balances, particularly for the Nirex Sellafield studies, which they have applied also in the West Midlands, even though data limitations generally prohibit much meaningful analysis. There is a good data set showing the effect of fertilisers on shallow groundwater at Sellafield (Nirex Reports S/95/008 and SA/97/079).

The wider picture of groundwater abstraction impacts on river flows is being considered through the current National R&D Programme of the Environment Agency.

With reference to relevant research topics that Entec UK think should be funded over the next 5 years, it is recommended that consideration should be given to the recent River Mimram/Upper Lee study. Reports of this study have been delivered to the Environment Agency, Thames Region and provide good examples of how to tie together geology, river stage, groundwater level and river flow data (spot gauging & continuous gauging) in 'integrated river profiles'. This highlights the need for good basic survey data (river stage/bed/width) combined with purpose drilled bankside boreholes, and temporary flow gauging structures (both fitted with loggers to look for run-off/recharge relationships, base flow constraints or responses to nearby groundwater abstractions). This type of river focused field data is currently very sparse across the UK and should be collected in the LOCAR programme and more widely to provide the basic physical flow constraint data after which geochemical issues might be considered. These detailed studies could be cross-referenced to the Environment Agency's strategy for diffuse pollution R&D.

3.4.8.2 Enviros Aspinwall

No relevant projects have been worked on recently. Historically they looked at the interaction between the River Thames and the Thames Gravels in the Eton area. Most recent Enviros Aspinwall projects have been related to contamination. The LOCAR programme is considered a particularly interesting project and there may be an opportunity to look at other catchments.

There is likely to be a great deal of data produced from programmes such as LOCAR. Data assessment and computer modelling may provide further opportunities for research.

3.4.8.3 Environmental Simulations International (ESI)

The main involvement of ESI in the field of groundwater–surface water fluxes has been on behalf of the Environment Agency, where they were the contractor for IGARF (Impact of Groundwater Abstractions on River Flow). In IGARF their brief was to develop guidance for abstraction licensing on the possible consequences of single new abstraction licences on river flow rates. This involved the development of a tool to evaluate the analytical solutions regarding the river losses arising from nearby abstraction (see Hunt B., Groundwater 37(1), 1999). Analytical solutions provide a crude measure of these fluxes but do not consider the geochemical implications either for river or groundwater quality. The IGARF project is a NGWCLC project (see also Appendix B.3.2 Item 5).

A key limitation in evaluating the impact of abstractions on low flows is a lack of data on stream bed or bank properties. This is a key parameter both in simple analytical scoping tools such as IGARF 1 and in more realistic numerical models for many real UK rivers. The geochemistry may help us estimate these parameters or set bounds on their values and any additional work that would help quantify the fluxes between surface water and groundwater would be very helpful.

ESI have also been involved in a range of more specific UK projects on behalf of the Agency, and in many of these, river aquifer interactions have to be estimated or matched by calibration. They also have been working on baseline water quality studies for the Agency and on wetlands where again surface water - groundwater fluxes are important. ESI are also working on a new project (R&D W6-066) through Entec UK to develop a more consistent approach to catchment based evaluation of water resources, integrating protected flows with groundwater abstraction policy.

With respect to the LOCAR thematic programme, ESI recently carried out a detailed study on the Shropshire Permo-Triassic, including the Tern catchment as a precursor to a decision on the possible development of a new Regional water resource model. This project included a detailed water balance for the Tern, and was carried out for the Midlands Region of the Agency.

ESI, in the 1980's and 90's also looked at the interaction of groundwater and surface water at the low level radioactive waste repository at Drigg.

3.4.8.4 Golder Associates (UK)

Golder Associates (UK) have done no work relevant to groundwater-surface water fluxes. They do a considerable amount of groundwater impact assessment work and assume that where groundwater is in hydraulic continuity with surface water, it provides the base flow element, and that the discharging groundwater will need to meet the same criteria as the surface water. They do not normally assume that dilution in the receiving watercourse is an acceptable means of resolving contamination problems and do not have any information relating to the actual interactions between groundwater and surface water.

3.4.8.5 Mott MacDonald

Mott MacDonald have been involved for many years with the modelling of river catchments in the UK, largely to assess the impacts of groundwater abstractions and climatic variation/changes on low river flows. These models fully integrate the surface water and groundwater systems, although the representation of the river/aquifer interface can obviously only be approximate. Over the past five years they have modelled catchments of the rivers Dour, Darent and Upper Stour in Kent, the Wyre and its tributaries in Lancashire, the Little Ouse and its tributaries in Norfolk and several others. Most recently they have worked on regional models of the Chilterns and the London Basin, including the North Downs. The Chiltern model, which was carried out for Three Valleys Water, showed the significant influence of effluent return on river flows. These returns are generally not well defined, particularly for historical periods, and, if not properly appreciated, may result in models that simulate river/aquifer interaction incorrectly. Also in this model, the effects of urban recharge on river flows were investigated. Urban recharge is generally poorly defined, because of very limited historical data to define it. Some of the modelling work also involves environmental and ecological work to determine target flows and assess impacts.

Mott MacDonald have expressed interest, together with Geography Department of Cambridge University, to be pre-qualified for some of the work with LOCAR. They have always believed it necessary to obtain better understanding of the influence of the riparian zone on river flows. Research in this area could be very valuable. Research into delayed recharge also should be a worthy topic of future research, since it influences the delayed response of rivers to wet weather events. Other research may relate to urban influences on recharge and therefore on river flows.

3.4.8.6 Water Management Consultants (WMC)

WMC have undertaken several relevant projects on groundwater-surface water fluxes. A hydrogeological study to accompany a groundwater abstraction licence renewal for South Staffordshire Water included an assessment of the effect of the abstraction on a sensitive ecological site, mainly by examining hydrographs of monitoring wells on the site. A tracer test for Southern Water used bacteriophage to establish whether or not there is a direct link between a lake and a nearby groundwater abstraction. Other projects for Southern Water involved a detailed hydrogeological investigation of a spring source, as part of a risk assessment for *Cryptosporidium* contamination, and the development of a semi-quantitative risk assessment methodology for *Cryptosporidium*, which includes an assessment of connections between surface water and groundwater. A similar project was done for Yorkshire Water where a tracer test was designed to identify possible sources of bacteriological contamination of a groundwater source (well and adits).

A full hydrological and hydrogeological study of an aquifer management unit was made for the Environment Agency, Midlands Region to obtain a better estimate of the sustainable resources of the unit, including an assessment of groundwater-surface water interaction using draft versions of IGARF (see Section 3.4.8.3 and Appendix B.3.2 Item 5) and ARM.

Environmentally targeted projects included a hydrogeological investigation for the Shropshire Wildlife Trust of a former wetland site, now drained and under arable farming, to establish the feasibility of returning it to wetland by careful management of groundwater levels. Also for the Shropshire Wildlife Trust hydrogeological investigations of 24 Wildlife Sites were to establish their vulnerability to groundwater abstraction. Hydrogeological investigations were made of 180 SSSIs (Site of Special Scientific Interest) for the Agency, Midlands Region, to establish their vulnerability to groundwater abstraction.

WMC would advocate new research with the establishment of well-instrumented field sites to get some real data on surface water-groundwater interaction, because there is a limit to how far models and analytical approaches can be taken without knowledge of real processes. These field sites would provide better values for critical parameters such as streambed conductance.

3.4.8.7 WRc

WRc has been involved for a number of years in the modelling of catchments such as the Great Ouse Resource Model (Oakes and Keay, 1990) as discussed in Section 2.5.5 and the development of POPPIE (Oakes *et al*, 1995) as discussed in Section 2.5.6. WRc has also been involved for a number of years with diffuse pollution studies such as the effects of pesticides, nitrates and MTBE on groundwater and surface waters, with fluxes often being estimated, as well as detailed studies of specific catchments such as the River Po in Italy (Oakes, 1999) and the River Granta in Cambridgeshire, UK (Clark *et al*, 1995). Full references to these papers are given in Appendix C.

A number of recent projects carried out by WRc have included aspects of groundwater/ surface water interactions. For example, the interaction between the groundwater and surface water has been studied as part of risk assessments carried out at potentially contaminated sites, including sites in Buckinghamshire and Anglesey.

A five-year study was also carried out as part of proposals to deepen a quarry in the Mendips. The objective of the study was to determine the actual and potential effects of sub-water table quarrying on groundwater resources in the Carboniferous Limestone aquifer, particularly with respect to a number of springs which rose on the northern edge of the limestone outcrop. Water levels in 18 boreholes, the quarry sump and 8 springs and streams were measured using electronic datalogging equipment. Abstraction rates from the sump, and rainfall and effective rainfall data for the area were also recorded.

3.5 New Initiatives

The NERC LOCAR Thematic Programme with the two supporting NICHE initiatives are likely to be the framework for research into geochemical fluxes in groundwater and surface water interactions for the next few years. The designated catchments, when instrumented, will be a National asset open for use by research organisations. It is understood that the NERC budget will be available for NERC- approved projects and organisations. Other organisations are expected to have to provide the operational costs for any approved research projects. BGS made the following points:

1. The surface- groundwater inter-relations will vary with the position in a catchment. To some extent this has been recognised by the division between the NICHE-LOCAR and NICHE-CHASM catchments. In any research project this distinction will need to be acknowledged.

2. A related factor that must be recognised is that in many areas of UK aquifers, the Sherwood Sandstone of Eastern England for example, the groundwater in the aquifer is almost totally utilised and, other than in recharge, there is no groundwater-surface water interaction.

3. Although it is not a pre-requisite of the Water FD, studies into geochemical fluxes should also include particulate matter, particularly pathogens, on health grounds. In karstic aquifers, the transport of pathogens from surface water to groundwater sources is one of the most pressing problems for our water utilities.

LOCAR and, if accepted, the suggested Agency catchment in Eastern England, would provide over-arching research into entire catchments. Within this broad field of research of catchment management would be the facility to undertake specialised focused research into specific aspects of the groundwater-surface water fluxes. Specific items for focusing research identified by these active researchers include:

Recharge - Precipitation characteristics;

- Unsaturated Zone Processes;

Discharge - Discharges/seepages at the hyporheic zone;

- Surface water/groundwater interactions along floodplains and recharge areas;
- Geochemical fluxes in closed catchments (i.e. catchments where groundwater discharges to boreholes only);
- Surface water flux relations within stream systems.

3.6 UK Information Status Summary

3.6.1 Ongoing work

The main funding agencies in UK for existing research work into groundwater-surface water geochemical fluxes are NERC and the Environment Agency. Other important sources of research funding are the European Community, the Water Utilities, MAFF (now part of Department for Food and Rural Affairs (DEFRA)) and commercial companies with environmental interests. The organisations undertaking relevant research include the universities, government research centres and environmental consultants/ contractors.

NERC funding is extremely important in the academic world, including the government research centres but commonly is not available to the commercial environmental consultants. It is considered unfortunate that the expertise developed in the commercial research industry is largely isolated from the NERC-funded academic programmes through this policy. NERC funds post-graduate research for individual MSc and PhD courses, research to cover large areas of related research and very large thematic research programmes.

In the field of groundwater fluxes, traditionally, work would have been done in recognised ‘groundwater centres’ holding MSc Hydrogeology courses or promoting groundwater research; universities such as University College London, Birmingham, Reading or Newcastle. The research now is spread much more widely into more universities and into different departments, Environmental Sciences, Civil Engineering or Geography. Similarly, traditionally, groundwater would have been studied almost in isolation whereas now there is much more integration of different disciplines: Hydrogeology, Hydrology, Meteorology, Ecology, Chemistry and Statistics.

NERC funding covers numerous individual postgraduate research projects related to the groundwater-surface water fluxes but the most important funding will be the LOCAR Thematic Programme and the related NICHE-LOCAR and NICHE-CHASM Programmes (See below). The postgraduate research tends to be on specific sections of the groundwater-surface water flux pathway or process whereas the LOCAR programme is on a catchment scale. Individual pieces of work may be undertaken in the LOCAR catchments but the value of this programme is that it will give opportunity for long-term multidisciplinary research covering the geochemical fluxes of an entire catchment.

The Environment Agency (and one of its predecessor bodies, the NRA) has been the major funding agency for groundwater research outside the academic community. Research funding tends to be in response to immediate environmental problems but also includes planned long-term research programmes, including studies directly related to the identification and quantification of geochemical fluxes. The most important has been the work on the origins and transport of nitrate through aquifer systems. The fundamental research on the origin of nitrate, the transport through the unsaturated and saturated zones of aquifers, chemical, physical and biological processes of attenuation will be applicable to any flux research. In addition the development of modelling methods for nitrate transport will be applicable to flux studies. Similar large-scale studies have included the impact of sewage effluent recharge, agricultural chemicals, waste disposal and contaminated land on groundwater and surface water quality. All these studies have included aspects of the quantification of geochemical flux through the groundwater and surface water systems. Relevant research at present funded by the Agency continues with the large programmes identified above with particular emphasis on contaminated land. The Agency also is co-operating with NERC on LOCAR by providing their databases on the relevant catchments.

Other Agency projects include the 'Impact of Groundwater Abstractions on River Flows' ("IGARF") with Newcastle University (see also Sections 3.4.6, Sections 3.4.8.3 and Appendix B.3.2- Item 5) and the funding of regionally important projects (detailed in Appendix B.1.1). The Agency maintains the Harmonised Monitoring Network data and the most comprehensive database on nitrate concentrations in UK groundwaters is held by the Agency. The Agency is not currently undertaking research into groundwater-surface water geochemical fluxes on a catchment scale that would allow a mass balance to be made of such fluxes.

The former MAFF (now part of DEFRA) funded a significant amount of research into the origins of nitrates from agriculture. This tended to concentrate on the impact of applied agricultural nitrates on the quality of surface and groundwaters but also included flux studies.

The research funded by utilities or commercial companies tends to be strictly related to problems met by the water industry or the specific industries. Such research commonly is confidential but some may be relevant to the geochemical fluxes. Research funded by UKWIR tends to be in the public domain and includes important work on the recharge mechanisms in karstic aquifers related to the *Cryptosporidium* problems.

3.6.2 New initiatives

The LOCAR and NICHE-CHASM programmes and experimental catchments are important because they will give the opportunity for large multidisciplinary projects to be organised. Indeed, a multidisciplinary approach will be needed to take full advantage of the facilities, with individual projects possibly being focused on the scale of an MSc or PhD project to study very specific aspects of groundwater-surface water interactions. The value of an instrumented catchment, however, is that it allows the identification and quantification of fluxes from initial precipitation, through groundwater flow, to the final discharge by a surface river from the mouth of the catchment.

Specific areas of research deficit are being identified, including the absence of a suitable research catchment in the dry East of England, the problems of defining and quantifying surface water - groundwater interactions in areas where the groundwater utilisation rate approaches that of natural replenishment, and the general absence of projects incorporating the study of the transport and fate of pathogens on a basin scale.

4 CATCHMENT MANAGEMENT TOOLS

4.1 Background

There is a continuing need to balance the demands for, and supply of, fresh water. About half of the present demand is for water to be put into public supply, and the water resources which have been developed to meet this demand are highly integrated; in many cases they involve a combination of water drawn from rivers, aquifers, and reservoirs.

The Environment Agency has a duty under the Water Resources Act 1991 to take action, as and when it considers necessary, in order to conserve, re-distribute, or otherwise augment water resources in England and Wales, and to secure the proper use of water resources. Excessive abstraction of water can result in low flows in rivers, and falling groundwater levels. These in turn may adversely affect river water and groundwater quality, the ecological health of rivers and wetlands and other users of the catchment, such as farmers and industry. Most of the problems have been caused by "licences of right", which were granted under the Water Resources Act 1963. These authorisations legalised existing abstractions without reference to their environmental impact. The Agency is currently working to resolve these problems with the co-operation of the relevant abstractors.

The Agency makes assessments of the balance between the total available water resources and current demands. The Agency also makes assessments of the forecast balance between demands and available water resources. It also prepares plans aimed at achieving a proper future balance. These plans not only consider engineering options, such as new reservoirs or transfer schemes, but also include water demand management opportunities, such as leakage control and water metering.

These assessments and plans may be categorised as *catchment management tools.* Such tools have been used in various forms for several years within the Agency, and are particularly necessary in highly integrated catchments. Mismanagement of a catchment can lead to serious problems for water users with regard to both quantity and quality, and ecological damage.

4.2 Specific Objective of Task

The key aim of this task has been the collation and review of existing modelling tools in the areas of surface water and groundwater management.

This task also involved the examination of existing commercial and research models from software suppliers and universities. Model suitability has been assessed on the basis of the underlying algorithms, the robustness of the tool, the range of existing applications (including calibration experience) and the direct relevance to assessing diffuse loads and concentrations. The ability to include point and diffuse inputs is also important.

This stage ran in parallel and linked in with the literature review and the review of existing projects and new initiatives.

4.3 Section Structure

Section 4.4 provides information on the ways in which the gathering of information was carried out. Section 4.5 outlines "What is a Model?" and Section 4.6 details the available tools for catchment management. The UK information status summary is given in Section 4.7. Details of the persons consulted are included in Appendix A.

4.4 Review Methodology

A review has been undertaken of tools, available commercially or as outputs from research studies, for the management of water resources. Suitability has been assessed on the basis of the underlying principles, range of applicability, data requirements and relevance to the study in hand.

A second review has been undertaken of catchment management tools currently used by the Agency for the management of integrated surface water and groundwater resources.

The gathering of information has been undertaken by the use of telephone and e-mail communication with targeted contacts. The list of existing tools used by the Agency has been drawn up by personal and telephone contacts with selected Agency experts, in consultation with the Project Board. The efficacy of these tools for the purpose of effectively managing resources has been reviewed, and recommendations made for further development to fully meet Agency requirements. The names and affiliation of the individual consultees who have contributed information are listed in Appendix A.

4.5 What is a Model?

It has been said that a model is 'representation with the reality', that is the model represents some behaviour of the real world without the need for measurements or experiments in the real world. This is attractive because measurement and experimentation are expensive. Additionally, in water resource systems the response to experimentation may be very slow, on a time scale of years. Some experiments, for example to gain insight into pollution movement, may also damage the environment. In some cases models do not need real world measurements at all. For example, finite element models used to design new bridge structures commonly use tables of material properties to accurately characterise the system. With water resources, however, the system can rarely be characterised accurately, and measurements and experiments are needed to calibrate and validate any model. Nevertheless, the same principles apply that a water resources model can be used to test numerous future management options prior to major capital expenditure or damage to the resource. This is the key to the widespread use of models in the water industry.

A model is based around concepts and equations which describe some aspects of a water resource system, usually implemented on a computer. Some models are very simple and do not need computation, but use approximate analytical solutions presented as graphs or tables. The Theis solution for drawdown in an observation borehole close to a pumping well is an example. Such a model has very limited application. Most water resource systems are relatively complex, and require computer-based models for satisfactory simulation. Before starting a modelling study it is important to develop a conceptual model of the system to use as a basis for the study. The conceptual model will detail all of the important processes operating in the system, the manner in which they interlink and the sources of data to be used to describe the processes quantitatively. For the Theis solution, for example, the conceptual model would comprise a well in an infinite, uniform aquifer. There may be streams in the vicinity, or the aquifer boundary may be close by, but these would be ignored. The validity of these assumptions could be tested with the model, once developed.

The concepts on which models are based are simple:

- mass balance – water and solute masses must be conserved; even when chemicals degrade the conservation principle applies to the total load;
- Darcy's law – the rate of flow of water through a unit cross section of porous medium is equal to the hydraulic conductivity multiplied by the head gradient;
- solutes dissolved in water move at the velocity of the water phase, but may undergo dispersion (spreading) and interaction with the solid phase (adsorption/desorption).

In models, these principles are combined within a conceptual framework to provide a means of simulating the behaviour of water and any chemicals. It has often been stated that the best model is one to which nothing can be added – in other words it has all the conceivable bells and whistles which make a model sophisticated. In practice, however, the best model is one from which nothing can be taken away – it is as simple as possible but embodies all of the important processes operating in the water system. There has been a tendency in recent years to make models more sophisticated because increasing computer power has allowed complex mathematical calculations to be undertaken. The HSPF (Hydrological Simulation Program – Fortran) model is an example of an over complex model. Its aim is to simulate all water-related processes in a catchment, but it is so complicated and so data hungry that it is rarely used in its entirety. Instead, sub-models of HSPF have been used to provide insight into separate parts of the hydrological cycle.

In starting a modelling project it is recommended that the following rules are followed:

1. Clearly define the requirements of the project, though it may be necessary to modify these at a later stage;

2. Develop a conceptual model, incorporating all of the important features of the system;

3. Identify data requirements for the conceptual model;

4. Identify data sources to meet those requirements; if some data items do not exist, set up a program to acquire the data;

5. Seek out a suitable model, which may be commercially available or may need to be developed. Use the simplest model which meets the requirements;

6. Build the model, incorporating the data which has been collated;

7. Calibrate/validate the model against monitoring data. Assess the sensitivity of the simulations to uncertainties in the data;

8. Revisit 1 – 4 above, particularly with regard to the project requirements, components of the conceptual model, data availability and model sensitivity. Amend the model and collect additional data if required;

9. Undertake predictions of future scenarios.

It is, of course, not always possible to precisely define the data requirements prior to modelling. It will commonly be necessary to collect more data after modelling has started in order to better define some parameter which the model has shown to be particularly sensitive. It is better, therefore, to treat project requirements specification, data collection, conceptual model development and modelling as one continuous processes towards providing scientifically based information for sound catchment management decisions, as illustrated in Figure 4.1.

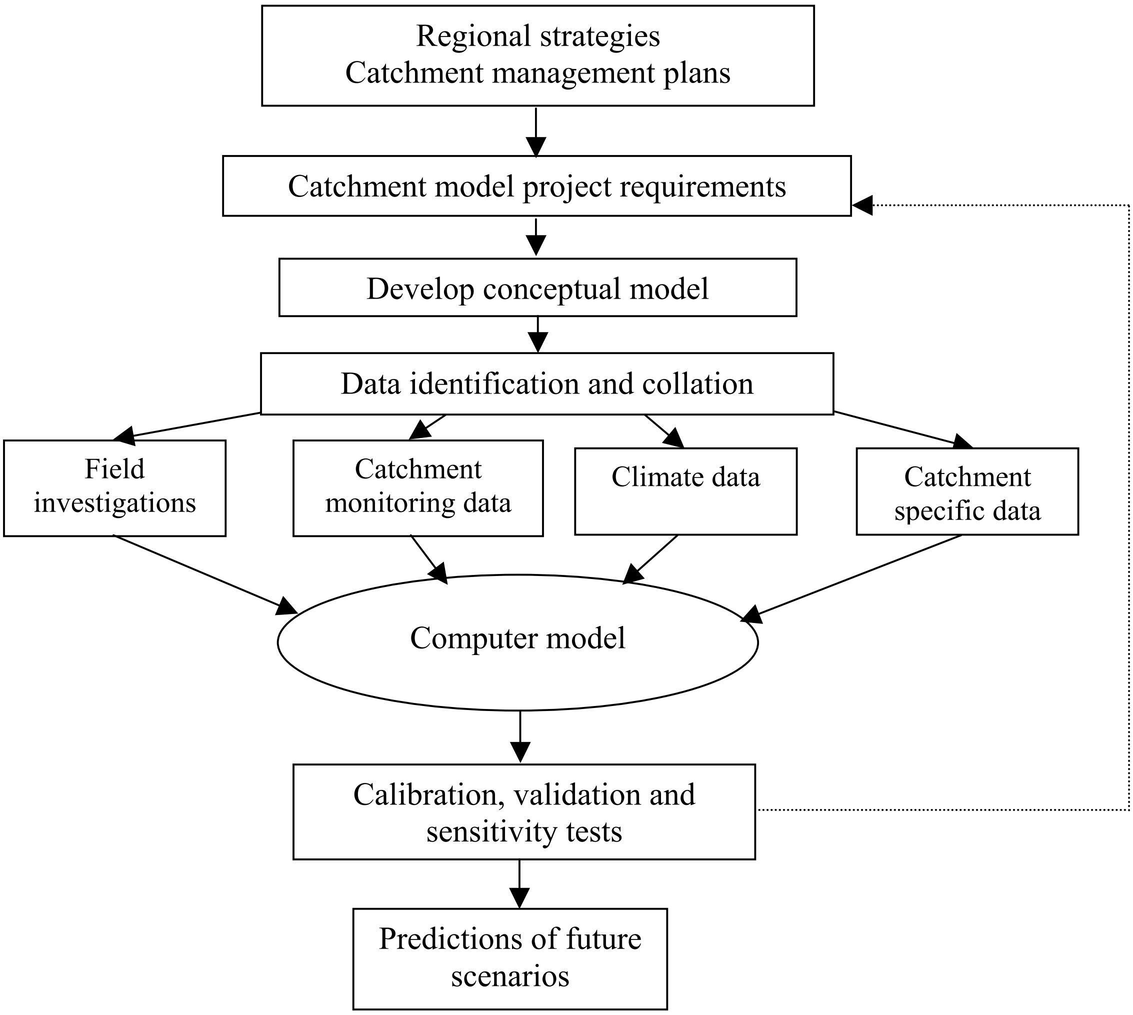


Figure 4.1 Overview of the modelling process

4.6 Available Mathematical Tools for Catchment Management

Licensing of abstractions represents perhaps the first catchment management tool used in the UK. These permits to abstract water from rivers, reservoirs or aquifers were initially based on measurements of river flow or groundwater level, and the perceived ability of the resource to support the abstraction without derogating other users. Prior to the 1963 Water Act, resources were developed in a somewhat parochial manner, and many permits to abstract were granted. Under the Act these permits became licences of right, commonly for excessive quantities. The wider consequences of abstractions were not considered. Licensing is still a vital management tool, but it is now recognised that resources must be managed across entire catchments. It is also recognised that groundwater and surface water interact in a significant way. Water resource developments are commonly highly integrated to meet increasing demands and to offer increasing security; in many cases they involve a combination of water drawn from rivers, aquifers, and reservoirs.

The range of problems for which catchment management tools are required may be summarised as follows:

- safe yield assessment under conditions of short and long term meteorological variability;
- location of new sources;
- delineation of well capture zones;
- licensing of new sources;
- assessment of the impact of changes in abstraction patterns;
- artificial recharge of groundwater;
- impact of groundwater abstraction on river flows;
- conjunctive use of sources;
- river regulation by reservoir releases or by groundwater pumping;
- coastal saline intrusion;
- dilution of effluents in rivers (discharge consent setting);
- pollution of sources by other users of the catchment (e.g. farming, industry, waste disposal);
- environmental/ecological assessment of water management;
- accidental spills;
- consequences of air pollution (e.g. acid rain).

Some of the catchment management tools which are available to tackle these problems are briefly described below (additional comments on catchment management tools from conversation with the Regional Agency Officers and Water Utility contacts is provided in Section 4.6.7). Catchment management tools range from the relatively simple to the extremely complex, and usually the data requirements increase, as does the complexity. Nearly all are implemented on a computer, though type curves are still used to a limited extent for pumping test analyses and for reservoir control.

4.6.1 Spreadsheets

Spreadsheets provide a way of undertaking repetitive calculations, and can be stored and re-used for regular updating. This is ideal for simple accounting of a water balance within a catchment or set of sub-catchments. As an example, an Excel spreadsheet can be readily implemented to provide a monthly account of the water balance in a catchment, using effective rainfall as input and abstractions as the outputs. However, no account will normally be taken of water stored in the catchment, for example in aquifers, in the soil or in the river channel. These are significant omissions from the conceptual model of the catchment, but have in cases been included in a simplistic manner in spreadsheet models. For example, a distributed groundwater model (with some of the capabilities of MODFLOW) has been built into an Excel spreadsheet. However, the effort required, and the compromises which must be made, mean that it would be better to use a model such as MODFLOW rather than a spreadsheet equivalent.

Spreadsheet calculations are relatively easy to use, to distribute to colleagues and to maintain. The data requirements are modest. By looking at long-term means, such models can provide initial answers to questions such as:

- what is the balance of resources by sub-catchment?
- how will the balance change if abstractions are increased?

An example of a spreadsheet calculation is shown in Figure 4.2

		CATCHMENT ANYWHERE			AREA = 65 km^2		
YEAR	MONTH	EFFECTIVE RECHARGE (mm/month)	MONTHLY RESOURCE (cum)	MONTHLY ABSTRACTION (cum)	RESIDUAL RESOURCE (cum)	ANNUAL RESIDUAL (cum)	ANNUAL RESIDUAL AS BASE FLOW (cum/d)
1999	Jan	81	5265000	335195	4929805		
1999	Feb	3	195000	335195	-140195		
1999	Mar	39	2535000	335195	2199805		
1999	Apr	0	0	360100	-360100		
1999	May	0	0	360100	-360100		
1999	Jun	0	0	360100	-360100		
1999	Jul	0	0	360100	-360100		
1999	Aug	0	0	360100	-360100		
1999	Sep	0	0	360100	-360100		
1999	Oct	0	0	335195	-335195		
1999	Nov	0	0	335195	-335195		
1999	Dec	0	0	335195	-335195	3823230	10475

Figure 4.2 Water resources balance by spreadsheet analysis

4.6.2 Lumped parameter model – quantity

The next stage in complexity from a spreadsheet calculation is a lumped parameter model. In such a model inputs and outputs are defined as in a spreadsheet model, but the important components of storage are included by hypothesising a relationship between flow and storage. Such a relationship has a scientific basis and is commonly used in models. The area modelled is, however, represented as spatially uniform – or lumped. In some cases, the model can also include a representation of the river network, with the flow out of one reach becoming the flow into the next downstream; such a model can be considered as multi-lumped, but with each lump homogeneous. There is a significant difference here to distributed models, such as MODFLOW, which can incorporate spatially heterogeneity across a catchment.

Figure 4.3 shows an output from a lumped parameter model with effective rainfall divided between aquifer recharge and run-off, and storage simulated for both elements.

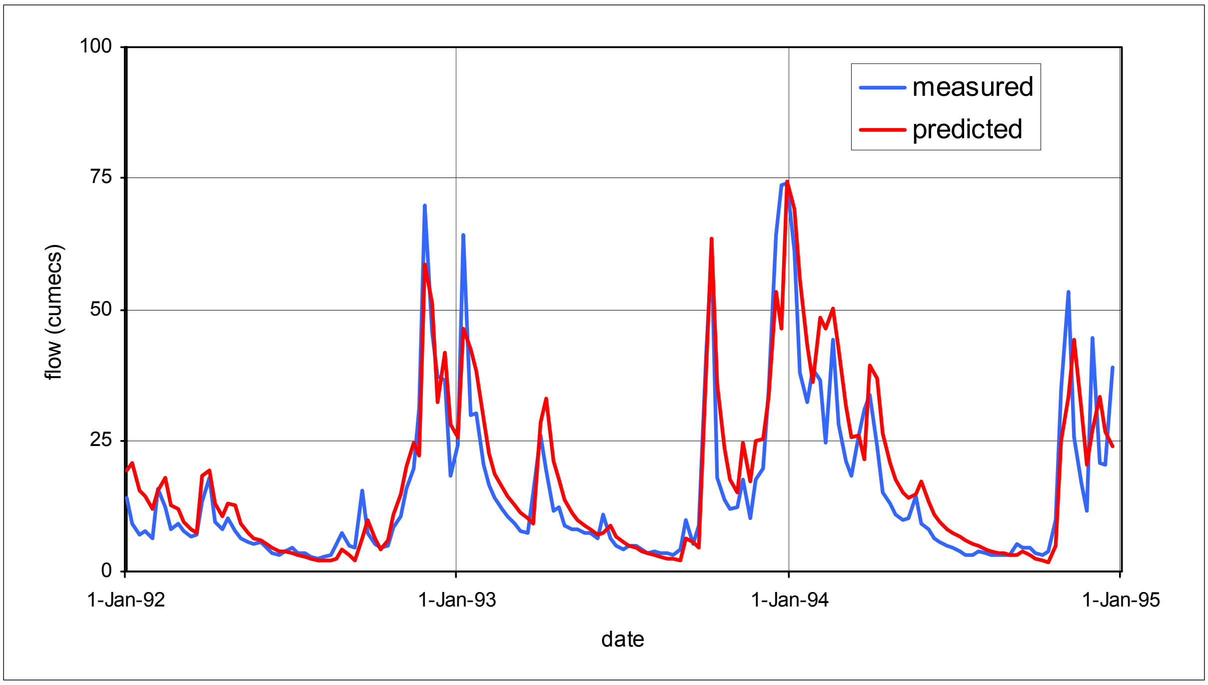


Figure 4.3 Measured and predicted flows for the River Stour, Hampshire

Base flow will commonly be released slowly from aquifer storage, but run-off will be released quickly from soil and bank storage. The relationships between storage and flow will be determined in a calibration exercise in which simulated flows and storage states are compared with measured values.

Lumped parameter models can be used to answer questions such as:

- what will happen to base flows and total river flows if a drought period continues?
- what extreme ranges of flow can be expected (by using a long record of effective rainfall)?
- what extreme ranges of aquifer storage and base flow can be expected?
- what are the consequences of increasing, or decreasing abstractions?
- what are the consequences of moving abstractions to another sub-catchment?

4.6.3 Lumped parameter model – quality

Having established the flow regime within sub-catchments and associated river reaches, it is possible to add diffuse pollutants into the model. Diffuse pollutants, such as those from agriculture, fit the concept of spatial homogeneity, which forms the underlying principle of the lumped parameter approach. It would be inappropriate to simulate point source pollutants within this framework.

If polluting loads can be estimated, for example from agricultural statistics, they can be added into the surface water and groundwater components of the lumped parameter model to calculate concentrations. Concentrations in groundwater will be transported into the river system with base flow, and water abstracted from the catchment will be carrying the pollutant concentrations for the appropriate river or aquifer. The method is potentially very powerful but the data requirements are significant. By subdividing the catchment into smaller 'lumps' the model approaches the spatial resolution of more detailed simulators such as MODFLOW and HSPF.

Example outputs are shown in Figures 4.4 and 4.5, for a lumped parameter model study of the River Po in northern Italy, these were produced for a Report to the River Po Authority. The basic unit of resolution in this case was a 'commune', the equivalent of an English parish. The model results for diffuse pollutants were subsequently used in SIMCAT (SIMulated CATchments) type analyses of the impact of point sources inputs to the river system.

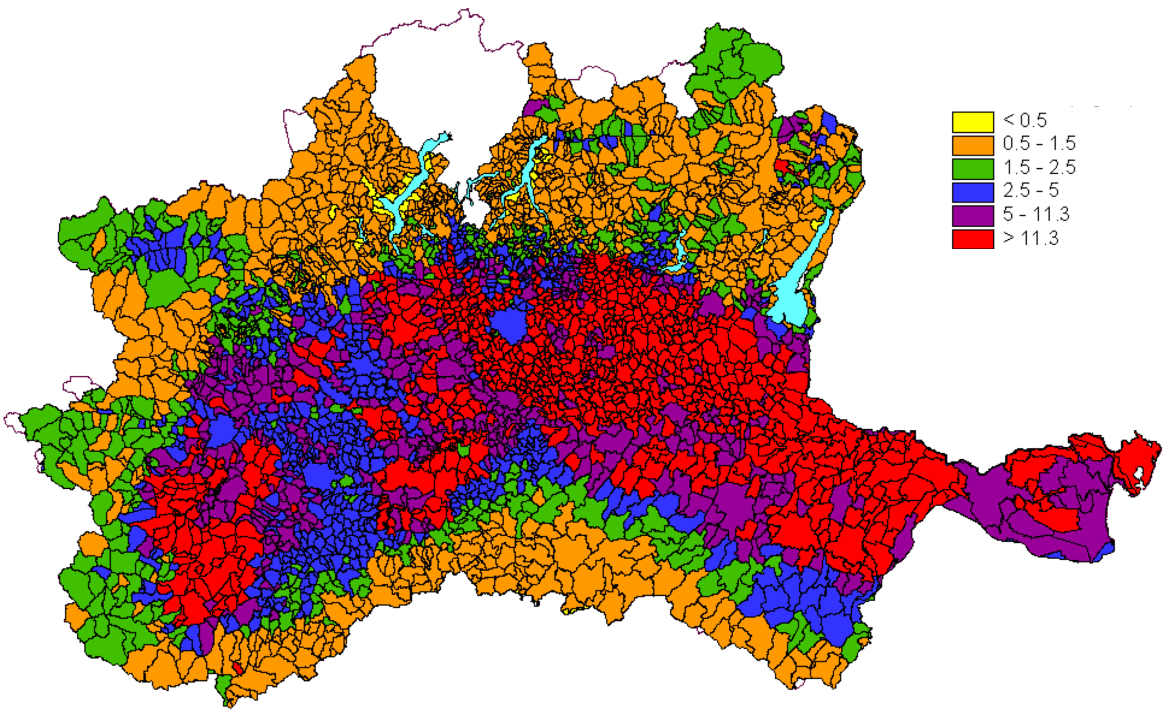


Figure 4.4 Mean annual nitrate concentration (mg/l N) in run-off in the Po Basin

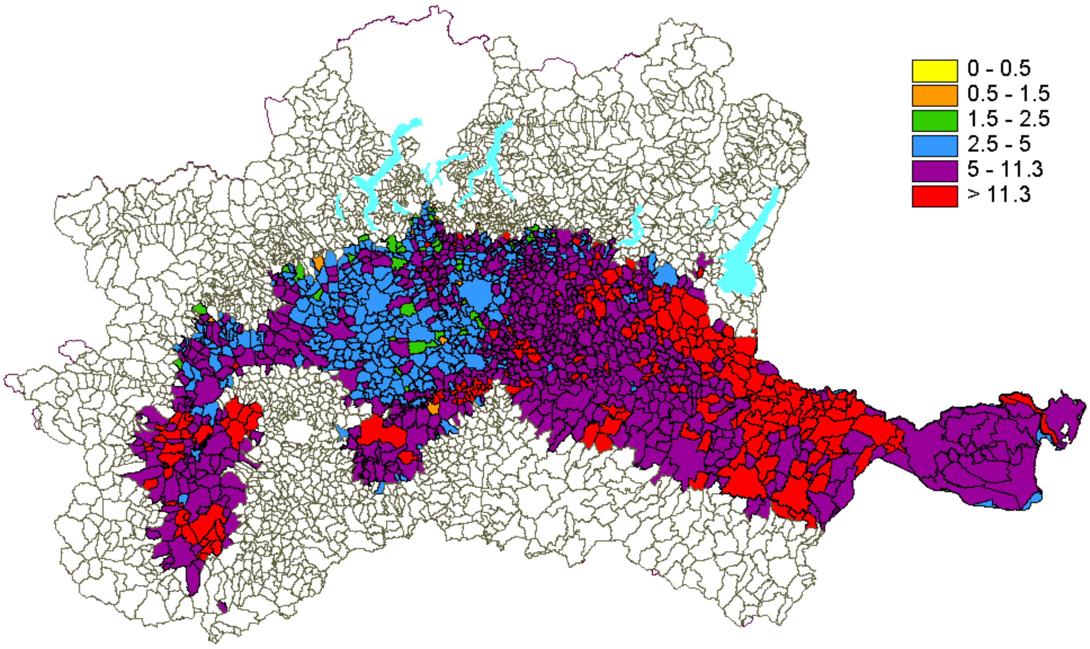


Figure 4.5 Mean annual nitrate concentration (mg N/l) in base flow in the Po Basin

4.6.4 GIS, quantity and quality

The ultimate extension of the lumped parameter approach is into a GIS (Geographical Information System). A large amount of spatial data is required to simulate water quantity and quality in a river basin, and a GIS is extremely good at storing, manipulating and presenting spatial data. A GIS does not handle temporal data so easily, but time steps can be accommodated. For example, effective rainfall can be stored as successive time slices of a week, or month to cover a period of several years. Data which are stored in the POPPIE GIS (see Section 2.5.6) cover all of England and Wales and include:

- rivers;
- river catchments;
- coastline;
- aquifers;
- soils;
- effective rainfall (MORECS grid squares);
- landuse;
- depth to water table;
- pesticide loadings.

A GIS can overlay one data set on another, so in the case of POPPIE can calculate for any catchment the river network, the extent of underlying aquifer and the mean depth to water table, the soils, the effective rainfall sequence (as successive time slices), the landuse, and the pesticide loadings. These data can be presented by the GIS as computed screen displays or printouts, or presented to lumped parameter models supported by the system. Figures 4.6 and 4.7 give some typical model outputs from POPPIE models. Although the model predictions differ somewhat from measurements, the simulation is nevertheless considered to be very good. This is because modelling of pesticides is notoriously difficult, mainly because over 99% of the applied product is degraded in the soil before reaching a river or aquifer. Small errors in the calculated loss by degradation will give rise to large errors in the mass entering water.

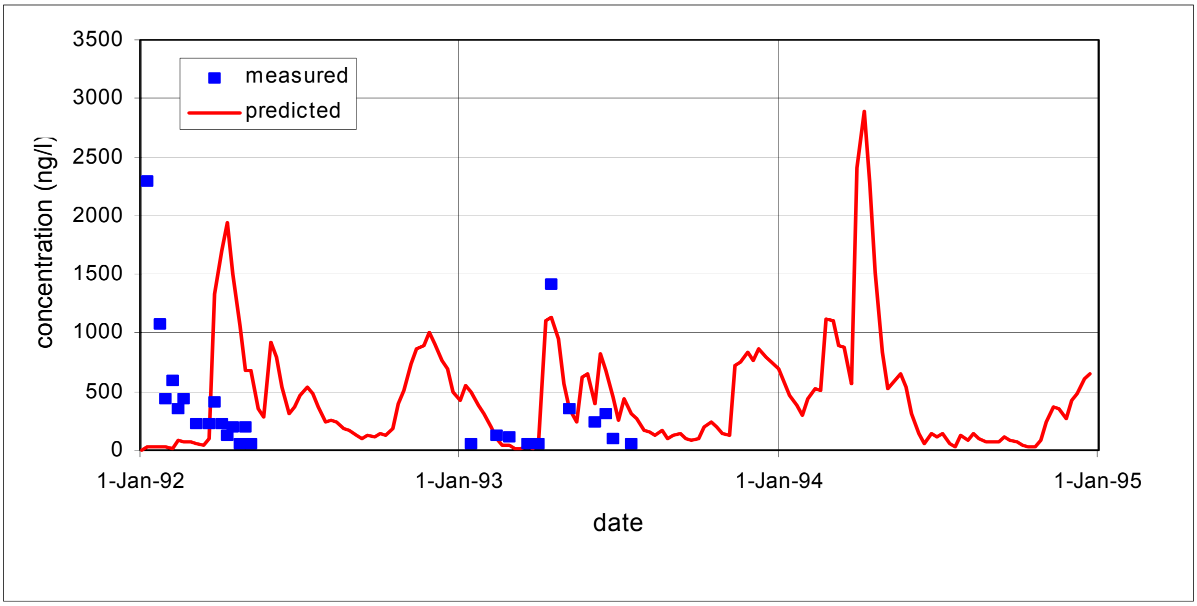


Figure 4.6 River Leam isoproturon concentrations

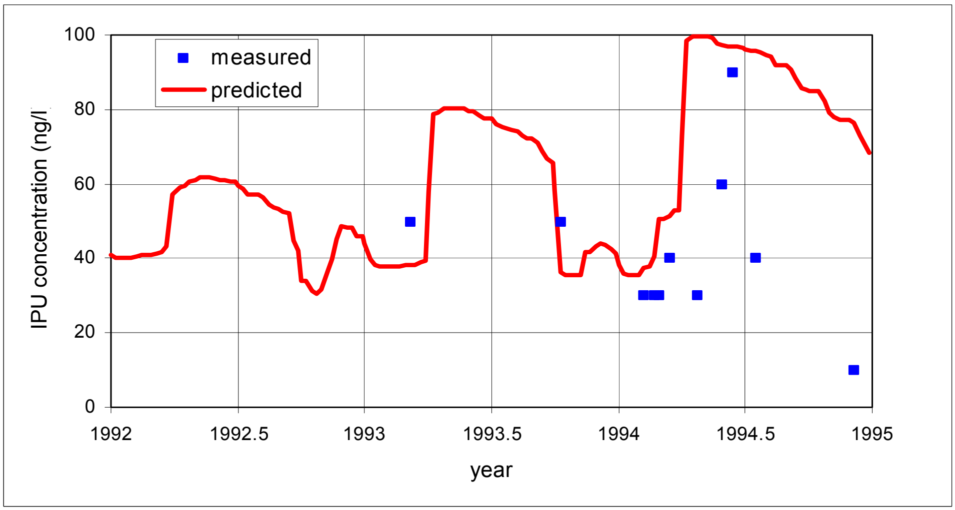


Figure 4.7 Colne groundwater isoproturon concentrations

GIS can have regional coverage if appropriate, but a national coverage achieves economies of scale in the purchase of data, maintenance and updating (for example, MORECS data needs to be added from time to time). Although POPPIE was designed as an investigative tool for pesticide studies, it contains data sets appropriate to a much wider range of studies.

Detailed studies, for example of well field design, need models capable of higher resolution than lumped parameter models can provide. While GIS can supply some data for such detailed studies, much of the data must come from additional measurements.

4.6.5 Groundwater quantity and quality

Many models have been written to simulate the movement of water and contaminants through aquifers. The Environment Agency has opted for consistency of approach by selecting MODFLOW and MT3D as its preferred models. Both are USGS developed models, which are relatively difficult to use. However, numerous pre and post processors have been developed to facilitate data input and results analysis.

MODFLOW simulates groundwater flows in multiple aquifer systems under the action of external stresses, such as recharge and pumping. MT3D handles miscible contaminants, and may be used once the flows have been calculated with MODFLOW. Both models allow an aquifer to be discretised into small cells, typically from 10m to 1000m in size. Wells, rivers receiving base flow and other boundary conditions are applied to relevant cells. Rainfall recharge to the aquifer is input as distributions at successive time steps. The model distribution of aquifer properties will usually be based on measurements, but will require some refinement. This is done in a calibration phase, in which simulated groundwater levels are compared with measurements, and the aquifer properties are adjusted where there is evidence to support such change to obtain an acceptable match.

A typical output of groundwater level contours is shown in Figure 4.8; this is the result for a particular time during the simulation period.

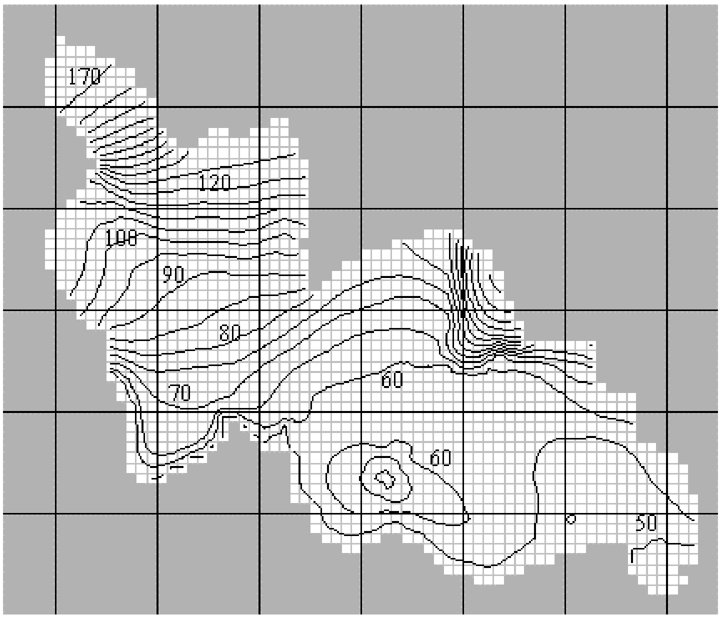


Figure 4.8 Simulated groundwater levels using MODFLOW

Base flows are calculated concurrently with groundwater level elevations. Although surface flows are not simulated, the simulated base flows may be checked by comparison with base flow accretion profiles.

Such models may be used to answer questions such as:

- is seepage to wetlands maintained?
- will increases in abstractions up to licensed rates be detrimental to the abstractors, water quality or surface water features?
- can abstractions be better distributed to improve environmental conditions?
- where can new abstractions be located?
- how will the system operate under extreme conditions?

The related USGS model MT3D, undertakes water quality calculations on the same grid of cells as used in MODFLOW, and using the groundwater flow rates generated. The model is commonly used in point source studies to simulate, for example, the movement of pollution plumes.

Such models may be used to answer questions such as:

- will leachate from a landfill (or other potential source) travel to abstraction wells?
- will leachate from a landfill (or other potential source) travel to a river?
- will increases in abstractions up to licensed rates change regional flow patterns?
- can the movement of a contaminant plume be controlled by selective pumping?

4.6.6 Rivers, quantity and quality

Many models have been developed to simulate river hydrology and water quality. Typical of these is MIKE SHE, a professional engineering software tool for the simulation of hydrology, hydraulics, water quality and sediment transport in estuaries, rivers, irrigation systems and other inland waters. Since its first introduction as a purely river based model, a groundwater component has been added in the form of lumped parameter model.

MIKE SHE is a deterministic, distributed and physically based modelling system, which enables the simulation of water, solutes and sediments in the entire land phase of the hydrological cycle. As part of the Danish Hydraulics Institute (DHI) software, it is a user friendly modelling tool for the analysis, planning and management of a wide range of water resources and environmental problems related to surface water and groundwater, in particular when the effect of human interference is to be assessed.

MIKE SHE is an integrated modelling environment with a modular structure. Individual components can be used independently and customised to local needs depending on data availability and aims of the given study. Powerful pre-processing and results presentation tools are included in the MIKE SHE software package.

MIKE SHE is operated through an interactive Graphical User Interface including both graphical and tabular editing of data. Furthermore, GIS environments can be fully integrated in the result analysis and model preparation utilising ARCVIEW interfaces and programs developed by DHI.

The core of MIKE SHE is the Water Movement module (WM), which contains a number of process simulation modules which, in combination, describes the entire land phase of the hydrological cycle: evapotranspiration, unsaturated zone flow, saturated zone flow, overland and channel flow.

Further add-on modules are used for advection/dispersion (AD) solute transport, particle tracking (PT), adsorption/degradation, geochemistry (GC), biological degradation, crop yield and nitrogen consumption macro pore flow, soil erosion and plant yield.

Based on the flows computed by the water movement module, the AD module simulates distributed concentrations of dissolved species on land, in rivers, in the unsaturated zone and in the saturated zone. For integrated studies the migration of contaminants from surface water to subsurface water or vice versa is accounted for.

It is possible to include various types of point or area pollution sources with fixed or time varying pollution load in the model.

The main purpose of the PT component is to estimate flow paths and transport times in the groundwater. Subsequently, groundwater delineation zones, groundwater age and pollution risk may be calculated.

The GC module uses the USGS program called PHREEQC, which allows complexation, mineral precipitation and dissolution and redox processes to be modelled as equilibrium reactions. The program facilitates incorporation of:

- wide range of hydrologic modules;
- cohesive and non-cohesive sediment transport modules;
- comprehensive water quality and eutrophication modules;
- links to hydrological, sewer and coastal modelling tools.

Some typical uses of MIKE SHE include:

- conjunctive use of water;
- surface water groundwater interaction;
- water resources management;
- irrigation management;
- changes in land use practices;
- farming practices including fertilisers and agrochemicals;
- wetland protection;
- contaminant transport in the subsurface.

4.6.7 Environment Agency and Water Utility comment

Agency Regions

Through conversation with the Agency Regions it appears that a variety of catchment management models are used. Preference is given to integrated groundwater and surface water models where available, preferably on a regional setting. The models used are based on sound hydrogeological understanding and commonly developed on a case by case basis. All new

Agency models use MODFLOW, although there are still a number of existing models which use code developed by individual consultants or universities.

The use of spreadsheet models is common through the Regions, however, there is regional variation in use of GIS and access to more specific information sources for incorporation within the modelling process. For example, Thames Region utilises geophysical logging data, and makes unique usage of WINFLOW on desktop (Aquawin 32 version 2). Whereas within the North West Region PETCALC is used to calculate potential evapotranspiration, and a spreadsheet developed by Ken Rushton (Ex Birmingham Department of Civil Engineering) is used for the calculation of potential groundwater recharge.

An additional catchment management tool, Low Flows 2000 (the successor to Micro Low Flows 2.1) is now being distributed for Regional use. Individual Regions are also geared for the forthcoming introduction of Catchment Abstraction Management Strategies (CAMS), which is intended for introduction in 2001 (see Appendix B.3.2 Item 3).

The Agency, in collaboration with ESI and Newcastle University are using numerical modelling techniques in the "impact of groundwater abstractions on river flows" (IGARF) project. IGARF II is currently underway (see Appendix B.3.2, item 5 and Section 3.4.8.3 for more details).

Water Utilities

With the exception of spreadsheet models, the use of groundwater - surface water models within the water utility companies is mainly centred on the use of MODFLOW. Commonly variations are made to MODFLOW to incorporate case specific aspects of study areas, for example variable permeability with depth. In general, modelling studies are out-sourced to environmental consultancies for development, with the introduction of specific computer coding where appropriate.

4.7 UK Information Status Summary

Numerous models are available in the public domain, in universities and consultancies. These will cover most situations where the Agency wishes to undertake predictive simulations. There is some sense in utilising standard codes within the Agency for common problems, but this can lead to conflicts. For example, MODFLOW (a finite difference code) is the preferred groundwater modelling software package in the Agency and the Water Utilities, whereas finite element models can offer many advantages in some situations. What is most important is the availability of well written user manuals, and developer help when problems arise.

It is important that modelling is approached as part of an overall investigation, rather than as a separate entity. Modelling should form part of the catchment management decision making process as set out in Figure 4.1. It may be necessary to change the modelling objectives part way through a study, and this should not be considered as a failure, but rather part of the learning process. Similar ideas have been propounded in the Agency's *Strategic Review of Groundwater Modelling*. Modelling is not a cheap option. It is estimated that a modelling study could cost about £1000 per km^2 of catchment, though some of this expenditure is on data collation which will be required in any case. However, it should be remembered that a properly developed model can provide the best means of testing future management options prior to major capital expenditure or damage to the resource.

5 DISCUSSION

5.1 Integrated Catchment Management and Geochemical Flux

The relative importance of groundwater and surface water as sources of supply is linked intimately to the geological structure of the region. In England and Wales the proportion varies from over 70 percent groundwater in the south-east, to less than 10 percent in the north-east and Wales. In continental Europe groundwater provides, overall, 70 percent of supplies, with countries such as Denmark almost wholly dependent on groundwater and only the Republic of Ireland having a lower groundwater proportional usage than the United Kingdom.

The uncritical use of surface water and groundwater abstraction data to indicate the relative importance of the sources may be misleading and this effect can be simply illustrated by reference to the catchment area of the River Thames, in which groundwater provides about 40 percent of supplies. An estimate of the proportion of flow in a river which derives from groundwater may be made using the technique of base flow separation to provide a Base Flow Index (BFI) (see Section 2.5.5 for more details). In the case of the Thames, the BFI for the lowest (most downstream) gauge at Kingston is 0.64 (that is, 64% of the mean flow of 77.75 m^3/s derives from groundwater rather than surface run-off). The catchment above that gauge has an area of 9948 square kilometres and contains a further 96 gauges on the main river and tributaries for which BFIs have been computed. The BFI values range from 0.16, which suggests almost total surface run-off, to 0.98, which indicates derivation totally from groundwater, with a flow-weighted mean BFI of 0.64. Taking these data the overall contribution of groundwater to freshwater resources can be re-estimated as:-

[Groundwater abstraction] + [proportion of surface water from base flow], or

[40] + [(100 – 40) x 0.64] = 40 + 38 = **78 % of supplies in the region are derived from groundwater**

Similar calculations may be made for the other principal lowland river systems (e.g. Severn, Trent) which provide water resources to large parts of England and Wales.

The velocity of groundwater flow is typically several orders of magnitude lower than that of surface water (metres per day rather than metres per second) so that quality changes mediated through groundwater may take many years to be propagated through a catchment, whereas surface water pollution may spread through a catchment in a matter of days or weeks. However, the disparity in flow rate is compensated by the greater volumes of groundwater, with active groundwater flows in England and Wales having been estimated at about 10 000 000 000 m^3 per year (10^{10} m^3 per year), compared with stored surface waters at about 2 000 000 000 m^3 per year (2×10^9 m^3 per year) (Day, 1986). Consequently, the geochemical flux from groundwater to surface water (and occasionally in the United Kingdom from surface water to groundwater) is beginning to be recognised as a critical element in the understanding of the behaviour of freshwater basins.

5.2 Requirements of the Water Framework Directive

The themes of integrated water management and protection and restoration of water quality have been placed centre-stage by the provisions of Directive 2000/60/EC of the European Parliament and of the Council of 22 December 2000 establishing a framework for Community action in the field of water policy. The emphasis is moving strongly towards integrated approaches based on environmental/ ecological objectives, rather than on limited 'engineering' targets (fix it a bit at a time approach). Specific sections which reflect the change in the way water management is viewed are:-

- **Preamble item 1** - which says that water is not a commercial product, but a heritage which should be defended.

- **Preamble item 26** – which indicates that the existing quality of water should not merely be maintained, but that it has to be improved if it doesn't qualify for 'good' status. This reading is confirmed by the wording in Article 4, section 1 (a) for surface water and in Article 4 section 1 (b) for groundwater.

- **Preamble item 28** – in which the slow rate at which groundwater reacts to pollution and clean up is recognised.

- **Preamble item 31** – which requires that even though it may not be feasible to restore a specific body of groundwater to 'good' status, it will not generally be permissible to 'dump' contaminants into the aquifer.

- **Article 2 - Definitions -** No.11 "Aquifer" - defined as a geological material of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of **significant quantities** of groundwater. The importance is that this negates claims that clays and similar strata should be treated as aquifers.

The Directive covers inland surface waters, groundwaters, transitional waters (estuarine water) and coastal waters. The principal hydrometric entity is the "*River Basin District"* (RBD), which is an area of land and sea comprising one or more river basins (defined by their surface water catchments) and their associated groundwater and coastal water units. Item 25 of the Preamble to the Water FD says that environmental objectives will be set for each RBD, so as to achieve to good quality status in both surface water and groundwater. If the accumulated pollution load at the lowest point in the RBD is the critical control, then any activity up-catchment which adds to 'pollution' may be ruled out, even though at the local point of impact the effect is not classed as pollution. This will affect not just activities which may be expected to release contaminants, for example, agriculture, manufacturing, mining and commercial activity, but also urbanisation because of the potential for impacts on the size of resources from reduced or increased run-off or infiltration. In order to meet the environmental objectives it is going to be essential to understand surface water - groundwater interactions in each catchment, so that meaningful statements can be made (and acted upon) such as, how much of pollutant Y at a particular location on a river, estuary or coastal water comes from surface water and how much is contributed by groundwater.

5.3 Conceptual Models of Geochemical Flux

Simple flow chart models have been included in this report in Section 1.3 to introduce the concept of geochemical fluxes through freshwater systems, and to explain the terminology associated with water basin management. Section 2 through to Section 4 have reviewed the extent of understanding of the physical, chemical and biological processes which control the geochemical flux and, in order to more fully discuss the implications for basin management in England and Wales, the model is restated in a diagrammatic form in Figure 5.1. This figure identifies sources which provide inputs or sinks for the geochemical flux.

In the broad sense the sources may be derived from industrial, agricultural or urban activities. Industrial and urban areas give rise to point source pollution, a typical example of which is disposal to land, whereas agricultural use tends to be associated with diffuse sources of pollution.

In order to arrive at an understanding of the flux through a complete basin it may be possible to break it down into sub-units comprising, for example, the flows into and out of each tributary stream. Examples of the complexity of hydrogeological situations which must be understood are shown in Table 5.1, which begins to develop a classification of the types of models needed to adequately describe the increasingly complex scenarios. If the assessment is being made in terms of a mobile, persistent compound using long-term averaged flow and concentration information (steady-state model) then the effects of pathway attenuating processes and their time dependency may be ignored. However, if consideration is to be given to compounds which may be transformed or attenuated within the pathway it becomes essential for appropriate relationships to be built into the estimations of fluxes through each module, with a significant rise in the data requirements for verifiable modelling of the flux systems.

It follows that the reliability of the output from the models is determined by the level of confidence which can be placed in the element of the balance for which the least information is available, making allowances for overall input of this element in the balance. Consequently, it is important that development of models and management tools should first be validated against simple, possibly lumped parameter, systems before moving to more complex models, and that the temptation should be resisted to proceed with simulations based only on those parameters for which the greatest level of information is available.

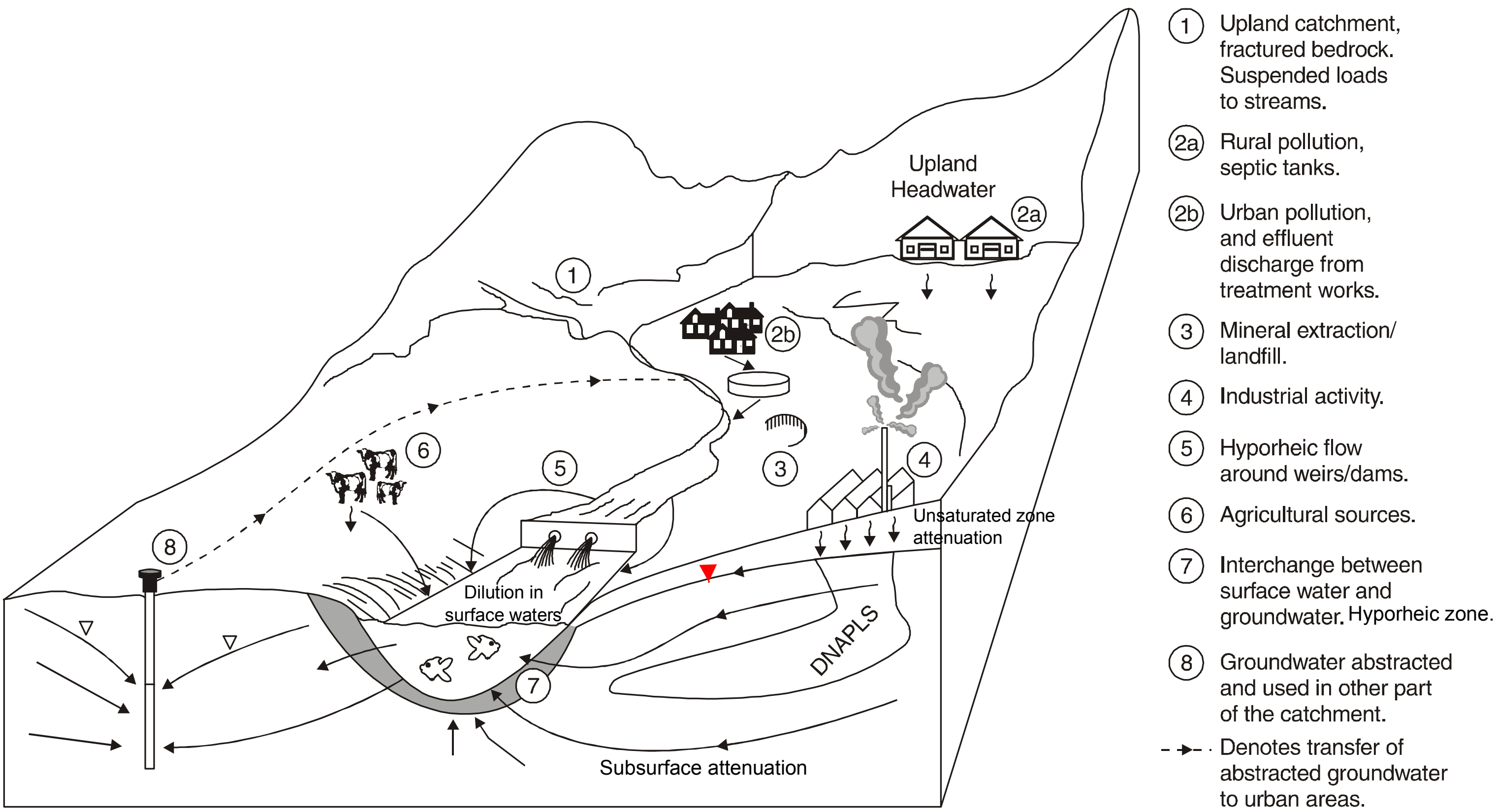


Figure 5.1 Conceptual model of groundwater flux

Table 5.1 Levels of assessment (from simplest to most complex)

Type	**Data requirements**	**Comments**
Simple mass balance.	Based on annual means, assume conservative compounds, assume all BFI is groundwater. BFI not based on naturalised flows.	Black box approach. Dynamics of groundwater flows/delays etc. ignored. Potentially significant error if BFI contains a high proportion of effluent discharge. Possible example would be a small stream with headwaters in urban area.
Mass balance, naturalised flow data, conservative compounds.	Annual mean compositions, conservative compounds. Naturalised BFI.	Better estimate, but may still contain non-aquifer storage elements.
Mass balance, naturalised flow data, non-conservative compounds.	Annual mean compositions, non-conservative compounds. Naturalised BFI.	As above. May need to include both declining source term and pathway attenuation.
Mass balance, naturalised flows, seasonal effects, conservative compounds.	Seasonal mean compositions, conservative compounds. Naturalised seasonal BFI.	Similar constraints to above, but better time discrimination.
Mass balance, naturalised flows, seasonal effects, non-conservative compounds.	Data on attenuation dynamics required in addition to flows dynamics.	As above. May need to include both declining source term and pathway attenuation, complex models likely to be required.

5.4 The Current UK View of Integrated Basin Management

Much current perception in the United Kingdom of the state of understanding of basin-wide geochemical fluxes is aligned with current thinking world-wide. The requirement for integrated catchment management is now formalised in EU legislation by the Water Framework Directive.

In the US, recent publications by the United States Geological Survey work include:

- Winter *et al*, 1998. Ground Water and Surface Water: A single resource. USGS Circular 1139. This presents an overview of current understanding of the interaction of groundwater and surface water, in terms of both quantity and quality, as applied to a variety of landscapes across the United States;

- EPA/542/R-00/007. Proceedings of the Groundwater / Surface Water Interactions Workshop held by the United States Environmental Protection Agency (USEPA) at Denver in January 1999 (USEPA, July 2000).

These papers (see Appendix D.3 for more details) contain much useful information and speculation, both at the general conceptual level and in relation to site specific investigations in various parts of North America. These papers acknowledge the contribution to the basic understanding of the processes provided by UK work on the calculation of Base Flow Indices (Winter *et al*, 1998, page 12, Figure B-1 refers to Institute of Hydrology Low Flow Studies Report 1980).

Review of the information provides many parallels with hydrogeological situations in the United Kingdom, but it is noticeable that the scale of many of the basic hydrogeomorphic units which are employed by the USEPA and USGS is greater than those encountered in England or Wales. A pertinent example being hyporheic zones developed between meanders of the Missouri River, which extend over several kilometres in width and up to ten kilometres in length.

Neither the Circular nor the Proceedings contain statements of the type "*50% of the water and nutrient load that enters Chesapeake Bay in the USA first travels through the groundwater system*", but information of that type is found in a study of the discharge of nitrate to Chesapeake Bay by Bachman *et al* (1998). The study covered a catchment of some 165,800 square kilometres, containing about 500 river gauging points (approximately one gauge per 300 square kilometres). The data sets for the stations were non-naturalised measurements and, in order to remove distorting effects which could arise, data from stations with the following characteristics were deleted from the analysis, leaving 276 compliant stations (one station per 600 square kilometres):-

- catchments with significant discharges from wastewater plants, industrial outfalls and irrigation;

- catchments regulated by dams;

- catchments over 2,600 square kilometres – that is about one quarter of the entire Thames catchment above Kingston weir.

On the basis of the data, Bachman *et al* concluded that the median value of the streamflow entering the Chesapeake Bay is 54% (with individual catchments contributing between 16 and 92% base flow), and that, on the basis of 57 sampling stations for which nitrate concentrations were available, the median value for groundwater contribution of nitrate to Chesapeake Bay is 56% (range 26 to almost 100%). The authors concluded that "*Separation of the effect of landuse from the effect of the amount of groundwater discharge is difficult with the data* *available, however. Many of the relationships between Hydrogeomorphic Regions and groundwater nitrate discharge are inconclusive ---".*

In light of this conclusion, it is suggested that statements of equal validity could be made regarding UK catchments, based on existing available data. For example, as previously stated in Section 2.5.5, using the "Hydrometric Register and Statistics data 1991 – 1995", it is possible to say that:

- *Approximately two thirds of the water flowing into the Thames estuary, on average, is derived from groundwater (BF1 = 0.64, that is 64% of the flow is derived from groundwater).*

The factors which should be addressed in order to improve the reliability of UK estimates of geochemical fluxes are further discussed in the recommendations outlined in Section 7, and build on existing work and partially assembled databases.

In general, it is considered that the quantitative movement of water in rivers and in aquifers is quite well understood and has been analysed by the traditional methods of hydrology and hydrogeology. With regard to quality issues the situation is less encouraging. A number of specific studies pertaining to anthropogenic pollutants, for example to nitrates and pesticides, and regional data collation exercises have been undertaken in the past by several of the Regional Water Authorities. However, the data are in many cases nearly twenty years old and the parameter list is limited. Such work may provide information on quality variations in the longer term, but the review suggests that the current level of information on surface water and groundwater quality may limit the extent to which confident statements may be made regarding geochemical fluxes. Future collection of water quality data should be linked to the current water quantity gauging network.

6 APPLICATION OF UK DATA IN UNDERSTANDING GEOCHEMICAL FLUXES

6.1 Introduction

At the basic level, the provisions in the Water Framework Directive (Water FD) directed at maintaining and improving the quality of water resources would be satisfied by the ability to prepare reliable mass balances of the flux of water and its constituents in the terrestrial segment of the hydrological cycle. Consequently, the dynamic understanding of geochemical fluxes in hydrological systems must include adequate knowledge of the controls on flows and interactions of surface water and groundwater, and of the ways in which solute concentrations may vary in time and space. In many ways the information requirements are similar to those which are demanded by risk assessments base on the "Source – Pathway – Receptor" protocol.

6.2 Risk Assessment Approach

Taking the risk assessment protocol as a starting point, a number of simple model scenarios may be proposed, which summarise the range of conditions generally present in England and Wales (Table 6.1). As a first approximation, the Source terms may be considered of two types:-

- Point discharges of effluents, either directly to surface water or by soakaways to groundwater;

- Mobilisation of soluble components, or particulate matter including pathogens, from either point source (for example, leaching from landfilled wastes) or diffuse sources (for example, leaching of agrochemicals) in ways that allow them to be transported with surface water or groundwater.

The Pathway segment would then comprise the routes by which the water and its included components travels towards the Receptor(s), with the properties and processes *en route* which determine the partition between groundwater and surface water and those which decide the fate of the contaminants. In the case of water the simple mass balance equation:

Input = Output +/- change in storage

may be applied sequentially to each subset of the pathway. The situation for contaminants is more complex. The balance for mobile, persistent contaminants is similar in form to that for water, but in other cases account must be taken of processes which either remove the material from solution (sorption, precipitation, assimilation) or change the form of the material degradation, sulphate reduction for example):

Input = Output +/- change in mass stored in water phase +/- mass transformed

In practice, the balance may change at a number of points during the progress through the catchment:

- Within the soil and subsoil, often mediated by the activity of macro- and micro-flora and fauna, and in a zone in which temperatures and oxygen tension may vary with time and place, for example, floodplains;
- Within deeper strata (aquifers) where microbial activity may be limited, temperatures remain relatively constant and where low oxygen status may persist;
- In spring lines and groundwater seepage zones where water re-emerges to the surface, passing through sediments with significant life activity and, possibly, strong nutrient and oxygen status gradients including the hyporheic zone where water movement may be from the surface water body to groundwater;
- Within flowing surface waters, with significant gaseous interchange, photo-degradation and phyto-remedial impacts.

Concluding the analogy with risk assessment, the Water FD indicates that the Receptor is the most downstream point on a river system at which gauging is carried out. This target is appropriate to a very high proportion of catchments in England and Wales and is represented by three of the four scenarios summarised in Table 6.1. In a small number of cases (scenario 4, Table 6.1) groundwater catchments discharge directly to the sea, which may then be considered to be the Receptor.

Table 6.1 Schematic of Source - Pathway - Receptor scenarios.

Risk Assessment Stage	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Comments on availability of data
SOURCE	Effluent discharges + Leaching from Point and Diffuse sources.	Effluent discharges + Leaching from Point and Diffuse sources.	Effluent discharges + Leaching from Point and Diffuse sources.	Effluent discharges + Leaching from Point and Diffuse sources.	Licensed discharges well documented. Diffuse losses or poorly quantified
PATHWAY	Percolation through unsaturated zone.	Run-off / interflow (Data limited mainly to nutrients)	Run-off / interflow (Data limited mainly to nutrients)	Percolation through unsaturated zone.	Data on natural attenuation limited, but accruing.
	Groundwater	Surface water	Surface water	Groundwater	Relatively extensive data sets, limited determinand lists.
	Spring / seepage		Percolation through unsaturated zone.		Significant information on Base Flow Indices
	Surface water		Groundwater		Data sets on quality and levels variable.
			Spring / seepage		As above
			Surface water		As above
RECEPTOR	Receptor (most downstream gauge)	Receptor (most downstream gauge)	Receptor (most downstream gauge)	Receptor (submarine/littoral spring). Abstractors.	

Note: The shaded text boxes within the comments column relate only to the shaded Scenario text boxes in the corresponding row.

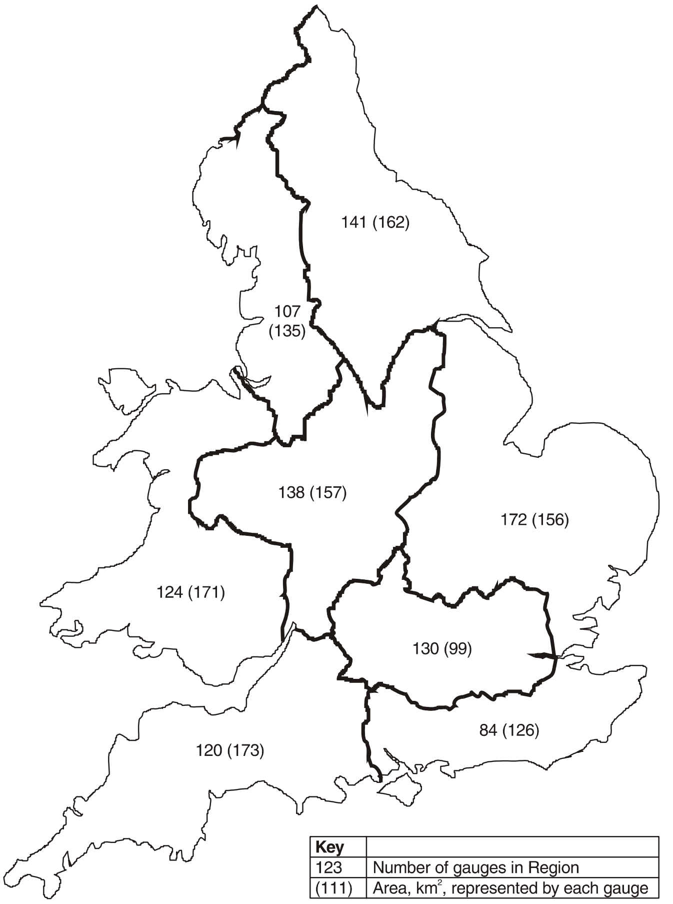
In practical terms the great majority of recognisable water basins in England and Wales are likely to fall into scenarios 1 and 2. An extensive database of Base Flow Indices (BFIs) is already in place through the quinquennially produced Hydrometric Register and Statistics, see Section 2.5.5 and Section 6.3 below. BFIs represent a convenient way of estimating the proportion of flow at a gauging point which is attributable to release from storage. Published BFI estimates are made on an annual basis, but it is possible to calculate Indices for other periods, so that the influence of seasonal and longer term trends may examined. The geology of the catchments measured at each gauge exert a major influence on the BFI, as for example the BFI for the River Pang, a Chalk fed stream in Berkshire, is in excess of 0.90, whereas the River Ribble, the catchment of which has extensive boulder clay cover in Lancashire has a BFI of less than 0.35. Major river systems have many gauges on their tributaries, which should allow significant discrimination of the geographical sources of groundwater contribution. For example, the Thames above Kingston (most downstream gauge) has 78 gauges on the main river and tributaries, whilst even small rivers, such as the Waveney on the Norfolk / Suffolk border has four gauges along its length.

6.3 Application of Base Flow Indices to Assess Water Flux

Systematic estimation of the Base Flow Indices (BFIs) at river gauges has been carried out by the Institute of Hydrology (now a component part of the Centre for Ecology and Hydrology, (CEH)) since the early 1980's. The results are published quinquennially as registers of statistics, the most recent of which, the "Hydrometric Register and Statistics 1991-95" collates information for the period 1991-95. Summaries are provided of over 1,400 gauges in the United Kingdom (England, Scotland, Wales and Northern Ireland) of which some 1,016 in England and Wales are furnished with BFI estimates (see Section 2.5.5). The distribution of BFI estimates in England and Wales is relatively uniform, with an average density of one gauge point per 150 km^2, ranging from one per 173 km^2 in the Agency's South West Region to one per 99 km^2 in the Agency's Thames Region (see Figure 6.1).

The BFI concept was developed during the 1970's during the study of low flows (Institute of Hydrology, 1980) as a means of assessing the proportion of flow in a river attributable to storage in the catchment above the gauge. In broad terms the BFI is likely to reflect the hydrogeological structure of the catchment, with BFIs exceeding 70% for those comprised of porous, permeable aquifer materials, but less than 35% for low permeability ('impervious') clay based catchments. In practice, even catchments found entirely on clay strata posses BFIs of greater than 10% because of short-term water storage within the soil profiles, inhibiting instantaneous run-off. However, the presence of natural storage in the form of lakes and ponds and marshland areas and of artificial storage in drains, storm overflows and balancing tanks may significantly influence the derived BFI. Consequently, it is necessary to apply hydrological and hydrogeological experience, and a knowledge of the types of activities within a catchment, when interpreting BFI data.

Further caution may be needed because the published values (Hydrometric Register and Statistics) are based exclusively on the measured flows, without account being taken of the upstream contributions from effluent discharges (Lees, 2001). The discharge rate of effluents may be independent of the factors which control natural flows (both surface and sub-surface). If the effluents are derived from water abstracted within the catchment then the impact on BFI estimation may be small or insignificant at mean or high flows, but can become important at low flows. If the water discharged as effluent is wholly or partially obtained from outside the catchment, the distorting effect may be magnified. The 'naturalisation' (removal) of impacts of effluent discharges prior to estimation of BFIs is of particular relevance to the detailed study of low flows and a facility for accounting for effluent discharges is built into the micro-low flow studies currently underway at CEH.



NOTE: The boundaries shown are the Hydrometric area groupings used in the Hydrometric Register and Statistics, these are broadly based on the Regional divisions of the Environment Agency.

Figure 6.1 Distribution of BFI gauges (adapted from Hydrometric Register & Statistics 1991-95)

However, it has already been noted that studies in the Great Ouse basin by Oakes and Keay (1990) (Section 2.5.5) have indicated a good statistical correlation between BFIs calculated from naturalised and measured flows in the form:

$$\text{BFI (naturalised)} = 1.12 \times \text{BFI (measured)}$$

In view of the uncertainties which currently exist in the reliability of the available data sets, the examination of non-naturalised BFI data may provide useful indications of the probable flux characteristics of a basin as a prelude to undertaking more detailed assessments of geochemical fluxes. This is illustrated by reference to the relationships between non-naturalised BFI (Hydrometric Register and Statistics 1991-95) and the outline hydrogeology of the Thames Region (taken from the Geological Survey 1:50 000 maps) which have been overlain in Figure 6.2.

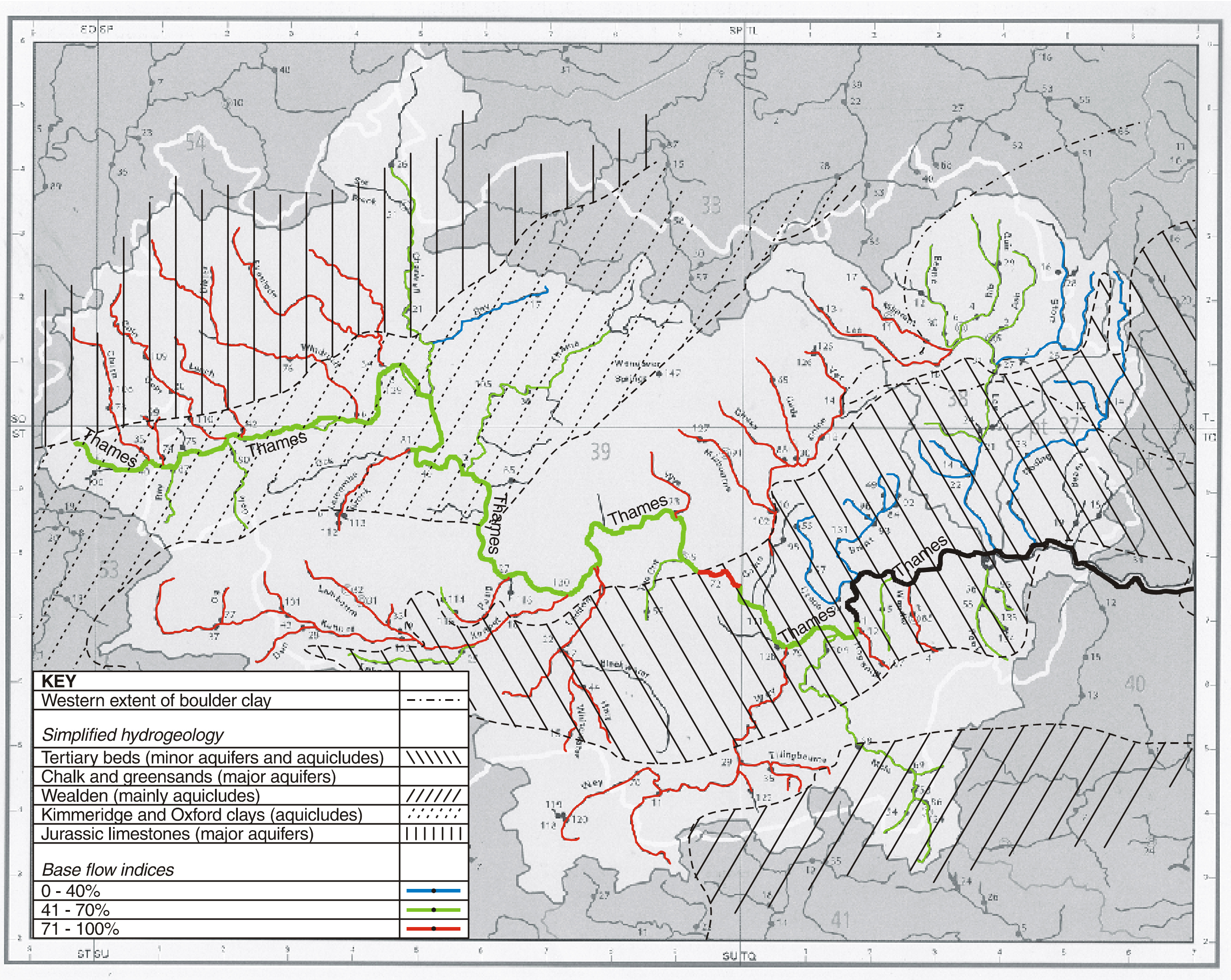


Figure 6.2 Schematic of relationship between non-naturalised Base Flow Indices and geology in Agency's Thames Region (adapted from Hydrometric Register and Statistics 1991-95 and Geological Survey maps)

A clear distinction is seen between streams of low BFIs which rise and flow entirely within low permeability Tertiary strata (Brent/Crane/ Roding and lower Lee in the east, and the Ray to the north west on the Oxford Clay) and those which have headwaters on highly permeable aquifers (the Kennet/Lambourn system to the west and the Colne system to the north of the Tertiary beds on the Chalk) and the dip-slope streams draining the Jurassic limestones in the north western part of the region (Churn/Coln/Leach/Windrush/Evenlode). The headwaters of the Thames are on the Kimmeridge/Oxford Clays and associated thin sands and limestones, with the result that the non-naturalised BFI for the main river lies in the 41 – 70% range (mean value c. 64%) almost continuously from its source to the most downstream gauge at Kingston, gauging point 1 – 'Teddington weir'. This gauge is located at the tidal limit of the Thames and has a BFI of 0.64, so it can be stated that 64% of the water entering the Thames estuary is derived from groundwater. A single exception to the BFI's in the range 41 – 70 % is noted at gauging point 72, where the river cuts through the emergent Chalk of the Windsor dome.

Figure 6.2 also demonstrates the extent to which geological conditions influence the hydrological performance of streams in two other examples:

- The adjacent Rivers Mole and Wey to the south of the axis of the London Basin syncline;
- The tributaries of the River Lee, to the north of the syncline.

In the former case, the headwaters of the Wey rise on the Chalk and Lower Greensand aquifers at the point where the outcrop broadens into the western closure of the Wealden anticline to generate a system with a BFI in the range 70 – 90+%. In contrast, only a few kilometres to the east the Mole rises on claylands of the Wealden sequence and flows across the Greensand/Chalk outcrop close to its narrowest point, resulting in a system in which less than 50% of flows are drawn from storage.

The northern tributaries of the River Lee, when traced from west to east (Figure 6.2) rise on the Chalk outcrop (Rivers Lee and Mimram), on boulder clays overlying the Chalk (Rivers Beane, Rib and Quin) and on thicker boulder clay at about the stratigraphic overlap of Tertiary strata on the Chalk (River Ash). During the early 1980's these streams were the subject of studies (Hill, 1984) to assess the nitrate contributions from various sources to the river. Hydrographs for the period October 1980 – September 1981 are shown in Figure 6.3.

Figure 6.3 confirms the conclusions which may be drawn from the BFI indices, that the River Mimram, and to a lesser extent the Beane, with headwaters on open Chalk, display steady hydrographs typical of groundwater base flow dominated streams (BFI for Mimram 94%, for Beane 77%). In comparison, the Ash, Quin, and Rib systems show the 'flashy' hydrographs characteristic of run-off from lower permeability catchments (BFI's 54%, 45% and 59% respectively).

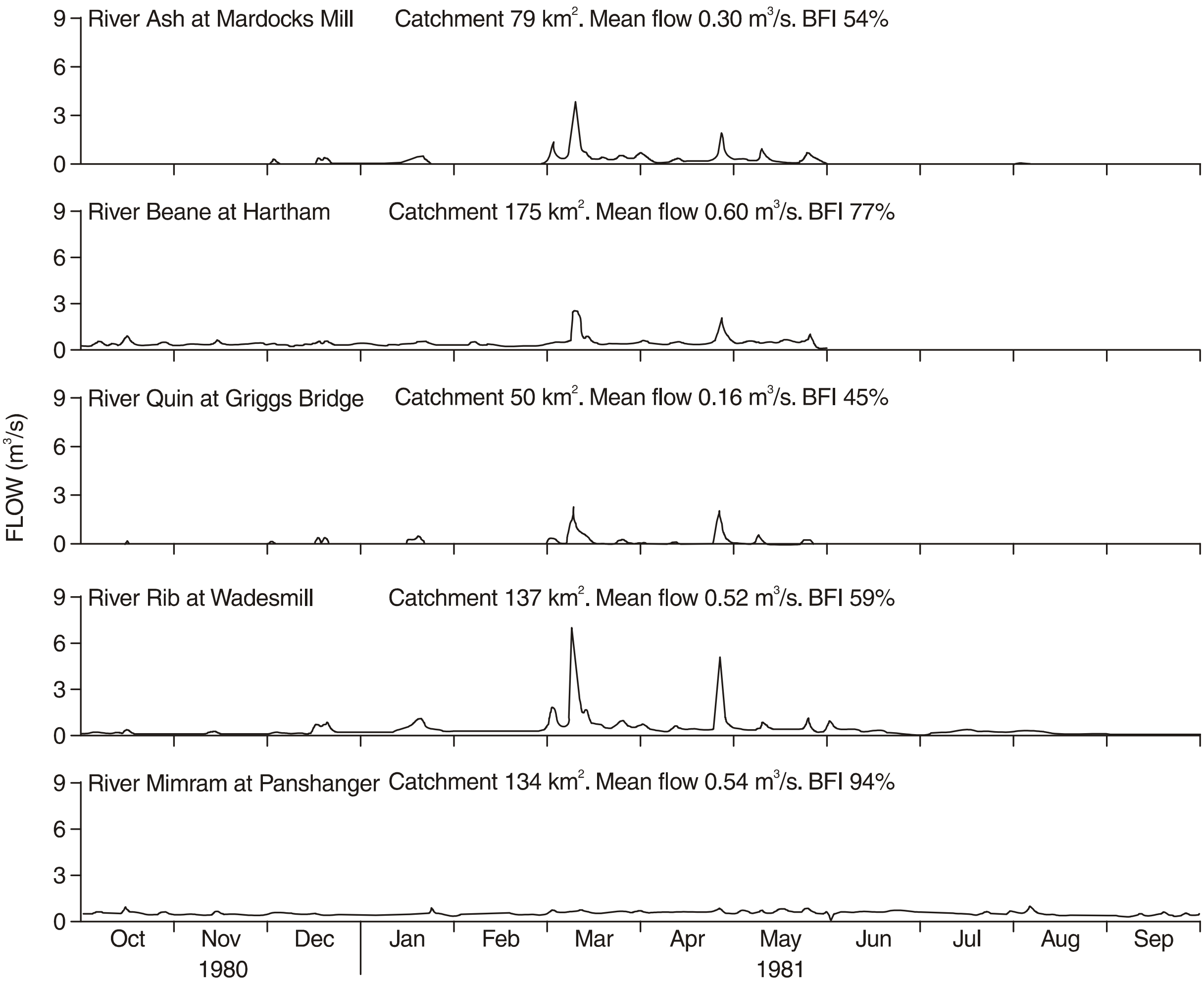


Figure 6.3 Hydrographs for the River Lee tributaries, October 1980 – September 1981

The variation in concentrations of total oxidised nitrogen (nitrate and nitrite) in river water during the same time interval (Figure 6.4) provides strong evidence for a consistent groundwater base flow contribution of about 4 mg/l (as N – Rivers Mimram and Beane), with similar base flow fluxes into the Ash, Quin and Rib. The latter streams provide clear evidence of increased concentrations of nitrate at times of increased surface run-off.

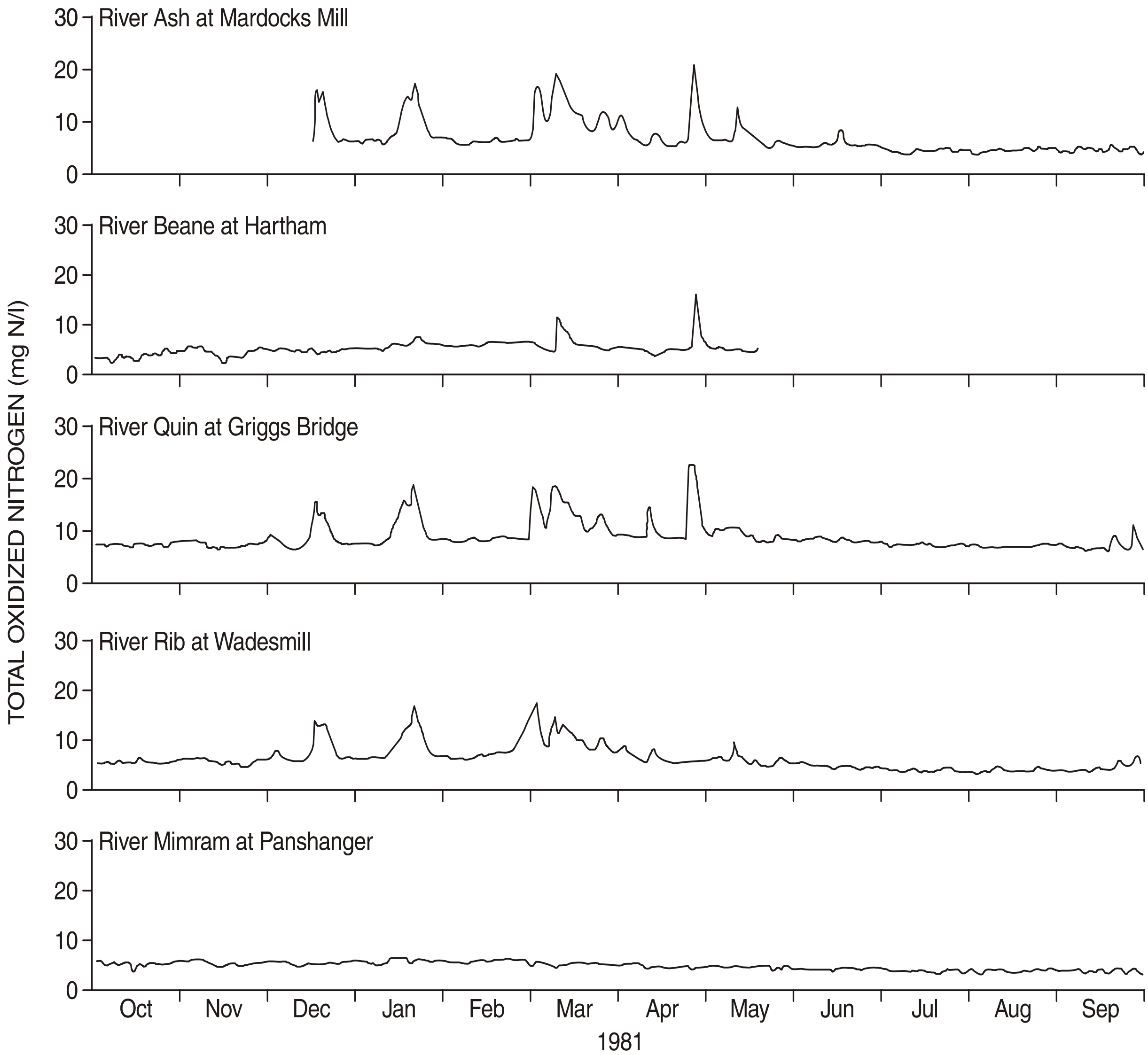


Figure 6.4 Flow-weighted daily mean concentrations of TON

The contrasts in nitrate flux are made more obvious by conversion of the data to mass fluxes and normalisation to yield per unit catchment area (Figure 6.5). The peaks in flux for the River Rib can be attributed to flash flows, if it is assumed that base flow in the River Rib is similar to that of the Mimram, a subtraction provides data on nitrate inputs attributable to surface run-off. In the example given, the flux curve suggests that during the winter of 1979-1980 about 34% of the nitrate flux in the Rib could be attributed to groundwater sources, but that over the year December 1979 – November 1980 closer to 46% of the nitrate came from groundwater.

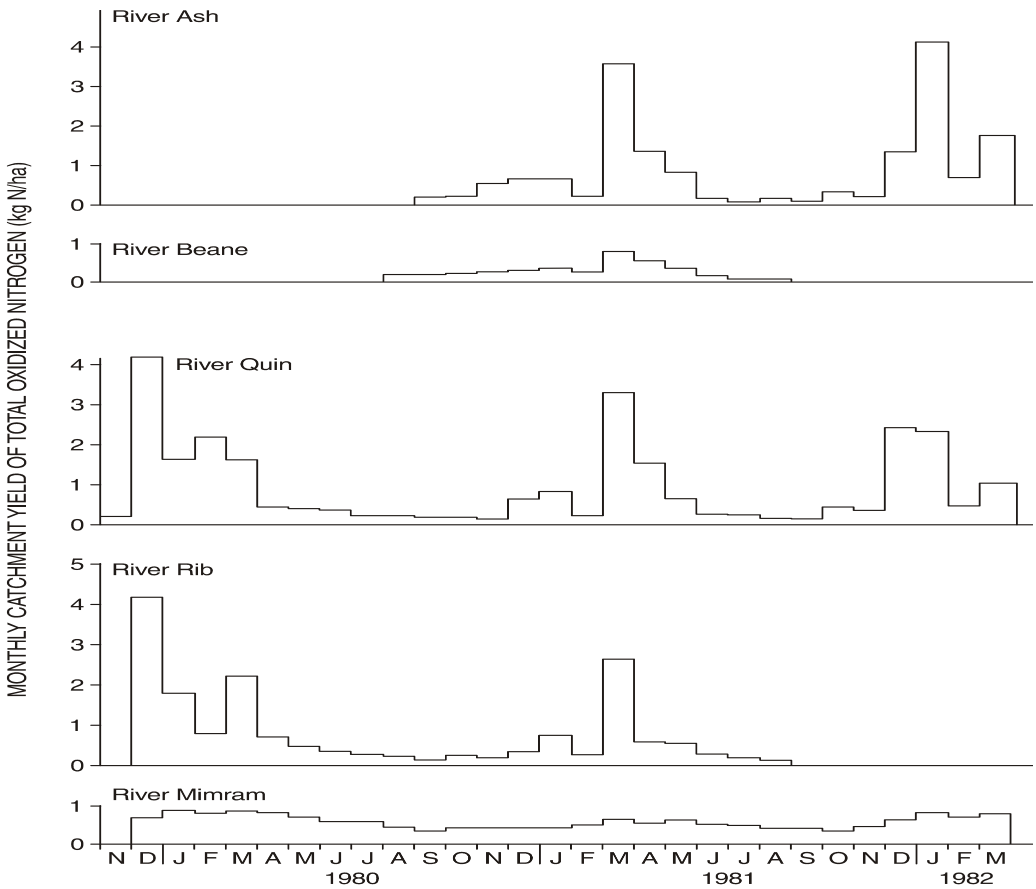


Figure 6.5 Monthly yield of TON, November 1979 – March 1982

The estimates made above highlight another factor that must be addressed if complex flux models are to be employed as catchment management tools. The BFI values estimated in the Hydrometric Register and Statistics are based on five year data sets and *cannot represent seasonal variations in base flow* which my occur. An example of changes in the base flow of a stream when totals flows vary abruptly is provided by the River Ribble at Samlesbury weir in the months leading up to a flood event in late October 2000 (Figure 6.6).

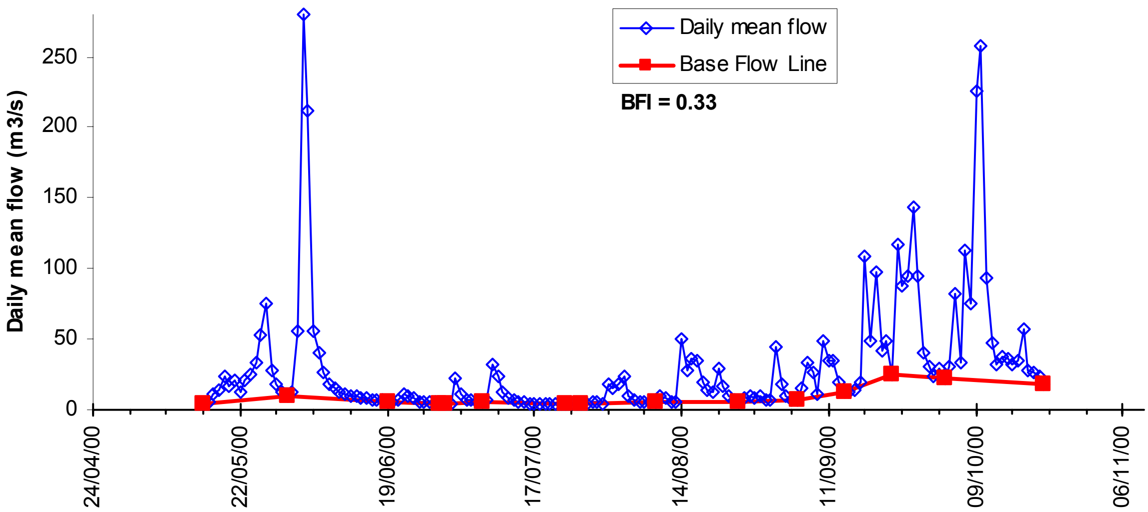


Figure 6.6 Variation in base flow in the River Ribble at Samlesbury weir preceding a flood event in October 2000

6.4 Example of a Simple Mass Balance (based on data available in Severn River Authority 1977 and Natural Environment Research Council 1998)

In this section, information contained in the Severn River Authority 1977 (as listed in Appendix E) and the Natural Environment Research Council 1998 reports, are used to estimate a balance for chloride in the upper Severn above Shelton (SJ 467 138) for which a mean chloride content of 28 mg/l is quoted. The nearest flow gauge for which data are available is at Montford (SJ 412 144) about 8 km upstream, and beyond the confluence with the River Perry. The non-coincidence of gauging and quality monitoring points introduces uncertainty into the estimate. For the purposes of this example, the mean flow at Shelton is estimated in Table 6.2.

Table 6.2 Mean flow estimates at Shelton, 1997

Gauge	Mean flow m^3/s	BFI
Montford (Severn)	42.37	46%
Yeaton (Perry tributary)	1.61	65%
Ruyton Bridge (Perry)	1.21	67%
Total	*45.19*	*47%* *

* flow-weighted mean

Upstream from Shelton twenty effluent discharges to the Severn/Perry/Vyrnwy system are recorded, with a total discharge of 0.060 m^3/s, which is equal to less than 0.15% of the total river flow and it is considered unlikely that this small contribution will significantly influence the estimated BFI. However, the absence of chloride concentration data, make it impossible to assess whether these relatively insignificant point sources contribute a significant chloride contribution to the water quality at Shelton.

Assuming a flow of 45.19 m^3/s, and a chloride concentration of 28 mg/l, the total mean flux was 1.27 kg Cl/s. Upstream on the Severn, at Llandinam (SO 021 894), chloride concentrations were reported to be 13 mg/l, indicating a local flux of 0.19 kg Cl/s, derived from surface run-off from the upland headwater areas of the river. Groundwater chloride concentrations recorded from the upper Severn and Perry catchments are in the 25 – 30 mg/l range. If the top end of this range is typical, then the groundwater component of the flux at Shelton may be estimated as:

BFI (%) x	Flow (l/s) x	Concentration (kg/l)	= Groundwater component of flux (kg/s)
0.47 x	45190 x	30×10^{-6}	= 0.64 kg Cl/s

If the surface run-off of chloride continues to yield 0.19 kg/s, then it would suggest that the effluent discharges contribute about 0.45 kg/s (i.e. groundwater component minus surface run-off = 0.64 – 0.19 kg/s).

These estimates are shown diagrammatically in Figure 6.7, which illustrates the importance of the groundwater component on the chloride loads in the river.

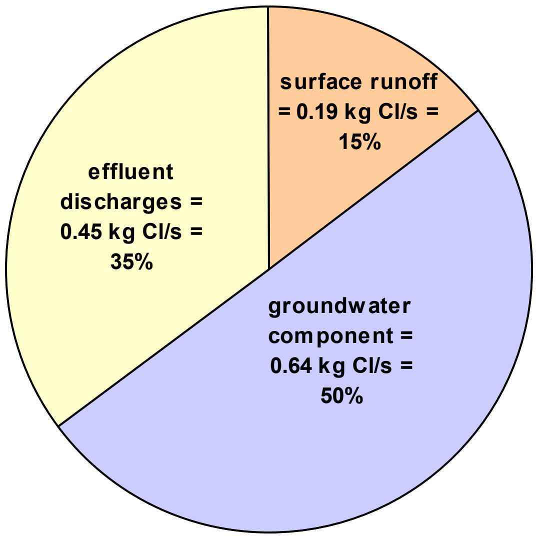


Figure 6.7 Geochemical flux estimates at Shelton, 1997

The total discharge of effluents has been estimated at 0.06 m^3/s (60 litres/s), and the effluent discharge has been estimated to contribute 0.45 kg/s (450,000 mg/s). This therefore implies a mean chloride concentration in the effluents of 7500 mg Cl/l (i.e. 450,000 mg/s divided by 60 litres/s). Whilst such a concentration is chemically possible the veracity of the estimate cannot be checked in the absence of the relevant data.

6.5 Trial Balance for Nitrogen Flux at Shelton, River Severn (based on data available in Severn River Authority 1977 and NERC 1998)

Although the data are incomplete, WRc has used the available information (as listed in Appendix E) to undertake a trial balance for nitrogen flux at Shelton.

Gauging and water quality monitoring points are as for the chloride balance (Section 6.4), with additional assumptions as follows:-

- Balance based on total N (sum of ammonia and nitrate);
- 0.83 mg N/l at Llandinam (Abermule gauge 14.13 m^3/s) – local flux 0.0117 kg N/s;
- 1.69 mg N/l at Shelton (45.19 m^3/s) – total flux 0.076 kg N/s;
- Total N in groundwater 6 mg N/l (range from 3 – 12, based on data in Severn River Authority 1974 (Severn River Authority (1974) Shropshire Groundwater Investigation Second Report and Severn Trent Water Authority 1977);
- mean BFI 47%;
- load from effluent plants (see Table 6.3 below).

Table 6.3 Effluent plant loadings

Site	Flow Ml/d	N mg/l	Load kg N/d
Baschurch	1.0	5.6	5.6
Berriew	0.088	8.4	0.74
Caersws	0.11	2.0	0.22
Carno	0.10	11.6	1.16
Churchstoke	0.04	7.3	0.29
Ellesmere Wharf Meadow	0.55	11.4	6.27
Ford	0.28	1.8	0.50
Guilsfield	0.12	4.1	0.49
Llandinam	0.047	4.8	0.23
Llandidloes	0.56	0.3	0.17
Llanrhaeardr	0.059	13.2	0.78
Llansantffraid	0.08	10.0	0.8
Llanwyddyr	0.033	13.4	0.44
Maifod	0.045	4.1	0.18
Pant	0.37	3.2	1.18
Ruyton XI Towns	0.083	1.7	0.14
Trewern	0.041	15.1	0.62
Welshpool	1.28	2.0	2.56
West Felton	0.10	5.6	0.56
Total			**22.93**

A value of 22.93 kg N/d is equivalent to 0.00027 kg N/s, or c.0.3% of the total N flux at Shelton. It was previously estimated that the contribution of effluents to the total flow at Shelton was 0.15%, from which it may be deduced that the potential impact of the effluents was about twice that of other waters, on an equal volume basis. If it is assumed that the concentrations found in the upper reaches of the Severn (at Llandinam) are representative of the surface run-off to the river then, ignoring the minor contribution from effluents, the required input (Y) from groundwater may be estimated by solving:

$$\frac{\text{conc. attributed to surface run-off} \times \text{proportion of flow from surface waters} + \text{conc. in groundwater (Y)} \times \text{proportion of flow from stored waters}}{\text{Total flow}} = \text{Conc. in river}$$

As the mean flow is 45.19 m^3/s (see Table 6.2) and the BFI is 47%, then the proportion of flow from 'stored'/groundwater is (45.19 x 0.47) = 21.24 m^3/s, with the proportion of flow from surface water being (45.19 x (1-0.47)) = 23.95 m^3/s, then:

$$\frac{(0.83 \times 23.95) + (Y \times 21.24)}{45.19} = 1.69$$

$$\text{Therefore } Y = 56.493/21.24$$

$$Y = 2.66 \text{ mg N/l}$$

This value is approximately half the measured concentration in local groundwaters, possibly suggesting that significant attenuation of the nitrate nitrogen takes place, either by assimilation or denitrification in the hyporheic zone, or within the river.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

The conclusions and recommendations discussed in this section are aimed at ensuring that new research initiatives compliment the current knowledge base, rather than re-inventing the wheel. The principal legislative driver is the Water Framework Directive (Water FD). The main requirements of the Water FD, directed at maintaining and improving the quality of water resources, would be satisfied by the ability to prepare reliable mass balances of the flux of water and its constituents in the terrestrial segment of the hydrological cycle and of the ways in which solute concentrations may vary in time and space.

A large amount of historic and current data relevant to the assessment and quantification of geochemical fluxes in the UK already exists in reports and databases. Much of these data are held on a regional basis rather than in terms of the "River Basin Districts" defined in the Water FD. The review and comparison of water quality data between Regions and the re-evaluation of existing water quantity data can be used to develop a series of preliminary conceptual models of geochemical fluxes and of processes controlling surface and groundwater interactions on a catchment level. This valuable groundwork, which could be achieved at relatively low costs, will provide a baseline on which future research requirements should be based.

Potential research topics arising as a result of this project, and to fulfil the UK's requirements in terms of the Water FD, are discussed below. A summary table is also given, (Table 7.1), which broadly attempts to put priorities, timescales and outline costs to these research topics.

7.2 Conclusions

7.2.1 Current status and water quality data collection network

The Environment Agency are currently updating their national Oracle database system, WIMS, which contains both surface and groundwater quality data. However, a large percentage of these data relate to treated water rather than raw water. With the exception of localised, and often relatively short-term water quality databases derived from research or consultancy studies during the 1990's, there are few significant compilations providing up to date information on raw water quality. These studies do however, provide invaluable information on the relationships between catchment base flows and surface water - groundwater chemical fluxes. During the 1970's and 80's, a number of the Regional Water Authorities compiled extensive databases of the quality of raw, treated and 'in supply' water in their Areas. These data sets remain valuable because they allow a view to be taken of the overall quality of water on a catchment or sub-catchment basis, but are insufficiently detailed for use in completing any but the most basic mass balance flux estimates.

An initial R&D priority should therefore be to revise the current surface water quality data network and align it to the current water quantity gauging network in order to gain optimum information on geochemical flux. The groundwater monitoring network should also be reviewed with a view to creating further links between surface water and raw groundwater monitoring points. This is discussed in Section 7.3.1.2.

7.2.2 Using BFI data to assess water flux

The BFI concept was developed during the study of low flows (Institute of Hydrology, 1980) to provide a means of assessing the proportion of flow in a river attributable to storage in the catchment above the gauge. Estimated BFIs for 1,400 river gauges in the UK are published quinquennially as registers of statistics (Hydrometric Register and Statistics). In broad terms the BFI is likely to reflect the hydrogeological structure of the catchment, with BFIs exceeding 70% for those comprised of porous, permeable aquifer materials, but less than 35% for low permeability ('impervious') clay based catchments.

Although these data represent non-naturalised flows they can still be used in conjunction with currently available hydrogeological information to provide a valuable indication of the probable flux characteristics of the basin as a precursor to undertaking more detailed assessments of geochemical flux. It should be noted that the presence of natural storage in the form of lakes and ponds and marshland areas and of artificial storage in drains, storm overflows and balancing tanks may significantly influence the derived BFI. Consequently, it is necessary to apply hydrological and hydrogeological experience, and a knowledge of the types of activities within a catchment when interpreting BFI data.

A worked example is provided in Section 6.3 and Figure 6.2 to illustrate such an approach. WRc suggest that a priority research initiative should be to undertake similar assessments for all RBDs within the UK, to support UK implementation of the Water FD and these are discussed below in Section 7.3.1.1.

7.3 Recommendations

7.3.1 Complete review of existing data

7.3.1.1 Water flow and quantity

This scoping report has revealed that readily available information on Base Flow Indices (BFI) greatly exceeds that for both groundwater and surface water quality. It would appear prudent therefore to address this inequality in availability before pursuing the wide scale quantification of geochemical fluxes.

WRc suggest that to minimise cost and maximise benefits, initial studies should be focused on a number of selected key catchments in order to refine the working procedure and data requirements, in addition to providing an opportunity to evaluate initial findings and further prioritise any subsequent catchment assessments.

The selection and detailed evaluation of key study catchments could also be used to extend the findings of Oakes and Keay (1990) on the relationship between naturalised and measured flow BFIs and to determine more widely the magnitude of error that would be incurred if flux estimation were to proceed without taking account of effluent discharges.

The published BFI values (Hydrometric Register and Statistics, 1991-95) are based exclusively on the measured flows, without account being taken of the upstream contributions from effluent discharges (Lees, 2001). The BFI under actual flow conditions will generally be less than the equivalent BFI under naturalised conditions, since under actual conditions, groundwater abstractions reduce base flow, with most of the abstracted water being returned to the river as effluent. The integrity of the relationship determined for the Great Ouse basin by Oakes and Keay (1990) should be verified using data from the selected study catchments which represent a range of BFI and hydrogeological/ landuse scenarios.

To carry out the assessment it is suggested that a moderate number (between 10 and 20) of catchments could be selected, for which the naturalisation of flows would be carried out and compared with the results based on 'as measured' values. The selection should include examples with high (>0.75), moderate (>0.26, < 0.74) and low (< 0.25) BFIs, high / low ratios of urban to rural development, examples where surface flows are controlled by headwater reservoirs, examples where significant compensation flows are added to surface waters at times of drought, and areas with high and low rainfall totals. In the case of catchments subject to compensation flows, account should be taken of whether the compensation water originates within or outside the natural catchment boundary. The size of the catchments should also be considered.

The exercise would require discussions with Regional Agency staff to identify potential study catchments and an initial evaluation of BFI data in the hydrometric yearbook data. The selection of catchments is likely to be influenced by the availability of reliable historic quality and quantity data.

The selection and analysis of the test catchments would be expected to generate a platform of understanding that can be applied to other catchments. Information gained on important areas of interaction between key physical, chemical and biological processes, and the magnitude of these effects, can be used to fine tune the focus of future investigations on remaining catchments and thereby minimise costs. Although there are a number of **research catchments**, these are generally spatially limited and are inclined to be undertaken in response to immediate environmental problems, for example, nitrate sensitive zones. There is certainly a paucity of research undertaken within the drier region of eastern England. With the emphasis of the Water FD on reviewing larger scale catchments, it is important to reflect this in future research and to seek to address data anomalies. That said, any previously identified priority catchments could be added to the basic selection list. Any future work should be linked where possible to projects being undertaken by NICHE-LOCAR and NICHE CHASM (see Section 3.4).

7.3.1.2 Water quality data

Following the selection of key catchments there would be a need to collate historic quantity and quality data for surface and groundwater. This data is probably best collated by individual Agency Regions, as the Agency will be ultimately responsible for data interpretation. Collation is likely to be labour intensive, but should be centrally managed for consistency. It is considered that Agency staff would be well placed to undertake this role. However, should staff availability dictate, the contract could be managed externally.

For consistency, data should be collated using a proforma for each selected catchment as this exercise may be extended to other Regions following the initial evaluation exercise. Potential costs would include ‘set-up, management, catalogue collation and database provision’. It will be essential to make available sufficient time to contact all pertinent data sources: Agency records / archives, water companies, BGS, CEH etc., in addition to archived water quality data of the type of data previously collected by Severn Trent Water Authority. Treated water quality data may be relevant, dependent on the level of treatment, as there may have been little change in basic water quality parameters. Some of these data may be old, but in the spirit of the Water FD, long-term monitoring and understanding of historic quantity trends are important. In those cases where land-use and/or processes discharging potential contaminants have remained essentially constant over a long time, quality data may not have changed significantly.

7.3.1.3 Land use data

In order to minimise costs it is recommended that the services of specialist organisations which provide land use data-sets should be engaged in the project. A variety of data files are maintained by governmental and non-governmental bodies, relevant examples being:

1. Data related to the rate of pesticide use (loading) is available from Produce Studies Research. Agricultural loading data are available on a 2 x 2 km grid square basis for each month of the year (i.e. in $kgha^{-1}month^{-1}$). Non-agricultural loading data is only available on a five year basis and it will be necessary to assume that loadings each year within the five year period are the same. Further data may be available from the Highways Agency, British Rail and other potential non-agricultural pesticide users, such as HM Prison service and the RAF to gain additional information on pesticide use.

2. Soil property data, which already underpins the Agency’s aquifer vulnerability mapping. More detailed information, where needed, should be available through SSLRC at Cranfield University.

7.3.1.4 Data evaluation

The first phase of work should encompass an initial screening exercise.

Firstly, simple conceptual models of the water system dynamics of each catchment would be generated, based on the hydrological and hydrogeological reviews.

Secondly, simple mass balance calculations would be undertaken through each catchment, using the BFI and water quality data, previously collected and collated. The results of this exercise would then be reviewed to assess “what it shows” and used to refine the simple conceptual models.

Subsequently, there may be a need move into a second phase of data acquisition for the selected catchments and potentially to move towards more sophisticated modelling tools. It is possible that paucity of certain types of information, for example groundwater flows or quality, may necessitate an iterative approach before an acceptable level of overall knowledge is reached.

Once data sets are judged to have reached a sufficient level of reliability and comprehensiveness, it may be possible to employ or modify existing models which manipulate land use and environmental impact data. A good example is the POPPIE system, developed for the Agency by WRc, SSLRC and Southern Science IT, which combines databases of soils, rivers, aquifers, land use, rainfall recharge and pesticide applications in a GIS. POPPIE includes model functions for rivers and aquifers, thus providing the means of combining the data sets to give predictions of the environmental risk posed by pesticides. Interactions between rivers and aquifers are handled using the Base Flow Index (BFI) concept, and included in the soil data is the Base Flow Index for each soil type.

POPPIE provides a valuable tool for the investigation of pesticide problems but could, with further development, be more widely used. POPPIE contains large databases which could be readily applied to other problems (including water resources as well as water quality). The concepts applied in POPPIE have the potential to be used for water resource assessment and to assess the fate of other diffuse contaminants such as nitrate. The system could form a valuable part of a basin scale water and contaminant flux management tool.

7.3.2 New work

7.3.2.1 Increase current understanding of the fate and behaviour of potential pollutants

Driven largely by EC Directives, research into the quality of groundwater increased significantly during the 1980's, with a number of studies of sewage effluents, landfill leachates, nitrate and pesticides in aquifers, closely followed by investigations of oils and more esoteric chemicals such as MTBE. Fluxes between groundwater and surface water were estimated, often using modelling procedures to allow surface water impacts to be calculated. This initial research needs to be consolidated with up to date data and effort put into the further development of models for these anthropogenic pollutants which pose a significant and growing problem for water resources. Processes in soils and aquifers are still not fully understood, and research is required to provide quantitative understanding for use in environmental impact studies (using models or not). This information can then be used to validate and develop catchment level conceptual models. Once the fate and impact of potential pollutants on groundwater and ultimately surface water is better understood on a catchment level, this provides a mechanism for prioritising remedial actions that will enable the Water FD target of 'good status' to be met for those waters.

The other area where more work is needed is in the movement of immiscible pollutants (i.e. pollutants which are not soluble) in water. Some models are available to simulate oil spills in rivers, or onto aquifer outcrops, but they have not been widely used, and the results produced have not been considered credible. Hydrocarbon releases are likely to occur in the future, whether as leakages at refineries, along pipelines or at industrial, commercial or residential premises or as spills on roads and railways. A major spill on an important aquifer could have devastating effects and effort should be given to developing models for simulating clean up of rivers and aquifers contaminated by hydrocarbons.

It is recommended that the research should include specific work on pathogens, in particular with a view to increasing our understanding of the mechanisms and processes controlling their movement and fate through the aquatic environment.

7.3.2.2 Quantification of transport pathways

New initiatives are required that focus on specific points within the transport pathways from precipitation to the sea. The two most important elements on a catchment scale are:

- the quantification of geochemical fluxes in precipitation events and through the subsequent run-off/recharge events; and

- the groundwater - surface water interactions along floodplains or bankside seepage zones (hyporheic zones).

The quantification of both flow and geochemical fluxes in these elements is difficult because they are both zones of geochemical activity and spatial variability. Chemical fluxes in precipitation are known to vary greatly through the period of a single event yet the quantities of contaminants introduced to a catchment can be significant. The quantification of the vertical geochemical fluxes through the unsaturated zone is still not exact, despite improvements in transport modelling. Accurate measurement of base flow additions to a stream is notoriously difficult. The quantification of the transport of the geochemical flux in the groundwater within an aquifer through the superficial floodplain sediments to a receiving river is even more difficult.

One of the least understood elements of surface water - groundwater interactions is that along floodplains or bankside seepage zones (hyporheic zone), where groundwater and surface water interaction is most active. Chemical and biological processes within the hyporheic zone may play a key role in attenuating contamination. In the upper parts of a catchment it is probable that surface water will actively recharge groundwater. In the lower parts of a catchment groundwater may replenish surface water at times of high rainfall or surface water replenishes the groundwater during droughts. The hyporheic zone includes, but is not confined to, the floodplain of a river system. This zone is important in the research field of geochemical fluxes because it is one with significant geochemical, hydraulic and possibly microbially mediated gradients between generally free flowing, aerated surface water and potentially reduced, low nutrient groundwater, and thus may have a significant effect on behaviour of the geochemical flux under both influent and effluent streams. The quantification and protection of groundwater ecosystems in such zones may be important in facilitating the sustainable degradation of anthropogenic contaminants.

To further research within this specific area it is suggested that for a selected catchment an array of investigation boreholes could be placed within a floodplain, forming a reticulation transverse to and parallel with the river channel. The boreholes could be used to assess head variation, chemistry and microbiology variation across the floodplain, and could be completed as part of a university research program. The fieldwork could be backed by laboratory simulations and the construction of microcosms. Alternatively, a larger scale in-situ core could be removed from the field for more realistic flow measurements. An investigation using traverse boreholes was undertaken in the 1970's at Peplow Mill on the River Tern in Shropshire as part of the Shropshire Groundwater Scheme investigations (STWA, 1977). This work will provide a sound scientific basis for establishing the need for land remediation and land management strategies to control diffuse pollution sources.

7.3.2.3 Information exchange workshops

Successful completion of the suggested programmes of work will involve many individuals and organisations and will be expected to produce large volumes of new information and to generate new ideas and concepts. In order to maintain the maximum synergy between the participants it is suggested that the lessons learned during the intensive investigations of point and diffuse pollution sources during the 1970's should be applied and workshops held at intervals at which participants in the various programmes would be expected to present their findings and developing concepts in an open manner. The organisation and timing of the workshops should be the responsibility of the body which assumes overall responsibility for the management and co-ordination of the work programmes.

7.4 Summary

The overall objective of the proposed work programme is to advance the understanding of geochemical fluxes through catchments so that the water resource management requirements which will flow from implementation of the Water FD can be achieved. Although, potentially, there is a very large number of combinations of target substances and catchment characteristics, in reality it is likely to be possible to reduce the complexity by assessing fluxes for particular groups of substances (for example nutrients, toxic metals, hydrocarbons, solvents) within the context of catchments classified in terms of the pathways and attenuation routes which they offer to the substances.

Because of the uneven distribution of knowledge and information related to the flux through catchments, the proposed work programme summarised in Table 7.1 proceeds from the general to the focused, before returning to the development of generalised management concepts and tools.

Table 7.1 Priority research initiatives with timeframes and indicative costs

Priority /Phase	Research Initiative	Timeframe	Indicative costs
1	***Complete review and collation of current status of necessary data sets.*** Completion of this phase to be marked by the generation of initial conceptual models.	6 – 9 months (assuming parallel working in each Agency Region).	100 man days per Region. Allow £5K per Region T&S.
2	***Apply conceptual models and evaluate requirements for additional studies.*** a) Select test catchments on the basis of outcome of Phase 1. b) Review influence of naturalisation of flows on calculated BFI in test catchments. c) Complete trial contaminant flux balances for test catchments. d) Refine initial conceptual models and identify shortfalls in knowledge and databases.	9 – 12 months (assuming parallel studies in a number of test catchments).	50 – 100 man days per catchment, dependent on complexity.

Priority /Phase	Research Initiative	Timeframe	Indicative costs
3	***Improve understanding of the behaviour, fate and flux of pollutants in water catchments.*** a) Programmes to remedy shortfalls in databases of source terms. The programmes are likely to include additional studies attached to existing catchment studies and studies of new catchments b) Programmes to increase knowledge of behaviour of potential pollutants through catchments, and especially in the hyporheic zone. Programmes based on existing and new research catchments. c) Modification and adaptation of existing source ~ pathway ~ receptor models (e.g. POPPIE) to simulate geochemical fluxes and interchanges.	1 – 2 years (minimum).	Between 100 and 200 man days per year, reflecting catchment size & complexity. Allow £15K per year per catchment for routine analyses, £30K if GCMS required.
4	***Development of catchment management tools to satisfy requirements of the Water FD.***	Ongoing through Phase 3, plus 1 year.	50 man days.
5	***Information exchange workshops.***	At intervals over 3 years.	Allow 4 man days per year for lead body, and 2 man days per year for participating bodies. Allow £5K per year T&S.

APPENDIX A LIST OF CONTACTS

A.1 BACKGROUND

In order to obviate the potential for ‘re-inventing the wheel’, the criteria for the literature review was developed at the start of this project by a one day internal WRc workshop meeting of senior project personnel, including two ex-WRc senior employees. These project members have direct experience and memory of relevant data collection and analysis extending back to the early 1970’s and were included in the project team to ensure pertinent studies were not overlooked.

A1.1 Academic, industry and regulator contacts

As part of the literature review (see Section 2), and in conjunction with the identification of existing projects and new initiatives (see Section 3), a number of contacts within the academic and research fields were identified and contacted, either in person or by telephone. These contacts were able to provide an extensive range of key references to relevant studies, in addition to information on existing projects and new initiatives. A list of the academic and research organisations, and the contacts with whom discussions were held, is given in Appendix A.2.

A number of contacts within the Environment Agency and Water Utilities were also identified and contacted by telephone and e-mail (see Appendix A.3 and A.4 respectively).

As an integral part of the literature review, Regional Environment Agency Officers were approached to ascertain how the various Regions collect and collate data pertaining to both ground and surface waters. The objective of this exercise was to determine what databases are available and whether a similar methodology for dealing with data for both water quality and quantity is practised across the Regions.

The information gathering exercise from the Agency and the Water Utilities was facilitated by the development of a questionnaire, presented in Appendix B.1.

To complete the review of existing projects and new initiatives, a number of environmental consultants were also contacted for information (see Appendix A.5).

In summary, the following contacts were made:

- Universities and Research organisations – 39 contacts;
- Environment Agency – 39 contacts;
- Water Utilities – 9 contacts;
- Environmental consultants – 11 contacts.

A.2 ACADEMIC AND RESEARCH ORGANISATIONS

Organisation	Contacts	Comments
ADAS	Eunice Lord	
Aberdeen University Dept. of Geography and Environment	Chris Soulby	Niche-Chasm Partner, working on Feshie catchment
Birmingham University: Geography Dept. Dept. of Earth Sciences Dept. of Earth Sciences Dept. of Earth Sciences	Geoff Petts Paul Ellis Mike Rivett John Tellam	Niche-Locar Partner PhD study on impacts of contaminated land and groundwater upon urban surface water quality Supervisor on above PhD
Bristol University, Geography Dept.	Paul Bates	Research into groundwater fluxes
British Geological Survey	Dave Allen Brian Adams Mike Edmunds Brian Morris Nick Robins The Library	 Geochemistry of major aquifers and Framework V project *Cryptosporidium* project
Cambridge University, Geography Dept.	Dr. Francine Hughes	Research related to riparian zones.
Centre for Ecology and Hydrology	Dick Bradford Graham Leeks Andrew Mackenzie Terry Marsh The Library	 LOIS NERC project on the Humber Well-Master Database
Cranfield University, Silsoe College	Richard Carter Peter Howsam Ken Rushton	Working on River Flit near Shefford
Durham University Geography Dept.	Tim Burt	Niche-Chasm Partner – Eden catchment
Imperial College, London	Howard Wheater	Co-ordinator Niche-Locar
London University - Royal Holloway College	John Mather	
London University - UCL	Willie Burgess Glyn Jones	Head of MSc Hydrogeology Course Retired Head of Hydrogeology Course
Lancaster University Dept. of Environmental Science.	Keith Beven	Niche-Chasm Partner – Eden catchment
Newcastle University: Civil Engineering Dept. Civil Engineering Dept.	 Paul Younger Prof. O'Connell	 LOCAR project – Eden catchment, IGARF-II project Co-ordinator Niche-Chasm
Oxford University, Dept. of Geography	Heather Viles Colin Clarke	No relevant work at Oxford
Reading University, PRIS	Mike Price Paul Whitehead	No relevant work at Reading
Sheffield University, Dept. of Civil & Structural Engineering	David Lerner	Head of Groundwater Protection & Restoration Group. No relevant work.
Trinity College, Dublin Civil Engineering Dept.	Bruce Misstear	
University College London	Tim Atkinson - seconded from UEA	Groundwater-surface water relations in karstic aquifers.
University of East Anglia (UEA), Dept. of Environmental Sciences	Adrian Green	Coastal carbonate aquifer, Norfolk study
University of Exeter. Dept. of Geography	Des Walling	Niche-Locar Partner

A.3 ENVIRONMENT AGENCY CONTACTS

Region	Contact	Work area
NORTH EAST		
Leeds Office	Mark Morton	Regional Groundwater Resources
Northumbria	David Cameron	Hydrologist
Dales	Mike Stokes	Hydrologist, Surface flow, rainfall gauges
	Jeff Pacey	Hydrogeologist, Groundwater Resources
	Richard Bourne	Water Quality Officer
	Neil Wootton	Groundwater Resources
Ridings	Ian Hampson	Hydrologist, Surface flows
	Jeff Meynell	Customer Services
ANGLIAN	Paul Hart	Regional Officer
Southern	David Seacombe	Groundwater Resources
Northern	Mike Hutchinson	Groundwater Resources
Central	Chris Taylor/ Vivien English	Groundwater Resources
Central	Graham Horton	Water Quality Technician
Central	Peter Ord	Environment Planning
Central	Yvonne Daly	Environment Planning
Central	Ian Hogg	Area Hydrometric Team Leader
NORTH WEST	Clare Wheeler	Hydrometric Information Officer, Surface water
	Catherine Saxon	Hydrometric Information Officer, Surface water
	Rob Paddison	Surface Water Quality
	Simon Gebbett	Hydrogeologist, Groundwater Modeller
	Keith Seymour	Team Leader
SOUTHERN	Anne Wilkinson	Hydrometric and Hydrology Officer
	Marcus Polley	GIS Officer
	Katherine Mason	Regional Groundwater Quality Officer
	Tony Matthews / Ian Walker	Licensing Officers
THAMES	Tim Besien	Monitoring network and diffuse pollution
	Andrew Longley	Groundwater Resources
	Richard Davis	Surface Flow Monitoring
	Jenny Thomas	Hydrogeologist - Point source pollution issues
	Vin Robinson	Principal Hydrogeologist
SOUTH WEST	**South Wessex Area**	
Blandford Forum	John Phillips	Groundwater Resources
	Jenny Watkinson	Team leader, Surface & Groundwater Monitoring
	Sue Pulman	Water Resources Officer (Groundwater Levels)
	Jim Grundy	Groundwater Resources
Exeter	Giles Bryan	Senior Hydrogeologist
	Paul Doherty	Groundwater Level Information
MIDLANDS	Bob Harris	NGWCLC
WALES	No success in contacting	

NOTE: The questionnaire was circulated to the Regions (see Appendix B.1) with kind assistance from Kamrul Hasan from the NGWCLC.

A.4 WATER UTILITY AND SUPPLY COMPANY CONTACTS

Organisation	Contact
GU Projects	Lucy Lytton
Hydrological Data UK	Martin Lees, Project Manager
Mid Kent Water Company	
Southern Water	Mike Packman
South Staffordshire Water Company	Liz Swarbrook
Thames Water Utilities	Dr P Aldous Principal Corporate Advisor Thames Water Environment and Quality
Wessex Water	Luke de Vial
Yorkshire Water	Hilda Beatty
BGS Wallingford	Nick Robins

A.5 ENVIRONMENTAL CONSULTANTS CONTACTS

Company Name	Contact
ES International	Alan Herbert
Entec UK Ltd	John Heathcote
Enviros Aspinwall	Chris White
Golder Associates (UK) Ltd	David Hall
Mott MacDonald	Jan van Wonderen Paul Ashley
WMC, Water Management Consultants	Richard Boak
WRc plc	Chris Young Lewis Clark David Oakes
WS Atkins	Ron Morley

APPENDIX B LITERATURE SEARCH DETAILS

B.1 AGENCY/ WATER UTILITY QUESTIONNAIRE

The management of water resources has historically focused on surface water and groundwater as separate entities. In reality, as development of both of these resources increases, the use of one often affects the other. The objectives of the above project are to undertake a scoping study which provides a sound basis for itemising the research needs surrounding groundwater/surface water interactions and identifies what work is already underway within England & Wales. The scoping study will provide a basis for prioritising future R&D initiatives, with a particular focus on supporting the implementation of the Water Framework Directive.

This questionnaire is being used to identify all relevant fundamental reports detailing groundwater/surface water interactions in UK aquifers from relevant agencies and academic establishments. Please complete with any projects or studies, funded by the Agency or "Other" and of which you have knowledge within your Region.

Region:
Name of person(s) completing questionnaire:
Date completed:
Contact Address:
Contact Telephone No.:
1. Which catchments are within the jurisdiction of the Region?
2. What databases are maintained for Groundwater Quality and Surface Water Quality?
3. What databases are held for Groundwater Levels or Aquifer Properties?
4. In what form are the databases held (GIS, Excel spreadsheets, paper records)? For Groundwater Quality? For Groundwater Levels? For Surface Water Quality? For Surface Flow Gauging? For Aquifer Properties?
5. What time period do the monitoring records / database cover? For Groundwater Quality? For Groundwater Levels? For Surface Water Quality? For Surface Flow Gauging? For Aquifer Properties?
6. Are monitoring locations the same for river flow gauging and river water quality?
7. Do groundwater level and groundwater quality measuring points coincide?
8. Have there been any studies reviewing groundwater and surface water interaction, including flows and quality aspects? If yes, please provide details.
9. Is the information easily accessible? If so, at which office (s)? For Groundwater Quality? For Groundwater Levels? For Surface Water Quality? For Surface Flow Gauging? For Aquifer Properties?
10. Other than NALD (National Abstraction Licence Database) are there other relevant datasets held within your Region of which you are aware but do not have responsibility (e.g. water undertakings, major industrial users)?
11. Who would be a preferred contact? For Groundwater Quality? For Groundwater Levels? For Surface Water Quality? For Surface Flow Gauging? For Aquifer Properties?
Additional information not covered by the above:
12. What catchment management tools (e.g. GIS, databases, spreadsheets, models) are used for groundwater and/or surface water systems? Please give brief objectives, descriptions and contact names.
13. Do you see a need for additional catchment management tools (additional to those above) Give brief requirements.

B.1.1 Environment Agency Regional studies

With regard to regional studies focusing on groundwater and surface water interaction, the following have been identified in communication with Regional Officers:

1. **The Rye Sub Catchment, Dales Area, North East Region:** This tributary of the River Derwent has been extensively studied since the 1970's, giving rise to a series of reports. Studies have been directed to review the nature of the non-existent or very low surface flows that predominate in summer due to the presence of sink holes. Tracer tests have been undertaken which have proven a rapid 8 hour time lag between the sink holes and Yorkshire Water abstraction boreholes at Irton, a distance of 8km. The geochemical analysis suite of the abstracted groundwater replicates that which would be anticipated from river waters. The groundwater source at this point is effectively a disguised river.

   An adapted MODFLOW model has been developed for the Corallian Limestone of this area, which at the time of writing is being converted into Groundwater Vistas. Over the last 10 years there have been a series of reports completed, focusing on low flows, general hydrogeology, environmental appraisals of blocking the sink holes, and most recently a resource protection report for Yorkshire Water in 1997.

2. **The Devils Brook, South Wessex Area, South West Region:** This investigation arose from the desire to abstract groundwater from a borehole in close proximity to a seemingly perched river, the study was undertaken during 2000. Both groundwater and surface waters were analysed for organic tracers to examine hydraulic continuity. Early results using fluorescence have shown a connection to be apparent. This technique is currently being researched and developed by Newcastle University, where effort is being directed at solving point source pollution issues.

3. **Low Flow Study, River Piddle, South Wessex Area, South West Region:** In collaboration with the BGS this study focused on the impact of Public Water Supply boreholes and Ministry of Defence abstractions on the River Bourne. Work commenced in April 1999, with the resultant conceptual model for the catchment likely to become available in spring 2001. The bulk of the fieldwork relating to this project was completed during spring and summer 2000.

   To attain data for the model, the BGS remapped the entire catchment and provided geophysical logging of boreholes drilled by the Agency. Geochemical analysis was performed for both the Agency boreholes and selected spring locations. All field data was combined with Agency groundwater level, rainfall and flow data to form the basis of the model. Preliminary results reviewing the age of the river waters showed a mix of younger waters attributable to recharge, and older waters that are thought to derive from outside of the catchment. A preliminary exploratory phase (Phase II) has been approved for this study. A copy of the Phase I report is held at the BGS Wallingford.

4. **Low Flow Study, River Bourne, South Wessex Area, South West Region:** This study focused on reviewing the impact of Wessex Water groundwater abstractions on the River Piddle. Marcus Hodge Environmental compiled two reports in 1999 and 2000 to collate all recently recorded data, which in turn has been summarised by Halcrow to produce the 'Piddle Model'. The model is focused on low flow assessment. Unlike the River Bourne

study, this model reviews only geology, groundwater and surface water flows and does not include geochemical modelling. Reports are available from the Agency Exeter office.

5. **Additional Low Flow studies, South Wessex Area, South West Region**: Work is currently in progress on the River Darent, Font Hill Brook and South Winterbourne watercourses. The work is being carried out as part of the Resource Sustainability Abstraction Programme (RSAP). Additional information can be obtained from the Agency office in Blandford Forum.

6. **Sawston River Study, Anglian Region:** The Sawston River study was undertaken following a pollution incident in 1983, whereby tannery effluent was discharged into the River Sawston. Although the majority of the discharge drained directly into the Sawston River, local public water supplies were also impacted. The study was completed for the Agency by Dames and Moore, and involved computer modelling of the natural loss of river water to the underlying aquifer. The study was last updated in 1998.

7. **Fylde Aquifer / Wyre Catchment, North West Region:** A 30 year integrated catchment model was completed in 1997 for the purpose of water resource planning. The study concluded that recharge from the aquifer was an important component of river flow, and that over licensed sections of the aquifer were noted to effect river flows. The study did not address water quality issues.

8. **Calder Valley, North West Region:** This is an Agency internal investigation to review BNFL Water Supplies in the Calder Valley. The investigation comprised pumping tests to assess the impact of borehole abstraction on surface watercourses. The investigation included water quality analysis of both boreholes and surface waters. Two reports have been issued in connection with this investigation: Reports No. 111, April 1982 and No. 133, February 1983. The substantive part of the work is contained within Report No. 133. Further detail is available from the Agency office at Warrington.

9. **Vale of Eden, North West Region:** A study of the hydrochemistry of the Vale of Eden as a guide to groundwater resources, completed Newcastle University MSc Thesis, September 1994. No further detail is held at the Regional Agency office. In addition, the Vale of Eden has been identified for study as part of the proposed Catchment Hydrology and Sustainable Management (CHASM) programme to look at river / aquifer interactions.

10. **Vale of York Groundwater Scheme, North East Region:** The scheme originated in 1996 as a groundwater and river augmentation study, involving the drilling of several boreholes and the execution of pumping tests over a period of 2 years. There was considerable concern over the impact of abstraction on surface water features within this ostensibly arable area, and the likelihood of desiccation of the drift deposits. As part of this study, geochemical analysis of boreholes drilled into the sandstone was undertaken; analysis of waters from the drift deposits might also have been completed. The main thrust of the study was to look at quantity issues rather than quality. This project is no longer active.

11. **Sherwood Sandstone Group, south of York, North East Region:** A study undertaken by Leeds University in 2000 to examine the possibility of saline intrusion resulting from upconing within the Sherwood Sandstone. It was believed that boreholes within the Region had punctured the Upper Permian Marls and had been advanced into the

Magnesian Limestone. The project incorporated the use of stable isotopes and general groundwater chemistry. Additional boreholes were completed to continue this assessment. Currently Leeds University is seeking additional funds to continue the study.

12. **Selby Area, Northumbria Region**: This is an ongoing study into the relationship between drift deposits and the underlying aquifer system. The study has concentrated on producing a MODFLOW model, which is currently being converted to Groundwater Vistas. Additional boreholes have been advanced to further this study. To date the study has not incorporated geochemical analysis.

13. **West Berkshire Groundwater Scheme Trials, Thames Region:** Completed in the late 1960's and 1970's for the Kennet Valley and the River Lambourn. The study incorporated pumping trials, spot flows, river gauging and quality measurements. The purpose of the study was to quantify fluxes during periods when pumping trials applied stress to the system. One result of the trials demonstrated that the Lambourn has low bed permeability.

14. **Taplow / Dorney, Thames Region:** The estimation of induced recharge of river water into chalk boreholes at Taplow / Dorney using hydraulic analysis, geophysical logging and geochemical methods. IGS Report 76/5, Mike Edmunds (1976), IBSN 0118812408. To assess the induced effects of groundwater abstraction, geophysical flow logging was undertaken in boreholes within 100m of the river covering a 0.5km stretch of the River Thames at Taplow, Berkshire. The study utilised hydrochemical analysis to review chemical signatures of river water within chalk boreholes.

B.1.2 Water Utilities responses

1. **Anglian Water:** Undertaking a Water FD project on phosphorus and also a review of designations under the Nitrate Directive.

2. **GU Projects**: Routine raw water quality samples taken between 4 and 6 times per year from each 'source (source may be a single bore or a group of bores). Full set of parameters probably measured over 12 month period, but not all on each occasion. Areal distribution is variable. Linking quality to quantity measurements (borehole discharge) difficult; old type telemetry overwrote data tapes every 4 weeks, so much flow/ pumping rate data has been lost. Chemical data are captured and archived more effectively.

3. **Hydrological Data UK**: Confirms that BFIs are not naturalised – but that naturalised values could be computed if the data were available. The facility to estimate naturalised BFIs is built into micro-low flow studies.

4. **Mid Kent Water**: Confirmed that data sets for Chilham/Godmersham boreholes typical of their sources. (Ammonium, TOC, Cl, Nitrate, Nitrite, TDS approx. quarterly on raw water. Turbidity, E coli., Faecal colis, colony 1 day 37C, colony 2 days 22C weekly (since 95 – earlier data c. monthly) Post 91 data on computer files, earlier as paper or fiche records.

5. **Southern Water**: Raw water analyses dominated by Drinking Water Regulations lists. Full Drinking Water Regulations analysis annually. Check analyses roughly monthly. Analyses very reactive, if problem known (nitrate, solvents, pesticides, *Cryptosporidium*) then lots of parameter specific data, to the exclusion of all else. However, SW have started

some proactive monitoring for MTBE following recent Agency Report. Full raw water database has been sent to BGS in connection with North Downs, South Downs and Wessex Basin Chalk studies. South Downs study is completed, the North Downs study is ongoing but the Wessex Basin study is suspended. The frequency of monitoring has decreased significantly since privatisation (especially with respect to raw water).

6. **South Staffs**: Routine raw water on both surface and groundwater sources. Most frequent are turbidity, temperature and other instrumental parameters, which may be online for surface sources. Monitoring at many sources is based on experience of past performance. A number of analytical suites applied, not all carried out weekly. List I/Red list occasionally. Current database goes back 12 years. Also hold much older data but on fiche/punched tape format.

7. **Thames Water**: Routine collection of raw water data (c.f. STWA Water Quality 'bible') by Regional Water Authorities ended in 1989 (privatisation). Since then they have been driven by quality of water in mains and raw water data not collected. Storage of pre-89 data uncertain – some paper copies, some on computer files. Water only companies may have more raw water data. Agency believed to continue to collect data on surface water quality.

8. **Wessex Water**: Confirmed that raw water quality data for all their sources at frequency and determinand list as per Shepherds Shore etc.

9. **Yorkshire Water**: Analysis of groundwater dominated by Drinking Water Regulations requirement for treated waters. Some raw water analysis, when boreholes are commissioned and again if quality problems develop or new regulations appear. Few single source supplies, so that even 'raw' analyses may represent mixed waters in pipes before treatment, rather than quality at the point of abstraction.

10. **BGS Wallingford**: Sceptical about the reliability of available data. They have recently completed work on groundwater quality in Scotland and found only 400 reliable analyses for the whole country. Nearly all water supply data were incomplete, similarly with industrial data sets. The few reliable data are from BGS/WRc/University research projects, which are mainly of limited areal cover and time limited. EA/Framework 5 project – BASELINE – is collecting groundwater samples from all over UK for analysis.

B.2 ON-LINE SEARCH STRATEGY

B.2.1 STN search

The world-wide scientific literature, compiled within 14 of the major international abstracting databases, was scrutinised by an STN International (Scientific and Technical Information Network) 'on-line' computer search using search strategies and keyword search tools. This search allowed for a wide range of scientific journals, periodicals, conference proceedings, reviews and reports to be accessed.

The search databases utilised included:

- AQUASCI;
- BIOSIS;
- CABA;
- CONFSCI;
- GeoRef;
- POLLUAB.

The search phrases used for the Express STN are listed below:

1. Surface or river water and groundwater and (mass balance# or interaction# or flow system#)
2. As above 'and UK'
3. As above 'and quality and quantity'
4. Base flow and (index or indices) and UK
5. Base flow and UK
6. Hydrogeochemical fluxes and UK
7. Geochemical and flux# and water and UK
8. Groundwater and (river or surface water) and monitoring network
9. As above 'and UK'
10. Groundwater and (river or surface water) and hyporheic
11. As above 'and UK'
12. Groundwater and (river or surface water) and ecosystem
13. As above 'and UK'
14. (Contribution or impact) and diffuse source# and groundwater pollution
15. (Contribution or impact) and diffuse source# and (surface or river) water pollution
16. (Contribution or impact) and chemical pollutant# and groundwater (quality or quantity)
17. (Contribution or impact) and microbiological pollutant# and groundwater (quality or quantity)
18. (Contribution or impact) and chemical pollutant# and (surface or river) water and (quality or quantity)
19. (Contribution or impact) and microbiological pollutant# and (surface or river) water and (quality or quantity)
20. Groundwater and (surface or river) water and diffuse pollutants
21. Groundwater and (surface or river) water and chemical pollutants
22. Groundwater and (surface or river) water and microbiological pollutants.

This extensive search gave rise to in excess of four hundred overseas and UK references. These were then critically reviewed and reduced to 62 overseas and 28 UK references, which are listed in Appendix D. A number of the key UK and overseas references have also been added to the Literature Review Database (Appendix C).

B.2.2 Key words and phrases

The following lists of key words and phrases, mostly in combination, were used to search the various databases and web-sites:

- Surface water - groundwater interaction
- Groundwater- surface water interaction
- UK
- England
- Geochemical fluxes
- Groundwater quality UK
- Surface water quality UK
- Freshwater quality UK
- Base flow / Base flow index (BFI)
- Run-off
- Nitrate
- Pesticides
- Diffuse pollution/contamination
- Dispersed pollution/contamination
- BFI and water quality
- Ecosystem
- Hyporheic

B.2.3 "Current Contents" CD-ROM search

A search of the ISI Thompson Scientific 'Current Contents': CD-ROM Version 1994 to 2001 – Agricultural, Biological and Environmental Sciences was also completed using the keywords listed in Appendix B.2.2. Numerous references were reviewed whilst searching the 1994 – 2001 CD-ROMs. The key references (No. = 65) were printed off and further reviewed to produce a list of twenty-four papers. Of these, ten had already been highlighted by the STN search, giving 14 unique key references, one of which was UK based. These references are included in Appendix D, with the most pertinent references also included in the Literature Review Database (Appendix C).

B.2.4 On-line organisations

As well as a general internet search, a number of groundwater related organisations with information on-line were visited and searched, using the key words and phrases listed in Appendix B.2.2, including:

- Danish Hydraulic Institute (DHI);
- Environment Agency;
- European Union;
- UK Groundwater Forum;
- United States Geological Survey (USGS);
- United States Environmental Protection Agency (US EPA);
- WRc Reports database;

The results from these searches are given in Appendix B.3.

B.3 Results from organisations with information available "on-line"

B.3.1 Danish Hydraulic Institute (DHI)

A major aspect of work carried out at the DHI is water resources software, including;

- MIKE 11;
- MIKE BASIN;
- MIKE SHE;
- Geo Editor;
- DaisyGIS.

The MIKE SHE model is being used as part of a study on "Integrated Surface Water - Ground Water Modelling in Florida". The hydrological conditions in Florida are complex and largely governed by direct interaction between surface and groundwater. The community in Florida (i.e. regulators, stakeholders and consultants) have in recent years realised the need for an integrated approach to water resources assessments. South Florida Water Management District (SFWMD, www.sfwmd.gov) is the responsible water manager in South Florida and has through a continued co-operation with DHI developed and applied MIKE SHE in a number of projects. The model applications are diverse with different objectives, but common for all are the requirement of describing flow in both surface water (e.g. canals and wetlands), in the soil, in the groundwater aquifers and not least the interaction.

DHI has recently launched Catchment Version 2, which has been developed as a support tool for the public authorities to map and structure data on the load from point- and non-point sources.

B.3.2 Environment Agency web-site

As well as discussions with Agency personnel, a search of the Agency web-site was also carried out using a selection of key words (as listed above in Appendix B.2.2). A number of references were identified, a selection of key references are described below:

1. National Joint Hydrology & Hydrogeology Seminar – March 2000

The central theme of the seminar was to understand how surface waters and groundwaters interact, both from a point of view of groundwater providing base flow support to rivers and how river flows can be influenced by groundwater pumping. The Agency's National Groundwater and Contaminated Land Centre (NGWCLC) has worked with Regions and Areas to produce a five-year plan aimed at improving current estimation methods for estimating the effects of groundwater abstraction on river flows, including the IGARF (Impact of Groundwater Abstractions on River Flows) project (see Section 3.4.8.3 and Appendix B.3.2 Item 5). Current methodologies date from 1970 and are clearly inadequate for the high profile application now generated by the Water Framework Directive.

The programme was designed to ensure that the National Hydrology Group and the Groundwater Resources Group gained a better appreciation of each others work and current research projects, which will help in the planning of the future research programme in a more collaborative way. The seminar explored the need for a more integrated approach to a range of activities including resource estimation and impact assessments. Surface water flow estimation and naturalisation was presented alongside groundwater estimation techniques.

There was a separate session dealing with the interaction of water flows and levels on ecology.

2. Groundwater quality in the Upper and Middle Lee catchments

Groundwater quality for the Chalk aquifer in the Upper and Middle Lee catchments is monitored using selected public supply and private abstraction boreholes. The monitoring network is incomplete at present.

The interaction between surface water and groundwater impacts on the quality of groundwater and this is seen particularly at one site. Here water is derived from outside the catchment, from the Mimmshall Brook via swallow holes at North Mimms. At times, the site and others closer to Hertford have been affected by pollutants in this way and there may be ongoing effects on the major ion chemistry.

Groundwater quality reports for the Lower Greensand, Leatherhead, Loddon-Wey, and Chilterns are also described on the web-site.

3. Integrated River Basin Management

Integrated river basin management (IRBM) has been widely recognised as an effective way of managing the environment and human activities as they interact with it. IRBM, sometimes known as Catchment Management, is seen as a key planning and management tool in parts of the United States of America, South Africa, Australia and New Zealand. In these countries the process has been developed to include an involvement of local people in the care of their environment. Only in this way is it considered possible for solutions to environmental and socio-economic problems to be found.

In Europe, the Water Framework Directive will impose a requirement on all Member States to assign their land area to "River Basin Districts". Management Plans for these river basins are to be prepared every six years. The Directive therefore enshrines, into European Legislation, the principle of integrated river basin management. Although not yet confirmed, it is assumed that the competent authority to manage each district in England and Wales will be the Environment Agency.

In England and Wales, IRBM plans have been prepared for several years. In Wales, Catchment Management Plans (CMPs) were prepared for many rivers by the former Welsh Water Authority. Later, this approach was adapted and applied by the NRA to all catchments in England and Wales. More recently, the Environment Agency embarked on a programme of Local Environment Agency Plans (LEAPs), a successor to CMPs, providing coverage of all catchments in England and Wales.

IRBM is clearly a process which has been taken seriously by governments in many parts of the world. Through the mechanism of the European Water Framework Directive, it will become increasingly influential.

Proposed changes to the abstraction licensing system in England and Wales (set out in "Taking Water Responsibly" (1999)), require the effective provision for the sustainable management of the nations water resources. In response to this initiative is a proposal for the Environment Agency to develop at a local level Catchment Abstraction Management Strategies (***CAMS***). To manage water resources effectively the Agency will need to take a holistic approach to catchment management, considering the needs of abstractors alongside those of fisheries, recreation and navigation as well as the need to protect water quality and generally conserve the aquatic environment. CAMS will set out a strategy for achieving the sustainable management of water resources within a catchment or group of catchments. CAMS will be the vehicle for reviewing the proposed new time limited abstraction licences. CAMS will be reviewed on a six year cycle and therefore represent a responsive and effective approach to water management. To successfully implement the proposed CAMS information will be required on geochemical fluxes within the catchment.

4. Action Plan For 'Upper Ouse' Area, Anglian Region

Flood and drainage management and water quality in the upper reaches of the River Ouse and its tributaries are the two main issues covered in the recently published Environment Agency Action Plan for the 'Upper Ouse' Area.

5. R&D Project Number W6-046 - IGARF II

Start Date: 11-99 Planned End Date: 09-02. Commissioning Function: Water Resources. Region: Midlands. Project Manager: S Kirk. Project Status: On-going with Newcastle University. The Agency is seeking to establish 'best practice(s)' with respect to methods of determining the impact of groundwater abstraction on river flows (IGARF). At present no nationally accepted methodology exists, and Agency Regions and Areas often have different practices for determining the groundwater abstraction impact on river flows. Accordingly there is an immediate need to develop a nationally acceptable methodology that is suitable for a wide range of aquifer and river characteristics, including those situations for which little technical data are available. By these means a consistent approach to determining the impact of groundwater abstraction on river flows across the Agency can be adopted, reducing inconsistencies and errors, and providing for a more robust and technically-supported justification and (if necessary) defence of resource management determinations resulting from its use.

This project will complement the earlier IGARF (Impact of Groundwater Abstractions on River Flows) project by ESI (see Section 3.4.8.3) that was restricted to consideration of simple analytical techniques which greatly limits their range of application and accuracy. This ongoing project will allow more accurate estimates of impacts on river flows and will also allow estimates to be produced for a wider range of hydrogeological environments. This will be achieved by the use of numerical modelling techniques applied to the study of river-groundwater interactions that are stressed by groundwater abstractions.

This work is seen as complementary to the use of 'Surface Water Abstraction Licence Procedure' (SWALP) and other licensing and resource management procedures.

Specific objectives are:

- To produce a technical evaluation of a selection of numerically based methods, involving computer simulation models, for determining the impact of groundwater abstractions on river flows;

- To produce an easy to use tool to assist in the establishment of best practice and a consistent approach to this problem within the Agency.

B.3.3 European Union

The COSTS and CORDIS websites were searched but revealed little information pertinent to this study.

B.3.4 UK Groundwater Forum

A number of relevant publications have been issued by the UK Groundwater Forum, namely:

- A Strategic Study of the UK Groundwater Research Agenda – one of the priority research topics being study of interaction between streams and aquifers;

- Groundwater Issues Report – a follow on from the Strategy Study;

- How Rivers Work – the Role of Groundwater;

The following list of projects were identified under surface water - groundwater interactions:

- River Basin Management;
- Stochastic space-time rainfall forecasting system for real-time flow forecasting;
- WATERWARE: A Decision-Support System for Integrated River Basin Planning (EUREKA EU487);
- Wetland protection and groundwater abstraction at Thetford;
- Wetlands Investigation, North Wales.

B.3.5 United States Geological Survey (USGS)

The USGS has produced a major overview of surface water - groundwater interactions in the publication "USGS Circular 1139 – Ground Water and Surface Water A Single Resource", by Winter *et al*, 1998. Another important study in this field is "Water Resources Investigations Report 98-4059 – Groundwater Discharge and Base Flow Nitrate Loads of Nontidal Streams, and their Relation to a Hydrogeomorphic Classification of the Chesapeake Bay Watershed, Middle Atlantic Coast" by Bachman *et al.* The abstracts to these papers is given in Appendix D.3.

As well as research programs, the USGS also collects data as part of it NAWQA (National Water Quality Assessment) program. The program began in 1991, and systematically collects chemical, biological, and physical water quality data from study units (basins) across the nation. The data warehouse currently contains and links the following data:

- Chemical concentrations in water, bed sediment, and aquatic organism tissues for about 500 chemical constituents;
- Site, basin, well and network characteristics with many descriptive variables;
- Daily stream flow information for fixed sampling sites;
- Groundwater levels for sampled wells;
- 2,800 stream sites and 5,000 wells;
- 26,000 nutrient samples and 15,000 pesticide samples as well as 5,000 VOC samples;
- 1,200 samples of bed sediment and aquatic organism tissues;

The USGS also operates **The Ground-Water Resources Program**, which encompasses regional studies of ground-water systems, multidisciplinary studies of critical ground-water issues, access to ground-water data, and research and methods development. The program provides unbiased scientific information and many of the tools that are used by Federal, State, and local management and regulatory agencies to make important decisions about the Nation's ground-water resources.

National Aquifer Database

- Critical Aquifer Systems
    - Middle Rio Grande Basin Study

- Issue-Based Regional Assessments
    - Southwest Ground-water Resources
        - Issues and activities in the Desert Basins of the Southwest (FS 086-00)

- Regional/National Overviews
    - Freshwater-Saltwater Interactions along the Atlantic Coast
        - Issues and activities in the Atlantic Coastal Zone (FS 085-00)

Other projects include:

- Groundwater Discharge to the Great Lakes;
- Seney national Wildlife Refuge, Water Budget for C-3 Pool;
- Rapid Creek, western South Dakota;
- South Platte River alluvial aquifer;
- Groundwater-surface water interactions and relation to water quality in the Everglades.

B.3.6 United States Environmental Protection Agency (US EPA)

Two main reports were identified:

- EPA/542/R-00/00 – Proceedings of the Groundwater-surface water Interactions Workshop July 2000;

- Biological Indicators of Groundwater- Surface water Interactions. September 1998.

For a brief summary of these reports see Section 2.4.5 and for more details Appendix D.3.

B.3.7 WRc reports database

Key reports and studies undertaken by WRc are identified in the Literature Review Database in Appendix C and are further discussed in Section 3.4.8.7.

APPENDIX C LITERATURE REVIEW DATABASE

APPENDIX C.1 REFERENCES LISTED BY AUTHOR

Status	Reference
Report	Allen, D. J., The Physical Properties of Major Aquifers in England and Wales, WD/97/34.
Report	**Anderson M. T., 1995, Use of hydrologic budgets and hydrochemistry to determine groundwater and surface water interactions for Rapid Creek, western South Dakota. USGS.**
Proceedings	Annual Meeting of the American Institute of Hydrologists, 28. Oct 1998. p. 125-130.
Existing Project	Assessing Contaminant Transport in the Permo-Triassic Sandstone (Duration: Ongoing). Funding: ICI
Existing Project	Barrett Dr. M. H., 1998-2001, Depth and Penetration of Urban Recharge and Contamination in UK Aquifers. Concentrating on Nottingham and Birmingham conurbation's. NERC funded.
Existing Project	Baseline Geochemistry - UK Groundwaters, Synthesis of regional groundwater quality from selected aquifers in England & Wales to characterise baseline chemistry to benchmark future pollution risk.(EA/BGS)
Future	Better Baseline Conditions / Improve regionalisation of existing modelling procedures / Integrate monitoring and modelling more effectively. LOCAR will act as a framework.
Proceedings	**Beven, K. J., 1991, Hydrograph separation. Proc. BHS Third National Hydrology Symposium, Institute of Hydrology, Wallingford, 3.1-3.8.**
Report	BGS Hydrogeology Group, 1996-1998, Baseline Quality of Aquifers. (Sponsor EA NGWCLC).
Report	BGS Hydrology Group, 1996, Groundwater Quality in the Yorkshire Chalk.
Report	**BGS Hydrology Group, 1997-1998, Low Flow, Groundwater and Wetland Interaction Scoping Study. (Sponsor EA North West Region, Central Area Office).**
Report	BGS, 1989, *Trace Element Occurrences in British Groundwaters* . Research Report SD/89/3. Hydrogeology Series.
Report	BGS, 1999, Study of the South Downs Chalk, aquifer description and resources. (Part of the ongoing BGS National Groundwater Survey).
Database	BGS, Aquifer Properties Manual, 1997, to collect, collate, review aquifer physical property data for England & Wales. Comprehensive digital database. Complete 1998. Funded: BGS / NRA.
Report	BGS, Baseline Geochemical Surveys (Part EC, part EA, plus Science Budget).
Report	BGS, Cryptosporidium Research (Duration: Completed 31 March 2000. Funded: UKWIR).
Report	BGS, Cryptosporidium Research on Groundwater, review of past work on movement through groundwater, identified where operational monitoring could be improved.
Models	BGS, Groundwater Vulnerability Maps, vulnerability to contamination covering all England and Wales. (Completed: End 1998). Funded: EA.
Database	BGS, Physical Properties of Minor Aquifers of England & Wales, 1999, to update national aquifer properties database established for Aquifer Properties Manual (1997). Funded: BGS / EA.
Future	Bio Reduction within the Floodplain
Unpublished	Birmingham University, Heavy metal fluxes at EMI from stabilised waste dumps. (6 years ago?)
Report	**Birtles A B. 1978. Identification and separation of major base flow components from a stream hydrograph. Cent. Water Plann. Unit, Reading, Engl., UK. Water Resour Res, (1978) 14 (5), 791-804**
Report	**Birtles, A. B., 1977, River water quality models models based on stream hydrograph components, CWPU Technical Report 23, Reading.**
Journal	Birtles, A. B., 1978, Identification and separation of major baseflow components from stream hydrographs, WRR 14, pp 791-803.
Report	Blackmore J. and Clark I., WRc, 1994, The disposal of sheep dip waste: effects on water quality, NRA R&D Report 11.
Report	Brewerton, L.J., *Baseline Geochemistry Database Documentation* , WD/97/65R.
Journal	**British Hydrological Society, March 1995, Modelling river - aquifer interactions, Occasional Paper No. 6. (Editor Paul Younger).**
Existing Project	Burt T. P., and Bates, P., Reviewing Slope-Floodplain-River interactions on the river Severn below Shrewsbury.
Journal	Burt, T. P, Haycock, N. E., 1996. Linking floodplains to rivers. In Anderson M. G., Walling D. E., and Bates P. (eds), Floodplain Processes, Wiley, 461-492.
Report	Cable, C.J., Fielding, M., Gibby, S., Hegarty, B.F., Moore, K., Oakes, D and Watts, C.D., 1993, Pesticides in drinking water sources and supplies, DoE 3376/1.
Report	Cambridge Water Company, Thetford Scheme, ground and surface water interactions.
Report	**CEC, 1982, Balance of groundwater resources of the UK.**
Report	CEC, 1982, Groundwater resources of the European Community synthetical report. Brussels and Luxembourg.
Report	Chilton, P. J., et al, Transport and Fate of Pesticides in the Unsaturated and Saturated Zones of the Chalk. WD/97/71.
Report	Clark L., et al, WRc, 1995, Pesticides in major aquifers, NRA R&D Report 17.
Report	Clark, K.J. and Oakes, D.B.,1994, ROSANN – River nitrate model. WRc Report to Anglian Water, UC 2344.
Unpublished	Conant, B., 1999, Groundwater plume behaviour near the groundwater surface water interface of a river. Unpublished, Dept. of Earth Sciences, University of Waterloo, Ontario, Canada.
Report	CWPU, 1997, Nitrate and water resources with particular reference to groundwater, Reading.
Report	De Wit, M., Meinardi, C., Wendland, F., Kunkel, R. Modelling water fluxes for the analysis of diffuse pollution at the river basin scale. Hydrological Processes. 14(10):1707-1723, 2000 Jul
Report	Department of Scientific and Industrial Research (1964). Effects of polluting discharges on the Thames Estuary. Water Pollution Research Technical Paper No. 11. HMSO, London.
Report	Digest of Environmental Statistics, No.20, 1998, Government Statistical Services, DETR. (No. 22 out soon).
Report	Dils R.M. et al. The controversial role of tile drainage in phosphorus export from agricultural land. Water Science & Technology, 1999. pp. 55-61.
Existing Project	Dowle, J., Groundwater Discharge to Urban Surface Water - River Tame Study. Unpublished MSc, School of Earth Sciences, University of Birmingham, 2000.
Report	Downing, R. A. & Williams, B. P. J., 1969, The Groundwater Hydrology of the Lincolnshire Limestone. Publ. Water Res. Board, Reading 160 pp. (from Edmunds).
Report	**Downing, R. A. and Skinner, A. C., 1988, Groundwater in the UK. BGS Report WD/88/1, Wallingford.**
Journal	Downing, R. A.& Wilkinson, W. B., 1993, Applied Groundwater Hydrology. Groundwater Resources, Development & Management in the UK: Historical Perspective. Quart. Jour. Eng.Geol. 26.4 pp 335-358.
Journal	Downing, R. A., 1993, Groundwater Resources, their Development and Management in the UK: AN Historical Perspective. Quart. Jour. Eng. Geol. 26.4 P 335-358.
Report	Downing, R. A., Land, D. H., Allender, R., et al, 1970, The Hydrogeology of the Trent River Basin. Water Supply Papers, Hydrogeological Report No 5, Inst.of Geological Sciences, London, 101 pp.
Database	EA National Archive of NO_3 at NGWCLC, EA, in response to Nitrate Vulnerable Zones.
Report	Eatherall, A.; Warwick, M. S.; Tolchard, S. Identifying sources of dissolved organic carbon on the River Swale, Yorkshire. Science of the Total Environment, May, 2000. Vol. 251-252,
Journal	Ede, D. P., 1975, Limestone Drainage Systems, J. Hydrology. Vol. 27. pp. 297-318
Report	**Edmunds, et al, 1987, *Baseflow Geochemical Conditions in the Chalk Aquifer, Berkshire, UK* . (a basis for groundwater quality management).**
Journal	**Edmunds, W. M. & Walton, N. R. G., *The Lincolnshire Limestone – Hydrochemical Evolution Over a Ten-year Period,* Journal of Hydrology, 61 (1983) 201–211.**
Report	**Edmunds, W.M. et al, A Guide to the Natural (Baseline) Quality Study. WD/97/51.**
Report	Edmunds, W.M.; Kinniburgh, D.G.; Moss, P.D. Trace metals in interstitial waters from sandstones: acidic inputs to shallow groundwaters. Environmental Pollution, 1992. Vol. 77, No. 2&3, pp. 129-141.
Existing Project	Ellis, P., The Impact of Contaminated Land and Groundwater Upon Urban Surface Water Quality, University of Birmingham.(Funding: EA NGWCLC).
Report	**Eunice Lord. ADAS, MAFF funded. Nitrate flux in 2 catchments (1 being the Great Ouse). Circa 1993-96.**
Report	Ferrier, R. C et al Hydrological and hydrochemical fluxes through vegetation and soil in Allt a'Mharcaidh, Cairngorms, Scotland:their effect on streamwater quality. Jour of Hydrology (1990) Vol.116, No1-4
Journal	**Finch, J.W. 2001 Estimating change in direct groundwater recharge using a spatially distributed soil water balance model.Quart. J. of Eng. Geology and Hydrogeology, 34, p71-83.**
Report	Flood Studies Report, 1993, IOH, originally published by NERC, 1975, 5 volumes. (Designed to improve techniques of flood protection).
Journal	Ford, M. & Tellam, J. H., 1994 Source type and distribution of inorganic contamination within the Birmingham aquifer system, UK Journal of Hydrology, 156, 101-133.
Report	Foster, S. D., 1968, Report on hydrology & resources of Hydrometric Area 26 (Hull River): Part 1 Jurassic rocks of Market Weighton & Humber. Inst. Geol. Sciences. Internal Rep. No WD/68/4, 22 pp.
Unpublished	Fretwell, B., 1999, Distribution of contaminants in seasonally unsaturated zone of the Chalk aquifer, University College London. (Potential significance of unsaturated zone controlling stream baseflow quality).
Models	FRIEND, Programme in European Collaboration on how to use data in representation of catchments (may tie in with LOCAR).
Database	GBASE - Geochemical Baseline Survey of the Environment. Includes stream sediments & waters. 1 sample / 1km ^{2} for sediments.
Database	GBASE (Completed for: Scotland, Wales, N. England, Humberside, Walsy in east and Central England. NERC funded).
Report	Geochemical Survey of Stream Sediments, BGS Keyworth.
Report	Gray, D. A., Allender, R., et al, 1969, Groundwater Hydrology of Yorkshire Ouse River Basin (Hydrometric Area 27). Water Supply Papers, Hydrogeol. Report No 4, Inst.Geol. Sciences, London 40 pp.
Existing Project	Green, A., (Ongoing) Determination of groundwater and nutrient fluxes to a coastal zone, Second year PhD, University of East Anglia.
Existing Project	Greswell, R., 1992, The modelling of Groundwater Rise in the Birmingham Area. Unpublished MSc Thesis, School of Earth Sciences, University of Birmingham.
Existing Project	Groundwater / Surface Water Interaction Studies, £1 million into the instrumentation for this. Went live in Dec 2000.
Report	Groundwater Year Books, 1967 - 1981. Only water levels, includes rainfall evaporation and soil moisture deficit. (Replaced now by Hydrological Data UK).
Report	Gustard, A., Bullock, A., and Dixon, J.M., 1992. Estimating Low River Flows in the United Kingdom. Institute of Hydrology Report number 108. (Low Flow 2000 software updates the processes).
Report	Gustard A., Marshall D. C. W. and Sutcliffe M. F., Low flow estimation in Scotland. IH Report 101, Wallingford.
Legal	Habitats Directive. Cotswold Water park and floodplains. Looking at interactions of floodplain/groundwater/surface water.
Database	Harmonised Monitoring Network (Set up late 1970's. Up to 25 years data. Held by IOH until 1996, then transferred to the EA, Bristol).
Database	Harmonised Monitoring Network (tied to the National Water Quality Database, held by the EA). 200 tidal limit stations & up to 80 determinands. To assess fluxes to the North and Irish Seas.
Database	Harper, D.M. et al A catchment-scale approach to the physical restoration of lowland UK rivers. Aquatic Conservation: Marine and Freshwater Ecosystems. 1999. vol. 9, no. 1, pp. 141-157.
Report	Harvey, J. W., Bencala, K. E., 1992, Stream / subsurface transport interactions; groundwater model interpretation of lumped parameters for solute storage, Eos, Transactions, American Geophysical Union.
Journal	**Haycock, N.E. Burt, T.P., The role of floodplain sediments in reducing the nitrate concentration of subsurface runoff: a case study in the Cotswolds, UK. Hydrological Processes 7, 287-295.**
Report	Heathwaite, A. L.; Dils, R. M. Characterising phosphorus loss in surface and subsurface hydrological pathways. Science of the Total Environment, 5 May, 2000. Vol. 251-252, pp. 523-538.
Existing Project	Henstock, J., 2000, Determine whether inorganic groundwater quality can be identified impacting overall surface water quality of River Tame. Unpublished MSc, School of Earth Sci, Uni. of Birmingham.
Existing Project	Herne, D., Groundwater Flux to the Swan River, Australia. PhD, CSIRO.
Future	High Recharge Events, need to study catchment response., possible wash out nutrients.
Report	Hill, J M (1984). Nitrates in surface waters: observations from some rivers in the Lee drainage basin. WRc Technical Report TR 203 April 1984.40 pp.
Report	Hill, T; Neal, C. Spatial and temporal variation in pH, alkalinity and conductivity in surface runoff and groundwater for the Upper River Severn catchment. Hydrology and Earth System Sciences, 1, 3. Sep 1997.
Report	Hiscock, K. M. et al. Hydrochemical and stable isotope evidence for the extent and nature of the effective Chalk Aquifer of North Norfolk, UK. Journal of Hydrology, 180, 1-4. May 1996.
Journal	Holmes, N.T.H. Recovery of headwater stream flora following the 1989-1992 groundwater drought. Hydrological Processes, 1999. vol. 13, no. 3, pp. 341-354. Special Issue: Groundwater dominated rivers.
Report	Hooda, P. S. et al Soil and land use effects on phosphorus in six streams draining small agricultural catchments in Scotland.Soil Use and Management, 1997 Vol. 13, No. 4, pp. 196-204.
Report	Hornung, M. et al Water quality changes from input to stream. Acid waters in Wales, 1990. pp. 223-240. In Monographiae Biologicae, No.66 Kluwer Academic Publishers. Dordrecht.
Report	Hughes, J. [EDITOR]; Heathwaite, L. [EDITOR]. Hydrology and hydrochemistry of British wetlands 1995. pp. xi + 486. John Wiley & Sons. Chichester. ISBN: 0-471-95759-3.
Database	**HYDAT. Groundwater Level Data. Held regionally in consistent manner. EA sends data for strategic boreholes to the BGS. (approximately 170 boreholes).**
Report	**Hydrochemical Process Group, Colin Neal & Richard Williams. Studied groundwater age and ground/surface interaction. (Fits with LOCAR well)**
Existing Project	Hydrogeology and Hydrogeochemistry of the Lower Greensand, PhD, University of Reading, PRIS (EA sponsor)
Report	**Hydrometric Register and Statistics, 1986-1990, Hydrological Data UK, NERC publication, replaces Surface and Ground water yearbooks.**
Report	**Hydrometric Register and Statistics, 1991-1995. Hydrological Data UK series, IOH and BGS, published 1998. ISBN 0 948540 84 2. Comprehensive archive. Includes a base flow register.**
Proceedings	IAH, 1998, Physical, Chemical and Biological aspects of aquifer - stream relations. Las Vegas Volume.
Report	**IGARF, Impact of Groundwater Abstraction on River Flows (EA NGWCLC funded).**
Existing Project	IGARF-II Project, (EA NGWCLC funded).
Models	IHACRES, modelling package developed by the Inst. of Hydrology
Journal	Ineson, J. and Downing, R.A. (1964). The groundwater component of river discharge and its relationship to hydrogeology. J. Inst. Water Eng. 18, 519-541.
Report	**Ineson, J., 1967, Groundwater conditions in the Coal Measures of the South Wales Coalfiled. Water Supply Papers, Hydrogeological Report No. 3, Geol Surv. Gt Britain, London 69 pp.**
Report	Institute of Hydrology, 1980, Low River Flows, Report No. 1 Research Report. (Baseflow Index Procedure).
Journal	Jackson, D. & Lloyd, J. W., 1983, Groundwater chemistry of the Birmingham Triassic Sandstone aquifer and its relation to structure. Quarterly Journal of Engineering Geology London, 16, 135-142.
Proceedings	Jones, C. and Pearce, J. 'The use of an Integrated Catchment Model in Low Flow Rivers in South East Hampshire', CIWEM Regional Groundwater Resources Modelling Symposium Reading, 199!
Proceedings	Jones, C. 'The Spey River Gravel Abstraction Scheme', presentation to ICE Scottish Hydrological Group, Perth, October 1995
Report	**Jones, J. B. and Mulholland P. J., 2000, Streams and Groundwater. Academic Press. pp. 425.**
Journal	Jorgensen, D. G., et al, 1989, Accounting for intracell flows in models with emphasis on water table recharge & stream-aquifer interaction 1. Problems & Concepts. WRR, 25, 669-676.
Report	Kendrick M A P, Clark L, Baxter K M, Fleet M, James H A, Gibson T M and Turrell M B (1985). Trace organics in British aquifers - a baseline survey. WRc TR 223. Nov 1985. WRc plc. 50 pp.
Journal	Koyabashi, M., 1983, QuanTity and quality of seepage groundwater into Lake Biwa observed by direct measurement. Hydrology (Japan), 13, 51-59.
Journal	Leeks, G.J.L.; Walling, D.E. River basin sediment dynamics and interactions within the UK Land-Ocean Interaction Study: the context. Hydrological Processes, 1999. vol. 13, no. 7, pp.931-934.
Per. Comm	Lees, M. 2001. Pers. Comm. 16.01.01, with Martin Lees, Project Manager, Hydrological Data, CEH.
Existing Project	Littlewood N, An investigation of the hydrogeology of the Malmesbury catchment of Wiltshire, with special reference to the Inferior Oolite, MSc, University of Reading PRIS.
Report	Littlewood, E. G., 1992, Estimating contaminant loads in rivers: a review. IOH, Wallingford.
Journal	Lloyd, J. W., Harker, D. & Baxendale, R. A. 1981. Recharge Mechanisms and Groundwater Flow in the Chalk and Drift Deposits of Southern East Anglia. Q. J. Eng. Geol. 14, 87-96.
Existing Project	LOCAR (Lowland Catchment Research). NERC Thematic Programme. To look at 3 catchments: Tern(Permo-Trias) / Pang-Lambourne(Chalk) / Frome - Piddle(Chalk).
Database	LOIS Programme. Focused on the Humber / Ouse. Extensive database. Possibly not including groundwater.
Report	**Low Flow Studies, 1980, IOH. Conclusion of a 5 year study for ungauged catchments. Includes methodology for Baseflow derivation.**
Database	Low Flows 2000 (successor to Micro Low Flow 2.1)

Status	*Reference*
Report	**Mainstone, C., Turrell, J., Clark, L., Libero, A., Parr, W. and Morgan, N., 1997, Integrated appraisal of water quality and pollution loads in the Po Basin. Report to the Po River Authority.**
Journal	Mather and Smith, 1973, Thermonuclear Tritium: Its use as a tracer in local hydrogeological investigations, J. Inst. W. Eng, Vol 127, 187 - 196.
Journal	Mau, D. P. and Winter, T. C., 1993, Estimating groundwater recharge from streamflow hydrographs for a small mountain watershed, New Hampshire, USA, Groundwater, 35, 291-304.
Report	McMahon, P. B., Bolke, J. K., 1995, Effect of groundwater / surface water interactions on nitrate concentrations in discharge from the South Platte River alluvial aquifer, Colorado. USGS.
Future	Measuring Devices for Seepage Measurements.
Journal	Meyboom, P., 1961, Estimating groundwater recharge from stream hydrographs. Journal of Geophysical Research, 676, 1203-1214.
Database	Micro Low Flow 2.1
Report	Monkhouse, R. A. & Richards, H. J., 1982. Groundwater Resources of the United Kingdom. Environment and Consumer Protection Service, EEC, Brussels, 252 pp.
Report	Monkhouse, R. A., 1974, An assessment of the groundwater resources of the Lower Greensand in the Cambridge-Bedford Region. Water Resources Board, Reading, 37 pp.
Report	Monkhouse, R. A., 1983, Vulnerability of aquifers and groundwater quality in the United Kingdom. Final report for Director of the Environment & Consumer Protection, EEC.
Proceedings	Morris, B. L., *Providing the Tools: The British Experience in Groundwater Protection Zoning* . The Second Latin American Groundwater Congress.
Existing Project	Mott McDonald (For the EA), Preliminary study / conceptual model, on the relationship between groundwater and surface water within the Woburn Sands.
Report	Muller, Francois L. L.; Balls, Philip W.; Tanter, Martyn Annual geochemical mass balances in waters of the Firth of Clyde.Oceanologica Acta, 1995. Vol. 18, No. 5, pp. 511-521. ISSN: 0399-1784.
Report	Muscutt, A.D et al. Buffer zones to improve water quality: a review of their potential use in UK agriculture. Agriculture, Ecosystems & Environment, (1993) Vol. 45, No. 1-2, pp. 59-77. 78 ref. ISSN: 0167-8809.
Database	***National Groundwater Level Archive (NGLA)***
Existing Project	National Groundwater Survey, 'comprehensive description of major British Aquifers including physical & chemical properties & processes. (Duration: Ongoing). Funding BGS.
Database	***National River Flow Archive (NRFA) (1300 gauging stations, 35000 station years) 95% of gauging stations measured by EA, sent here for archiving.***
Database	National Water Archive, CEH. Designated data centre for NERC to hold the NRFA and NGLA. Limited Quality databases for experimental catchments.
Database	***National Well Record Archive on 'Well Master Database' (national boreholes at certain points). It uses and links varied datasets, including HYDAT and WIMS 2.***
Report	Neal, C et al. The water quality of the River Kennet: Initial observations on a lowland chalk stream impacted by sewage inputs and phosphorus remediation. Science of Total Environment, May 2000 Vol. 251-252
Report	Neal, C et al; The water quality of a tributary of the Thames, the Pang, southern England. Science of the Total Environment, 5 May, 2000. Vol. 251-252
Existing Project	NICHE Programme (JIF- Funded), 'groundwater - surface water interaction experimental facility' in the Eden Catchment (Cumbria).
Journal	**Nield, S. P., Townley, L. R., & Barr, A. D., 1994, A framework for quantitative analysis of surface water-groundwater interaction: Flow geometry in a vertical section. WRR, 30 (8), 2461-2475.**
Report	NRA, March 1993, Low Flows and Water Resources. Facts on the top 40 low flow rivers in England and Wales.
Report	Oakes, D. B. and Pontin, J., 1976, Mathematical modelling of a Chalk Aquifer. WRc, Technical Report TR24.
Report	Oakes, D., 1998, Prediction of pesticide pollution in the environment (POPPIE) - the PESTCAT and PESTAQ models. WRc CO 4502.
Report	**Oakes, D., 1999, Water resources and quality model of the river Po, Italy. WRc Report to the Po River Authority.**
Report	***Oakes, D., Cima, J., Woodrow, D. and Hollis, J., 1995 Development of a computer system for prediction of pollution in the environment (POPPIE) -Technical design scoping study. WRc CO 4005.***
Report	Oakes, D., Fielding, M. and Hegarty, B., 1998, QuanTifying point source inputs of pesticides to river catchments. Development of a decision tree. EA R&D Report P109.
Report	Oakes, D.B. & Wilkinson, W.B., 1972, Modelling groundwater & surface water systems. Theoretical relationships between groundwater abstraction & baseflow. Water Res. Board, Pub. 16.
Report	***Oakes, D.B. and Keay, D., 1990, A resource model of the Great Ouse river system. CO 2504-M.***
Journal	Oakes, D.B., Young, C.P. and Foster, S.D.D.,1981, The Effects of Farming Practices on Groundwater Quality in the United Kingdom. Sci Total Envir, 21, 17-30.
Existing Project	Pang-Lambourne, overview paper will be out next year. CEH and BGS collaboration.
Journal	Parissopoulos, G. A, and Wheater, H. S., 1992, Effects of hysteresis on groundwater recharge from ephemeral flows, Water Resources Research, 28, 11, 3055-3061.
Report	Parr, W. and Turrell, J.,1996, Procedure for estimating pollutant loads to surface and groundwaters in the Po Basin, Italy. WRc report to the Po River Authority.
Proceedings	Peter Ripon, P. and Wyness, A. 'Water Resources Management using Integrated Catchment Models.' Presented at the IWEM Conference on Groundwater - Managing a Scarce Resource: Gatwick 1994
Journal	Petts, G.E.; Bickerton, M.A.; Crawford, C.; Lerner, D.N.; Evans, D. Flow management to sustain groundwater-dominated stream ecosystems. Hydrological Processes, 1999. vol. 13, no. 3, pp.497-513.
Report	Plater, A.J et al. Historical Contaminant Fluxes in the Tees Estuary, UK: Geochemical, Magnetic and Radionuclide Evidence. Marine Pollution Bulletin,1998. vol. 37, no.3-7, pp. 343-360.
Report	Price, M., Fluid Flow in the Chalk of England. From Goff, J. C. & Williams, B. P. J. (eds), 1987, Fluid Flow in Sedimentary Basins and Aquifers, Geol. Soc. Special Pub No. 34, pp. 141–156.
Report	Reeves, M. J., Birtles, A. B., et al, 1974, Groundwater Resources of the Vale of York. Water Resources Board, Reading, 90 pp.
Journal	Reeves, M. J., Parry, E. L. and Richardson, G., 178, Preliminary evaluation of the groundwater resources of the Vale of Pickering. Quart. Jour. Eng. Geol., 11, 253-262.
Report	Richards, H. J., 1957, Outline of the groundwater resources of the Old Red Sandstone of part of South Wales and the Welsh Borders. Geol. Surv. Gt. Britain, Internal Report No. WD/57/7, 22 pp.
Proceedings	Rippon, P. 'Integrated Surface Water and Groundwater Modelling.' Presented at the 1999 International Association of Hydrogeologists (Irish Group) Seminar in Portlaoise
Proceedings	Rippon, P., Wyness, A., and Wardlaw, R. 'Application of an integrated model to Chalk catchments.' Presented at the International Conference on Groundwater - Drought, Pollution & Management: Brighton 1994
Proceedings	Roberts, S C.; McArthur, J M. Surface-groundwater interactions in a UK limestone aquifer. Proceedings of the Joint Meeting of the Congress of the International Association of Hydrologists and the
Existing Project	Roberts, S., 2000, Hydrochemistry of the Lincolnshire Limestone aquifer. (Addressed flux of DOC from surface run-off direct via shallow holes to the aquifer). Paper in recent IAH Conference, Cape Town.
Report	Robins, N. S., 2000. The Water Resources of Jersey: an overview. Report British Geological Survey, Wallingford (WD 00 28). Specialist assistance from Young, C. P., WRc Medmenham.
Journal	**Rushton, K., and Ward, 1979, Estimation of groundwater recharge. Journal of Hydrology, 41, 345-361.**
Existing Project	Rushton, K., 'groundwater-surface (stream) water flux'- title to be checked. Papers presented at Geol. Soc. Geoscience meeting on sustainability in April 2000. Drafts for upcoming special publication.
Journal	Sage, R. C. and Lloyd, J. W., 1978, Drift deposit influences on the Triassic sandstone aquifer of North-West Lancashire as inferred by hydrochemistry. Quart. Jour, Eng. Geol., 11, 209-218.
Journal	Scahfran, G. C., and Driscoll, C. T., 1993, Flow path-comparison relationship for groundwater entering an acid lake. Water Resources Research, 29, 1454-154.
Unpublished	Schurch, Mark. Bere Regis study of NO_3 flux in groundwater - surface water. Swiss funded Post Doctorate.(Follows work on the Rhone. Hydrogeology Journal Vol. 5, 5 October 2000).
Report	Sear, D.A.; Armitage, P.D.; Dawson, F.H. Groundwater dominated rivers. Hydrological Processes 1999. vol. 13, no. 3, pp.255-276. Special Issue: Groundwater dominated rivers.
Report	SEPA, 1998, An Overview of Scottish Groundwater.
Report	Severn River Authority (1974) Shropshire Groundwater Investigation Second Report. January 1974. The Authority36 pp, 5 Appendices.
Report	Severn Trent Water Authority (1977) Water Quality 1976/77. The Authority, Birmingham B46 3AU.566 pp.
Proceedings	Seymour, K. J.; Wyness, A. J.; Rushton, K.; 1998. The Fylde Aquifer - a case study in assessing the sustainable use of groundwater resources. Hydrology in a changing environment.
Unpublished	Sherratt, D. J., 1985, Regional soil moisture modelling, PhD, Imperial College.
Proceedings	Singleton, A., 'Groundwater Management of the River Dour Catchment', Seventh National Hydrology Symposium of the BHS at Newcastle upon Tyne, September 2000
Journal	Soulsby, C. et al. Impact of groundwater development on Atlantic Salmon spawning habitat in a Scottish river. Hydrology in a Changing Environment Volume I. 1998. pp. 269-280. John Wiley & Sons, Ltd.
Report	Southern Water Global (Inc. John Lloyd, David Ball, Paul Johnston), 'The South Galway Flood Study', involving surface and groundwater interaction, for the OPW.
Report	Southern Water, 1985, Report on the Thanet nitrate investigation, Worthing.
Journal	Stewart, M. D., Bates P. D., Anderson M. G., Price D. A. and Burt T. P., 1999, Modelling floods in hydrologically complex lowland river reaches. Journal of Hydrology 223, 85-106.
Existing Project	Strategic Study Report on groundwater research issues in the UK, GWF Ref: FR/GF1.(Survey on South Downs Chalk already published, Dec 1999).
Report	Strobel, M. L., 1995, Assessment of information on groundwater / surface water interactions in the northern Midcontinent. USGS.
Report	STWA, 1977, The Shropshire Groundwater Scheme. Birmingham.
Report	Surface Water Year Books, to 1987 (Replaced now by Hydrological Data UK).
Existing Project	TOPMODEL, surface / subsurface interactions on hillslopes and modelling of contributing areas. Lancaster University.
Report	UNESCO (1980) Studies and reports in hydrology 28. Casebook of methods of computation of quantitative changes in the hydrological regime of river basins due to human activities
Report	University of Bradford, 1997, Impact of cities on the quality and quantity of their underlying groundwater.
Proceedings	US EPA (2000). Proceedings of the Ground-water/surface-water Interactions workshop. EPA/542/R-00/007. July 2000.
Report	US EPA Office of Water (1998): Biological Indicators of Ground Water - Surface Water Interaction: Update. EPA 816-R-98-018. September 1998.
Report	US EPA Office of Water: Nonpoint Source News-Notes Issue #9 NOTES ON GROUND-WATER/SURFACE-WATER INTERACTION MANAGEMENT
Proceedings	van Wonderen, J. & Wyness, J. 'Modelling Recharge Through Drift Around Thetford', Seminar on Recharge Through Drift, Hydrogeological Group at the Geological Society, London, February 1995
Proceedings	van Wonderen, J. & Wyness, J. The validity of Methods Used for Modelling River-Aquifer Interactions', Meeting at the British Hydrological Society/Geological Society Hydrogeological Group, London, March 1995.
Proceedings	van Wonderen, J., Watt, G.D., Mellanby, J.F., Burley, M.J. 'Groundwater Investigations in the Lower Spey Valley near Fochabers', AGM of Institution of Water Engineers & Scientists, Perth, 1986.
Proceedings	Verstraeten, I. M., et al., 2000, Use of geochemical & isotopic tracers to evaluate groundwater / surface water interactions. Proceedings of The Nebraska Acad. Sciences & Affiliated Societies.
Proceedings	Volume II. Proceedings of the British Hydrological Society International Conference, Exeter, UK, July 1998,pp. 253-267.
Legal	Water Act, 1963. Set up the basis for Hydrometric networks, this put in place the basis for flow monitoring.
Database	Water Level Database.
Report	Water Resources Board, 1966, Water Supplies in South East England.
Report	Water Resources Board, 1970, Water Resources in the North.
Report	Water Resources Board, 1971, Water Resources in Wales and the Midlands.
Report	Water Resources Board, 1972, The Hydrogeology of the London Basin.
Report	Water Resources Board, 1972, The Trent Research Programme.
Report	Water Resources Board, 1973, Groundwater resources of the Vale of Clwyd. Reading.
Report	Water Resources Board, 1974 Combined use of surface and groundwater in the Ely, Ouse and Nar catchments by C. Wright
Report	Water Resources Board, Groundwater Resources of the Vale of Clwyde.
Report	Water Resources Board, The Groundwater Hydrogeology of the Lincolnshire Limestone.
Report	WD/9757-58, parts 1-8 of the Natural Baseline Quality of Aquifers in England and Wales.
Report	White, C.C. Smart, R., Cresser, M.S. Spatial and temporal variations in critical loads for rivers in NE Scotland: A validation of approaches. Water Research 34(6):1912-1918. 2000 Apr.
Model	Whitehead, P. G. Modelling nitrate from agriculture into public water supplies. Biological Sciences, (1990) Vol. 329, No. 1255, pp. 403-410.
Report	Williams, A. T., A Method for the Prediction of the Impact of Groundwater Abstractions on East Anglian Wetlands, WT/95/5R.
Database	**WIMS 2. EA quality monitoring data. (8 regional databases held at EA Twerton).**
Journal	**Winter, T. C, 1999, Relation of streams, lakes and wetlands to groundwater flow systems. Hydrogeology Journal, 7, 28-45.**
Report	**Winter, T. C., Judson, W., Frankie, O. L., Alley, W. M., 1998, Groundwater and surface water a single resource. United States Geological Survey, Circular 1139, Denver, Colorado.**
Journal	Wood, P.J.; et al Instream mesohabitat biodiversity in three groundwater streams under base-flow conditions. Aquatic Conservation: Marine and Freshwater Ecosystems, 1999. vol. 9, no. 3, pp. 265-278
Report	Wood, P.J.; Petts, G.E. The influence of drought on chalk stream macroinvertebrates. Hydrological Processes. 1990. vol. 13, no. 3, pp.387-399. Special Issue: Groundwater dominated rivers.
Unpublished	Yorkshire Water Services Ltd, Low Flow / Groundwater / Wetlands interaction. (Sponsor UKWIR).
Existing Project	Younger P., Impact of Groundwater Abstractions on River Flow. For the EA NGWCLC.
Unpublished	**Younger, P., 1990, Stream-Aquifer Systems of the Thames Basin: Hydrogeology, Geochemistry and Modelling. PhD Thesis, University of Newcastle.**
Existing Project	Younger, P., and Parkin, P., Unpublished work for NIREX on natural groundwater discharge to streams in West Cumbria.

References which are a major source of UK data or databases

98 **Key papers**

Groundwater Quality
Groundwater Quantity
Surface Water Quality
Surface Water Quantity
Surface and Groundwater Interaction - Quality
Surface and Groundwater Interaction - Quantity
Surface and Groundwater Interaction - Quantity and Quality
Future Research Requirements: Quality
Future Research Requirements: Quantity

Abbreviations:

BGS	British Geological Survey
CEC	Commission of the European Communities
CEH	Centre for Ecology and Hydrology
CWPU	Central Water Planning Unit
EA	Environment Agency
GWF	Ground Water Forum
IAH	International Association Hydrologists
IOH	Institute of Hydrology
NERC	Natural Environment Research Council
NGWCLC	National Groundwater and Contaminated Land Centre, Environment Agency
SEPA	Scottish Environmental Protection Agency
STWA	Severn Trent Water Authority
UKWIR	UK Water Industry Research Limited
WRc	Water Resources Centre
WRR	Water Resources Research

APPENDIX C.2 REFERENCES BY CATEGORY

Category	*Status*	*Reference*
Groundwater Quality		
GWQual	Database	BGS, Aquifer Properties Manual, 1997, to collect, collate, review aquifer physical property data for England & Wales. Comprehensive digital database. Complete 1998. Funded: BGS / NRA.
GWQual	Database	BGS, Physical Properties of Minor Aquifers of England & Wales, 1999, to update national aquifer properties database established for Aquifer Properties Manual (1997). Funded: BGS / EA.
GWQual	**Database**	**HYDAT. Groundwater Level Data. Held regionally in consistent manner. EA sends data for strategic boreholes to the BGS. (approximately 170 boreholes).**
GWQual	**Database**	***National Groundwater Level Archive (NGLA)***
GWQual	**Database**	***National Well Record Archive on 'Well Master Database' (national boreholes at certain points). It uses and links varied datasets, including HYDAT and WIMS 2.***
GWQual	Database	Water Level Database.
GWQual	Existing Project	Assessing Contaminant Transport in the Permo-Triassic Sandstone (Duration: Ongoing). Funding: ICI
GWQual	Existing Project	Baseline Geochemistry - UK Groundwaters, Synthesis of regional groundwater quality from selected aquifers in England & Wales to characterise baseline chemistry to benchmark future pollution risk.(EA/BGS)
GWQual	Journal	Birtles, A. B., 1978, Identification and separation of major baseflow components from stream hydrographs, WRR 14, pp 791-803.
GWQual	Journal	Downing, R. A.& Wilkinson, W. B., 1993, Applied Groundwater Hydrology. Groundwater Resources, Development & Management in the UK: Historical Perspective. Quart. Jour. Eng.Geol. 26.4 pp 335-358.
GWQual	Journal	Downing, R. A., 1993, Groundwater Resources, their Development and Management in the UK: AN Historical Perspective. Quart. Jour. Eng. Geol. 26.4 P 335-358.
GWQual	Journal	Ede, D. P., 1975, Limestone Drainage Systems, J. Hydrology. Vol. 27. pp. 297-318
GWQual	Journal	Lloyd, J. W., Harker, D. & Baxendale, R. A. 1981. Recharge Mechanisms and Groundwater Flow in the Chalk and Drift Deposits of Southern East Anglia. Q. J. Eng. Geol. 14, 87-96.
GWQual	Journal	Mather and Smith, 1973, Thermonuclear Tritium: Its use as a tracer in local hydrogeological investigations, J. Inst. W. Eng, Vol 127, 187 - 196.
GWQual	Journal	Parissopoulos, G. A, and Wheater, H. S., 1992, Effects of hysteresis on groundwater recharge from ephemeral flows, Water Resources Research, 28, 11, 3055-3061.
GWQual	Journal	Reeves, M. J., Parry, E. L. and Richardson, G., 178, Preliminary evaluation of the groundwater resources of the Vale of Pickering. Quart. Jour. Eng. Geol., 11, 253-262.
GWQual	**Journal**	**Rushton, K., and Ward, 1979, Estimation of groundwater recharge. Journal of Hydrology, 41, 345-361.**
GWQual	Models	FRIEND, Programme in European Collaboration on how to use data in representation of catchments (may tie in with LOCAR).
GWQual	Models	IHACRES, modelling package developed by the Inst. of Hydrology
GWQual	**Proceedings**	**Beven, K. J., 1991, Hydrograph separation. Proc. BHS Third National Hydrology Symposium, Institute of Hydrology, Wallingford, 3.1-3.8.**
GWQual	Proceedings	Morris, B. L., *Providing the Tools: The British Experience in Groundwater Protection Zoning*. The Second Latin American Groundwater Congress.
GWQual	Proceedings	Singleton, A., 'Groundwater Management of the River Dour Catchment', Seventh National Hydrology Symposium of the BHS at Newcastle upon Tyne, September 2000
GWQual	Report	Allen, D. J., The Physical Properties of Major Aquifers in England and Wales, WD/97/34.
GWQual	Report	BGS, 1999, Study of the South Downs Chalk, aquifer description and resources. (Part of the ongoing BGS National Groundwater Survey).
GWQual	**Report**	**CEC, 1982, Balance of groundwater resources of the UK.**
GWQual	Report	CEC, 1982, Groundwater resources of the European Community synthetical report. Brussels and Luxembourg.
GWQual	Report	Digest of Environmental Statistics, No.20, 1998, Government Statistical Services, DETR. (No. 22 out soon).
GWQual	Report	Downing, R. A. & Williams, B. P. J., 1969, The Groundwater Hydrology of the Lincolnshire Limestone. Publ. Water Res. Board, Reading 160 pp. (from Edmunds).
GWQual	**Report**	**Downing, R. A. and Skinner, A. C., 1988, Groundwater in the UK. BGS Report WD/88/1, Wallingford.**
GWQual	Report	Downing, R. A., Land, D. H., Allender, R., et al, 1970, The Hydrogeology of the Trent River Basin. Water Supply Papers, Hydrogeological Report No 5, Inst.of Geological Sciences, London, 101 pp.
GWQual	Report	Foster, S. D., 1968, Report on hydrology & resources of Hydrometric Area 26 (Hull River): Part 1 Jurassic rocks of Market Weighton & Humber. Inst. Geol. Sciences. Internal Rep. No WD/68/4, 22 pp.
GWQual	Report	Gray, D. A., Allender, R., et al, 1969, Groundwater Hydrology of Yorkshire Ouse River Basin (Hydrometric Area 27). Water Supply Papers, Hydrogeol. Report No 4, Inst.Geol. Sciences, London 40 pp.
GWQual	Report	Groundwater Year Books, 1967 - 1981. Only water levels, includes rainfall evaporation and soil moisture deficit. (Replaced now by Hydrological Data UK).
GWQual	Report	Gustard A., Marshall D. C. W. and Sutcliffe M. F., Low flow estimation in Scotland. IH Report 101, Wallingford.
GWQual	Report	Hiscock, K. M. et al. Hydrochemical and stable isotope evidence for the extent and nature of the effective Chalk Aquifer of North Norfolk, UK. Journal of Hydrology, 180, 1-4. May 1[illegible]
GWQual	**Report**	**Ineson, J., 1967, Groundwater conditions in the Coal Measures of the South Wales Coalfiled. Water Supply Papers, Hydrogeological Report No. 3, Geol Surv. Gt Britain, London 69 pp.**
GWQual	Report	Monkhouse, R. A. & Richards, H. J., 1982. Groundwater Resources of the United Kingdom. Environment and Consumer Protection Service, EEC, Brussels, 252 pp.
GWQual	Report	Monkhouse, R. A., 1974, An assessment of the groundwater resources of the Lower Greensand in the Cambridge-Bedford Region. Water Resources Board, Reading, 37 pp.
GWQual	Report	Oakes, D. B. and Pontin, J., 1976, Mathematical modelling of a Chalk Aquifer. WRc, Technical Report TR24.
GWQual	Report	Oakes, D.B. & Wilkinson, W.B., 1972, Modelling groundwater & surface water systems. Theoretical relationships between groundwater abstraction & baseflow. Water Res. Board, Pub. 16.
GWQual	Report	Price, M., Fluid Flow in the Chalk of England. From Goff, J. C. & Williams, B. P. J. (eds), 1987, Fluid Flow in Sedimentary Basins and Aquifers, Geol. Soc. Special Pub No. 34, pp. 141–156.
GWQual	Report	Reeves, M. J., Birtles, A. B., et al, 1974, Groundwater Resources of the Vale of York. Water Resources Board, Reading, 90 pp.
GWQual	Report	Richards, H. J., 1957, Outline of the groundwater resources of the Old Red Sandstone of part of South Wales and the Welsh Borders. Geol. Surv. Gt. Britain, Internal Report No. WD/57/7, 22 pp.
GWQual	Report	Robins, N. S., 2000. The Water Resources of Jersey: an overview. Report British Geological Survey, Wallingford (WD 00 28). Specialist assistance from Young, C. P., WRc Medmenham.
GWQual	Report	SEPA, 1998, An Overview of Scottish Groundwater.
GWQual	Report	Southern Water, 1985, Report on the Thanet nitrate investigation, Worthing.
GWQual	Report	STWA, 1977, The Shropshire Groundwater Scheme. Birmingham.
GWQual	Report	Water Resources Board, 1966, Water Supplies in South East England.
GWQual	Report	Water Resources Board, 1970, Water Resources in the North.
GWQual	Report	Water Resources Board, 1971, Water Resources in Wales and the Midlands.
GWQual	Report	Water Resources Board, 1972, The Hydrogeology of the London Basin.
GWQual	Report	Water Resources Board, 1973, Groundwater resources of the Vale of Clwyd. Reading.
GWQual	Report	Water Resources Board, Groundwater Resources of the Vale of Clwyde.
GWQual	Report	Water Resources Board, The Groundwater Hydrogeology of the Lincolnshire Limestone.
Groundwater Quatity		
GWQuanT	Database	EA National Archive of NO_3 at NGWCLC, EA, in response to Nitrate Vulnerable Zones.
GWQuanT	Existing Project	Greswell, R., 1992, The modelling of Groundwater Rise in the Birmingham Area. Unpublished MSc Thesis, School of Earth Sciences, University of Birmingham.
GWQuanT	Existing Project	Herne, D., Groundwater Flux to the Swan River, Australia. PhD, CSIRO.
GWQuanT	Existing Project	Hydrogeology and Hydrogeochemistry of the Lower Greensand, PhD, University of Reading, PRIS (EA sponsor)
GWQuanT	Existing Project	Littlewood N, An investigation of the hydrogeology of the Malmesbury catchment of Wiltshire, with special reference to the Inferior Oolite, MSc, University of Reading PRIS.
GWQuanT	Existing Project	LOCAR (Lowland Catchment Research). NERC Thematic Programme. To look at 3 catchments: Tern(Permo-Trias) / Pang-Lambourne(Chalk) / Frome - Piddle(Chalk).
GWQuanT	Existing Project	National Groundwater Survey, 'comprehensive description of major British Aquifers including physical & chemical properties & processes. (Duration: Ongoing). Funding BGS.
GWQuanT	Existing Project	Pang-Lambourne, overview paper will be out next year. CEH and BGS collaboration.
GWQuanT	Existing Project	Strategic Study Report on groundwater research issues in the UK, GWF Ref: FR/GF1.(Survey on South Downs Chalk already published, Dec 1999).
GWQuanT	**Journal**	**Edmunds, W. M. & Walton, N. R. G., *The Lincolnshire Limestone – Hydrochemical Evolution Over a Ten-year Period*, Journal of Hydrology, 61 (1983) 201–211.**
GWQuanT	Journal	Ford, M. & Tellam, J. H., 1994 Source type and distribution of inorganic contamination within the Birmingham aquifer system, UK Journal of Hydrology, 156, 101-133.
GWQuanT	**Journal**	**Haycock, N.E. Burt, T.P., The role of floodplain sediments in reducing the nitrate concentration of subsurface runoff: a case study in the Cotswolds, UK. Hydrological Processes 7, 287-295.**
GWQuanT	Journal	Jackson, D. & Lloyd, J. W., 1983, Groundwater chemistry of the Birmingham Triassic Sandstone aquifer and its relation to structure. Quarterly Journal of Engineering Geology London, 16, 135-142.
GWQuanT	Journal	Oakes, D.B., Young, C.P. and Foster, S.D.D.,1981, The Effects of Farming Practices on Groundwater Quality in the United Kingdom. Sci Total Envir, 21, 17-30.
GWQuanT	Models	BGS, Groundwater Vulnerability Maps, vulnerability to contamination covering all England and Wales. (Completed: End 1998). Funded: EA.
GWQuanT	Report	BGS Hydrogeology Group, 1996-1998, Baseline Quality of Aquifers. (Sponsor EA NGWCLC).
GWQuanT	Report	BGS Hydrology Group, 1996, Groundwater Quality in the Yorkshire Chalk.
GWQuanT	Report	BGS, 1989, *Trace Element Occurrences in British Groundwaters*. Research Report SD/89/3. Hydrogeology Series.
GWQuanT	Report	BGS, Baseline Geochemical Surveys (Part EC, part EA, plus Science Budget).
GWQuanT	Report	BGS, Cryptosporidium Research on Groundwater, review of past work on movement through groundwater, identified where operational monitoring could be improved.
GWQuanT	Report	BGS, Cryptosporidium Research (Duration: Completed 31 March 2000. Funded: UKWIR).
GWQuanT	Report	Brewerton, L.J., *Baseline Geochemistry Database Documentation*, WD/97/65R.
GWQuanT	Report	Chilton, P. J., et al, Transport and Fate of Pesticides in the Unsaturated and Saturated Zones of the Chalk. WD/97/71.
GWQuanT	Report	CWPU, 1997, Nitrate and water resources with particular reference to groundwater, Reading.
GWQuanT	**Report**	**Edmunds, et al, 1987, *Baseflow Geochemical Conditions in the Chalk Aquifer, Berkshire, UK*. (a basis for groundwater quality management).**
GWQuanT	**Report**	**Edmunds, W.M. et al, A Guide to the Natural (Baseline) Quality Study. WD/97/51.**
GWQuanT	Report	Edmunds, W.M.; Kinniburgh, D.G.; Moss, P.D. Trace metals in interstitial waters from sandstones: acidic inputs to shallow groundwaters. Environmental Pollution, 1992. Vol. 77, No. 2&3, pp. 129-141.
GWQuanT	Report	Kendrick M A P, Clark L, Baxter K M, Fleet M, James H A, Gibson T M and Turrell M B (1985). Trace organics in British aquifers - a baseline survey. WRc TR 223. Nov 1985. WRc plc. 50 pp.
GWQuanT	Report	Monkhouse, R. A., 1983, Vulnerability of aquifers and groundwater quality in the United Kingdom. Final report for Director of the Environment & Consumer Protection, EEC.
GWQuanT	Report	Severn River Authority (1974) Shropshire Groundwater Investigation Second Report. January 1974. The Authority36 pp, 5 Appendices.
GWQuanT	Report	WD/9757-58, parts 1-8 of the Natural Baseline Quality of Aquifers in England and Wales.
GWQuanT	Unpublished	Schurch, Mark. Bere Regis study of NO_3 flux in groundwater - surface water. Swiss funded Post Doctorate.(Follows work on the Rhone. Hydrogeology Journal Vol. 5, 5 October 2000).
Surface water Quality		
SWQual	Database	GBASE - Geochemical Baseline Survey of the Environment. Includes stream sediments & waters. 1 sample / 1km^2 for sediments.
SWQual	Database	GBASE (Completed for: Scotland, Wales, N. England, Humberside, Walsy in east and Central England. NERC funded).
SWQual	Database	Harmonised Monitoring Network (Set up late 1970's. Up to 25 years data. Held by IOH until 1996, then transferred to the EA, Bristol).
SWQual	Database	Harmonised Monitoring Network (tied to the National Water Quality Database, held by the EA). 200 tidal limit stations & up to 80 determinands. To assess fluxes to the North and Irish Seas.
SWQual	Database	Harper, D.M. et al A catchment-scale approach to the physical restoration of lowland UK rivers. Aquatic Conservation: Marine and Freshwater Ecosystems. 1999. vol. 9, no. 1, pp. 141-157.
SWQual	Database	National Water Archive, CEH. Designated data centre for NERC to hold the NRFA and NGLA. Limited Quality databases for experimental catchments.
SWQual	**Database**	**WIMS 2. EA quality monitoring data. (8 regional databases held at EA Twerton).**
SWQual	Report	Department of Scientific and Industrial Research (1964). Effects of polluting discharges on the Thames Estuary. Water Pollution Research Technical Paper No. 11. HMSO, London.
SWQual	Report	Dils R.M. et al. The controversial role of tile drainage in phosphorus export from agricultural land. Water Science & Technology, 1999. pp. 55-61.
SWQual	Report	Eatherall, A.; Warwick, M. S.; Tolchard, S. Identifying sources of dissolved organic carbon on the River Swale, Yorkshire. Science of the Total Environment, May, 2000. Vol. 251-252,
SWQual	**Report**	**Eunice Lord. ADAS, MAFF funded. Nitrate flux in 2 catchments (1 being the Great Ouse). Circa 1993-96.**
SWQual	Report	Ferrier, R. C et al Hydrological and hydrochemical fluxes through vegetation and soil in Allt a'Mharcaidh, Cairngorms, Scotland:their effect on streamwater quality. Jour of Hydrology (1990) Vol.116, No1-4
SWQual	Report	Geochemical Survey of Stream Sediments, BGS Keyworth.
SWQual	Report	Heathwaite, A. L.; Dils, R. M. Characterising phosphorus loss in surface and subsurface hydrological pathways. Science of the Total Environment, 5 May, 2000. Vol. 251-252, pp. 523-538.
SWQual	Report	Hill, J M (1984). Nitrates in surface waters: observations from some rivers in the Lee drainage basin. WRc Technical Report TR 203 April 1984.40 pp.
SWQual	Report	Hooda, P. S. et al Soil and land use effects on phosphorus in six streams draining small agricultural catchments in Scotland.Soil Use and Management, 1997 Vol. 13, No. 4, pp. 196-204.
SWQual	Report	Hornung, M. et al Water quality changes from input to stream. Acid waters in Wales, 1990. pp. 223-240. In Monographiae Biologicae, No.66 Kluwer Academic Publishers. Dordrecht.
SWQual	Report	Hughes, J. [EDITOR]; Heathwaite, L. [EDITOR]. Hydrology and hydrochemistry of British wetlands 1995. pp. xi + 486. John Wiley & Sons. Chichester. ISBN: 0-471-95759-3.
SWQual	Report	Littlewood, E. G., 1992, Estimating contaminant loads in rivers: a review. IOH, Wallingford.
SWQual	Report	Muller, Francois L. L.; Balls, Philip W.; Tanter, Martyn Annual geochemical mass balances in waters of the Firth of Clyde.Oceanologica Acta, 1995. Vol. 18, No. 5, pp. 511-521. ISSN: 0399-1784.
SWQual	Report	Muscutt, A.D et al. Buffer zones to improve water quality: a review of their potential use in UK agriculture. Agriculture, Ecosystems & Environment, (1993) Vol. 45, No. 1-2, pp. 59-77. 78 ref. ISSN: 0167-8809.
SWQual	Report	Neal, C et al. The water quality of the River Kennet: Initial observations on a lowland chalk stream impacted by sewage inputs and phosphorus remediation. Science of Total Environment, May 2000 Vol. 251-252
SWQual	Report	Neal, C et al; The water quality of a tributary of the Thames, the Pang, southern England. Science of the Total Environment, 5 May, 2000. Vol. 251-252
SWQual	Report	Plater, A.J et al. Historical Contaminant Fluxes in the Tees Estuary, UK: Geochemical, Magnetic and Radionuclide Evidence. Marine Pollution Bulletin,1998. vol. 37, no.3-7, pp. 343-360.
SWQual	Report	Severn Trent Water Authority (1977) Water Quality 1976/77. The Authority, Birmingham B46 3AU.566 pp.
SWQual	Report	UNESCO (1980) Studies and reports in hydrology 28. Casebook of methods of computation of quantitative changes in the hydrological regime of river basins due to human activities
SWQual	Report	University of Bradford, 1997, Impact of cities on the quality and quantity of their underlying groundwater.
SWQual	Report	White, C.C. Smart, R., Cresser, M.S. Spatial and temporal variations in critical loads for rivers in NE Scotland: A validation of approaches. Water Research 34(6):1912-1918. 2000 Apr.
SWQual	Unpublished	Birmingham University, Heavy metal fluxes at EMI from stabilised waste dumps. (6 years ago?)
Surface water Quatity		
SWQuanT	Database	LOIS Programme. Focused on the Humber / Ouse. Extensive database. Possibly not including groundwater.
SWQuanT	Database	Low Flows 2000 (successor to Micro Low Flow 2.1)
SWQuanT	Database	Micro Low Flow 2.1
SWQuanT	**Database**	***National River Flow Archive (NRFA) (1300 gauging stations, 35000 station years) 95% of gauging stations measured by EA, sent here for archiving.***
SWQuanT	Journal	Burt, T. P, Haycock, N. E., 1996. Linking floodplains to rivers. In Anderson M. G., Walling D. E., and Bates P. (eds), Floodplain Processes, Wiley, 461-492.
SWQuanT	Journal	Stewart, M. D., Bates P. D., Anderson M. G., Price D. A. and Burt T. P., 1999, Modelling floods in hydrologically complex lowland river reaches. Journal of Hydrology 223, 85-106.
SWQuanT	Legal	Water Act, 1963. Set up the basis for Hydrometric networks, this put in place the basis for flow monitoring.
SWQuanT	Report	Cable, C.J., Fielding, M., Gibby, S., Hegarty, B.F., Moore, K., Oakes, D and Watts, C.D., 1993, Pesticides in drinking water sources and supplies, DoE 3376/1.
SWQuanT	Report	Flood Studies Report, 1993, IOH, originally published by NERC, 1975, 5 volumes. (Designed to improve techniques of flood protection).
SWQuanT	Report	Gustard, A., Bullock, A., and Dixon, J.M., 1992. Estimating Low River Flows in the United Kingdom. Institute of Hydrology Report number 108. (Low Flow 2000 software updates the processes).
SWQuanT	**Report**	**Hydrometric Register and Statistics, 1986-1990, Hydrological Data UK, NERC publication, replaces Surface and Ground water yearbooks.**
SWQuanT	**Report**	**Hydrometric Register and Statistics, 1991-1995. Hydrological Data UK series, IOH and BGS, published 1998. ISBN 0 948540 84 2. Comprehensive archive. Includes a base flow register.**
SWQuanT	**Report**	**Low Flow Studies, 1980, IOH. Conclusion of a 5 year study for ungauged catchments. Includes methodology for Baseflow derivation.**
SWQuanT	Report	NRA, March 1993, Low Flows and Water Resources. Facts on the top 40 low flow rivers in England and Wales.

APPENDIX C.2 REFERENCES BY CATEGORY

Category	*Status*	*Reference*
SWQuanT	Report	Oakes, D., Fielding, M. and Hegarty, B., 1998, QuanTifying point source inputs of pesticides to river catchments. Development of a decision tree. EA R&D Report P109.
SWQuanT	Report	Surface Water Year Books, to 1987 (Replaced now by Hydrological Data UK).
SWQuanT	Report	Water Resources Board, 1972, The Trent Research Programme.
SWQuanT	Report	Williams, A. T., A Method for the Prediction of the Impact of Groundwater Abstractions on East Anglian Wetlands, WT/95/5R.
SWQuanT	Unpublished	Sherratt, D. J., 1985, Regional soil moisture modelling, PhD, Imperial College.
Surface water and Groundwater Quality		
SWGWQual	**Journal**	**British Hydrological Society, March 1995, Modelling river - aquifer interactions, Occasional Paper No. 6. (Editor Paul Younger).**
SWGWQual	**Journal**	**Finch, J.W. 2001 Estimating change in direct groundwater recharge using a spatially distributed soil water balance model.Quart. J. of Eng. Geology and Hydrogeology, 34, p71-83.**
SWGWQual	Journal	Holmes, N.T.H. Recovery of headwater stream flora following the 1989-1992 groundwater drought. Hydrological Processes, 1999. vol. 13, no. 3, pp. 341-354. Special Issue: Groundwater dominated rivers.
SWGWQual	Journal	Ineson, J. and Downing, R.A. (1964). The groundwater component of river discharge and its relationship to hydrogeology. J. Inst. Water Eng. 18, 519-541.
SWGWQual	Journal	Jorgensen, D. G., et al, 1989, Accounting for intracell flows in models with emphasis on water table recharge & stream-aquifer interaction 1. Problems & Concepts. WRR, 25, 669-676.
SWGWQual	Journal	Leeks, G.J.L.; Walling, D.E. River basin sediment dynamics and interactions within the UK Land-Ocean Interaction Study: the context. Hydrological Processes, 1999. vol. 13, no. 7, pp.931-934.
SWGWQual	Journal	Mau, D. P. and Winter, T. C., 1993, Estimating groundwater recharge from streamflow hydrographs for a small mountain watershed, New Hampshire, USA, Groundwater, 35, 291-304.
SWGWQual	Journal	Meyboom, P., 1961, Estimating groundwater recharge from stream hydrographs. Journal of Geophysical Research, 676, 1203-1214.
SWGWQual	**Journal**	**Nield, S. P., Townley, L. R., & Barr, A. D., 1994, A framework for quantitative analysis of surface water-groundwater interaction: Flow geometry in a vertical section. WRR, 30 (8), 2461-2475.**
SWGWQual	Journal	Scahfran, G. C., and Driscoll, C. T., 1993, Flow path-comparison relationship for groundwater entering an acid lake. Water Resources Research, 29, 1454-154.
SWGWQual	Journal	Soulsby, C. et al. Impact of groundwater development on Atlantic Salmon spawning habitat in a Scottish river. Hydrology in a Changing Environment Volume I. 1998. pp. 269-280. John Wiley & Sons, Ltd.
SWGWQual	**Journal**	**Winter, T. C, 1999, Relation of streams, lakes and wetlands to groundwater flow systems. Hydrogeology Journal, 7, 28-45**
SWGWQual	Legal	Habitats Directive. Cotswold Water park and floodplains. Looking at interactions of floodplain/groundwater/surface water.
SWGWQual	**Report**	**BGS Hydrology Group, 1997-1998, Low Flow, Groundwater and Wetland Interaction Scoping Study. (Sponsor EA North West Region, Central Area Office**
SWGWQual	**Report**	**Birtles A B. 1978. Identification and separation of major base flow components from a stream hydrograph. Cent. Water Plann. Unit, Reading, Engl., UK. Water Resour Res, (1978) 14 (5), 791-804**
SWGWQual	Report	Cambridge Water Company, Thetford Scheme, ground and surface water interactions.
SWGWQual	Report	Clark, K.J. and Oakes, D.B.,1994, ROSANN – River nitrate model. WRc Report to Anglian Water, UC 2344.
SWGWQual	Report	Institute of Hydrology, 1980, Low River Flows, Report No. 1 Research Report. (Baseflow Index Procedure).
SWGWQual	**Report**	**Jones, J. B. and Mulholland P. J., 2000, Streams and Groundwater. Academic Press. pp. 425.**
SWGWQual	***Report***	***Oakes, D.B. and Keay, D., 1990, A resource model of the Great Ouse river system. CO 2504-M.***
SWGWQual	Report	Southern Water Global (Inc. John Lloyd, David Ball, Paul Johnston), 'The South Galway Flood Study', involving surface and groundwater interaction, for the OPW.
SWGWQual	Report	Strobel, M. L., 1995, Assessment of information on groundwater / surface water interactions in the northern Midcontinent. USGS.
SWGWQual	Report	Water Resources Board, 1974 Combined use of surface and groundwater in the Ely, Ouse and Nar catchments by C. Wright
SWGWQual	Unpublished	Yorkshire Water Services Ltd, Low Flow / Groundwater / Wetlands interaction. (Sponsor UKWIR).
SWGWQual	**Unpublished**	**Younger, P., 1990, Stream-Aquifer Systems of the Thames Basin: Hydrogeology, Geochemistry and Modelling. PhD Thesis, University of Newcastle.**
Surface water and Groundwater Quatity		
SWGWQuanT	Journal	Koyabashi, M., 1983, QuanTity and quality of seepage groundwater into Lake Biwa observed by direct measurement. Hydrology (Japan), 13, 51-59.
SWGWQuanT	Journal	Petts, G.E.; Bickerton, M.A.; Crawford, C.; Lerner, D.N.; Evans, D. Flow management to sustain groundwater-dominated stream ecosystems. Hydrological Processes, 1999. vol. 13, no. 3, pp.497-513.
SWGWQuanT	Journal	Sage, R. C. and Lloyd, J. W., 1978, Drift deposit influences on the Triassic sandstone aquifer of North-West Lancashire as inferred by hydrochemistry. Quart. Jour, Eng. Geol., 11, 209-218.
SWGWQuanT	Journal	Wood, P.J.; et al Instream mesohabitat biodiversity in three groundwater streams under base-flow conditions. Aquatic Conservation: Marine and Freshwater Ecosystems, 1999. vol. 9, no. 3, pp. 265-278
SWGWQuanT	Proceedings	Annual Meeting of the American Institute of Hydrologists, 28. Oct 1998. p. 125-130.
SWGWQuanT	Proceedings	IAH, 1998, Physical, Chemical and Biological aspects of aquifer - stream relations. Las Vegas Volume.
SWGWQuanT	Proceedings	Roberts, S C.; McArthur, J M. Surface-groundwater interactions in a UK limestone aquifer. Proceedings of the Joint Meeting of the Congress of the International Association of Hydrologists anc
SWGWQuanT	Proceedings	Seymour, K. J.; Wyness, A. J.; Rushton, K.; 1998. The Fylde Aquifer - a case study in assessing the sustainable use of groundwater resources. Hydrology in a changing environment.
SWGWQuanT	Proceedings	Volume II. Proceedings of the British Hydrological Society International Conference, Exeter, UK, July 1998,pp. 253-267.
SWGWQuanT	Report	Blackmore J. and Clark I., WRc, 1994, The disposal of sheep dip waste: effects on water quality, NRA R&D Report 11.
SWGWQuanT	Report	Clark L., et al, WRc, 1995, Pesticides in major aquifers, NRA R&D Report 17.
SWGWQuanT	Report	Hill, T; Neal, C. Spatial and temporal variation in pH, alkalinity and conductivity in surface runoff and groundwater for the Upper River Severn catchment. Hydrology and Earth System Sciences, 1, 3. Sep 1997.
SWGWQuanT	**Report**	**Hydrochemical Process Group, Colin Neal & Richard Williams. Studied groundwater age and ground/surface interaction. (Fits with LOCAR well)**
SWGWQuanT	Report	McMahon, P. B., Bolke, J. K., 1995, Effect of groundwater / surface water interactions on nitrate concentrations in discharge from the South Platte River alluvial aquifer, Colorado. USGS.
SWGWQuanT	Unpublished	Fretwell, B., 1999, Distribution of contaminants in seasonally unsaturated zone of the Chalk aquifer, University College London. (Potential significance of unsaturated zone controlling stream baseflow quality).
Surface water and Groundwater Quality and Quantity		
SWGWQTQL	Model	Whitehead, P. G. Modelling nitrate from agriculture into public water supplies. Biological Sciences, (1990) Vol. 329, No. 1255, pp. 403-410.
SWGWQTQL	Proceedings	Jones, C. and Pearce, J. 'The use of an Integrated Catchment Model in Low Flow Rivers in South East Hampshire', CIWEM Regional Groundwater Resources Modelling Symposium Reading, 1995.
SWGWQTQL	Proceedings	Jones, C. 'The Spey River Gravel Abstraction Scheme', presentation to ICE Scottish Hydrological Group, Perth, October 1995
SWGWQTQL	Proceedings	Peter Ripon, P. and Wyness, A. 'Water Resources Management using Integrated Catchment Models.' Presented at the IWEM Conference on Groundwater - Managing a Scarce Resource: Gatwick 1994
SWGWQTQL	Proceedings	Rippon, P. 'Integrated Surface Water and Groundwater Modelling.' Presented at the 1999 International Association of Hydrogeologists (Irish Group) Seminar in Portlaoise
SWGWQTQL	Proceedings	Rippon, P., Wyness, A., and Wardlaw, R. 'Application of an integrated model to Chalk catchments.' Presented at the International Conference on Groundwater - Drought, Pollution & Management: Brighton 1994
SWGWQTQL	Proceedings	US EPA (2000). Proceedings of the Ground-water/surface-water Interactions workshop. EPA/542/R-00/007. July 2000.
SWGWQTQL	Proceedings	van Wonderen, J. & Wyness, J. `Modelling Recharge Through Drift Around Thetford', Seminar on Recharge Through Drift, Hydrogeological Group at the Geological Society, London, February 1995
SWGWQTQL	Proceedings	van Wonderen, J. & Wyness, J. The validity of Methods Used for Modelling River-Aquifer Interactions', Meeting at the British Hydrological Society/Geological Society Hydrogeological Group, London, March 1995.
SWGWQTQL	Proceedings	van Wonderen, J., Watt, G.D., Mellanby, J.F., Burley, M.J. `Groundwater Investigations in the Lower Spey Valley near Fochabers', AGM of Institution of Water Engineers & Scientists, Perth, 1986.
SWGWQTQL	Proceedings	Verstraeten, I. M., et al., 2000, Use of geochemical & isotopic tracers to evaluate groundwater / surface water interactions. Proceedings of The Nebraska Acad. Sciences & Affiliated Societies.
SWGWQTQL	**Report**	**Anderson M. T., 1995, Use of hydrologic budgets and hydrochemistry to determine groundwater and surface water interactions for Rapid Creek, western South Dakota. USGS.**
SWGWQTQL	**Report**	**Birtles, A. B., 1977, River water quality models models based on stream hydrograph components, CWPU Technical Report 23, Reading.**
SWGWQTQL	Report	De Wit, M., Meinardi, C., Wendland, F., Kunkel, R. Modelling water fluxes for the analysis of diffuse pollution at the river basin scale. Hydrological Processes. 14(10):1707-1723, 2000 Jul
SWGWQTQL	Report	Harvey, J. W., Bencala, K. E., 1992, Stream / subsurface transport interactions; groundwater model interpretation of lumped parameters for solute storage, Eos, Transactions, American Geophysical Union.
SWGWQTQL	**Report**	**Mainstone, C., Turrell, J., Clark, L., Libero, A., Parr, W. and Morgan, N., 1997, Integrated appraisal of water quality and pollution loads in the Po Basin. Report to the Po River Authority.**
SWGWQTQL	Report	Oakes, D., 1998, Prediction of pesticide pollution in the environment (POPPIE) - the PESTCAT and PESTAQ models. WRc CO 4502.
SWGWQTQL	**Report**	**Oakes, D., 1999, Water resources and quality model of the river Po, Italy. WRc Report to the Po River Authority.**
SWGWQTQL	***Report***	***Oakes, D., Cima, J., Woodrow, D. and Hollis, J., 1995 Development of a computer system for prediction of pollution in the environment (POPPIE) -Technical design scoping study. WRc CO 4005.***
SWGWQTQL	Report	Parr, W. and Turrell, J.,1996, Procedure for estimating pollutant loads to surface and groundwaters in the Po Basin, Italy. WRc report to the Po River Authority.
SWGWQTQL	Report	Sear, D.A.; Armitage, P.D.; Dawson, F.H. Groundwater dominated rivers. Hydrological Processes 1999. vol. 13, no. 3, pp.255-276. Special Issue: Groundwater dominated rivers.
SWGWQTQL	Report	US EPA Office of Water (1998): Biological Indicators of Ground Water - Surface Water Interaction: Update. EPA 816-R-98-018. September 1998.
SWGWQTQL	Report	US EPA Office of Water: Nonpoint Source News-Notes Issue #9 NOTES ON GROUND-WATER/SURFACE-WATER INTERACTION MANAGEMENT
SWGWQTQL	**Report**	**Winter, T. C., Judson, W., Frankie, O. L., Alley, W. M., 1998, Groundwater and surface water a single resource. United States Geological Survey, Circular 1139, Denver, Colorado.**
SWGWQTQL	Report	Wood, P.J.; Petts, G.E. The influence of drought on chalk stream macroinvertebrates. Hydrological Processes. 1990. vol. 13, no. 3, pp.387-399. Special Issue: Groundwater dominated rivers.
SWGWQTQL	Unpublished	Conant, B., 1999, Groundwater plume behaviour near the groundwater surface water interface of a river. Unpublished, Dept. of Earth Sciences, University of Waterloo, Ontario, Canada.
Existing Projects		
SWQual	Existing Project	Ellis, P., The Impact of Contaminated Land and Groundwater Upon Urban Surface Water Quality, University of Birmingham.(Funding: EA NGWCLC).
SWQual	Existing Project	Henstock, J., 2000, Determine whether inorganic groundwater quality can be identified impacting overall surface water quality of River Tame. Unpublished MSc, School of Earth Sci, Uni. of Birmingham.
SWGWQual	Existing Project	Burt T. P., and Bates, P., Reviewing Slope-Floodplain-River interactions on the river Severn below Shrewsbury.
SWGWQual	Existing Project	Green, A., (Ongoing) Determination of groundwater and nutrient fluxes to a coastal zone, Second year PhD, University of East Anglia.
SWGWQual	Existing Project	Roberts, S., 2000, Hydrochemistry of the Lincolnshire Limestone aquifer. (Addressed flux of DOC from surface run-off direct via shallow holes to the aquifer). Paper in recent IAH Conference, Cape Town.
SWGWQuanT	Existing Project	Barrett Dr. M. H., 1998-2001, Depth and Penetration of Urban Recharge and Contamination in UK Aquifers. Concentrating on Nottingham and Birmingham conurbation's. NERC funded.
SWGWQuanT	Existing Project	Dowle, J., Groundwater Discharge to Urban Surface Water - River Tame Study. Unpublished MSc, School of Earth Sciences, University of Birmingham, 2000.
SWGWQuanT	Existing Project	Groundwater / Surface Water Interaction Studies, £1 million into the instrumentation for this. Went live in Dec 2000.
SWGWQuanT	Existing Project	IGRAF-II Project, (EA NGWCLC funded).
SWGWQuanT	Existing Project	Mott McDonald (For the EA), Preliminary study / conceptual model, on the relationship between groundwater and surface water within the Woburn Sands.
SWGWQuanT	Existing Project	NICHE Programme (JIF- Funded), 'groundwater - surface water interaction experimental facility' in the Eden Catchment (Cumbria).
SWGWQuanT	Existing Project	Rushton, K., 'groundwater-surface (stream) water flux'- title to be checked. Papers presented at Geol. Soc. Geoscience meeting on sustainability in April 2000. Drafts for upcoming special publication.
SWGWQuanT	Existing Project	TOPMODEL, surface / subsurface interactions on hillslopes and modelling of contributing areas. Lancaster University.
SWGWQuanT	Existing Project	Younger P., Impact of Groundwater Abstractions on River Flow. For the EA NGWCLC.
SWGWQuanT	Existing Project	Younger, P., and Parkin, P., Unpublished work for NIREX on natural groundwater discharge to streams in West Cumbria.
SWGWQuanT	**Report**	**IGARF, Impact of Groundwater Abstraction on River Flows (EA NGWCLC funded).**
Future		
Qual	Future	Bio Reduction within the Floodplain
Qual	Future	Measuring Devices for Seepage Measurements.
QuanT	Future	Better Baseline Conditions / Improve regionalisation of existing modelling procedures / Integrate monitoring and modelling more effectively. LOCAR will act as a framework.
QuanT	Future	High Recharge Events, need to study catchment response., possible wash out nutrients.
	Per. Comm	Lees, M. 2001. Pers. Comm. 16.01.01, with Martin Lees, Project Manager, Hydrological Data, CEH.

KEY:

Oakes, 1990	***References which are a major source of UK data or databases***
Winter *et al*, 1998	**Key papers**

GWQual	Groundwater Quality
GWQuanT	Groundwater Quantity
SWQual	Surface Water Quality
SWQuanT	Surface Water Quantity
SWGWQual	Surface and Groundwater Interaction - Quality
SWGWQuanT	Surface and Groundwater Interaction - Quantity
SWGWQTQL	Surface and Groundwater Interaction - Quantity and Quality
Qual	Future Research Requirements: Quality
QuanT	Future Research Requirements: Quantity

Abbreviations:

BGS	British Geological Survey
CEC	Commission of the European Communities
CEH	Centre for Ecology and Hydrology
CWPU	Central Water Planning Unit
EA	Environment Agency
GWF	Ground Water Forum
IAH	International Association Hydrologists
IOH	Institute of Hydrology
NERC	Natural Environment Research Council
NGWCLC	National Groundwater and Contaminated Land Centre, Environment Agency
SEPA	Scottish Environmental Protection Agency
STWA	Severn Trent Water Authority
UKWIR	UK Water Industry Research Limited
WRc	Water Resources Centre
WRR	Water Resources Research

APPENDIX D KEY REFERENCES FROM ON-LINE LITERATURE SEARCH

NOTE: References are given in alphabetical order, by author. If an abstract is available this is given in Appendix D.3. For clarity, UK references are separated from overseas references.

D.1 OVERSEAS REFERENCES

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Battin, T. J. Hydrologic flow paths control dissolved organic carbon fluxes and metabolism in an alpine stream hyporheic zone. Department of Ecology, University of Vienna, Vienna, Austria. Water Resources Research, 1999. Vol. 35, No. 10, pp. 3159-3169. 50 ISSN: 0043-1397.

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APPENDIX D.3 ABSTRACTS

Overseas References

Bachman, L. Joseph; Lindsey, Bruce; Brakebill, John; and Powars, David S. **Ground-Water Discharge and Base Flow Nitrate Loads of Nontidal Streams, and Their Relation to a Hydrogeomorphic Classification of the Chesapeake Bay Watershed, Middle Atlantic Coast.**

Abstract - Existing data on base flow and ground-water nitrate loads were compiled and analysed to assess the significance of ground-water discharge as a source of the nitrate load to nontidal streams of the Chesapeake Bay watershed. These estimates were then related to hydrogeomorphic settings based on lithology and physiographic province to provide insight on the areal distribution of ground-water discharge. Base flow nitrate load accounted for 26 to about 100 percent of total-flow nitrate load, with a median value of 56 percent, and it accounted for 17 to 80 percent of total-flow total-nitrogen load, with a median value of 48 percent.

Hydrograph separations were conducted on continuous streamflow records from 276 gauging stations within the watershed. The values for base flow thus calculated were considered an estimate of ground-water discharge. The ratio of base flow to total flow provided an estimate of the relative importance of ground-water discharge within a basin.

Base flow nitrate loads, total-flow nitrate loads, and total-flow total-nitrogen loads were previously computed from water-quality and discharge measurements by use of a regression model. Base flow nitrate loads were available from 78 stations, total-flow nitrate loads were available from 86 stations, and total-flow total-nitrogen loads were available for 48 stations. The percentage of base flow nitrate load to total-flow nitrate load could be computed for 57 stations, whereas the percentage of base flow nitrate load to total-flow total-nitrogen load could be computed for 36 stations. These loads were divided by the basin area to obtain yields, which were used to compare the nitrate discharge from basins of different sizes.

The results indicate that ground-water discharge is a significant source of water and nitrate to the total streamflow and nitrate load. Base flow accounted for 16 to 92 percent of total streamflow at the 276 sampling sites, with a median value of 54 percent. It is estimated that of the 50 billion gallons of water that reaches the Chesapeake Bay each day, nearly 27 billion gallons is base flow.

Generalised lithology (siliciclastic, carbonate, crystalline, and unconsolidated) was combined with physiographic province (the Appalachian Plateau, the Valley and Ridge, the Blue Ridge, the Piedmont, including the Mesozoic Lowland section, and the Coastal Plain) to delineate 11 hydrogeomorphic regions. Areal variation of base flow and base flow nitrate yield were assessed by means of nonparametric, one-way analysis of variance on basins grouped by the dominant hydrogeomorphic region and by correlation analysis of base flow or base flow nitrate yield with the percentage of land area of a given hydrogeomorphic region within a basin.

Base flow appeared to have a significant relation to the hydrogeomorphic regions. The highest percentages of base flow were found in areas underlain by carbonate rock, Chesapeake Bay Watershed, Middle Atlantic Coast crystalline rock with relatively low relief, and unconsolidated sediments. Lower percentages were found in areas underlain by siliclastic rocks and crystalline rocks with relatively high relief.

The relation between base flow nitrate yield and hydrogeomorphic region is less clear. Although there is a relation between low nitrate yields and areas underlain by high-relief siliciclastic rocks, and a relation between high yields and carbonate rocks, much of this relation can be explained by the strong association between the hydrogeomorphic units and land use. In addition, most basins are mixtures of several hydrogeomorphic regions, so the nitrate yield from a basin depends on a large number of complex interacting factors. These unclear results indicate that the sample of available data used here may not be adequate to fully assess the relation between base flow nitrate yield and the hydrogeomorphic setting of the basin. The results appear to show, however, that ground-water discharge is an important component of the total nontidal streamflow, and that ground-water discharge varies according to the hydrogeomorphic regions. Environmental management of the nontidal streams in the Chesapeake Bay watershed will thus have to consider the prevention of nutrient infiltration into aquifers as well as prevention of overland run-off of high-nitrogen waters.

Battin, T. J. **Hydrologic flow paths control dissolved organic carbon fluxes and metabolism in an alpine stream hyporheic zone**. Department of Ecology, University of Vienna, Vienna, Austria. Water Resources Research, 1999. Vol. 35, No. 10, pp. 3159-3169. 50 ref.ISSN: 0043-1397 **Abstract**: The reach-scale stream bed reactive uptake of dissolved organic carbon (DOC) and dissolved oxygen (DO) was linked to subsurface flow paths in an alpine stream (Oberer Seebach, Austria). The topography adjacent to the stream channel largely determined flow paths, with shallow hillslope groundwater flowing beneath the stream and entering the alluvial groundwater at the opposite bank. As computed from hydrometric data, OSB consistently lost stream water to groundwater with fluxes out of the stream averaging 943 plus or minus 47 and 664 plus or minus 45 litres/m2 per h at low (Q < 600 litres/s) and high (Q > 600litres/s) flow, respectively. Hydrometric segregation of stream bed fluxes and physicochemical mixing analysis indicated that stream water was the major input component to the stream bed with average contributions of 70-80% to the hyporheic zone (i.e. the subsurface zone where shallow groundwater and stream water mix). Surface water was also the major source of DOC with 0.512 plus or minus 0.043 mg C/m2 per h to the stream bed. The DOC flux from shallow riparian groundwater was lower (0.309 plus or minus 0.071 mg C/m2 per h) and peaked in autumn with 1.011 mg C/m2 per h. The relative proportion of downstream discharge through the stream bed was computed as the ratio of the downstream length (Ssw) a stream water parcel travels before entering the stream bed to the downstream length (Shyp) a stream bed water parcel travels before returning to the stream water. The relative stream bed DOC retention efficiency, calculated as (input-output)/input of interstitial DOC, correlated with the proportion (Ssw/Shyp) of downstream discharge (r2=0.76, P=0.006). Did the stream bed metabolism (calculated as DO uptake from mass balance) decrease with low subsurface downstream routing, whereas elevated downstream discharge through the stream bed stimulated DO uptake (r^2=0.69, P=0.019). Despite the very short DOC turnover times (approx. equal to 0.05 days, calculated as mean standing stock/annual input) within the stream bed, the latter constitutes a net sink of DOC (approx. equal to 14 mg C/m2 per h). Along with high standing stocks of sediment associated particulate organic carbon, these results suggest microbial biofilms as the major retention and storage site of DOCin an alpine stream where large hydrologic exchange controls DOC fluxes.

Boulton, A. J.; Findlay, S.; Marmonier, P.; Stanley, E. H.; Valett, H. M. **The functional significance of the hyporheic zone in streams and rivers.** Division of Ecosystem Management, University of New England, Armidale, 2351 New South Wales, Australia. Annual Review of Ecology and Systematics, (1998) Vol. 29, pp. 59-81. 163ref. ISSN: 0066-4162. **Abstract:** The hyporheic zone is an active ecotone between the surface stream and groundwater. Exchanges of water, nutrients, and organic matter occur in response to variations in discharge and bed topography and porosity. Upwelling subsurface water supplies stream organisms with nutrients while downwelling stream water provides dissolved oxygen and organic matter to microbes and invertebrates in the hyporheic zone. Dynamic gradients exist at all scales and vary temporally. At the microscale, gradients in redox potential control chemical and microbially mediated nutrient transformations occurring on particle surfaces. At the stream-reach scale, hydrological exchange and water residence time are reflected in gradients in hyporheic faunal composition, uptake of dissolved organic carbon, and nitrification. The hyporheic corridor concept describes gradients at the catchment scale, extending to alluvial aquifers kilometres from the main channel. Across all scales, the functional significance of the hyporheic zone relates to its activity and connection with the surface stream.

EPA/542/R-00/007, JULY 2000. Proceedings of the Groundwater/Surface Water Interactions Workshop.

INTRODUCTION - Although ground water and surface water are usually evaluated as separate water masses, they are connected by the ground-water/surface-water transition zone in a hydrologic continuum. Understanding contaminant fate and transport in this zone is important to the U.S. Environmental Protection Agency's (EPA's) hazardous waste site cleanup programs across the nation because about 75% of RCRA and Superfund sites are located within a half mile of a surface water body, and almost half of all Superfund sites have impacted surface water. Investigations of ground water and surface water need to be integrated and incorporate recent advances in investigative techniques. Ecological risk assessments for surface water bodies have all too often focused on the water column (where the ground-water contaminant plumes become extremely diluted), or on the sediments. Typically there has been little or no evaluation of contaminated ground-water discharges. Impacts from the discharge of contaminated ground water on the transition zone ecosystem have been ignored, even though this ecosystem provides important ecological services and is the most exposed to ground-water contaminants. Based on these considerations, the need to evaluate the transition zone is clear. To address the technical concerns related to ecological impacts in the transition zone, the EPA's Office of Solid Waste and Emergency Response (OSWER) sponsored a workshop in January 1999, which was planned jointly by the Ecological Risk Assessment Forum and the Ground Water Forum. The workshop was organized around answering two fundamental questions:

- How important is the transition zone ecologically?

- How can we measure hydrogeological, chemical, and biological conditions and changes in this zone?

There was a consensus among workshop participants that protecting this zone is important, and that there is a need for studies by interdisciplinary teams to ensure that valid data are obtained from the correct locations and at the right times so that valid conclusions are reached. Both forums plan to use the workshop information to submit research recommendations to EPA's Office of Research and Development, develop a list of suggested tools for investigating hydrogeological fate and transport and ecological effects at contaminated sites, develop Agency guidance, and conduct a pilot study using this methodology. The workshop and these proceedings provide a first step to understanding the fundamentals of evaluating the effects of contaminated ground water discharging through the transition zone.

CONCLUSIONS - General consensus was reached that protecting the transition zone is important, and there is a need for interdisciplinary studies to understand and document the changes that occur in it. Conclusions related to the two fundamental organizing questions are discussed below.

How Important is the Transition Zone Ecologically? The ground-water/surface-water transition zone is an ecological community with important ecosystem functions affecting several trophic levels from microbes to fish. As an ecotone (i.e., a transition from the ground-water ecosystem to the surface-water ecosystem), this zone provides key ecological services to the surface water ecosystem:

- Provides food for benthic macroinvertebrates. The microbial community serves as the food base to the small organisms within the zone that in turn are food for the benthic macroinvertebrates.
- Provides and maintains unique habitats or refugia, particularly in upwelling zones.
- Cycles nutrients and carbon in aquatic ecosystems.

The microbial and biological activity within this zone also may be important for natural attenuation, because large gradients can be created, which can result in subsurface conditions that change from anaerobic to aerobic over short distances. Biodegradation can cause organic contaminant concentrations to change over several orders of magnitude within this zone.

How Can We Measure Hydrogeological, Chemical, and Biological Conditions and Changes in this Zone? Despite many unanswered questions there are many tools from each of the disciplines that can be used to evaluate fate, transport, and effects in the transition zone. It was recognized that the types, locations, and times of measurements required to characterize this zone can vary depending on the questions being asked. Hydrogeologists and ecologists must work together to obtain information that is useful to both and to efficiently and properly evaluate this zone.

Fraser, B. G.; Williams, D. D. **Seasonal boundary dynamics of a groundwater/surface-water ecotone.** Surface Water and Groundwater Ecology Group, University of Toronto at Scarborough, 1265 Military Trail, Scarborough, Ontario, M1C 1A4, Canada. Ecology, 1998 Vol. 79, No. 6, pp. 2019-2031. 58 ref. ISSN: 0012-9658 **Abstract**: Interstitial water, faunal samples, and hydrogeological data were collected beneath a riffle on the Speed River, southern Ontario, Canada. The location and seasonal fluctuation of the hyporheic/groundwater interface was determined and several aspects of water mass chemical signatures and the dynamics of the interstitial fauna were examined. Concentration discontinuities in several water chemistry parameters delineated the chemical boundary between the true groundwater and hyporheic habitats. The groundwater mass had higher levels of ammonium, alkalinity, and conductivity, and lower nitrate levels. Differences in water chemistry between the hyporheic and groundwater zones persisted throughout the year, though no single variable differed quantitatively between these two zones on all occasions. The location of the chemical discontinuity varied seasonally. Whereas hyporheic and groundwater faunal sub-units of the interstitial community were identified and the location of the sub-units coincided with the chemical breaklines, response to shifts in the position of the hyporheic/groundwater interface was taxon rather than sub-unit based. Fauna therefore provided poor spatial resolution in terms of pinpointing the location of the interface. Boundary fluctuation coincided with extremes in seasonal discharge patterns and was regulated by the relative strength of the upward force of base flow and the downward force of advecting surface water. Identifying patterns of fluctuation of the hyporheic/groundwater interface, and consequently hyporheic habitat volume, may have important consequences for the storage, retention, and cycling of nutrients in lotic eco-systems.

Winter, T.C.; Harvey, J.W.; Franke, O.L.; and Alley, W.M. **Ground Water and Surface Water A Single Resource – USGS Circular 1139**.

As the Nation's concerns over water resources and the environment increase, the importance of considering ground water and surface water as a single resource has become increasingly evident. Issues related to water supply, water quality, and degradation of aquatic environments are reported on frequently. The interaction of ground water and surface water has been shown to be a significant concern in many of these issues. For example, contaminated aquifers that discharge to streams can result in long-term contamination of surface water; conversely, streams can be a major source of contamination to aquifers. Surface water commonly is hydraulically connected to ground water, but the interactions are difficult to observe and measure and commonly have been ignored in water-management considerations and policies. Many natural processes and human activities affect the interactions of ground water and surface water. The purpose of this report is to present our current understanding of these processes and activities as well as limitations in our knowledge and ability to characterise them.

Foreword - Traditionally, management of water resources has focused on surface water or ground water as if they were separate entities. As development of land and water resources increases, it is apparent that development of either of these resources affects the quantity and quality of the other. Nearly all surface-water features (streams, lakes, reservoirs, wetlands, and estuaries) interact with ground water. These interactions take many forms. In many situations, surface-water bodies gain water and solutes from ground-water systems and in others the surface-water body is a source of ground-water recharge and causes changes in ground-water quality. As a result, withdrawal of water from streams can deplete ground water or conversely, pumpage of ground water can deplete water in streams, lakes, or wetlands. Pollution of surface water can cause degradation of ground-water quality and conversely pollution of ground water can degrade surface water. Thus, effective land and water management requires a clear understanding of the linkages between ground water and surface water as it applies to any given hydrologic setting.

This Circular presents an overview of current understanding of the interaction of ground water and surface water, in terms of both quantity and quality, as applied to a variety of landscapes across the Nation. This Circular is a product of the Ground-Water Resources Program of the U.S. Geological Survey. It serves as a general educational document rather than a report of new scientific findings. Its intent is to help other Federal, State, and local agencies build a firm scientific foundation for policies governing the management and protection of aquifers and watersheds. Effective policies and management practices must be built on a foundation that recognises that surface water and ground water are simply two manifestations of a single integrated resource. It is our hope that this Circular will contribute to the use of such effective policies and management practices.

UNITED KINGDOM ABSTRACTS

Dils, R.M.; Heathwaite, A.L.; Novotny, V. [editor]; D'Arcy, B. [editor]. **The controversial role of tile drainage in phosphorus export from agricultural land** DIFFUSE POLLUTION '98. Environment Agency, National Centre for Ecotoxicological and Hazardous Substances, Evenlode House, Howbery Park, Wallingford, Oxon, OX10 8BD, UK Water Science & Technology, 1999. pp. 55-61. Elsevier Science Ltd. Pergamon. P.O. Box 800. Meeting: IAWQ 3. International Conference on Diffuse Pollution. Edinburgh (UK). 21 Aug-4 Sep 1998. ISSN: 0273-1223; , 0080434096. **Abstract:** Field drainage, in the form of permanently installed pipes or temporary mole drains, is extensively used in Britain to reduce the incidence of waterlogging, and increase the length of the grazing season. Whereas the installation of artificial drains significantly improves the structural stability of the soil, water quality in recipient streams may be adversely affected by the accelerated rate of nutrient transport, and the circumvention of critical storage areas such as buffer zones. This research investigates the importance of phosphorus (P) loss in tile drainage for a mixed agricultural catchment (120 ha) in the UK. Phosphorus concentrations in drain discharge were low (<100 mu g Total P l super(-1)) and stable during base - flow periods (<0.5 l min super(-1)), and generally lower than in the receiving stream. In contrast, temporary (hours) elevated P peaks exceeding 1 mg Total P l super (-1) were measured in drain-flow during high discharge periods (>10 l min super(-1)). Large sediment-associated particulate P losses were measured during the first major drain-flow events of the autumn. Field drains are evidently effective conduits for P export from agricultural catchments. Recommendations for controlling P loss from diffuse agricultural sources are therefore critically dependent on a better understanding of surface and subsurface transport pathways.

Dubus, I. G.; Hollis, J. M.; Brown, C. D.; Lythgo, C.; Jarvis, J. **Implications of a first-step environmental exposure assessment for the atmospheric deposition of pesticides in the UK**. Soil Survey and Land Research Centre, Cranfield University, Silsoe, Beds MK45 4DT, UK. Brighton Crop Protection Conference: Pests & Diseases - 1998: Volume 1: Proceedings of an International Conference, Brighton, UK, 16-19 November 1998, pp. 273-278. 20 ref. Publisher: British Crop Protection Council. Farnham. ISBN: 0-901396-50-9. **Abstract:** A review of existing information on the aerial transport and deposition of pesticides in the UK were used to calculate worst-case aerial deposition loadings for 3 benchmark compounds with different patterns of detection. The compounds studied were isoproturon, atrazine and lindane. The loadings were used to carry out simple first-step calculations of predicted environmental concentrations in soil, surface water and groundwater. In agricultural ecosystems, impacts of pesticides via aerial deposition were negligible compared to that from direct agricultural application. For most compounds, aerial deposition in remote, natural or semi-natural ecosystems also results in negligible environmental exposure, although for some highly volatile, persistent compounds there appears to be the potential for more prolonged exposure, albeit at low concentrations.

Eatherall, A.; Warwick, M. S.; Tolchard, S. **Identifying sources of dissolved organic carbon on the River Swale, Yorkshire**. Science of the Total Environment,5 May, 2000. Vol. 251-252, No. Special Issue, pp. 173-190.ISSN: 0048-9697. **Abstract:** A dissolved organic carbon (DOC) sampling study was carried out on the River Swale in Yorkshire as part of the NERC LOIS programme. Loads of DOC were calculated from the river and its tributaries. For the River Swale calculated loads varied between 1900 and 9000 kg/day and for the tributaries between 1 and 8500 kg/day. No relationship was found between the amount of organic carbon in the soil of the catchments and the DOC loads, perhaps because of the preceding dry summer. DOC loads were also estimated for sewage point sources and ranged between 7 and 287 kg/day. Some of the catchments draining to the River Swale respond with high DOC loads during high flow conditions, others do not. Some catchments are dominated by sewage point sources during low flows and diffuse sources during high flows. A mass balance for DOC on the Rive Swale was calculated, however, loads from inputs did not balance with outputs because of a lack of data and errors inherent in some of the approaches used. Despite this, results indicate in-stream losses of approx. 20%. A highly detailed measurement study of a stretch of river is recommended to identify all the sources and sinks of DOC, the relative size of their contribution and how they respond in differing conditions.

Edmunds, W. M.; Kinniburgh, D. G.; Moss, P. D. **Trace metals in interstitial waters from sandstones: acidic inputs to shallow groundwaters**. British Geological Survey, Wallingford, OX10 8BB, UK. Environmental Pollution, 1992. Vol. 77, No. 2 & 3, pp. 129-141. 19 ref.ISSN: 0269-7491. **Abstract:** The occurrence and mobility of Al, Ba, Fe, Mn, Cu, Zn, Ni, Co and Be were investigated in interstitial water profiles down to 12 m obtained from unsaturated sands or semi-consolidated sandstones from the Folkestone Beds (Lower Greensand) and the Sherwood Sandstone in the UK. The pH of the interstitial waters generally increased with depth. Most conc. were strongly pH-dependent but also reflected the geochemical characteristics of the parent sands or sandstones. H+ and trace element conc. were higher beneath forested areas than beneath heathlands. The downward fluxes of solutes were estimated using rainfall-derived chloride as a non-reactive solute. Cation exchange sites were probably depleted over a period of decades and there can be a significant decrease in the unsaturated zone pH as a result of increased or sustained acidic deposition. The shallow groundwater environment in non-carbonate terrains was therefore a sensitive environment where high metal conc. could be generated leading to water quality problems in shallow water supplies.

Ferrier, R. C.; Walker, T. A. B.; Harriman, R.; Miller, J. D.; Anderson, H. A. **Hydrological and hydrochemical fluxes through vegetation and soil in the Allt a'Mharcaidh, western Cairngorms, Scotland: their effect on streamwater quality**. Macaulay Land Use Research Institute, Craigiebuckler, AB9 2QJ, UK. Journal of Hydrology (Amsterdam), (1990) Vol. 116, No. 1-4, pp. 251-266. In special issue Transfer of elements through the hydrological cycle(edited by C. Neale and M. Hornung). 18 ref. ISSN: 0022-1694. **Abstract:** A detailed investigation of the hydrochemical alteration of input water by vegetation and soils was undertaken in an upland catchment in the Cairngorm Mountain region of Scotland. The composition of catchment outflow water reflects the hydrological routing of water through different soil horizons and the importance of long-residence-time water. Annual equivalent loss rates (based on a period from late 1985 to early 1986) for the catchment were 0.22, 3.86, 0.62, 5.40, -1.02, -0.98 and -3.64 kg/ha of K, Ca, Mg, Na, NH4-N, NO3-N and SO4-S, resp. There is uptake of nitrogen and neutralization of incoming anthropogenic acidity by the vegetation, and sulphate adsorption in the mineral soils. Streamwater quality is dominated by the contribution of long-residence-time water, especially during base flow. Sulphate retention

and cation release are the major neutralisation mechanisms buffering outflow chemistry at this site.

Finch, J.W. 2001 **Estimating change in direct groundwater recharge using a spatially distributed soil water balance model**. Institute of Hydrology, Wallingford, OXON. Quarterly Journal of Engineering Geology and Hydrogeology, 34, p71-83. **Abstract:** There is a requirement to estimate the impact of changes in land cover and climatic parameters on groundwater recharge. A simple, causal, spatially distributed soil water balance model for estimating direct groundwater recharge is described. The potential use of this model is illustrated by the results of a study carried out in a Chalk surface water catchment in southern England. The study estimates the response of mean annual groundwater recharge to land cover changes which took place between 1990 and 1997. It is concluded that, in this case, the change in land cover significantly alters the pattern of recharge but, by coincidence, that the total for the catchment is unchanged.

Hill, Timothy; Neal, Colin **Spatial and temporal variation in pH, alkalinity and conductivity in surface run-off and groundwater for the Upper River Severn catchment**. University of Reading, Department of Geography, Reading, United Kingdom;Institute of Hydrology, United Kingdom. Hydrology and Earth System Sciences, 1, 3. Sep 1997. p.697-715. 25 refs. European Geophysical Society, Katlenburg-Lindau, Federal Republic of Germany. Water quality of the Plynlimon catchments (UK) Neal, Colin [editor] Institute of Hydrology, Wallingford. ISSN: 1027-5606 **Abstract:** Measurements of pH, alkalinity and electrical conductivity are used to examine the extent of the spatial and temporal variation in stream and ground water chemistry for the Upper Severn catchment, Plynlimon. Wide temporal variations in stream waters broadly reflect flow conditions and complex soil and ground water interactions but not soil type, land usage or geology. The results have major implications for the use of critical load analysis and the development and application of models in upland catchments. They point to the value of field measurements for assessing the environmental management of upland catchments, rather than the present use of over simplistic or inappropriate models.

Hiscock, K. M.; Dennis, P. F.; Saynor, P. R.; Thomas, M. O. **Hydrochemical and stable isotope evidence for the extent and nature of the effective Chalk Aquifer of North Norfolk, UK.** University of East Anglia, School of Environmental Sciences, Norwich, United Kingdom. Journal of Hydrology, 180, 1-4. Pub. Date: 15 May 1996. p. 79-107. 36 refs. Elsevier, Amsterdam, Netherlands. ISSN: 0022-1694. **Abstract:** In eastern England the Chalk aquifer is covered by extensive Pleistocene deposits which influence the hydraulic conditions and hydrochemical nature of the underlying aquifer. In this study, the results of geophysical borehole logging of groundwater temperature and electrical conductivity and depth sampling for major ion concentrations and stable isotope compositions (delta (super 18) O and delta (super 2) H) are interpreted to reveal the extent and nature of the effective Chalk aquifer of north Norfolk. It is found that the Chalk aquifer can be divided into an upper region of fresh groundwater, with a Cl concentration of typically less than 100 mg l (super -1), and a lower region of increasingly saline water. The transition between the two regions is approximately 50 m below sea-level, and results in an effective aquifer thickness of 50-60 m in the west of the area, but less than 25 m where the Eocene London Clay boundary is met in the east of the area. Hydrochemical variations in the effective aquifer are related to different hydraulic conditions developed in the Chalk. Where the Chalk is confined by low-permeability Chalky Boulder Clay, isotopically depleted groundwater (delta (super 18) O less than -7.5 per mil) is present, in contrast to those areas of unconfined Chalk where glacial deposits are thin or absent (delta (super 18) O about -7.0 per mil). The isotopically depleted groundwater is evidence for groundwater recharge during the late Pleistocene under conditions when mean surface air temperatures are estimated to have been 4.5 degrees C cooler than at the present day, and suggests long groundwater residence times in the confined aquifer. Elevated molar Mg:Ca ratios of more than 0.2 resulting from progressive rock-water interaction in the confined aquifer also indicate long residence times. A conceptual hydrochemical model for the present situation proposes that isotopically depleted groundwater, occupying areas where confined groundwater dates from the late Pleistocene, is being slowly modified by both diffusion and downward infiltration of modern meteoric water and diffusive mixing from below with an old saline water body.

Hooda, P. S.; Moynagh, M.; Svoboda, I. F.; Thurlow, M.; Stewart, M.; Thomson, M.; Anderson, H. A. **Soil and land use effects on phosphorus in six streams draining small agricultural catchments in Scotland**. Scottish Agricultural College, Biochemical Sciences Department, Auchincruive, Ayr KA6 5HW, UK. Soil Use and Management, 1997 Vol. 13, No. 4, pp. 196-204. 37 ref.ISSN: 0266-0032. **Abstract:** Phosphorus concentrations and outputs were compared and contrasted in six small agricultural catchments in the west and northeast of Scotland,UK. The loss of P from soils to stream waters was more from catchments with intensive dairy cattle farming in the west than from the less intensively stocked/arable catchments in the north-east. In the north-east, intensive animal farming caused less P loss in drainage water than arable management. Larger mean annual concentrations were seen in the west (0.076-0.142 mg PO4-P/litre as molybdate-reactive phosphate-MRP)compared with the northeast (0.012-0.025 mg PO4-P/litre), a feature caused by the combination of limited P-retention in the western Gleysols and smaller inputs to the largely-podzolic north-eastern catchments. Stream concentrations were decreased by dilution during winter storm flows and increased during summer base flow and at the beginning of soil rewetting in autumn.

Hornung, M.; Reynolds, B.; Stevens, P. A.; Hughes, S.; Edwards, R.W. [EDITOR]; Gee, A.S. [EDITOR]; Stoner, J.H. [EDITOR]. **Water quality changes from input to stream**. ITE Merlewood Research Station, Grange-over-Sands, Cumbria LA11 6JU, UK. Acid waters in Wales, 1990. pp. 223-240. In Monographiae Biologicae, No.66 (edited by Dumont, H.J.; Werger, M.J.A.). 24 ref. Kluwer Academic Publishers. Dordrecht. ISBN: 0-7923-0493-4. Netherlands Antilles. **Abstract:** Data from a series of studies in upland Wales are presented to show the changes in chemistry as precipitation moves through vegetation, soil and bedrock. The three main study sites are Beddgelert Forest in north Wales, the Plynlimon experimental catchments, and the Llyn Brianne experimental catchments in central Wales. Together, the sites cover a range of vegetation types/land uses, soils and some variation in geology. The following headings are used: (1) precipitation-vegetation canopy interactions; (2) solute-soil interactions : soil water chemistry; (3) impact of land use on soil water chemistry; (4) solute chemistry and soil type, and (5) solute-bedrock interactions : groundwater chemistry.

Hughes, J. [EDITOR]; Heathwaite, L. [EDITOR] **Hydrology and hydrochemistry of British wetlands**. Department of Geography, University of Reading, Whiteknights, Reading RG6 2AB, UK. 1995. pp. xi + 486. John Wiley & Sons. Chichester. ISBN: 0-471-95759-3. **Abstract:** This book is divided into 3 sections: hydrology (7 chapters); hydrochemistry (8 chapters); and ecology and management (9 chapters). Topics covered include: the hydrology of British wetlands; the value of plants as indicators of water conditions in fens; modelling the form and distribution of peat mires; hydrological investigations of soil water and groundwater; the hydrochemistry and solute processes in British wetlands; setting a critical load for dystrophic peat; solute processes in fen peat; lysimeter studies of nitrogen leaching potential in wetlands peat and clays; the role of the hydrological regime on phosphorus dynamics in a seasonally waterlogged soil; the management of water colour in peatland catchments; hydrochemistry of raised bogs and fens, nitrate removal by river marginal wetlands; the ecology and management of British wetlands; wetland soil hydrology and ecosystem functioning; restoration of cut-over peatlands; the impact of disturbance on mire hydrology; the use of remotely sensed imagery for mapping wetland water table depths; wetland loss in Northeast England; and recreating wetlands in Britain.

Leeks, G.J.L.; Walling, D.E. **River basin sediment dynamics and interactions within the UK Land-Ocean Interaction Study: the context**. Department of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter, EX4 4RJ, UK. Hydrological Processes, 1999. vol. 13, no. 7, pp.931-934. Special issue: River Basin Sediment Dynamics. ISSN: 0885-6087. **Abstract:** A major Land-Ocean Interaction Study (LOIS) was launched by the UK Natural Environmental Research Council in 1992 as a Community Research Programme. The six-year programme, which was completed in 1998, aimed to estimate contemporary fluxes into and out of the coastal zone, to characterise the key physical and biogeochemical processes involved, to describe the longer term evolution of coastal systems and to develop coupled land-ocean models. The rivers component of the LOIS study focused on the Yorkshire Ouse and the other principal rivers draining to the Humber Estuary, and on the River Tweed. Most effort was directed to the Yorkshire Ouse. The river research programme emphasised sediment, water quality and biological investigations. In view of the general lack of information on suspended sediment transport by British rivers, particular attention was placed on investigating the suspended sediment dynamics of the study rivers and their tidal reaches and interactions between fine sediment and nutrients and contaminants. The 14 papers contained in this special issue report various aspects of these sediment studies, including several linked to the longer term behaviour of the river systems involved.

Muscutt, A. D.; Harris, G. L.; Bailey, S. W.; Davies, D. B. **Buffer zones to improve water quality: a review of their potential use in UK agriculture.** ADAS Soil and Water Research Centre, Anstey Hall, Trumpington, Cambridge,CB2 2LF, UK. Agriculture, Ecosystems & Environment, (1993) Vol. 45, No. 1-2, pp. 59-77. 78 ref. ISSN: 0167-8809. **Abstract:** The establishment of buffer zones between the pollutant source area and the receiving waters is a possible approach to the problem of reducing pollution from diffuse sources. The mechanisms of pollutant transport to surface waters are outlined: subsurface run-off and underdrainage; surface run-off; sediment transport. The impact of buffered zones on the transport of pollutants is reviewed with respect to the direct effects of the change in riparian land use, the impact of buffers on water and sediment, surface pollutant transport and subsurface pollutants transport. The design of buffer zones is considered. The data suggested that benefits could be obtained from the wider use of buffer zones. For clayey soils, where the subsurface drains may provide the major flow pathway through riparian areas, it was suggested that the effect on pollution could be minimal unless other additional measures were used.

Plater, A.J.; Ridgway, J.; Appleby, P.G.; Berry, A.; Wright, M.R. **Historical Contaminant Fluxes in the Tees Estuary, UK: Geochemical, Magnetic and Radionuclide Evidence**. Department of Geography, University of Liverpool, Roxby Building, P.O. Box 147, Liverpool L69 3BX, UK. Marine Pollution Bulletin,1998. vol. 37, no.3-7, pp. 343-360. Special Issue: Flux of Materials Between Rivers and Coastal Waters. ISSN: 0025-326X. **Abstract:** Geochemical, magnetic and radionuclide analyses were undertaken on deep and shallow cores from the Tees estuary in an investigation of sediment flux during the historical past, using the record of contamination from mining and industrial activity to link Holocene coastal change with present-day sedimentary processes. The extent of contamination can be identified from XRF and environmental magnetism data, and is variable in magnitude and thickness. Concentrations of Pb and Zn are particularly effective in the identification of far-field mining contamination, whilst As concentration and the concentration of magnetic minerals (chi , magnetic susceptibility) are used to characterise near-field industrial contamination. Radionuclide chronologies (super (210)Pb and super(137)Cs) confirm limited post-depositional disturbance of the shallow sedimentary record and place the onset of industrial contamination at c. 1925, with a peak level in the mid-1950s. Although contamination has decreased since the early-1980s, the marked spatial and vertical variation in the extent of this contamination adds a significant level of complexity to any future assessment programme where sediment erosion and redistribution are important concerns.

Sear, D.A.; Armitage, P.D.; Dawson, F.H. **Groundwater dominated rivers.** Department of Geography, University of Southampton, Highfields, Southampton, SO17 1BJ, UK. Hydrological Processes 1999. vol. 13, no. 3, pp.255-276. Special Issue: Groundwater dominated rivers. ISSN: 0885-6087. **Abstract:** This paper explores the significance of groundwater dominance in the surface water system through a combination of review and an exposition of the general hydrology, ecology and geomorphology of rivers draining the main UK aquifers. Groundwater dominance is shown to vary according to the nature of the aquifer lithology, the mechanism of groundwater:surface water interaction and the scale at which one examines this interaction. Using data derived from a range of studies including the UK Environment Agency River Habitat Survey and the UK Institute of Freshwater Ecology RIVPACS invertebrate database it is shown that the nature of the aquifer and mode of influent discharge strongly control the hydrological and ecological characteristics of the environment but that a specific groundwater ecology or hydrogeomorphology is masked by the overriding controls exerted by aquifer geology and catchment topography. Despite this, it is clear that river systems dominated by groundwater flows have specific hydrological characteristics and management issues that require holistic, multidisciplinary approaches that recognise the significance of groundwater and the nature of the interaction with the surface water environment.

Seymour, K. J.; Wyness, A. J.; Rushton, K.; Wheater, H [EDITOR]; Kirby, C.[EDITOR]. **The Fylde Aquifer - a case study in assessing the sustainable use of groundwater resources**. Environment Agency, North-west Region, UK. Hydrology in a changing environment. Volume II. Proceedings of the British Hydrological Society International Conference, Exeter, UK, July 1998,pp. 253-267. 8 ref. John Wiley & Sons Ltd. Chichester. Meeting: Hydrology in a changing environment. ISBN: 0-471-98685-2. **Abstract**: A study of the Fylde aquifer in northern England used an integrated, multi-functional approach to evaluate the mechanisms of groundwater recharge, groundwater flow and the interaction between groundwater and surface water. The work involved a review of a local conjunctive use scheme, the development of an integrated numerical model and the investigation of a series of abstraction/climatic scenarios.

Whitehead, P. G. **Modelling nitrate from agriculture into public water supplies**. Institute of Hydrology, Wallingford, Oxforshire, OX10 8BB, UK. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, (1990) Vol. 329, No. 1255, pp. 403-410. 13 ref. ISSN: 0080-4622. **Abstract:** A wide range of models and techniques are briefly reviewed within the context of the Thames nitrates study in which models were developed to assess impacts of agricultural practices on nitrate levels in the river system. Here a semidistributed approach was adopted in which a series of component models was developed to simulate hydrological and chemical behaviour of the Thames River basin. These components included: (a) a daily hydrological model for the Thames basin, which included 17 tributary sub-catchments and several major aquifer systems. The model provided input flows such as tributaries, groundwater, surface run-off, effluent returns as well as abstraction flows; (b) a soil zone and aquifer model for calculating the nitrate concentrations of surface run-off and groundwater given a particular land-use and fertiliser application rate; (c) an integrated model of flow and water quality for the main river, which provided a mass balance along 22 reaches of the main river, allowed for denitrification processes and incorporated all inputs from the non-point sources derived by (a) and(b) above. Model results are presented toget0her with an assessment of the major problems of nitrate modelling and predictions, which occur within the hydrologically active soil zone.

Wood, P.J.; Armitage, P.D.; Cannan, C.E.; Petts, G.E. **Instream mesohabitat biodiversity in three groundwater streams under base flow conditions**. Limestone Research Group, Geographical and Environmental Sciences, The University of Huddersfield, Huddersfield, HD1 3DH, UK Aquatic Conservation: Marine and Freshwater Ecosystems, 1999. vol. 9, no. 3, pp. 265-278.ISSN: 1052-7613. **Abstract:** 1.Concerns regarding the ecological functioning and biodiversity of groundwater-dominated rivers have been highlighted in the wake of increased water resource pressures, channel management activities and natural drought. 2. The macroinvertebrate communities within three groundwater-dominated streams in the UK, subject to different management strategies, were examined in relation to substratum mesohabitat diversity. 3. The mesohabitat structure was similar at all three sites examined but the number of taxa present at each site varied markedly. 4.Differences found at each site are related to (i) recent hydrological conditions (drought severity) and (ii) management activities, and are discussed with reference to the conservation and restoration of riverine systems.

APPENDIX E SUMMARY OF WATER QUALITY DATABASES

A summary of the data provisions of the Severn Trent Water Authority (STWA) Annual Report, 1977. This data was used in completing the flux mass balance calculations in Sections 6.4 and 6.5.

Data source	**STWA Water Quality 1976/77**	**STWA Water Quality 1976/77**	**STWA Water Quality 1976/77**	**STWA Water Quality 1976/77**	**STWA Water Quality 1976/77**	**STWA Water Quality 1976/77**
Data point	R Derwent @ Little Easton and Church Wilne (p.4)	R Severn @ Mythe, Strensham and Worcester (p.4)	Upper Severn raw water, 3 sources + 2 reservoirs (Also 45 treated waters, surface and ground)	Lower Severn raw water, 59 source + 1 reservoir. (and 26 treated waters)	Avon Division raw water, 41 wells, 4 river, 1 reservoir. Also 38 treated waters	Soar Division raw water. 17 sources, 6 reservoirs, 1 river (Dove). Also 24 treated
Dates	76/77	76/77	76/77	76/77	75/76	76
Colour	Y	Y	Y			
Turbidity	SS	SS	Y			
EC	Y	Y	Y			
pH	Y	Y	Y			
Alk			Y			
Total hardness			Y			
PV	BOD	BOD	Y			
Nitrate	Y	Y	Y			
Cl	Y	Y	Y			
Pb	Y	Y	Y			
Fe	Y	Y	Y			
Cu	Y	Y	Y			
Mn	Y	Y	Y			
Zn	Y	Y	Y			
F	Y	Y	Y			
SO_4	Y	Y	Y			
Other metals + organics	Y	Y				
			+ bacteriological summary and summaries of industrial discharges to streams '75/76.			

Notes:

1. STWA data annual data summarised as Max – min – mean (and previous mean)
2. Raw and treated water sites often correspond – possible to gauge effects of treatment.
3. Grid references supplied for most measurement points.

Data source	STWA Water Quality 1976/77	STWA Water Quality 1976/77	STWA Water Quality 1976/77	STWA Water Quality 1976/77	STWA Water Quality 1976/77	STWA Water Quality 1976/77
Data point	Lower Trent Division raw water. 2 river sources only. 31 treated waters	Derwent Division raw water. 30 wells, 6 rivers, 10 reservoirs. 39 treated	Upper Trent Division raw water20 wells, 1 river, 1 reservoir. 30 treated.	Tame Division raw water18 wells, 1 reservoir, 5 river. 7 treated.	East Worcs Waterworks Co. Raw water bacteria only. 19 wells treated water.	South Staffs Waterworks raw water 39 wells , 1 treatment works. 25 treated.
Dates	75/76	76/77	75/76	76/77	75/76	76/77
Colour						
Turbidity						
EC						
pH						
Alk						
Total hardness						
PV						
Nitrate						
Cl						
Pb						
Fe						
Cu						
Mn						
Zn						
F						
SO_4						
Other metals + organics						
	+ bacteriological summary and summaries of industrial discharges to streams '75/76.					

Notes:

1. STWA data annual data summarised as Max – min – mean (and previous mean)
2. Raw and treated water sites often correspond – possible to gauge effects of treatment.
3. Grid references supplied for most measurement points.

Data source	STWA Water Quality 1976/77	STWA Water Quality 1976/77	STWA Water Quality 1976/77	STWA Water Quality 1976/77
Data point	Severn catchment – river. 15 on R Severn	Trent catchment – river. 14 on R Trent	Garno (1), Vyrnwy (1) Perry (1) Rea Brook (1) Tern (2), Meese (1) Strine (1) Roden (1) Worfe (1), Stour (4) Smestow (1) Salwarpe (2) Teme (2) Onny (1) Corve (1) Rea (1) Avon (10) Sowe (2) Finham Brook (1) Leam (1) Dene (1) Stour (1) Arrow (3) Alne (1) Badsey Brook (1) Isbourne (1) Bow Brook (1) Swilgat (1) Chelt (2) Leadon (1) Frome (1)	Fowlea Brook (1) Sow (1) Penk (1) Blithe (1) Oldbury Tame (1) Wolverhampton Tame (1) Ford Brook (1) Tame (3) Rea (1)Cole (1) Blythe (1) Bourne (1) Anker 4) Mease (1) Dove (2) Manifold (1) Churnet (2) Tean (1) Derwent (3) Wye (1) Amber (1) Alfreton Brook (1) Soar (5) Wreake (2) Erewash (2) Leen (1) Devon (1) Meden (1) Poulter (1) Ryton (1) Idle/Maun (3) Bottesford Beck (1) Torne (1)
Dates	Means for 71/73, 74/77 and 76/77	Means for 71/73, 74/77 and 76/77		
Notes	6 schematic maps which include reservoirs and off-takes	10 schematic maps which include reservoirs and off-takes		

Notes: Different determinands (BOD; TOC; SS; ammonia; TON; Ec Cl; Alk; Total hardness; P; DO pH, Cd; Cr; Cu; Pb; Ni; Zn Fe; Mn; anionic detergents)

Data source	**Standing Technical Advisory Committee on Water Quality, 1984. Fourth Biennial Report February 1981 – March 1983 HMSO ISBN 0 11 751958 8**	**Standing Technical Advisory Committee on Water Quality, 1984. Fourth Biennial Report February 1981 – March 1983 HMSO ISBN 0 11 751958 8**	**Hill, J M 1984 Nitrates in surface waters: Observations from some rivers in the Lee drainage basin. TR 203. April 1984. WRc 40 pp.**	**Severn River Authority 1974. Shropshire Groundwater Investigation Second Report**
Data point	Rivers Sour, Frome, Thames, Dove, Gt Ouse	Groundwaters: Chalk @ Fowlmere, Fleam Dyke, Saffron Walden. Trias Sandstone @ Little Hay, Maple Brook, Seedy Mill. Lincs Limestone @ Waneham Bridge and Ashby.	Surface waters r. Ash at Mardocks Mill, r Beane at Hartham, r. Quin at Griggs Bridge, r. Rib at Wadsemill, r Mimram at Panshanger.	7 No. exploration boreholes, Triassic Sandstone Ion balance suites, some tritium values
Dates	28 / 80	Chalk/Trias 40-80. Lincs Lstn 75-80	1980 – 82	72/73
Notes	Graphical annual means for nitrate. Also average annual loads and concentrations from Harmonised Monitoring Network for 34 rivers (monitoring points identified and map included	Graphical annual means for Chalk and Trias. Monthly for Lincs lstn.	Flows and daily mean TON concs. Estimates of catchment yield and flux. Summaries of Orthophosphate and silica concentrations.	

Data source	**Severn Trent Water Authority, Directorate of Operations. Hydrometric Year Book 1974 & 1975**	**Clyde River Purification Board. Water Quality; A ten year review – 1976 – 1985.**	**DoE/Welsh Office. 1971. Report of the river Pollution Survey of England and Wales 1970. HMSO**
Data point	Daily flows at gauges, detailed and summary	Various points on streams. Min – mean – max.	All rivers Summary data on quality classifications. 3 volumes.
Dates	74/75	76/85	To 1970
Notes	551.482.215.1; 914.2	SS, BOD, PV, DO, Temp, % saturation, Amm - N, nitrite – n, nitrate – n, PO4, Alk, Cl, EC, pH. Also some flow data. 551.482. 213/214. 914.11	511.482.214

APPENDIX F RESEARCH COUNCIL PROJECTS

F.1 LOIS WEBPAGE

Introduction

LOIS is a 6 year project (1992 - 1998) of the UK's Natural Environment Research Council involving over 360 scientists from 11 institutes and 27 universities. This project is the United Kingdom's contribution to LOICZ. It aims to quantify and simulate the fluxes and transformations of materials (sediments, nutrients, contaminants) into and out of the coastal zone, extending from the catchment to the edge of the continental shelf. The main study area, embracing river catchments, estuaries and coastal seas, is the UK East Coast from Berwick upon Tweed to Great Yarmouth, concentrating on the Humber and its catchment, and to a lesser extent the River Tweed. The shelf edge study is focused on an area to the west of Scotland.

LOIS has 7 components studying riverine, atmospheric, estuarine, coastal and shelf processes. They include a major geological study of the sedimentary record in a traverse of the coastal zone to determine how sediment fluxes have influenced sea level, climate and land use. The large data sets from the riverine monitoring network, from long-term deployments of mooring systems, from cruises and from remote sensing are being handled by five Data Centres, which will ensure the maintainance of data standards, making data available to modellers and other scientists in the LOIS community.

- RACS(R): River Basins
- RACS(A): Atmosphere
- RACS(C): Coasts and Estuaries
- Land-Ocean Evolution Perspective Study (LOEPS)
- Shelf-Edge Study (SES)
- North Sea Modelling Study (NORMS)
- DATA

LOIS Projects

- Highlights of LOIS Research

Core Projects

- Airborne Remote Sensing
  - Archive of CASI and ATM Images
- RACS(C) GIS

Modelling

- Ecological Modelling of the Humber Plume Zone

Special Topics

Links to LOIS Data Centres

- British Oceanographic Data Centre, Bidston - RACS (Marine)
- Institute of Hydrology, Wallingford - RACS (Freshwater)
- University of East Anglia - RACS (Atmospheric)
- Institute of Terrestrial Ecology, Monks Wood - BIOTA Data Centre
- British Geological Survey, Keyworth - LOEPS, DATA Core Programme
- Nerc Data Centres Home Page and Index

Other LOIS Related Pages

Number of visits - 343

Last modified: 06 December, 2000

F.2 LOCAR NERC WEBPAGE

Lowland Catchment Research (LOCAR)

Welcome to the LOCAR website. These pages give details of the NERC thematic programme entitled "Lowland Catchment Research". LOCAR will undertake detailed, interdisciplinary programmes of integrated hydro-environmental research relating to the input-storage-discharge cycle and in-stream, riparian and wetland habitats within groundwater dominated systems. NERC has allocated £7.75 million to the LOCAR programme over five years.

A key component of LOCAR is to establish high quality field research facilities in contrasting permeable lowland catchments. This will be carried out in partnership with a £2m Joint Infrastructure Fund award in this area. The installation of the LOCAR infrastructure will commence as soon as a project manager is appointed. Negotiations are currently being carried out..

Any queries about this thematic programme should be addressed to the Programme Administrator: Dr A M McFarlane, NERC, Polaris House, North Star Avenue, Swindon SN2 1EU (01793 411777, ammcf@nerc.ac.uk).

- HOME
- PROGRAMME SUMMARY
- STEERING COMMITTEE
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- LATEST NEWS! - **last updated 24/8/00**
- PROGRAMME OBJECTIVES
- ORIGINAL PROGRAMME PROPOSAL

Last updated 24th August 2000

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NATURAL ENVIRONMENT RESEARCH COUNCIL

NATURAL ENVIRONMENT RESEARCH COUNCIL

PROPOSAL FOR A NERC THEMATIC PROGRAMME IN LOWLAND CATCHMENT RESEARCH (LOCAR) 1999-2004

What follows is the original proposal for funding of a thematic programme in Lowland Catchment Research. NERC Council has allocated £7.75m to this programme over a five year period. Please read this document in conjunction with the programme summary and objectives, which have more recently been agreed by the Steering Committee.

SUMMARY

1. Lowland permeable catchments contain vital groundwater resources and important aquatic habitats at the groundwater/surface water interface that are becoming increasingly subject to widespread and complex environmental pressures. The scientific understanding necessary to achieve environmental sustainability in lowland catchments is limited by a lack of catchment research facilities and an integrated science base. This has been recognised by NERC and TFSTB in their 1998 Strategy for Science and by recent strategic reviews of the water sector.

2. LOCAR will undertake detailed, interdisciplinary programmes of integrated hydro-environmental research relating to the storage-discharge cycle and groundwater-dominated aquatic habitats. An essential requirement is to establish high quality field research facilities in contrasting permeable lowland catchments.

3. The research programme has two main themes:

Measurement and modelling of the processes controlling the transfer of water and pollutants within permeable catchment systems and their associates aquatic habitats at different spatial and temporal scales, for different land uses and in different geomorphological settings.

Response of permeable lowland systems to direct and indirect anthropogenic influences, through the development and application of integrated models.

It will address the following questions:-

- **(a) What are the key hydrological processes controlling surface water-groundwater interactions and the movement of groundwater in lowland catchments?**
- **(b) What are the key physical, chemical and biological processes operating within the valley floor corridor which affect the surface water and groundwater ?**
- **(c) How do varying flow regimes control in-stream, riparian and wetland habitats?**
- **(d) How does land use management impact on lowland catchment hydrology, including both water quantity and quality?**
- **(e) How can the hydrological, hydrogeological, geomorphological and ecological interactions resulting from natural or anthropogenic changes be predicted using integrated mathematical models?**

4. The long-tem deliverables from the programme will include improved characterisation of subsurface flow and transport processes, improved knowledge of the impacts of land use and land use change, better understanding of the hydrological controls on stream and wetland ecology, and new holistic methods to evaluate the impacts of natural and anthopogenic change on lowland catchment systems.

5. LOCAR will provide unique long-term outdoor research facilities to bring together a range of environmental scientists. It will also promote national and international collaborations. The results of the LOCAR programme will form the scientific underpinning for the development of added value applied research that the water regulators and water industry will require to implement the forthcoming EU Water Framework Directive.

PROPOSAL FOR A NERC THEMATIC PROGRAMME IN LOWLAND CATCHMENT RESEARCH

(LOCAR) 1999-2004

1. BACKGROUND TO AND RELEVANCE OF THE PROPOSED THEMATIC PROGRAMME

1.1 Rationale

Lowland catchments in the UK are subject to a complex set of environmental pressures and associated management problems, and yet research has generally been fragmented and often site-specific, undertaken on a reactive basis to operational problems. There are important gaps in understanding of the fundamental hydrological, geomorphological and ecological processes in lowland catchments. But, above all, there is an urgent need to develop new interdisciplinary science, to understand the interdependence of processes and illuminate the complex contemporary issues of environmental management.

This requires high quality experimental facilities at catchment scale as a focus for integrated interdisciplinary research. The Plynlimon experimental catchments (the headwaters of the Wye and Severn) have been highly successful in providing such a focus for the upland environment dominated by surface water response. There are no comparable facilities in lowland Britain. A primary aim of this programme is therefore to establish such facilities as a basis for long term research, and hence to develop a focussed, multi-disciplinary research programme which will address important scientific gaps and promote new, integrating science.

It is in lowland catchments overlying a permeable geology that environmental problems are greatest and the lack of an adequate science base the most marked. The main thrust of this programme is therefore on permeable lowland catchments. However, within the programme the opportunity will be taken to compare permeable and impermeable responses within the designated experimental areas.

1.2 Relevance to environmental management

In lowland permeable catchments, groundwater is commonly a major influence on river flows and a major resource. Groundwater contributes over 50% of mains water supply over eastern, central and southern England, supports dry-weather flows in streams of significant environmental and/or amenity value and sustains numerous wetland habitats. Important issues of water resource management and environmental protection arise, as highlighted for 'over-abstracted' catchments. Abstractions from the main UK aquifers have almost doubled in the last 50 years and must be balanced against the environmental impacts of reduced streamflows, including changes to stream sediments and vulnerable ecosystems. Recent surveys report that 42% of river habitats have suffered from water abstractions and urbanisation, and up to 100 wetlands are at risk of drying out. Water demand could increase by 20% by 2020. Response to environmental stresses, including possible climate change, must be set in the context of an understanding of the effects of climatic variability.

Changing agricultural policies and practice and the growth of urban development result in land-use change which has a direct impact on both the quantity and quality of surface and ground waters. For example, it is said that 4 million new homes will be required by 2016. Water quality problems are diverse. They range from the diffuse impacts on surface and groundwater of agricultural fertilisers and pesticides, to the site-specific disposal of liquid and solid wastes by land application, landfill or discharges to streams.

1.3 Scientific needs and programme objectives

The lack of an integrated science base for lowland catchments has been recognised by NERC, in its 1998 Strategy for Science, and by TFSTB, in its 1998 Strategy for Terrestrial and Freshwater Sciences, in addition to numerous recent national and European reviews within the water sector (Appendix 1). These include the House of Commons Environment Committee (1996), the UK Round Table on Sustainable Development (1997) and the European Commission (1997). There is limited understanding of the underlying surface and subsurface hydrological processes and their interactions, the effects of land use change on water, sediment and solute fluxes, the associated transport and degradation of contaminants, the hydrological controls on ecological systems, in particular with respect to aquatic, riparian and wetland habitats, and the effects of climatic variability. Integrated models are required to provide a focus for integrated science and to combine understanding of process interactions for predictive studies. All of these aspects have been recognised as priority areas by the TFSTB, and the need for experimental facilities for integrated research has been explicitly endorsed.

The Programme will address the following scientific questions:

1. **What are the key hydrological processes controlling surface water-groundwater interactions and the movement of groundwater in lowland catchments?**
2. **What are the key physical, chemical and biological processes operating within the valley floor corridor which affect the surface water and groundwater?**
3. **How do varying flow regimes control in-stream, riparian and wetland habitats?**
4. **How does land use management impact on lowland catchment hydrology, including both water quantity and quality?**
5. **How can the hydrological, hydrogeological, geomorphological and ecological interactions resulting from natural or anthropogenic changes be predicted using integrated mathematical models?**

The long-term deliverables from the programme will include improved characterisation of subsurface flow and transport processes, improved knowledge of the impacts of land use, better understanding of the hydrological controls on stream and wetland ecology, and new holistic methods to evaluate the impacts of natural and anthropogenic change on lowland catchment systems.

1.4 Environmental policy, integrated management and the science base

The need for integrated management has been identified by the Environment Agency, through its LEAP (Local Environment Agency Action Plan) process as playing a major role in the future development of resource management policies. Also of major significance is the development by the CEC of its Water Framework Directive, the principal objective of which is protection of the environment. It highlights the need for the protection of ecological quality and the integrated protection and management of groundwater, focussing on the need for integrated treatment of surface and groundwater systems, and an understanding of their controls on ecological systems - issues which are central to this Thematic Programme. The timetable to initiate preparation of plans to meet the Directive is 2004. The science developed within this Thematic Programme will provide important support to effective implementation of the Directive, and it is therefore urgent, timely and of national strategic importance.

2. SCIENTIFIC OBJECTIVES

The proposed programme aims to improve the science required to support current and future management needs through an integrated and multi-disciplinary experimental and modelling programme.To provide focus, integration of effort and critical mass, the programme will be primarily concentrated on two or more small to medium-sized (of order 250km^2) experimental research catchments, located on major aquifer systems, including both permeable and impermeable subareas for comparative analysis. These will be long term facilities, supplemented by additional representative research sites to enable the benefits of comparative studies to be realised. The insights expected will be transferable to improved management of larger systems through model application. However, it is beyond the scope of this programme to address formally specific larger scale problems such as the management of large river floodplains and major hydrogeological units.

An important feature of permeable catchments is the dependence of the washland, riparian and aquatic environments on the interaction of surface and sub-surface processes, and one of the major challenges is to create a framework for the holistic modelling of these interactions which combines the expertise of the hydrological, hydrogeological, geomorphological and ecological research communities. Central to the catchment response (and its management) is the functioning of the groundwater system, recharged from the near-surface soil-vegetation system, and discharging to the stream. However, these interactions map onto a complex spatial pattern, which itself must be understood to determine, for example, the importance of valley bottom corridors in terms of sediment and nutrient fluxes, and habitat continuity and diversity. The scientific challenges relating to the need to develop understanding of component processes are outlined below. However, above all, integration is required across the disciplinary boundaries, to bring together improved understanding in an accessible way to inform and support management decisions.

2.1 Integrated modelling of hydrological, hydrogeological, geomorphological and ecological interactions

As noted above, a key element of the programme is the need for interdisciplinary integration. It is also important to note that natural catchments are complex and unique; simple replication is not possible in experimental research at catchment scale. Hence modelling has several important roles to play. Development of integrated models is required to provide an intellectual framework for interdisciplinary synthesis and experimental design. Application of models is an essential element of the analysis of complex data, including the representation of the long-term history of climatic variability and land-use change. And it is through modelling that the scientific insights from the experimental catchments will be transferable. Additionally, an essential requirement for the success of the programme in terms of support to users is the development of improved modelling tools to inform and support the integrated management of lowland catchment systems. Specific areas of science required to support this are outlined in sections 2.2 to 2.5 below. Important interdisciplinary developments include improved representation of the interaction between surface water and groundwater in terms of both flow and quality, the transfer of sediment and pollutants and the impact of land use management change, and the linkage of responses of aquatic, riparian and wetland biota to changes in hydrological regime, and hence to catchment management strategies and climatic variability.

2.2 The near-surface environment - runoff, recharge and sediment transport

Integrated catchment modelling must represent soil and vegetation interactions and their effects on water quantity and quality. The water balance is strongly influenced by surface vegetation, yet the effects of changing land use and changing agricultural and forestry management practices are poorly characterised. Agricultural management may have important implications for water quality, in terms of application to land of inorganic and organic fertilisers, the management of wastes, and soil erosion. There is increasing awareness of problems associated with surface transfer of sediment and sediment-associated contaminants to watercourses, yet surface pathways for transfer of sediment in permeable catchments have received little close attention. The delivery of fine sediment has great significance for in-channel storage of fines, which can have a deleterious effect on fisheries and may carry a high pollutant load. Urban development, in particular proposed new town developments such as Micheldever Station, can have a dramatic effect on surface hydrology, and stream quality; innovative management of water and wastes is required.

The primary natural recharge to the groundwater system occurs as residual percolation from vegetated soils, and transmission through the unsaturated zone is of crucial importance to the timing of groundwater response and the rate of downward migration of diffuse and point-source pollutants. However, unsaturated material properties are poorly characterised, especially for dual porosity media such as the chalk, and large uncertainty remains concerning the role of macropore and fissure flow paths in the mainly unsaturated recharge process. Aquifers are highly vulnerable to pollution, and improved science is needed to underpin the modelling required, for example, for aquifer protection from point and diffuse source pollutants.

2.3 Groundwater hydrological processes in lowland catchments

A basic requirement for integrated modelling is to characterise flow and solute transport in groundwater systems. Despite a long history of research, it remains the case that flow and transport processes in major aquifers such as the Chalk and Triassic Sandstone are poorly understood, as are the relationships between flow and transport properties determined at different scales (i.e.pore/borehole/catchment scale). Indeed, the UK lags seriously behind the USA and other European countries in intensively monitored research sites focussed on flow and transport processes. Heterogeneity is a dominant influence on contaminant dispersion, and yet is inadequately characterised for the major UK aquifers; in the Chalk and Sandstone this is further complicated by fissure flow. The role of drift deposits in influencing recharge and pollutant pathways is poorly characterised. Aquifer protection requires innovative research and improved representation of these processes in model applications. Similarly chemical interactions require an understanding of pore and fracture scale processes, their heterogeneity and scaling properties. The role of, and constraints on, microbial degradation are largely unknown, and hence the scope for natural attenuation of organic and inorganic pollutants. The aims of 2.3 are consistent with NERC's Earth Sciences Strategy priority theme on the long term fate of pollutants, and the 1995 Groundwater Forum strategic review (Grey *et al.*, 1995). Aquifer characterisation studies will provide pilot data for BGS's proposed initiative on the DGSM (Digital Geoscience Spatial Model).

2.4 Physical and chemical processes within the valley floor corridor

For permeable catchments, groundwater is the dominant source of streamflow, although both influent and effluent reaches are likely to occur. The hydraulic interaction between groundwater and stream channel and its temporal and spatial variability is poorly understood, and is a critical component in modelling the hydrology of permeable catchments. These interactions are also important in terms of in-channel sedimentation processes and hence the aquatic ecosystem in general, and fisheries in particular. Stream-bed biogeochemical interactions are important in the context of nutrients and pollutants, but the hydrochemical processes in aquifer-river exchange zones and in the hyporheic zone are largely unknown. In-stream water quality has received little attention with respect to spatial and temporal variability and sediment and groundwater interactions.

As noted above, the spatial functioning of the surface system must be mapped onto an understanding of surface water/groundwater interactions. Issues include the definition of sediment and nutrient storages and fluxes within and between the sectors which characterise the valley-floor corridor (i.e. the spring-head, permanent stream, riparian zones and washlands, and the underlying valley-fill deposits), and the functioning of the extended channel network in terms of ephemeral linkage of hillslopes and headwater channels.

2.5 In-stream, riparian and wetland habitats and their dependence on flow regimes

Rivers in lowland catchments on permeable strata are, naturally, the most productive and biologically diverse in the UK. However, because of a number of factors, including over-abstraction, these attributes, in particular for chalk streams, are under threat. In order to develop appropriate management practices to comply with the CEC directive on ecological quality of waters and at the same time optimise use of groundwater resources, improved understanding of the fundamental science controlling the dependence of aquatic ecosystems on flow regimes and water quality is required. Habitat suitability varies temporally at a range of scales, from individual flood or drought events, through seasonal change to inter-annual time scales. Important and poorly understood aspects include the relative importance, for in-stream, riparian and floodplain biota, of habitat fragmentation under extreme conditions and the interaction between flow, sediments and habitat suitability. For integrated modelling, the influence of flow regime on populations and communities at key life-cycle stages is required.

The near-stream environment is of particular importance for wetland habitats, which are often of special scientific interest, and little is known of the hydrological controls on these habitats, or of evaporation from riparian vegetation and its impact on water balances. Streams may have seasonally varying source emergence, the interannual variability of which is likely to have major ecological importance and yet be strongly influenced by groundwater management. Groundwater-fed wetlands are also under threat from groundwater abstraction, and similarly, hydrological controls on wetland ecology are poorly understood. Integrated hydro-ecelogical modelling must build in improved science in these areas.

3. BROADER PROGRAMME OBJECTIVES

As discussed above, specific areas of science have been defined (section 2), in the context of providing an underpinning science base for the requirements of the UK and CEC for ecological protection within a framework of sustainable and integrated river basin management (section1). In addition, an important objective is to establish flagship sites as a basis for long-term monitoring, to provide the necessary data- bases to define natural variability and response to environmental change.

The necessary scientific development can only occur by building strong inter-disciplinary links, and priority will be given to interdisciplinary proposals. Capacity building is an important performance objective, and will equip the UK research community to maximise opportunities for international collaboration and to bid in to international initiatives. In addition, training will be required to provide the expertise needed for integrated catchment management.

4. RELEVANCE TO SECTORAL/NERC SCIENCE STRATEGIES

The relevance of the LOCAR programme to sectoral strategy has been described in section 1 above, and reference made to the 1998 NERC, ESTB and TFSTB strategy documents. The latter explicitly endorses the concept of a lowland experimental research facility and identifies 3 key scientific challenges, which are wholly consistent with the aims of LOCAR, namely improved understanding of surface-groundwater interactions and sub-surface controls of evaporation and runoff, of relationships between river flows and aquatic habitats, and interactions between biogeochemical and hydrological processes and sediment fluxes. LOCAR is particularly relevant to three priorities identified recently by the TFSTB: hydrological processes, freshwater biodiversity and impacts of global change. It is also relevant to the ESTB priority themes on the long-term fate of pollutants and the dynamics of climatic and environmental change.

The programme has an integrated, multi-disciplinary research approach consistent with the NERC Mission Statement and incorporates activities that are compatible with the Strategic Aims of the NERC, such as improved understanding and prediction of environmental processes, data-basing activities, user community involvement, training, and the development of new tools and new scientific facilities. Having strong links between hydrology, hydrogeology, geomorphology and freshwater biology, the programme will contribute towards addressing the recent NERC SWOT analysis.

LOCAR is relevant to all five major issues on the environmental and natural resources agenda: biodiversity; environmental risks and hazards; global change; natural resources and management; and pollution and waste. Greatest emphasis is placed on pro-active techniques to underpin management strategies for threatened freshwater habitats in groundwater dominated river systems (Priority 1), planning for drought situations (Priority 2), and in particular on integrated studies of the full hydrological cycle of lowland rivers (Priority 4).

5. RESEARCH PROPOSED/SERVICE PROVIDED: THE FLAGSHIP EXPERIMENTAL SITES

A primary focus is on the development of high quality experimental catchment facilities. Within the context of lowland permeable catchments, a single site would not be sufficient to address all issues satisfactorily. It is envisaged that experimental sites will be needed in the outcrop areas of at least the two most important aquifer systems, the Chalk and Permo-Triassic Sandstones. The focus will be in establishing densely instrumented catchments for integrated research, supplemented by additional sites as necessary for comparative studies or to investigate scale-dependent effects. Comprehensive monitoring programmes will be developed at the 'flagship' sites to address the requirements of each of the science objectives, involving substantial capital investment and support for monitoring and data acquisition systems. An integrated programme of detailed experimental and modelling research will build on these facilities. This will require a particularly careful programme of experimental design and programme management.

It is likely that flagship sites will be selected in the South and the Midlands of England; the Pang/Lambourn catchments in the West Berkshire Downs are under consideration, as is the river Tern, a tributary of the R.Severn in Shropshire. These will allow detailed experimental programmes to build on long-term hydrological records of rainfall, river flow and groundwater levels. It should be noted that some subcatchments of the Tern and parts of the Pang/Lambourn catchments include significant drift cover. This therefore allows direct intercomparison of permeable and impermeable sites on the same underlying geology. The Dorset Frome will be included as an additional site, given its unique data-base of aquatic ecology. These various locations include numerous SSSI's and a RAMSAR site and their incorporation would build on existing UK and EU funding. It is expected that substantial support in provision of basic monitoring networks will be available from end-users. Additional locations could be included with appropriate end-user support, including a wetland site in East Anglia.

6. UTILITY AND BENEFICIARIES

The programme will have direct benefits to water and environmental management through the provision of improved process understanding, the development of improved ecological criteria to define ecological quality objectives, and the development of integrated modelling techniques and expertise. Beneficiaries include the Environment Agency, the Water Utilities, a wide range of governmental and non-governmental conservation bodies, planning bodies, and not least the general public.

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APPENDIX 1

Recent reviews within the water sector which highlight the need for research over a range of strategic issues in permeable lowland catchments include:

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Lowland Catchment Research (LOCAR)

Programme summary

1. Lowland permeable catchments contain vital groundwater resources and develop important aquatic habitats at the groundwater/surface water interface. Both are becoming increasingly subject to widespread and complex environmental pressures. The scientific understanding necessary to achieve environmental sustainability in lowland catchments is limited by a lack of catchment research facilities and an integrated science base.

2. LOCAR will undertake detailed, interdisciplinary programmes of integrated hydro-environmental research relating to the input-storage-discharge cycle and in-stream, riparian and wetland habitats within groundwater dominated systems. An essential requirement is the establishment of high quality field research facilities in 3 contrasting permeable lowland catchments - the Pang/Lambourn, Tern, and Frome/Piddle.

3. The research programme has two main themes:

- Measurement and modelling of the processes controlling water and material fluxes within permeable catchment systems and their associated in-stream, riparian and wetland habitats at different spatial and temporal scales, for different land uses and in different geomorphological settings.

- Predicting the response of permeable lowland systems to direct and indirect anthropogenic influences, through the development and application of integrated models.

It will address the following questions:-

(a) What are the key hydrological processes controlling surface water-groundwater interactions, the movement of groundwater, and material fluxes in lowland permeable catchments?
(b) What are the key physical, chemical and biological processes operating within the valley floor corridor which affect the surface water and groundwater?
(c) How do varying flow regimes control in-stream, riparian and wetland habitats?
(d) How does land use management impact on lowland catchment hydrology, including both water quantity and quality, and wetland ecology?
(e) How can the hydrological, hydrogeological, geomorphological and ecological interactions resulting from natural or anthropogenic changes be predicted using integrated mathematical models?

4. By addressing the above questions this programme will lead to improved characterisation of subsurface flow and transport processes, improved understanding of the impacts of land use and land use change, better understanding of the hydrological controls on stream and wetland ecology, and the development of integrated methods to evaluate the impacts of natural and anthropogenic change on lowland catchment systems.

5. LOCAR will provide unique long-term outdoor research facilities to bring together a range of environmental scientists. It will also promote national and international collaboration. The results of the LOCAR programme will form the scientific underpinning for the development of added value applied research that the water regulators and water industry will require to implement sustainable management and the forthcoming EU Water Framework Directive. This understanding will support the development of future approaches to the sustainable management of permeable catchments.

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NATURAL ENVIRONMENT RESEARCH COUNCIL

Lowland Catchment Research (LOCAR)

Programme objectives

The LOCAR programme aims to improve the science required to support current and future management needs for permeable lowland catchments through an integrated and multi-disciplinary experimental and modelling programme.

Scientific Aims:

- To develop an improved understanding of hydrological, hydrogeological, geomorphological and ecological interactions within permeable catchment systems, and their associated aquatic habitats, at different spatial and temporal scales and for different land uses;
- To develop improved modelling, database and GIS tools to inform and support the integrated management of lowland catchment systems.

These aims will be achieved through the study of:

a. The surface and near-surface environment - runoff, recharge and material transport;
b. Groundwater processes in lowland catchments;
c. Physical, chemical and biological processes within the valley floor corridor;
d. In-stream, riparian and wetland habitats and their dependence on flow regimes;
e. The impacts of society on the natural environment.

Broader Programme Objectives:

- To provide an underpinning science base for the requirements of the UK and CEC for environmental protection within a framework of sustainable and integrated river basin management;
- To establish flagship sites as a basis for long-term monitoring, to provide the necessary data to define natural variability and response to environmental change;
- To build strong inter-disciplinary links so as to better harness the science skill base to tackle problems of national importance;
- To promote research collaboration between universities, research institutes and user groups such as regulators and water utilities;
- To equip the UK research community in order to maximise opportunities for international collaboration and to contribute to international initiatives;
- To provide training in the scientific expertise required for integrated catchment management;
- To disseminate and exploit the research outputs effectively through close collaboration with users, workshops, seminars and the WWW, as well as through the usual channels;
- To provide suitable and effective data stewardship.

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Lowland Catchment Research (LOCAR)

Installation Management:

One aspect of the LOCAR programme is to create three instrumented catchments. It is important that the installation of the appropriate equipment and facilities is managed in a coordinated manner. Therefore, the NERC has sought tenders for the project management of the installation work. Negotiations are currently underway with the preferred organisation(s).

Progress towards catchment instrumentation

The LOCAR Steering Committee has agreed to proceed with a programme (worth approximately £5 million) of equipment installation and maintenance in the three flagship catchments, the Frome/Piddle in Dorset, the Pang/Lambourn in Berkshire and the Tern in Shropshire. The funding comes jointly from a JIF grant to a consortium of universities and institutes, led by Professor Howard Wheater of Imperial College, and from the £7.75 million allocated to the LOCAR thematic programme. The goal of the instrumentation is to provide:

- baseline monitoring of the distribution of fluxes in time and space within each of the catchments;
- possibilities of a medium- to long-term appraisal of the changes with time of these fluxes that can be related to changes in climate, catchment land use and land management practices;
- ways of establishing the nature of the processes involved in stream flow generation, especially by surface-groundwater interactions in riparian zones;
- basic data that can be used to calibrate and validate integrated hydrological, hydrochemical, hydrogeological, geomorphological and ecological models of the catchments that can be used predictively for catchment management schemes and to assess the impacts of environmental change.

The variety of existing facilities in the flagship catchments

The three catchments vary in geological and ecological characteristics, but all have considerable existing instrumentation and facilities that the £5 million investment will augment and extend. The main catchments range in size from 234.1 km^2 for the Lambourn at Shaw to 852 km^2 for the Tern at Walcot, with gauged sub-catchments ranging in size down to 5.1 km^2 on the Wool Stream in the Frome catchment and 15.7 km^2 on the Platt Brook tributary of the Tern. Existing groundwater instrumentation ranges from little in the Frome, to the dense borehole networks of the Shropshire Groundwater Scheme in the Tern and the Environment Agency's 124 boreholes in the Pang/Lambourn catchments. While the Pang/ Lambourn system has a wealth of hydrological and hydrogeological data and the reach of the Lambourn at Bagnor has been the subject of one of the most intensive long term ecological studies on any river in the UK, the River Laboratory of the Institute of Freshwater Ecology on the Frome, the last natural salmon chalk stream in the UK, provides unique facilities for hydro ecological research.

The new instrumentation in the flagship catchments

The new instrumentation will involve improvements to existing facilities and extra instrumentation, particularly to support interdisciplinary investigations of surface-groundwater interactions in riparian zones and wetlands at perennial stream heads. Detailed piezometer and borehole arrays will be established at key sites on the Pang and Lambourn. In the Tern, the existing Shropshire Groundwater Schemes borehole network will be extended to other parts of the catchment. Improvements to the River Laboratory on the Frome are underway.

Particular attention will be paid to characterising the evaporation and soil moisture recharge in the three catchments. Automatic weather stations will be added to the existing meteorological networks. Water quality data will be acquired for approximately 8 surface water sites and 20 groundwater sites in each catchment. New staff for each of the three catchments will be appointed to manage the routine data collection and to maintain the installations. All the data from the programme is likely to be managed at the Data Centre at the Centre for Ecology and Hydrology at Wallingford.

Progress towards an announcement of opportunities within the LOCAR thematic programme

Detailed project design for the installation of the equipment will be initiated as soon as possible. However, this cannot commentce until a project manager is in place (see above). Some of the equipment can be installed relatively rapidly, but major installations requiring planning permission and other consents will take many months. Full installation may not be complete for 18 to 24 months from the commencement date.

NERC and the Steering Committee are anxious to attract the highest quality proposals for work in this programme. The facilities will be world-class and will offer a unique opportunity for interdisciplinary research, including process studies linking all the fluxes of the water balance to land use, geological and ecological conditions. Developing, calibrating and validating models capable of supporting catchment management decision making at the scale of these catchments will require both intensive process studies and careful up-scaling analyses to deal with the complexity of these intensively used areas.

There is much research that can be started on these catchments in the LOCAR thematic programme relatively soon. As soon as the installation project design is completed to the satisfaction of the Steering Committee, and the Committee is able to give dates on which specific facilities will become available, a notice of research opportunities will be issued as quickly as possible.

Further information

In the meantime, interested researchers who would like to know more about these plans are invited to contact the LOCAR Science Coordinator, Professor Ian Douglas at:

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Lowland Catchment Research

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Prof Keith A Browning	University of Reading
Mr Brian Connorton	Thames Water
Prof Angela Gurnell	University of Birmingham
Dr Alan Gustard	Centre for Ecology and Hydrology
Prof Alan Hildrew	Queen Mary & Westfield College
Mr Peter Herbertson	Environment Agency
Prof John Hilton	Centre for Ecology and Hydrology
Dr Tim Malthus	University of Edinburgh
Dr Mike Owen	Environment Agency
Dr Denis Peach	BGS
Prof Des E Walling	University of Exeter
Prof Howard S Wheater	Imperial College
Professor Ian Douglas *(Science Co-ordinator)*	University of Manchester
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F.3 CHASM - Newcastle University Webpage

CHASM : Catchment Hydrology And Sustainable Management

A major UK initiative in catchment research

CHASM

- CHASM is a framework for a long-term programme of catchment research which presently involves UK universities, research institutes, and end-user organizations; it is planned to extend it internationally
- CHASM will be implemented through a series of research projects to be funded from various sources (UK research councils, EC etc.)
- The first major project to be funded is NICHE (National Infrastructure for Catchment Hydrology Experiments). Joint Infrastructure Fund (JIF) funding of £4M has been approved for catchment instrumentation

2

Key Issues

- The vast majority of catchment experiments have been conducted at the small scale (<10 km^2); only limited aspects of hydrological understanding can be transferred to larger scales (the scale issue)
- The range and intensity of anthropogenic influences within catchments is increasing and impacts are not fully understood, particularly in relation to ecological diversity and biogeochemical cycling
- A better understanding is needed of how catchments are likely to behave under future climatic conditions
- Sustainable management plans for catchments need to be underpinned by good scientific understanding, particularly of the influences of abstractions on the hydrological and ecological regimes of catchments

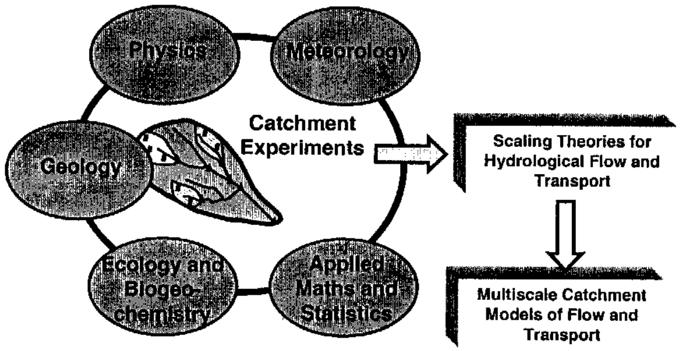
3

Key Elements of CHASM

- A new focus on mesoscale (~100 km^2) catchment research to bridge the CHASM (!!) between the typical scale of past experimental catchment research (~10 km^2) and the catchment scales which are the focus of sustainable management issues
- A major assault on the scaling issue, with new scaling theories to be developed and tested using multiscale experiments
- a set of *n* mesoscale nested catchment experiments which
  - (a) sample heterogeneity in rainfall/topography/soils/vegetation/geology comprehensively, and
  - (b) cover a range of anthropogenic impacts
- A scientific platform for new developments in hydroecological research

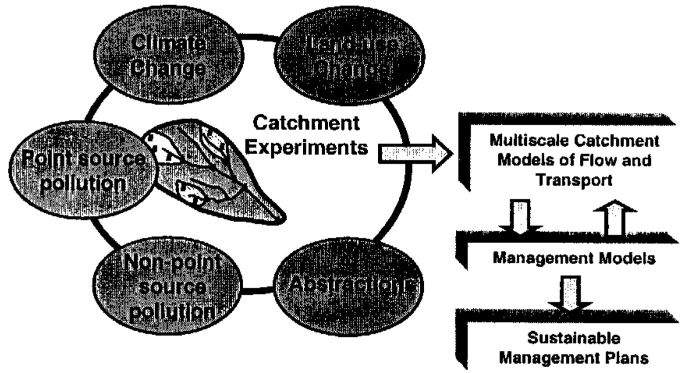
4

Science for Sustainable Management



5

Planning for Sustainable Management



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NICHE Project Structure

NICHE
National Infrastructure for Catchment Hydrology Experiments

NICHE-CHASM
Catchment Hydrology And Sustainable Management
4 catchments

Co-ordinator:
Prof. P.E. O'Connell
University of Newcastle upon Tyne

NICHE-LOCAR
LOwland CAtchment Research
3 catchments

Co-ordinator:
Prof. H. Wheater
Imperial College

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NICHE-CHASM Partner Organisations

Uni. Of Newcastle	Prof PE O'Connell (co-ordinator)
Uni. Of Aberdeen	Dr C Soulsby
Uni. Of Dundee	Prof A Werrity
Uni. Of Durham	Prof T Burt
Uni. Of Lancaster	Prof K Beven
Uni. Of Leeds	Prof M Kirkby
Uni. Of Ulster	Prof DN Wilcock
Institute of Hydrology	Prof JS Wallace
Institute of Freshwater Ecology	Prof AD Pickering

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NICHE-LOCAR Partner Organisations

Imperial College	Prof HS Wheater	(co-ordinator)
Uni. Of Birmingham	Prof GE Petts	
Uni. Of Exeter	Prof DE Walling	
Institute of Hydrology	Prof JS Wallace	
Institute of Freshwater Ecology	Prof J Hilton	

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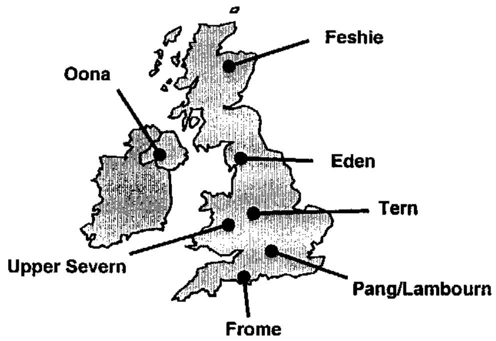
NICHE Catchments



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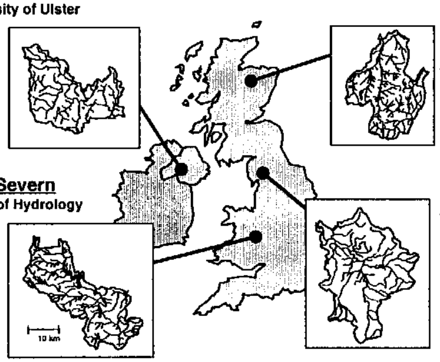
NICHE-CHASM Catchments

Oona Water
University of Ulster
92 km²

Upper Severn
Institute of Hydrology
187 km²



Feshie
University of Aberdeen
University of Dundee
200 km²

Eden
University of Newcastle
University of Lancaster
University of Durham
University of Leeds
Inst. of Freshwater Ecology
337 km² + 90 km²

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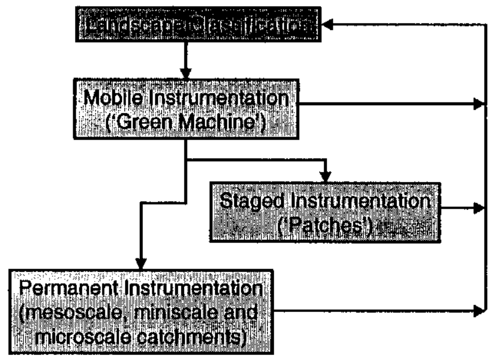
Experimental Design



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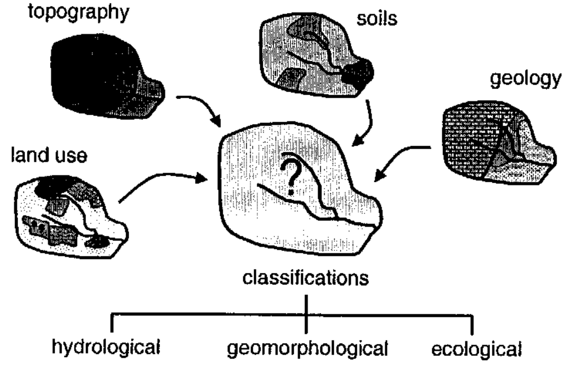
Landscape Classification



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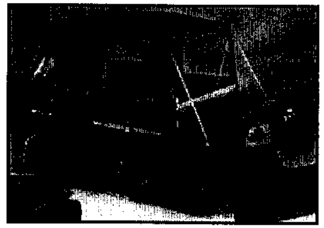
Mobile Instrumentation

- Rapid surveys (prior to installation of staged instrumentation, and for landscape classification)
- Lightweight all-terrain vehicle ('Green Machine'), with
  - drilling rig
  - differential GPS
  - surface geophysics



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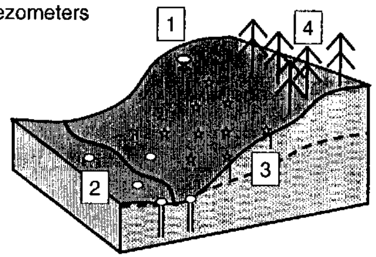
Staged Instrumentation

1 Raingauge
2 Nested multi-level piezometers
3 Soil moisture probes
Tensiometers
Gypsum blocks
suction lysimeters
4 Interception gauges
Sap flow meters



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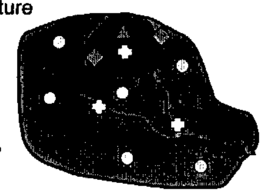
Permanent Instrumentation

- ▲ River gauging stations with nested structure
- ■ Observation boreholes and river-aquifer experiments
- ○ Hydrometeorological stations and raingauges
- ◇ Hillslope instrumentation (runoff troughs, lysimeters)
- ▲ Suspended sediment and water quality monitors
- ✣ Ecological monitors (e.g. fish tracking)



Mesoscale (~100 km^2)
Miniscale (~10 km^2)
Microscale (~1 km^2)

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End-User Participation

- Catchment Management Committees (CMCs) have been set up to create a partnership of NICHE participants and end-user organizations (e.g. Environmental Agencies, Water Companies, Conservation Bodies, Government Departments etc.)
- The CMCs will
  - identify key anthropogenic issues to be investigated
  - harmonize expenditure on instrumentation to meet both research and operational needs
  - co-ordinate research projects and monitor their progress

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National Forum for Catchment Hydrological Research

- Provide wider access to NICHE infrastructure
- Promote involvement in CHASM initiative
- Discuss research strategy and priorities
- Develop thematic funding initiatives
- First meeting at BHS National Symposium in September 2000
- Ecological and geomorphological forums to be convened in subsequent years

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International Context

- The UNESCO International Hydrological Programme (IHP) has identified Experimental Hydrology as a high priority activity for the 6th phase of IHP (2002-2007)
- The NICHE catchments may be potential candidates for inclusion in the proposed UNESCO Hydrology, Environment, Life and Policy (HELP) programme
- It is planned to expand the network of CHASM catchments through international collaboration with scientists interested in participating in the CHASM initiative. Those interested should contact the CHASM co-ordinator, Enda O'Connell (P.E.O'Connell@ncl.ac.uk).

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F.4 URGENT - NERC WEBPAGE

NERC

NATURAL
ENVIRONMENT
RESEARCH COUNCIL

Earth Science
& Technology

Urban Regeneration and the Environment (URGENT)

Programme Administrator: Dr Neville Hollingworth, Earth Sciences, NERC

Scientific Steering Committee Chairman: Professor Sir Geoffrey Allen, FRS, FRSC, FEng, Kobe Steel

Overall Aim of Programme: Over 90% of the population of the UK live in conurbations covering 10% of its land area. It is estimated that, by the year 2000, half of the world's six billion people will live in cities. Many urban centres in the developed world have experienced over 150 years of industrialisation and rapid urbanisation, leaving a legacy of contamination and dereliction. This presents risks to the health of urban inhabitants and ecosystems, inhibits safe and cost-effective redevelopment and diminishes the quality of life. The challenge is to clean up the legacy of the past and institute a sustainable development regime which will avoid repetition of past mistakes and reshape the structure and use of the urban environment.

To help meet this challenge URGENT will integrate urban ecological and environmental research across the geological, terrestrial, freshwater and atmospheric sciences and will work in partnership with city authorities, industry and regulatory bodies. The programme is expected to receive NERC funding of £9.7 million over the seven years, with additional support anticipated from organisations such as the Environment Agency. URGENT aims to stimulate the regeneration of the urban environment through understanding and managing the interaction of natural and man-made processes.

Summary of Approaches: Safe and effective urban regeneration requires a sound understanding of the mechanisms and pathways of pollutant transfer between soil, air and water, and the effects on urban ecosystems. The URGENT programme will evaluate:

- the magnitude of the problems and risks in order to understand the underlying patterns and processes, and;
- strategies for remediation and management.

The programme will link with the needs of decision-makers and users concerned with reclamation, reshaping and management of the urban environment. These comprise local and national statutory authorities, industry, funders of urban redevelopment and private individuals. Their needs include:

- diagnoses and characterisation of problems in relation to natural background;
- techniques for remediation of derelict land;
- strategies for development and management within the urban environment;
- prescription of standards, guidelines and targets for meeting the needs of urban areas.

URGENT will initially focus on two or three major urban conurbations in the UK, but is expected to develop generic models and solutions which can be applied more widely in the UK and internationally.

URGENT is collaborating with other NERC programmes, such as "Environmental Diagnostics", and other Research Council-supported initiatives, such as the EPSRC "Towards Sustainable Cities" programme, and the ESRC "Cities Competitiveness and Cohesion" programme. Joint calls for proposals have been issued and strong working relationships forged with the expected promotion of a cross-Council publication on urban programmes.

Click here for details of awards

★ESTB Thematic Programmes Index

★ESTB Home Page

★NERC Home Page

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http://www.nerc.ac.uk/es/urgent.htm
by es-webmaster@nerc.ac.uk