Catchment Ecosystem Research and Development - Scoping Study

A.G. Hildrew	Queen Mary and Westfield, London
J.D. Hutchinson	Queen Mary and Westfield, London
S.J. Ormerod	University of Wales, Cardiff

Research Contractor:
Queen Mary and Westfield, London

National Rivers Authority
Rivers House
Waterside Drive
Aztec West
Bristol
BS12 4UD

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ABBREVIATIONS AND ACRONYMS

To be included once final text has been agreed.

SUMMARY

The Feasibility and Scoping Study into Catchment Ecosystem Research commenced in April 1994 and was funded by the National Rivers Authority, the Natural Environment Research Council, English Nature and the Economic and Social Research Council. It has involved a wide process of consultation with many organisations. A workshop, held in Cardiff on 14 and 15 September 1994, formed an important part of the consultation process.

The overall objective of the Study was to examine the feasibility of undertaking a programme of research and/or development on man's impact on catchment ecosystems which is both of high scientific value and of significant practical value for enabling catchments to be better managed on a sustainable basis and, if affirmative, detailed plans outlining the programme were to be produced.

During the course of the Study current scientific knowledge was reviewed and 15 key science questions were identified and prioritised using three criteria - interest, feasibility and ability. Eleven key management issues were identified and prioritised on the basis of the frequency with which issues were mentioned or ranked during consultations with managers and the frequency with which they appeared as issues in NRA Catchment Management Plans.

The science questions and management issues were matched in order to target and prioritise research and to assess whether such research should be primarily science- or user-led, or whether there was a match of interests.

Development opportunities for optimising the transfer of science into management were identified.

Five options involving various blends of further development and new research were assessed on the basis of costs, benefit, constraints and risks/uncertainties in order to identify the option producing maximum benefit for the cost involved.

It was concluded that the most beneficial option would be for a programme of Development plus a collaborative programme of multi-disciplinary research undertaken through a partnership of scientists and users. The research programme has been named CERI, the Catchment Ecosystem Research Initiative. The CERI research programme was then described more fully, including the science programme, suggestions for scientific approach and location, plus costs, timetabling and a possible management structure.

1.0 INTRODUCTION

1.1 Background

This initiative to carry out a feasibility/scoping study to investigate ways of focusing and using ecological research to improve catchment management grew partly out of a conference on the "Ecological Basis for River Management" held at Leicester University in March 1993. It became apparent to delegates that an examination of the relationship between the freshwater sciences, and the knowledge and skills needed to manage and conserve British freshwater ecosystems in a sustainable manner, would be valuable.

It is clear that the needs of management have increasingly required a complex and integrated perspective of the physicochemical, biological and socio-economic status of rivers in the face of demand for water resources, improved water quality, flood defence, fisheries, conservation, recreation and navigation (e.g. Calow and Petts, 1992; 1994; Harper and Ferguson, 1995; Boon and Howells, 1996). A perceived decline in the outputs from fundamental freshwater sciences in Britain, however, threatens to restrict the development of appropriate knowledge (Hildrew 1993). In particular, there is a perceived mismatch between the scale at which much fundamental science was carried out (short-term/small scale), and the scales that are increasingly emphasised in management initiatives (long-term sustainability over whole catchments).

River catchments provide an appropriate focus for the scientific study of freshwaters and their management (Likens 1992). Water moving through catchments is the main agent of the transport of materials and energy through terrestrial ecosystems and thus catchments integrate many of the natural and human activities on earth. They comprise a 'nested hierarchy' of physical systems, and are thus ideal models for research and management at a range of scales. Fresh waters in the catchment hierarchy are excellent natural examples of patchy, divided habitats for the organisms that live in them. Interactions between this complex, physical system and the resulting distribution of organisms, provides the potential to examine processes controlling biodiversity from the regional to the local scale.

Not surprisingly, therefore, catchments have been chosen as the main units for freshwater management by authorities throughout the world, including the new Environmental Agency in England and Wales. The present economic commitment to managing the freshwater environment is huge. In England and Wales alone the NRA spends (1993/94) £400 million on its core functions, while the private sector invested about £7 billion in the three years from 1989, mainly on water and sewage treatment.

1.1.1 Catchment Change: a paradigm

A conceptual basis for consideration of the scientific input into catchment management is shown in Figure 1.1). It displays routes through which socio-economic factors in river catchments can have ecological effects through a range of mediating sub-systems, all of which contain important resources (see Text Box 1). Changes impinge ultimately on important features, which are here called targets, including all the end benefits arising from catchment

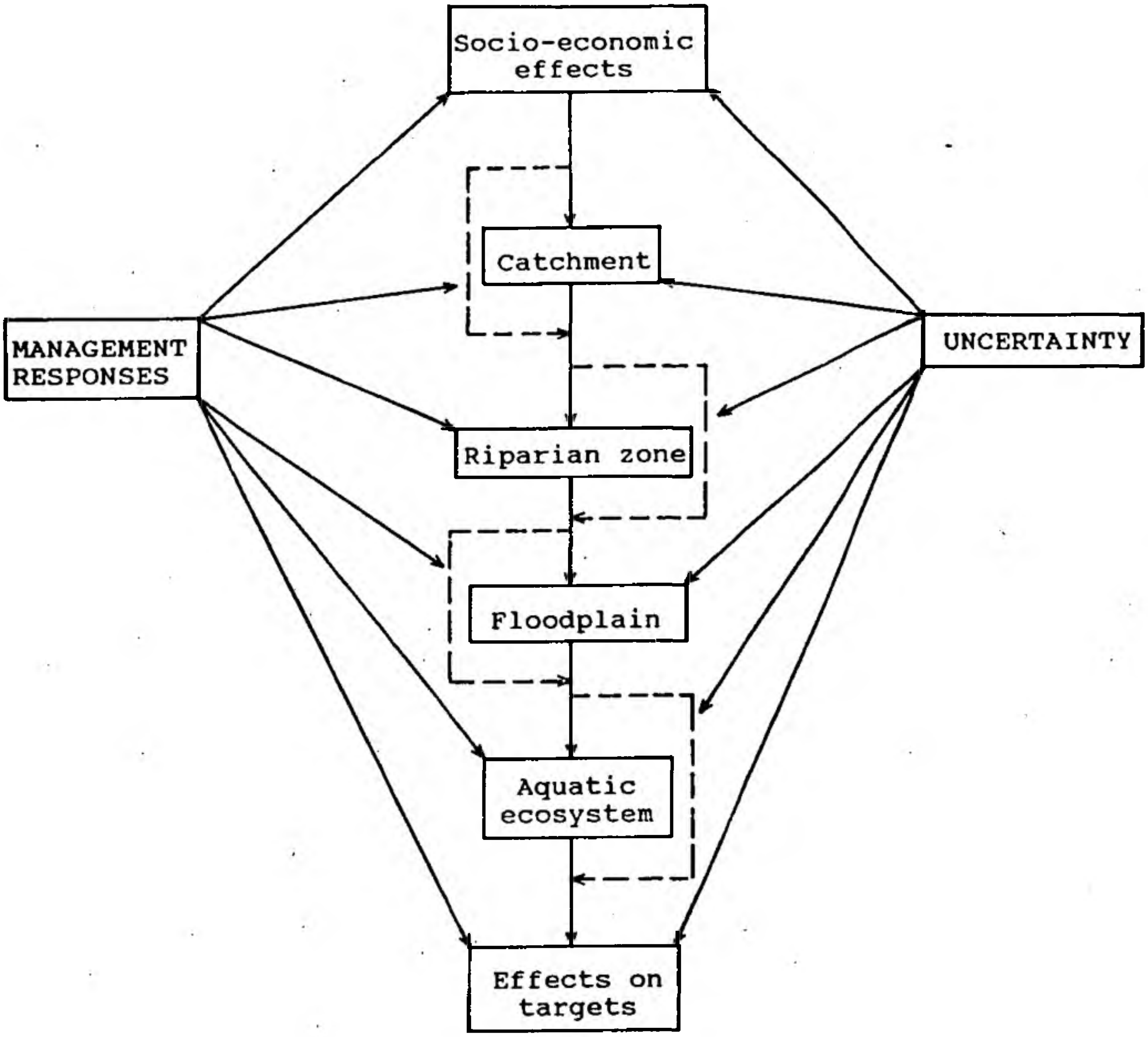

Figure 1.1 Conceptual diagram showing routes through which socio-economic changes in river catchments can have ecological effects through a range of mediating sub-systems

and river ecosystems: conservation, recreation, navigation, fisheries, avoidance of flood hazards, waste disposal, water supplies. The targets might be considered as broadly equivalent to the functions and responsibilities of the National Rivers Authority.

Catchment change: a paradigm

Figure 1.1 displays routes through which socio-economic factors in river catchments interact with natural and semi-natural features to have ecological effects through a range of mediating sub-systems. Changes impinge ultimately on important resources - called targets - which include all the resources for which we depend on catchment ecosystems.

Examples of socio-economic factors which cause change might be economic development, tourism, demographic change, urban development, or agricultural intensification and extensification. Natural and semi-natural factors which mediate change at the catchment level might include pedology, geology or altitude that, for example, influence susceptibility to acidification. In the riparian zone, factors which mediate change might include the presence, absence or character of bankside vegetation that influences stream habitat structure. In the aquatic system, mediating factors might include hydraulic residence time, which influences the extent to which nutrient additions promote increased algal production. In some cases, however, catchment changes may bypass some mediating factors, and examples are illustrated on the figure. Increased sediment loadings, from catchment erosion for example, might not be intercepted by riparian vegetation.

Through all stages, pathways of change can be energetic, chemical, physical and biological. Energetic changes include alterations in inputs to the river ecosystem of heat, light and terrestrial products; chemical changes include nutrient or pesticide additions; physical changes affect river hydrology, geomorphology and hydraulics with consequences for habitat structure; biological changes include species introductions, or altered food quality for a whole range of stream organisms.

In all these cases, the targets of change are the features and conservation attributes of the river system which exist at all ecological scales from the micro-habitat to the catchment. They might include habitat diversity, or biodiversity at genetic, species, community and landscape levels in all taxonomic groups. Conservation attributes also include the integrity of certain valued communities, the populations of individual species, and important ecological functions such as production and decomposition. Also, under the concept of sustainable use and in recognition of the economic value of rivers, important features include fish production, the quality of water abstracted directly for drinking and irrigation, or the capacity of rivers for waste disposal.

In addition, Fig. 1.1 represents an array of potential foci for management action at all levels from the potential targets (e.g. by species re-introduction programmes), through floodplain, catchment and riparian attributes (e.g. re-instating floodplain wetlands or protecting bankside buffer strips), to the impacts which drive ecological change in the first instances (e.g. reducing pesticide use). At the same time, because the forces behind much change in river catchments are socio-economic, management influence through socio-economic measures will be crucial.

In addition to outlining pathways, Figure 1.1 represents the potential foci for management action at all levels in catchment ecosystems aimed either at offsetting adverse change, promoting desirable change, or maintaining currently desirable status. At the same time, Figure 1.1 indicates that there are presently many uncertainties. In many respects, therefore, this paradigm represents both the opportunities and difficulties in the incorporation of scientific principles into catchment management. On the one hand, opportunities exist to use good science in the management of socio-economics, ecological changes, catchments, riparian zones, floodplains and aquatic ecosystems to derive a wide range of benefits, or avoid environmental costs. On the other hand, there are problems in taking these opportunities from a clear catchment perspective for reasons which include:

i) Scientific uncertainty in available knowledge;

ii) Gaps in scientific knowledge, particularly those that could form the basis of quantitative, process-orientated models that unite some or all of the components illustrated in Figure 1.1.

iii) Procedural difficulties, for example because catchment plans are widely recognised as being statements of issues, rather than true prescriptions for action relating scientific cause and effect.

iv) Organisational deficiencies, for example because use is made of river catchments for many purposes unconnected with aquatic ecosystems (such as agriculture, forestry, urbanisation, transport and tourism), and by bodies over whom river managers have little statutory influence, yet that have profound consequences for freshwaters.

v) Managerial decisions which reflect political relationships between organisations and individuals rather than purely scientific and environmental understanding.

vi) Inadequate use of scientific knowledge, or inadequate translation of available knowledge into usable 'tools';

vii) The complexity of catchment issues, coupled with a tendency for managerial decisions and science to reflect reductionism and isolated functions rather than holism and cross functional relationships.

viii) A general mis-match between what scientists deliver, and what managers need.

These themes are expanded in subsequent chapters. They indicate, however, that clear priorities in the development of catchment science, at least from the NRA and other sectors of the user community, would ideally be:

i) to provide scientific outputs of a form serviceable for management as indicated on Figure 1.1.

ii) to examine the science implicit or explicit in those tools used as part of current best practice.

iii) to evaluate scientifically the value of those tools currently used in catchment planning.

iv) to examine ways in which tools could be used more effectively.

v) to provide new tools.

1.2 The Feasibility and Scoping Study

To examine some of these issues more fully, a small working group was established and, with financial support from the National Rivers Authority, the Natural Environment Research Council, English Nature and the Economic and Social Research Council, the group commissioned a Feasibility and Scoping Study into Catchment Ecosystem Research and Development. The study began in April 1994 and was undertaken by Professor A G Hildrew and Dr J D Hutchinson (Queen Mary and Westfield College, University of London) and Dr S J Ormerod (University of Wales, Cardiff). Advice on the direction and progress of the study was given by a Steering Group, which met on seven occasions, and which consisted of the following academic scientists and managers/practitioners:

Mr M E Bramley	National Rivers Authority, Head Office
Dr J M Elliott	Freshwater Biological Association
Dr A J D Ferguson	National Rivers Authority, Anglia Region
Dr D M Harper	University of Leicester
Dr J M Hellawell	English Nature
Prof. A G Hildrew	Queen Mary and Westfield College
Dr J D Hutchinson	Queen Mary and Westfield College
Dr S J Ormerod	University of Wales, Cardiff
Prof. G E Petts	University of Birmingham
Prof. A D Pickering	Institute of Freshwater Ecology
Dr R A Sweeting	National Rivers Authority, Thames Region
Prof. P G Whitehead	University of Reading [previously NERC IH]

1.3 Aims and Objectives

1.3.1 Overall objective

The Terms of Reference of the Study are given in Appendix A[1]. The overall objective was to examine the feasibility of undertaking a programme of research and/or development on human impacts on catchment ecosystems that would be both of high scientific value and of significant practical value for the sustainable management of catchments. If affirmative, the study would produce detailed plans outlining the programme.

1.3.2 Specific objectives

The various specific objectives, and the chapters where these are discussed, are as follows:

1. Summarise the extent of present scientific knowledge and key on-going research initiatives and areas of scientific interest about river catchments (Chapters 2 and 4).

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[1] Please note: where reference is made to Appendices, these are bound into this report. Annexes are provided in a separate document which may be obtained from the R&D Coordinator, NRA Anglian Region.

2. Describe the key management issues/objectives about river catchments, including training (Chapters 3 and 6).

3. Identify the areas where greatest potential exists for achieving significant improvements in efficiency/effectiveness of catchment management, and describe the scale of benefits which would accrue from different management options (Chapters 5, 6 and 7).

4. Review options for a managed programme of research (including "do nothing") and identify the preferred option (including broad costs and timescales) (Chapter 7).

5. Identify main risks and uncertainties, and develop approaches which minimise these (Chapters 7 and 8).

6. Identify the component projects within any proposed programme. For each, set out key features, describe relevant scientific and management objectives, provide a breakdown into appropriate work packages and estimate resource requirements (Chapter 8).

7. Review options for, and propose programme/project management structure (Chapter 8).

8. Present results in the form of a feasibility report, complete with programme plans and project/package descriptions.

As a result of guidance from the Steering Group, it was decided that the feasibility study should include wide consultation with the scientific and management communities through a Workshop.

The results of consultations, designed to elucidate areas of scientific weaknesses and management concern where research could potentially provide greatest benefits (Objectives 1 and 3), produced lists demonstrating 15 main areas of scientific weakness (Table 2.1) and 37 areas of management concern (Table 3.1). These areas exhibit some overlap and were divided into several component topics. The Steering Group recognised that production of a detailed breakdown into project descriptions/work packages for each of these identified areas (Objectives 6 and 8) would be extremely complex, and consequently agreed that only the research programme would be devised at this stage (see Chapter 8 and Appendix 2 - Catchment Ecosystem Research Initiative - Thematic Programme Proposal to NERC). The detailed breakdown would be developed at the outset of any proposed research programme.

As part of the study, the project team attempted to provide a general review of the main areas of benefit and broad costs of a programme of research and development (see Chapter 7).

1.4 Approach

To satisfy specific objective 1 (see 1.3.2), which would guide all the others, the approach was to compile a database of present catchment research activities. For this purpose, information on R&D studies, projects and specific programmes was required as follows:

- NRA R&D projects,
- NERC studies and research initiatives,
- English Nature, Scottish Natural Heritage and Countryside Council for Wales projects,
- NGO/voluntary sector activities,
- research in universities and educational institutions in the UK, and
- projects being undertaken in overseas universities and institutes.

An important part of specific objective 3 was to identify the major gaps and uncertainties in catchment management and catchment science in order to identify priority target areas for potential future research and development. For this, the Project Team sought contact with as many people as possible with an interest in catchment management, the conservation of aquatic habitats, and/or academic research into catchment science in the UK and overseas, so that the views and knowledge base of this community were reflected accurately.

Letters outlining the background to the project and requesting information were sent to 177 members of the UK 'freshwater community' including representatives from the Universities, Institutes, Government Departments (MAFF, SOAFD, DoE, Welsh Office), Research Councils and potential 'End Users' (i.e. organisations which can use the outcome of scientific research in their management roles). Such End User organisations contacted during this study included English Nature, Scottish Natural Heritage, Countryside Council for Wales, the NRA, the Scottish River Purification Boards, SNIFFER, Wildlife and Countryside Link, Wildlife Trusts, RSPB, LEAF (Linking Environment and Farming), and the National Trust. [Annex 1]. The EU was also contacted (primarily on the basis of its role as a research commissioning organisation). In addition, comments were invited by letter from a further 326 relevant, overseas contacts (68.7% from USA and Canada, 18.4% from Europe, 8.3% from Australia and New Zealand, 4.6% from elsewhere, including the Far East, Africa, South America, India and Iceland) [Annex 2].

Questions varied slightly depending on whether the addressee was a fundamental scientist or a person or organisation using science in applied ways, from the UK or overseas, but, in general, covered their views on the following:

- management problems of local river systems,
- catchment-related research currently being undertaken,
- whether and, if so, how scientific knowledge obtained from research is interpreted and implemented in management and conservation activities,
- if there are any perceived gaps in scientific knowledge related to catchment management that could usefully be addressed,
- whether there are any uncertainties that could potentially be remedied by environmental research?

Details on specific site studies were requested from each respondent, as follows:

- Location of the project
- Geographical and temporal scales (i.e. how big an area, how long a time)

- Resolution (i.e. how many sampling sites, what frequency of observations)
- Targets (e.g. microbes, algae, fish, water quality, systems)
- Scientific aims of the project (if any)
- Management and/or conservation aims of the project (e.g was the project initiated to address a specific management problem, or will it be of potential use in dealing with an underlying problem, or is it of 'strategic' value (i.e. of long-term benefit but not necessarily of immediate management value?)
- Copies of any relevant documents.

The response rate from the UK was 46% and from overseas 17%. The quality of responses varied considerably; some letters only consisted of a list of further contact names, other replies provided detailed descriptions of current projects together with sets of reprints and other publications. Most respondents supplied information between these two extremes.

The data were then examined to determine whether effort was being expended (a) at geographic scales below that of the whole catchment (for instance, at the laboratory microcosm up to the river reach scale)?, (b) on studies which did not include both some level of study of the physico-chemical environment (hydrology, geomorphology, water quality) and some attention to any element of the biota?, and (c) whether most effort was being undertaken without potential management applications in view? (Chapter 4)

An Announcement introducing the study was published in the *Societas Internationalis Limnologiae (SIL) Newsletter*, the *British Ecological Society Bulletin*, *Freshwater News*, *Circulation* and *The Brief* (a newsletter published by the NRA), with the inclusion of a contact address for anyone interested in contributing to the project. A similar announcement was made at the Freshwater Biological Association's Annual Scientific Meeting on 21-22 July 1994.

More detailed consultations were held with 75 UK scientists and managers from a range of organisations involved in catchment issues, in order to obtain detailed information and comment. These organisations included MAFF, ESRC, WRc, IH, IFE, ITE, English Nature, CCW, the Welsh Office and the NRA [Annex 3]. In total, 60 NRA staff were consulted about this project either by letter, by formal discussion meetings or by informal conversations at conferences and meetings. The Project Team tried to ensure that all function areas were represented in these discussions.

Other approaches to gathering relevant information included perusal of the scientific literature and examination of the NRA's Catchment Management Plans, to identify key issues and uncertainties in catchment management and to determine whether these are national or regional problems, and then to identify a range of key practical questions to which environmental science could potentially provide answers. Forty-two CMP consultation reports were examined during the course of the scoping study [Annex 4].

A workshop on the Catchment Ecosystem Research Initiative was held in Cardiff on 14 and 15 September 1994. This formed part of the overall consultation process by exposing the preliminary findings of the Project Team to a wider community of scientists and managers. The Workshop was attended by two overseas delegates, Dr D D Hart (Academy of Natural Sciences, Philadelphia) and Dr P S Giller (University College, Cork), and by 48 members of the UK community [Annex 5]. Conservation organisations were represented by delegates from English Nature, Scottish Natural Heritage, The National Trust and Pond Action and other participants included representatives from the National Rivers Authority, NERC Institutes (IFE and IH), the FBA, WRc, Hydraulics Research and many Universities. Invitations were also sent to DoE, MAFF, ESRC and NERC (ITE) but representatives from these organisations were unfortunately unable to attend.

The specific objectives of the Workshop were:

- to identify areas in which transfer of existing knowledge or understanding could benefit management.
- to identify areas where existing knowledge and understanding is inadequate.
- to consider, and originate, general plans for new research organised around the theme of scale, pattern and process in catchment ecosystems.

A background paper was circulated to delegates before the Workshop. This included

- brief indications of some of the perceived gaps in current understanding, as articulated by staff of the NRA and other consultees.
- a few examples of what "technology" (concepts, knowledge, understanding, models) could be transferred and how this might be achieved.
- presentation of a conceptual framework for a programme of large-scale, co-ordinated research.

A full account of the Workshop can be found in a separate report (Hutchinson *et al* 1995)[2] but the main findings are represented in this document.

An iterative process was used to prioritise management issues of most concern (Chapter 3). This process involved noting the frequency with which such issues were mentioned during consultations with NRA and other management personnel and in responses to the circulated letter, consideration of issues listed in NRA Catchment Management Plan Consultation Reports, discussions of management issues during a meeting of senior managers held at the NRA Head Office, prioritisation by senior managers of a circulated list of issues, discussions at the Workshop, review by the Steering Committee, and professional judgement. A similar iterative process was used to identify and prioritise areas of scientific weakness (Chapter 2). This was based mainly on responses to the circulated letter and consultations with scientists, discussions with senior managers during a meeting at NRA Head Office, discussions at the Workshop, review by the Steering Committee and professional knowledge and judgement.

Both lists of priorities were scrutinised to identify:

- areas of scientific knowledge which presently were not being effectively used by managers;.
- areas where the science base was presently inadequate for use by managers but where scientific interests could be matched to management needs;

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[2] Copies of this report may be obtained from the R&D Coordinator, NRA Anglian Region.

- areas where management identified issues but scientific knowledge is inadequate and there is no immediate prospect of providing information.

The NRA's research portfolio was also examined during the course of the study. It is acknowledged that work is already ongoing and any future research programme will build on this sound base.

The results of the study were then reviewed and evaluated to identify/confirm:

- best present practice
- available research results not yet transferred into practice
- research 'in the pipeline'.

Potential options for future research and development were then identified and assessed as to feasibility and benefits. The process of prioritisation/feasibility sought to maximise benefits to managers and to develop a programme which aims to produce the maximum management and scientific benefits per £ spent. Costs of each suggested programme option were also appraised to determine which option provided greatest benefit relative to cost.

Thus, to summarise, during the course of this study, we have

- reviewed current scientific knowledge and identified and prioritised areas of weakness
- identified and prioritised management issues
- developed a programme of integrated research aimed to produce the maximum management and scientific benefits for the cost involved
- assessed the feasibility of the programme.

2.0 PRESENT SCIENTIFIC KNOWLEDGE AND ITS APPLICATIONS IN MANAGEMENT: WHAT DOES SCIENCE DELIVER?

This chapter deals, first, with the case for the scientific study of catchment ecosystems and then goes on to give a general statement of areas in which knowledge and understanding is relatively secure and of key gaps and questions remaining. Catchment science is dealt with separately under three headings - physical/chemical, life, and holistic ecosystem sciences - and the applied significance of each is briefly mentioned. Finally, the fifteen key science questions identified are prioritized on the basis of three criteria - interest, feasibility and ability.

2.1 The science landscape

2.1.1 Introduction - why catchment science?

The pathways by which water moves through the landscape are of crucial ecological significance. Water is the main agent of the biogeochemical processes that determine the retention and output of materials (including particles and dissolved substances) downslope and ultimately to the sea. The juxtaposition of the simple ideas that the landscape is naturally divided into hydrological catchments, separated by boundaries or 'watersheds', and that we can determine input/output budgets of materials and energy for such catchment units, has led to some of the most important advances in modern ecology. Such catchments are the ecosystem units of landscape, tending naturally towards the state in which most inputs/outputs of energy are in the form of light and heat, and within which nutrients are recycled with high efficiency so that recycling is quantitatively more important than the limited exchange with neighbouring systems.

There has been strong scientific interest on the control processes operating in catchment ecosystems, including those in the purely terrestrial subsystem (in forest soils, for instance), in the land/water interface and on control processes within channels (in nutrient retention, for instance). Understanding these controls has necessitated studying processes in inter- and multi-disciplinary teams, and at fairly large spatio-temporal scales (though this inevitably creates problems of experimental replication). There is also a great deal of wider relevance in such research, however, since it can identify the underlying determinants of state and sustainability in catchment ecosystems.

There are international examples of such large scale research that are encouraging in showing that large scale ecology can be linked with management problems. The Canadian Experimental Lakes Area (ELA) has been the focus of applied ecological research since 1968, and both communities and ecosystems have been studied in lakes that were deliberately perturbed with nutrients and strong acids to simulate contemporary lake management problems (Schindler 1994). While providing abundant first rate research, these studies also suggested a scientific basis for the management of eutrophication and acidification. They established base-line conditions against which to gauge environmental change, while demonstrating that it took 'several years for many features of communities and ecosystems to reach a steady state, revealing the pitfalls of using short-term studies to guide applied ecology.' Further, the classic, long-term studies at Hubbard Brook, led to the discovery of acid-precipitation in the United States and established, through their unique experiments, the impacts of land-use practices including forestry (Likens 1992). These and other long-term, large-scale projects demonstrate that such coordinated research is one way, and perhaps the surest way, to do rigorous fundamental science which is also of use to society.

2.1.2. The nature of the catchment science landscape

The environmental sciences of catchment ecosystems can be categorised into three broad subject areas. First, there are the physical sciences which address processes controlling the quantity and pattern of flow through catchments, the generation and transport of sediments, and the form and function of river channels and floodplains as well as a variety of other catchment features. Water 'quality', broadly the chemical constitution of natural waters, is also addressed by the physical environmental sciences. Secondly, the life sciences centre upon the nature, abundance and diversity of living things within catchments: how to categorise and classify them, how their populations are controlled, and how they interact with each other and their environment. They have intrinsic value, which is increasingly emphasised in the issue of biodiversity. Thirdly, physical, life and, crucially, socioeconomic sciences come together in the holistic study of catchment ecosystems: how both living (including human) and physical components interact to control biogeochemical cycles, for instance. Since key controlling processes in catchment ecosystems everywhere are so clearly modified by human activities, the socioeconomic sciences are central to the holistic study of catchments (because socioeconomists address decisions made by humans in their interactions with catchments).

In the following sections (2.1.3, 2.1.4 and 2.1.5) we survey the physical and life sciences, and 'holistic catchment science' and, at the end of each section, we describe key science gaps and questions.

2.1.3 Physical/chemical sciences

The importance of physical processes to the management of rivers has long been recognised: flood defence, the safe disposal and transport of pollutants, or the development of water resources, for example, all require sound knowledge of river hydrology, hydraulics and sediment dynamics. Increasingly, however, the physical environment and structure of rivers is seen as an important area of management in its own right; examples include emphasis on geomorphology in river conservation, river restoration, and the monitoring of river habitats (RHS). Fluvial processes, indeed, provide a pivotal link between catchment-scale change in land use and effects on important river resources (see Fig. 1.1).

There is a very extensive and relatively precise knowledge and model base dealing with the processes of runoff and stormflow from headwater (and particularly small) catchments. Lag-time and baseflow are well understood, and we have been able to classify and understand river regimes and flow duration curves. Linkage of hydrological processes and flow response becomes progressively less assured for large catchments and for rivers with an increasing contribution from ground water and with functional floodplains. There is, however, a sophisticated knowledge of the statistics and prediction of flood frequencies.

Processes controlling sediment yield from hill slopes are well understood at the small plot scale. Spatial and temporal variations, and the factors influencing them, are relatively well known. Other physical features, including water temperatures and dissolved gases such as oxygen, have been extensively studied. Problems and uncertainties remaining are mainly with large catchments and with integration of small with large scales in space and time.

In the context of spatial patterns of hydrological processes, we have a good understanding of the runoff pathways which generate discharge from headwater catchments and their relative dynamics under different antecedent and current hydrological conditions. We also have a variety of hydrological and hydraulic modelling tools which allow us to estimate the temporal pattern of discharge at different sites through the channel network at the scales of small to medium-sized catchments. Furthermore, our ability to model subsurface, particularly groundwater, movement is also good for small to medium-sized catchment areas. However, there are two major research needs if we are to develop models linking hydrology and geomorphology:

(i) the modelling of hydrological processes in areas of low relief, particularly the movements and interactions of surface and groundwaters through the river margin (i.e. the land-water interface).

(ii) although we have the ability to estimate flow frequency and duration characteristics for particular locations on river channel networks with reasonable accuracy, we know little of the significance of flows of particular frequencies or of the temporal sequencing of flows for aquatic communities.

Such flow characteristics are important in their own right and also because they relate to water quality.

With regard to sediment transport, we have a fairly good understanding of the fundamental controls on the erosion of hillslopes and floodplain surfaces at the plot scale, but our ability to model sediment delivery processes from small areas across entire hillslopes to river channel systems remains poor. Where floodplains are extensive, our knowledge of sediment delivery processes is particularly weak. Processes of in-channel sediment mobilisation, transport and deposition are associated with the discharge regime and the availability of sediment of particular sizes within the channel and riparian zone. From an ecological perspective, fine sediments are of particular significance, not only because of the physical effects of fine sediment on biota, but also because they influence the dynamics of pollutants.

Sediment transport and flow influence channel morphology and the calibre of sediments present on the channel banks and bed. We have a good understanding of the general principles of fluvial erosion, transport and deposition of sediment. Our knowledge becomes increasingly restricted, however, when we consider the nature of such processes at the local scale integrated in channels of complex morphology and that are influenced by factors such as the seasonal variation in the character and biomass of in-channel and riparian vegetation, tree roots and vegetation debris. Such influences may affect the nature and availability of physical habitat within the channel and also the degree to which the character of available physical habitat may evolve through time with adjustments in channel morphology and bed sediment character.

We have hydraulic models and an understanding of fluid dynamics which can accurately represent the broad character of three dimensional flow processes in large river channels. However, present knowledge/techniques cannot describe the detail of flow processes in channel systems of complex geometry and morphology and of high roughness to a degree which will enable us to understand subtle ecological impacts. In particular, mixing processes, which control the detailed three-dimensional character of water quality and temperature at the microhabitat to reach scales, may be critical to aquatic ecology but are not well represented by the modelling tools that are currently available.

In short, our ability to model hillslope, subcatchment and catchment-scale hydrological processes is good, as is our ability to model within-channel hydraulic processes, including those relating to the erosion, transport and deposition of sediment. However, all of these modelling abilities are available at a scale which is appropriate to water resources rather than to ecological management. The subtleties of ecological response require a higher spatial and temporal resolution than is currently feasible in our modelling, a clearer understanding of the interactions between hillslope-floodplain-riparian-channel processes, and new instrumentation to characterise the high-resolution interactions which are required to support the validation of new modelling tools. Natural and anthropogenic fluctuations in the physical environment (e.g. peak flow events) act as disturbances to ecological systems. A disturbance may be defined as any event which removes (e.g. kills) organisms or changes the relative supply of limiting resources to organisms. Understanding and relating the physical nature of disturbances (i.e. their frequency, intensity and spatial extent) to their ecological effects, is a crucial area in catchment ecosystems.

Like physical processes, the chemical environment links the catchment, river system and floodplain. Fluxes of materials between the atmosphere, drainage basin and aquatic ecosystems are clearly important to the transport of pollutants and nutrients. Perhaps most importantly, chemical processes are central to the exposure of organisms - including people - to potentially harmful substances. For this reason above all others, better understanding of the chemical environment of rivers is central to setting realistic 'safe' levels for contaminants.

Understanding the chemical environment is fundamental to understanding the processes involved in ecotoxicology, eutrophication, etc. Descriptions of the natural chemical constitution of surface waters are numerous, though detailed knowledge of processes, fluxes and controls is more problematic. Difficulties in extrapolating from simple ecotoxicological data (often laboratory based) to complex real ecosystems still bewilder attempts to make ecotoxicology environmentally relevant. We clearly understand the processes determining average concentrations of the major ions and their short term fluctuations. The control of acidity is very well known, as is its link with aluminium concentration. Knowledge of the spatial and temporal variations in the major plant nutrients is extensive but understanding the processes controlling them is much less certain (this compromises our ability to control eutrophication). A major concern is the management of 'safe' levels of contamination. Little research has been undertaken on this issue to date and particular focussing of scientific effort towards this aspect is, therefore, required. There are particular concerns about the biological

While a few of the macroinvertebrates with aquatic immature stages still present difficulty with the association of larvae and the named adults, we can identify the majority of macroinvertebrates in British freshwaters. This ability is quite remarkable yet now seems to be taken almost for granted, and it underlies a large number of the 'tools' available to managers. Similarly, the fish fauna of the British Isles is extremely well known as are the amphibians and aquatic birds. Algal assemblages and their taxonomy have been more thoroughly studied and generic identification is often fairly straightforward. Aquatic macrophytes can also be routinely identified.

Thus, with the exception of most microbes and many of the smaller invertebrates, our knowledge of the composition of our freshwater biota and our ability to identify the species is good, although there are many uncertainties in other aspects of their ecology.

Population ecology.

The exploitation of important fish species, the emphasis on individual species in British and European conservation legislation (e.g. pearl mussel *Margarifiter margarifiter*, salmon *Salmo salar*, otter *Lutra lutra*, bullhead *Cottus gobio*, Kingfisher *Alcedo atthis*), and the role of many species as indicator organisms all require knowledge of natural factors influencing distribution and abundance. In some instances, this may even include detailed population dynamics.

There are many descriptions and a good, site-specific knowledge of the distribution and abundance of single species in freshwater, undoubtedly built on our ability to identify a substantial fraction of the flora and fauna. This knowledge is strongly focused at small scales in space and, particularly, in time. Thus, there is relatively little information, for freshwater populations, of population dynamics over several to many generations of the species concerned (marked exceptions include planktonic algae and salmonid fish). Therefore, the stability and regulation of intergeneration population dynamics is not well understood. We know most about the relationship between organisms and physical/chemical environmental variables, such as temperature, oxygen, pH and calcium. There is also a fairly good store of ecophysiological information about tolerances and preferences. The behaviour of a small proportion of macroinvertebrates, and of some fish, has been studied and there is a big literature on the phenomenon and causes of stream drift (the downstream transport of normally bottom-living invertebrates).

Studies on species interactions, particularly competition and predation, are numerous and have yielded, in some situations, clear evidence of interference competition for space among sedentary species. The role of predation in controlling benthic populations has been shown clearly in a few cases, while predation by fish often impacts upon populations of large-bodied invertebrates. Field experiments revealed the important role of herbivory in controlling, in the short term, the biomass, production and community structure of attached algae. The role of herbivory on aquatic macrophytes is less certain.

The most important uncertainties are: a) that we know so little of microbial populations and of the micro- and meiofauna, b) that we still have too few long term records of freshwater populations in which the role of density dependent and density independent sources of mortality is clearly distinguishable and, c) that the dynamics of patchily distributed populations are not well understood.

Community ecology.

As with population ecology, there is a strong managerial interest in the communities of plants and animals in river systems. This includes features important to exploitation (e.g. on predator-prey interaction between fish and birds), the selection of river reaches for conservation (e.g. in SERCON and in the Holmes methodology employed by the Country Agencies), and in the use of communities as biological indicators. In the latter case, the use and appraisal of invertebrate communities in RIVPACS represents one of the most favoured conceptual approaches for river monitoring and surveillance in the World (e.g. Norris 1995). Communities also figure increasingly in ecotoxicological approaches to assessing river quality. All these areas imply knowledge of community dynamics and inter-specific interaction.

Descriptive studies of invertebrate communities are well advanced and the means of classifying water bodies, using multivariate statistical techniques, are widely available. We can thus correlate community composition and diversity with a range of measured environmental variables, though which is decisive is less clear. Geographical distributions within the British Isles and longitudinal patterns along streams and rivers are well known for some groups, mainly of macrophytes, fish and macroinvertebrates. Many community patterns, particularly a marked fall in diversity in acid waters, seem to be a consequence of aspects of alkalinity and hardness. The crucial role of disturbance (particularly due to high or low flows and to human activities) is well established, and the importance of the physical heterogeneity and refugia has recently been demonstrated. Various models of community structure have been proposed and seem to apply in different circumstances and in different organisms, but clarification of this area is needed. These models include: resource partitioning among coexisting species, 'metacommunity dynamics', patch dynamics, probability refugia, stochastic patch dynamics, and disturbance control. Theory is well ahead of test in all these fields.

Our knowledge of the structure of freshwater food webs is patchy, there being detailed descriptions of only a few rather simple examples. Information points to the view that stream and river food webs are very highly connected indeed and that omnivory is prevalent. It is possible that food web structure varies systematically with environmental circumstances such as the disturbance regime.

Overall, key scientific questions and/or knowledge gaps in the area of life sciences can be summarised as follows:

(4) • In the study of freshwater biodiversity:
  a) there are poorly known elements, many of which may be functionally significant,
  b) we know little of the factors controlling ecological and genetic diversity including the role of spatial scale and the relative importance of regional diversity and local ecological processes.

How does biodiversity 'sum up' across the landscale in catchments? At what spatial scale do the differences in biodiversity (for instance between streams draining different geological types) become apparent; is it at the local 'patch *scale' or are differences only apparent after the inclusion of a substantial number of patches?*

(5) • Fully quantitative, long-term data in population ecology is usually insufficient for modelling purposes:
- a) particularly for non-salmonids and for young or 'difficult' stages/species (eggs, adult insects, the meiofauna),
- b) it is difficult to distinguish between deterministic and stochastic processes and to model the population consequences of disturbance in spatially heterogeneous habitats.

There are very few multi-generational life tables for freshwater fauna which allow for the search for density dependence, for instance, or for the parameterization of population models. This is made more difficult because there are too many 'black-holes' in terms of unknown stages and rare or local species.

The heterogeneity of the natural habitat may impact on the balance between density-dependent, biotic interactions, on the one hand, and the role of density independent, stochastic mortality, on the other. Physically 'patchy' habitats may provide refugia from disturbances.

(6) • What are the spatial characteristics of freshwater populations in relation to the 'nested', physical hierarchy of fluvial systems?
- a) most existing studies are small scale and short term,
- b) do metapopulation dynamics apply?
- c) what is the role of patchiness and physical heterogeneity at a variety of scales in evolution and population dynamics?

Freshwater populations may be divided by the physical hierarchy of catchments into separate 'cells', within which local populations may persist for several/many generations and from which they can disperse. We need to examine genetic divergence of local isolates of populations and species and genetic exchange between them. Empirical studies of dispersal are also important.

(7) • We need to develop and parameterize models applying to freshwater communities at a range of spatio-temporal scales, including 'meta community' dynamics, probability refugia, stochastic patch dynamics and others. They must incorporate the continuous mobility of individuals, particularly between patches, that may act as physical refugia or as 'source-sink' habitats.

(8) • Too little is known of persistence and change in freshwater communities, including:
- a) natural variation and natural 'baselines', and
- b) responses to sustained, environmental change (including resiliance/resistance

across different scales)

We need to know more about natural variation and natural baselines and about the relative effects of pulsed and chronic disturbances.

(9) • Are patterns in freshwater food webs due to local ecological interactions or constraints, or are they consequences of the wider scale, historical processes that may determine regional diversity?

Are there patterns in connectance, omnivory, or predator-prey ratios, for instance, that are attributable to disturbance, spatio-temporal scale or to other factors? If we can improve the 'resolution' of food webs, and include species that have hitherto been largely ignored (such as the microbes and the meiofauna), do food web patterns change substantially?

2.1.5. Holistic catchment science: ecosystem processes and environmental economics

The responses of rivers to nutrient enrichment and acidification - two of the most pervasive problems of British rivers - involve substantial change to key ecosystem processes such as decomposition and production. Yet, the importance of such effects is often overlooked amid projects which more often focus on species and communities.

The 'metabolism' of freshwater systems is largely driven by catchment characteristics, and several large scale studies have addressed inputs of nutrients and energy from catchment to stream, particularly with respect to forestry practices and nitrogen inputs to stream water. Inputs and depositions from the atmosphere have also been quantified. Running water ecosystems are often mainly supported by allochthonous detritus of terrestrial origin. The decomposition and incorporation of leaf litter has been very widely studied and the rôle of microbes and animals clarified. The incorporation of dissolved detritus is known mainly through its uptake into biofilms which can be grazed by invertebrates. The microbial food web is poorly understood in streams and rivers, however. Interactions between ground and surface waters are presently being actively studied.

The longitudinal patterns in energy budgets (allochthonous vs autochthonous) and in functional feeding groups of animals are now regarded as 'continua' rather than occupying discrete, discontinuous zones, and a particular model of their sequential array, the 'river continuum concept', has been widely tested. The river continuum concept has, rightly, drawn our attention to linkages, in energy and materials, from upstream to downstream reaches of rivers. Nutrient cycling in rivers, added to the longitudinal transport of materials with water flow, has led to the 'nutrient spiralling' model. Studies of larger rivers in the Americas and Europe have thrown some doubt on the postulated over-riding influence of longitudinal linkages (i.e. transport from headwaters to downstream) as the providers of the 'nutrition' for downstream reaches. Lateral linkages to riparian forests and floodplains seem far more important in providing allochthonous carbon for large lowland rivers. None of these studies has been conducted on any river system in the UK, of whatever size.

'Holistic' catchment science necessarily includes the interactions between disciplines, such as the underpinning physical and life sciences. However, there are presently major problems in making syntheses between disciplines. These problems are partly due to the different scales of approach adopted in different fields. Most studies of population processes have been conducted at very small scales ('plots', 'stations', 'reaches') for instance, whereas the ecosystem approach demands study at the whole catchment scale. This makes it difficult to identify any importance attributable to any particular species (the focus of biodiversity) in ecosystem processes. We also still know too little about the way fluctuations in the physico-chemical environment (e.g. disturbances due to water quantity and quality) affect the biota. This problem to integration presents a particular challenge in the incorporation of socioeconomics within holistic catchment science, yet is clearly crucial to success.

It is impossible and undesirable to address whole fluvial systems as ecosystems without incorporating human activities, that are in turn related to socio-economic decision making at whatever level. One of the major problems in assessing the environmental damage or benefit of human activity has been the difficulty of appraising the socio-economic value of environmental features. 'Sure science' in this whole area is still difficult to define. To some extent, this applies more acutely to 'non-use' values in ecosystems like river catchments, such as recreation, landscape quality or the conservation of biodiversity. However, it has applied also to 'use' values, such as the abstraction from rivers of good quality water, because the importance of natural ecosystem process which control resource quality and quantity are niether easily recognised nor easily costed. Methods for making such assessments are under development (Turner, 1993), though are not without critics (e.g. O'Riordan, 1993). Nevertheless, work by Turner, Barber, Pearce and others in the UK has shown that the 'use' values of natural ecosystems can be large, so that the damage incurred either directly or indirectly as a result of environmental degradation can be equally substantial. This remains an area fertile for important research and development. For example, there is a need to predict the economic costs or benefits of different management options (e.g. see also 3.2.3), based perhaps on predictive models of ecological change (e.g. Ormerod et al. 1988). Such links have already been made in predicting the effects of different reductions in acid deposition on fish populations, linked in turn to the economic benefits derived in fishery management (M. Hornung, ITE Merlewood, pers. comm.)

The appraisal of non-use values in river catchment ecosystems is also under development, for example in the UK at the University of Stirling (Hanley, in press). Formerly, favoured methodologies assessed the travel costs of those who made journeys to river systems as an indication of their readiness to pay for fishing, recreation, bird-watching etc. However, increasingly, 'contingent valuation' involves assessing individuals' 'willingness to pay' for environmental features, for example through taxation; by this method, economic values can be given to apparently abstract ecosystem features such as biodiversity, and can be based on values given by individuals for whom it is sufficient to know that semi-natural ecosystems exist. In this way, the perceived value of catchment ecosystems can be appraised in a way which accounts for wide differences between members of the public, and between members of the public and the scientific community (e.g. Fordham, *in press*).

Key scientific questions and/or knowledge gaps in the area of holistic catchment sciences, therefore, can be summarised as follows:

(10) • What is the importance of relatively well known small-scale processes for large-scale, persistent patterns in catchments?

> *Catchment ecosystems are best known at the small ('plot') scale. Processes within such patches are of doubtful relevance to patterns as large scales in time and space. We need sustained, large scale research.*

(11) • What is the role of species and of biodiversity in ecosystem processes?

> *There are indications that many ecosystems are characterised by a few key species and/or strong interactions which may determine system state (sometimes species act crucially as 'ecological engineers').*

(12) • There are few catchment-scale models able to forecast the impacts of environmental change (including human-related impacts). Some within-discipline models exist but the integration of models has not yet been achieved. They will be crucial to forecasting the ecological effects of different management activities - perhaps involving socio-economic instruments.

(13) • There is a need for a credible, widely accepted assessment of the economic value of ecosystem "goods and services"; and the costs of restoration/rehabilitation work and an objective ecological basis for environmental 'targets' and standards relating to thresholds and system resilience.

> *This is a challenge in environmental economics and can serve both as an issue for research in its own right and also as a means of focussing new research in other areas.*

(14) • Ecological effects of the nature and temporal and spatial characteristics of chemical perturbations, for instance:

a) additive/synergistic effects,
b) repeated episodes,
c) multiple point sources throughout a catchment,
d) indirect effects of chemistry.

> *Chemical perturbations need to be brought within a conceptual framework of ecological disturbances. Experimental examination of repeated episodes is a high priority (how does the frequency and/or severity of disturbance influence ecosystem integrity?) Even more challenging is understanding the effect of small (e.g. point source) impacts repeated frequently at multiple points through ecosystems. A combination of empirical work on dispersal and recolonisation, with modelling of spatially patchy communities, might be effective.*

> *Indirect effects of chemistry may be brought about by*

> *'cascading' or 'ramifying' consequences of chemical removal/reduction of key species. These effects are known as a consequence of eutrophication or acidification of lakes, for instance.*

(15) • What are the direct and indirect effects of flows and sediment transport on a wide range of organisms (particuarly the long term effects), with particular reference to the frequency and duration of stress?

> *The longer term effects of flow changes and their temporal characteristics are still insufficiently known. This is particularly true for organisms other than fish. Interactions between hydraulics and intergenerational population dynamics, rather than merely with short-term distribution and behaviour, are likely to be complex and non-linear. The larger scale, longer term, role of flow refugia for populations and communities should be addressed.*

2.1.6 Prioritizing the science interests

Our survey of the 'science landscape' relating to catchment ecoystems drew on several sources:

a) the scientific literature, including several key reviews (e.g. Calow and Petts 1994; Giller *et al.* 1994; Harper and Ferguson 1995).
b) from a similar exercise carried out in the US 'Freshwater Imperative' (1994).
c) from discussions at the Cardiff Workshop (Hutchinson *et al.* 1995).
d) from our consultations with the science community in the UK and abroad.
e) from our own experience and expertise.

These have led to the identification of 15 key science questions and gaps identified under the three sections Physical Sciences (2.1.3), Life Sciences (2.1.4) and Holistic Catchment Science (2.1.5). We then iteratively prioritized them by the discussions and consultations mentioned above. Prioritization has been on the basis of three criteria. These are:

- 'interest' - whether the question is scientifically important and challenging and would, if progress was made, lead to a major increase in our ability to understand and/or predict the system.

- 'feasibility' - whether progress is likely to be achievable (there is thus a judgement of how 'difficult' the question is).

- 'ability' - whether the UK science community is well placed to attack the problem in terms of facilities and expertise.

Note that prioritization at this stage is mainly on the basis of science criteria and not directly on aspects of relevance (though the interests of scientists and users are interrelated to a substantial degree). Consideration of end-user priorities and matching of science and application comes in later chapters (3 and 5 respectively). The results of prioritization are given in Table 2.1, below. Key questions and gaps are identified in the Table by reference to the numbers previously shown in the left hand margin of Sections 2.1.3, 2.1.4 and 2.1.5 above, followed by the key words/phrases underlined in these sections. Subsequent columns in the Table rate each question as High (H), Medium (M) or Low (L) according to the three criteria (interest, feasibility, ability), and in three categories (H, M, L) of overall priority (Judgement has been applied in our assessment of overall priority). It should be stressed that all these key science gaps/questions are actually challenging and of great interest - this process simply tries to ascribe ranks to a group of very important topics.

Table 2.1 Prioritizing the science questions and gaps - see text for explanation.

Question/Gap	Interest	Feasibility	Ability	Overall
Physical Sciences				
(1) ..temporal and spatial characteristics of sediment transport...	M	L	M	M
(2) ..effects of flows and sediment transport...	H	M	M	M
(3) ..basic biogeochemical processes...	H	M	M	M
Life Sciences				
(4) ..freshwater biodiversity...	H	H	L	H
(5) ..quantitative, long-term population ecology...	H	H	M	H
(6) ..spatial characteristics of freshwater populations...	H	M	H	H
(7) ..models applying to freshwater communities...	M	L	M	M
(8) ..persistence and change in freshwater communities...	H	H	H	H
(9) ..patterns in freshwater food webs...	H	L	L	L
Holistic Catchment Science				
(10) ..small scale...large scale...patterns	H	M	M	H
(11) ..role of species...in ecosystems...	H	M	L	M
(12) ..catchment-scale models...	H	L	L	L
(13) ..assessment of...economic value...	H	M	M	M
(14) ..ecological effects of...chemical perturbations...	L	L	M	L
(15) ..effects of flows...on organisms...	M	M	M	M

3.0 CATCHMENT MANAGEMENT AND CATCHMENT MANAGEMENT PLANNING: WHAT DOES MANAGEMENT NEED?

This chapter, first, surveys present approaches to catchment management and catchment management planning in the UK. It then goes on to list key technical gaps identified by end-users. Possible links between science and management are identified and, finally, we have prioritized management concerns under a list of two general and eleven specific areas/questions.

Even where decision making is socio-economic and democratic,catchment management will, in ideal circumstances, operate from a rational basis of scientific understanding (cf Section 1.1.1). This principle, that good science should figure prominently in the activities of organisations like the NRA or Environmental Agency, is widely recognised in the academic (e.g. Ferguson and Harper, 1995) and government sectors (e.g. OST Technology Foresight Programme). Of course, there would be distinct advantages if the use of good science involved a predictive capability, based on holistic and integrated catchment models, through which alternative scenarios of management intervention could be compared. At the same time, the implementation of predictive, science-based management, can work only within the constraints of current approaches to management. Equally, it can work only where problems are effectively recognised and diagnosed. In this chapter, therefore, we review the current context of catchment management in England and Wales, and we outline current perceptions of management concern that were identified during our consultations.

3.1 Organisations in the UK with statutory responsibilities for river management

In the United Kingdom the main organisations with responsibilities for the riverine environment and/or catchment management and catchment management planning (either as funding/commissioning organisations or organisations which can use the outcome of scientific research in their management roles) are DoE, MAFF, the NRA, English Nature, CCW, SNH, the Countryside Commission, the Local Authorities, the Welsh Office (Environment and Agriculture Departments), the Scottish Office Agriculture and Fisheries Department (SOAFD) and Environment Department (SOEnD), River Purification Boards/Islands Councils, the District Salmon Fisheries Boards, the Department of the Environment for Northern Ireland, the Department of Agriculture for Northern Ireland, the Council for Nature Conservation and Countryside and District Councils. Other key organisations include the 10 water and sewerage companies and 22 water only companies, the Water Services Association, the Water Companies' Association, the Office of Water Services (OFWAT) and the Drinking Water Inspectorate (DWI).

The activities of these organisations need to be undertaken within the current relevant legislation such as the Water Resources Act 1991, the Land Drainage Act 1991 and the Salmon and Freshwater Fisheries Act 1975 (NRA 1994a). Activities are also influenced by certain EEC Directives, key examples of which are shown in Text Box 2. Any future

TEXT BOX 2: Key Examples of EC Directives and Decisions relevant to NRA activities.

- Directive 75/440/EEC concerning the quality required of surface water intended for the abstraction of drinking water in the Member States.
- Directive 76/160/EEC concerning the quality of bathing water.
- Directive 76/464/EEC on pollution caused by certain dangerous substances discharged into the aquatic environment of the Community.
- Decision 77/795/EEC establishing the common procedure for the exchange of information on the quality of surface fresh water in the Community.
- Directive 78/659/EEC on the quality of fresh waters needing protection or improvement in order to support fish life.
- Directive 79/869/EEC concerning the methods of measurement and frequency of sampling and analysis of surface water intended for abstraction for drinking in the Member States.
- Directive 80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances.
- Directive 80/778/EEC on the quality of water for human consumption.
- Directive 83/513/EEC on limit values and quality objectives for cadmium discharges.
- Directive 84/156/EEC on limit values and quality objectives for mercury discharges by sectors other than the chlor-alkali electrolysis industry.
- Directive 84/491/EEC on limit values and quality objectives for discharges of hexachlorocyclohexane.
- Directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture.
- Directive 86/280/EEC on limit values and quality objectives for discharges of certain dangerous substances included in List 1 of the Annex to Directive 76/464/EEC.
- Directive 86/574/EEC amending Decision 77/795/EEC establishing a common procedure for the exchange of information of the quality of surface fresh water in the Community.
- Directive 88/347/EEC amending Annex 2 to Directive 86/280/EEC on limit values and quality objectives for discharges of certain dangerous substances included in List 1 of the Annex to Directive 76/464/EEC.
- Directive 90/415/EEC amending Annex II of Directive 86/280/EEC on limit values and quality objectives for discharges of certain dangerous substances included on list I of the Annex to Directive 76/464/EEC.
- Directive 91/271/EEC concerning urban waste water treatment.
- Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources.
- Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora.
- Draft EC Directive on the ecological quality of surface water (Mandl, 1992)

research proposals would also need to take into account this legislative framework.

3.1.1 The new Environment Agency

A future influence will be the new Environment Agency, that will merge the NRA, HMIP and the Waste Regulation Authorities for England and Wales, while the equivalent Scottish regulators will be merged under a Scottish Environment Protection Agency. The Environment and Countryside Bill specifically states that, in pursuing its aims, the potential costs and benefits of the Agency's actions must be taken into account. An important point is that the objectives and targets of the Agency should be based on **sound science** (Anon 1994).

3.2 Key Management Issues and Objectives

The Mission and Aims of the NRA are set out in its Corporate Strategy document and its Strategy documents for the seven core functions and for R&D (NRA, 1993b-i). The Scottish River Purification Boards/Islands Councils do not have all the functions of the NRA in England and Wales and their roles have been described by Brown and Howell (1992) and Mackay (1994).

The role of the country agencies (EN, SNH, and CCW) with respect to river systems lies primarily in the identification and notification of features of nature conservation value, for example, Sites of Special Scientific Interest (SSSIs), Environmentally Sensitive Areas (ESAs) that impinge on rivers, and Ramsar sites that contain them or receive drainage. The three national country agencies are also involved in a series of schemes designed to provide financial aid for conservation. The Countryside Commission is responsible for the conservation and enhancement of natural beauty of the countryside and the opportunities for public enjoyment. Its Countryside Stewardship Scheme provides support for relevant management practices (Countryside Commission, 1991). Other UK agri-environment measures include Nitrate Sensitive Areas, the Countryside Premium Scheme, the Countryside Access scheme and Set-aside.

3.3 Present approaches to catchment management and catchment planning

3.3.1 The NRA

The NRA operates through eight Regions and 26 areas broadly based on natural river catchment boundaries. As a result of the multiple uses of rivers, the NRA endeavours to take an integrated approach to environmental management through the development of the catchment management planning concept. NRA (1993a) specifies the latest NRA guidelines for Catchment Management Planning as summarised in Figure 3.1.

Catchment Management Plans provide a valuable step in the process of integrated catchment planning as well as usefully collating information from diverse sources into one document. Examination of 42 CMP consultation reports (Annex 4) indicated that, numerically, most of the specified issues related to water quality although, once the final plan has been developed, the costs for implementing flood defence measures are usually greatest. Several points emerged during examination of the CMPs where there may be potential for making improvements. For example, most issues raised in the CMPs examined during the present study relate to amelioration of present problems rather than to ongoing management activities; most of the catchment plans take a site-specific rather than an holistic approach to the catchment issues; one or two cross-functional issues may be included but most of the issues are arranged according to the separate NRA functions; conflicts between function areas are not always addressed; and few catchment management plans include land use issues. Slater *et al* (1995) noted that, if the NRA wish to have influence over land use decision-making, there should be greater inclusion of land use data in CMP documents. Slater *et al* (1993) pointed out that, based on their study of nine CMPs and the relevant land use development plans (DPs), there was poor integration between CMPs and DPs and recommended more effective coordination.

The majority of the issues raised in the CMP consultation documents, therefore, lie under the direct regulatory or operational control of the NRA, that has the advantage of enabling it to provide a plan that can be implemented with more certainty. For areas outside its control, such as rural land use or urban development, external support is required if implementation is to proceed.

3.3.2 The country agencies

The country agencies are included among those many organisations consulted during the NRA's catchment management planning process. The country agencies have a statutory duty to notify owners and occupiers of SSSIs. Owners and occupiers of SSSIs are, thereafter, required to give notice to their country agency of any listed operations which they intend to carry out or permit to be carried out. English Nature currently plan in terms of 'natural areas' based on landform, geology, etc., which cut across catchments, although they are trying to fit catchment management into this "conceptual" framework and a report on this is due to be published in the near future (Hellawell pers. comm.).

Where SSSIs overlap between NRA regions and between country agencies, there is close collaboration (e.g. over the Wye and Dee between English Nature and CCW). Equally, the country agencies share the perspective that European legislation concerning Special Areas of Conservation (SACs), among which several major rivers figure (e.g. Usk, Wye, Teifi in Wales), will involve SSSI notification as a central conservation strategy. There is recognition, however, that SSSI notification with respect to rivers is only a 'stop-gap' measure, that has control only over some operations within the channel and riparian zone (Boon, 1991). Nature conservation at the catchment scale, along with landscape protection in the case of CCW, requires a wider perspective that might be possible only through larger schemes such as SERCON (Boon *et al.* 1994). Alternatively, the country agencies aid in the incorporation of nature conservation targets into catchment management plans, that are in turn recognised in structure plans; this provides one of the few legislatory vehicles for nature conservation planning at the river catchment scale.

3.4 Key perceived gaps in knowledge related to catchment management

Implicit in all these foregoing considerations is a view that catchment management and planning operate from the best information available, using current best practice, and using sound science where this is appropriate. Science uses, outlined in Sections 2.2.2 and 2.2.3, in this case will involve both assessing present catchment status, developing management options for maintenance or change, predicting their effects, and appraising their effectiveness following implementation. Catchment management plans which increasingly set targets and derive strategies for their achievement will be particularly dependent on this predictive capacity. However, consulations with a wide range of professionals involved with catchment management, have revealed many areas of concern. These are areas where understanding and, hence, the ability to manage effectively are currently limited; they are listed in Annex 7 and summarised in Table 3.1. It is important to note that the NRA are already addressing specific aspects of many of these needs under discrete projects in their R & D progcamme, and examples are also given in Table 3.1.

In this context, it is be important to consider several permutations through which catchment science and management may be linked (Table 3.2). These range between extremes in which scientific questions have no relevance to management (Case A), through those in which the best possible science is in either used (Case B) or or under-used in management (Case C), to those where real management problems exist, and are insoluble from the current science base (Case E). Case A represents instances likely to attract funding only from basic science budgets (e.g NERC, EPSRC); Case B represents instances where the only requirement is to continue the current use of science in management; Case C represents a need on the part of user bodies such as NRA to invest in development and science transfer; Case D represents a potential need for the user community to invest in R & D, but only once basic science has progressed. Case E, represents areas where there is need for funding from both basic science budgets and from the user community. This scheme clearly will guide priorities for decisions over science funding, and has formed part of the procedure for selecting areas for priority action out of Table 3.1. An important consideration also has been the need to build further research and development onto existing initiatives in areas that most maximise benefit; thus, the selection of priorities has involved considering how the greatest benefits arise where investment extends usable information to levels beyond those that would accrue from investment in wholly new areas.

wording?
insepara

?
where

Are these all the true management problems? [illegible] if a scientific approach is taken?

Table 3.1 Summary of management concerns arising from the consultation process.

Management Concerns	Description/Explanation	Examples of NRA R&D projects
	General or conceptual uncertainties	
Scale mismatch between scientific knowledge and management needs.	Management is aimed at the sustainable, multiple use of whole catchment ecosystems. The <u>safest</u> knowledge base yet available, however, (i.e. that with the greatest repeatability and predictability) concerns small-scale processes and simple systems.	
Relating species toxicity tests to ecosystem processes.	Toxicity testing normally involves assessing single species responses to toxic substances in the laboratory. 'Non-linearities' in ecological systems, as well as complex, indirect species interactions, limits the ability to predict whole system responses (i.e. what will be the actual impact in complex natural situations?)	Toxicity-based criteria for assessing receiving water quality: To develop and assess toxicity-based criteria in order to assess the general quality of receiving waters.
Provision of an objective case for conservation.	Identification of 'key species' and 'strong interactions' in catchment ecosystems will form part of an objective case for conservation. Key species are those whose loss, for instance, results in whole scale ecosystem change.	
Predictive management of catchments.	Predictive management needs predictive models and those presently available in the separate disciplines are often of restricted applicability.	
Holistic, cross-functional planning using predictive tools.	Resolution of more complex conflicts of use, moreover, requires integrated catchment or regional modelling (interfacing bio-physical and socioeconomic models, experience and research).	
Establishment of environmental quality objectives. Effective targeting of resources for environmental improvement.	Setting objective environmental standards needs a rigorous ecological assessment of their 'meaning' (i.e. what are the consequences to sustainability of the standards not being met?)	Development of environmental quality standards: To develop environmental quality standards (EQ's) for substances of concern to the NRA.
Defining targets for physical restoration projects.	What is a realistic or appropriate target for the physical nature of river systems in river restoration/wetland ecosystems? We need to provide the manager with a more precise and identifiable definition of objectives.	
Balancing environmental quality and local social/economic needs.	Environmental quality and sustainability can be given greater weight in strategic catchment and regional planning only if there is a widely accepted and credible assessment of the value of ecosystem 'goods and services'.	Cost benefit assessment: To develop an economic benefit methodology for evaluating enviromental benefits resulting from changes in water quality stemming from improvements in effluent quality.

.../cont

Biogeochemistry/water quality

Management of water quality.	Better management of water quality would be facilitated if we could provide authorities with an assessment of more reliable 'critical loads' - (levels of pollution entailing little or no impact on ecosystem sustainability). Managers need, further, to be provided with toxicity tests which are more appropriate to the risks being evaluated.	Sediment toxicity test development - insoluble substances: To develop internationally standardised toxicity tests for use with sediments contaminated with sparingly water-soluble substances. Effects of low level contaminants on marine and estuarine benthic communities: Experimental evaluation of the effects. Method development: To provide suitable selection tests for the ecotoxicological assessment of effluent and receiving water quality.
Predicting mobility, transformations, accumulation of toxic organics, metals, etc. through catchments (and their sediments) and development of pollution 'budgets'.	We need to work towards catchment-scale modelling of geo-chemical cycling which includes key transfers across boundaries between components (which would include soils and riparian zones, for instance). Generic understanding of hydrophobic chemical movements is particularly important.	Joint nutrient study (JoNuS): To understand the scale, trends and processes of nutrient cycling in major estuaries and coastal waters. Metal speciation in rivers and estuaries: To determine the chemical form of selected metals.
Use of rivers, riparian zones, for ameliorating declines in water quality.	Is the restoration, creation of particular riparian plant communities and/or hydrological pathways a useful tool in water quality management? It has been suggested, for instance, that the physical restoration of fluvial morphology provides a viable economic alternative to adopting even more rigorous water quality objectives.	Measures for protecting upland water quality: To develop management practices required for practical implementation of Forest and Water Guidelines, in particular the optimisation of buffer strip wi7dth in forest planting.
Protecting and sustaining 'ecosystem integrity' in relation to pollution. Indicators of environmental stress.	The knowledge base on the impact of pollutants needs to provide managers with broader measures of 'ecosystem integrity' (whether a natural range of species persists within a functioning ecosystem sustaining primary and secondary productivities and biogeochemical cycling).	Impact of pesticides on river ecology: To assess the impact of different pesticides on the structure and functioning of riverine ecosystems.
Assessing impacts of pollution incidents Resilient species for reclamation of degraded habitats. Impact and management of eutrophication.	We need to assess the impacts of pollution which are due to: • interactions among components of the effluent • acute episodes rather than chronic conditions • the degrading effects of large numbers of small point sources throughout the catchment. The performance of presently available 'tools' against known experimental disturbances will enhance their interpretation in operations.	

The physical environment and ecosystems

Reducing erosion.	Pollution by physical sediment can be a major problem in urban or intensively farmed landscapes. We need means of reducing sediment delivery to river systems.	Impact of erosion of forest roads on water quality: To study the natural erosion processes and rates from mixed aggregate built roads in upland forests and the impacts of heavy vehicles, in order to identify impact on water quality.
Managing the physical habitat for fish and other taxa.	This concerns the protection/provision by management of flows, hydraulic habitats, fluvial morphology and substratum suitable for particular elements of the biota.	Ecologically acceptable flows: To provide the framework for an objective method of evaluation of prescribed minimum flows based on the recognition of ecologically acceptable flows apposite to particular seasonal requirements of aquatic life forms.
Physical transport of pesticides and nutrients.	Particle-bound pesticides and nutrients are transported in seston and as bed-load in rivers. The basic science of these processes is of interest to managers.	Total impact assessment of pollutants in rivers: To investigate the pollution of streams draining agricultural catchments and specifically, to develop a simple model of the movement of pesticides from the point of application to streams.
Managing flows in regulated rivers.	The quantity and temporal characteristics of river flows are of great ecological importance. We need means of optimising flows which make a balance between maintaining minimum flow and the need for occasional flushing flows.	
Balancing water demand with in-stream uses.	Ecological-based guidelines are required which define the in-stream flow requirements for ecosystem integrity.	Determination of minimum acceptable flows: To determine a methodology in order to establish policy for setting minimum acceptable flows.
Ameliorating effects of water abstraction.	Can science provide indications of the least damaging strategies for abstraction?	
Combined management of water quality and quantity.	Chemical quality of water and discharge are linked in natural ecosystems. Managers can intervene in phytoplankton population dynamics (and in the determination of algal standing crop) by flow manipulations.	
Designing channels to render ecosystems more diverse and resistant to pollution events.	There are indications that naturally heterogenous stream channels, with a large fraction of storage ('dead') zones, render ecosystems more resistant (and resilient) in the face of pollution episodes. Such consideration could play a role in reducing risk.	
Assessing impacts of impoundments, inter-basin transfers and wetlands management on aquatic ecosystems.		
Environmentally 'friendly' aquatic weed management.		Aquatic weed control operation: To produce Best Practice guidelines to promote efficient and effective management practices.
Guiding river restoration projects.	The ecological science of resistance, resilience and recovery should provide a theoretical, underpinning basis, for river restoration.	

/...cont.

Population Ecology

Predictive modelling for the purposes of harvest or conservation.	Managers need models which guide them in setting catch quotas, in determining conservation strategies for particular species and in assessing restocking needs.	Eel and elver stock assessment: To assess elver stocks in the Severn Estuary together with elver exploitation and its implications for river stocks. Sea trout investigation: To review and evaluate current knowledge, research and stock assessment capability in relation to sea trout and to design a cost effective programme of investigations for effective, sustainable management of sea trout stocks.
Predictive management of the impact of exotic species.	At present our ability to predict the success and impact of exotic species is limited and is certainly not 'predictive'.	Conservation of freshwater crayfish: To assess the impact of introductions of non-native crayfish and outbreaks of crayfish plague on freshwater ecosystems and to formulate a strategy for the conservation of the native species (*Austropotamobius pallipes*).
Conserving particular species.	Species-specific knowledge is sometimes inadequate for the needs of conservation.	Status of rare fish: To determine the present status of rare fish in certain lakes of England and Wales, and to compile related information on the ecology and genetic variation of these species which is necessary to safeguard their population.
Habitat design, restoration and rehabilitation.	Managers need to combine ecological knowledge with hydraulic/fluvial morphology/hydrology models to restore or 'design' habitats for particular species or systems.	
How much woody debris is necessary?	The crucial role of woody debris in providing substrate, flow refugia, food, and in determining retention is well known. Quantitative guidelines need to be provided.	
Large scale conservation strategies.	Managers need to know if the effectiveness of reserves is enhanced by the presence of other protected patches elsewhere in the landscape (or is compromised by their absence).	
Designing river reserves.	What is the required minimum size of river reserves for particular purposes?	
Objective case for the preservation of 'natural' habitats.	We need to be able to define much more effectively the value of naturally functioning catchment ecosystems.	
Fisheries management.	Quantitative models of fish populations are the only safe basis for fisheries management.	Assessing salmon stocks using a hydroacoustic counter: To install, operate and evaluate a hydroacoustic fish counter in order to produce reliable data for stock management.

.../cont.

Community Ecology

Establishing conservation value, designing conservation measures. Defining ecological 'quality' for aquatic systems.	Knowledge of the scale and nature of patch-interactions (in the physical catchment hierarchy) offers a predictive base for assessing conservation value and for devising the means of conservation.	Faunal richness of headwater streams: To assess the conservation value of headwater stream and macroinvertebrates and their contribution to catchment macroinvertebrate richness and determine agricultural impacts upon them and propose a conservation strategy.
Defining "allowable damage to ecosystems". Measuring recovery.	Managers need to know the risks and powers of recovery of natural systems and what frequency of anthropogenic disturbance does not produce degradation. This entails measuring natural rates of recovery/recolonization at much larger scales than has commonly been attempted hitherto.	Appraisal of conservation enhancement of flood defence works: To develop a method for post-project appraisal of habitat conservation and enhancement works and to assess the value of such works in relation to natural recovery from NRA operational schemes.
Designing habitats for community resilience.	Resilient communities recover quickly from natural or anthropogenic disturbances, and the natural physical heterogeneity of catchments plays a role in this. We could encourage resilience, therefore, by restoring or protecting habitat heterogeneity of various kinds.	
Monitoring and detecting change. Statistical design of monitoring programmes.	We need better means of detecting community change, which is sustained or directional, against a background of natural variation. This requires better natural baseline information and first class statistical design of monitoring programmes. We also need to know how presently available metrics and indices perform in experimental trials with known perturbations.	
Measuring the resource.	Some elements of the biota are presently poorly known.	
Restoration/rehabilitation programmes.	These are presently empirical in nature, and could be made more effective (and their cost/benefit better calculated) if a theoretical basis was developed.	
New ecological indicators based on 'system' properties, as a basis for management.	Some 'system properties' (such as those of food webs, for instance) may change predictably under perturbation, and provide new kinds of indicators. This is also true of new indicators based on physiological or molecular markers or on various kinds of 'sentinel' organisms.	

Table 3.2 Possible permutations of links between science and management

Case	Science Base	Management Uptake	Implications	Ideal Action
A	Good	Irrelevant to management	Irrelevant to current practice effective contribution to	Further development only for fundamental reasons
B	Good, available	Use in management effective	~~Best possible~~ practice/ achieved can be.	Continue
C	Good, available	Use in management lacking	Improved practice possible	Invest in science transfer and development
D	Weak but relevant	Current management by intuition, expert judgement or derived protocol	Improved practice possible	Invest in research to improve/progress science base
E	Weak but relevant	Management lacking	Improved practice required	Invest in research and management

Other information that guided prioritisation has been the frequency with which issues were mentioned or ranked during consultations with NRA staff, or figure in catchment management plans. Direct inputs from the Steering Committee, and our own professional judgement, were also important, but not always central. Together, this procedure emphasised the list in Table 3.3, which can be organised around the following principal themes:

1. Environmental valuation and evaluation

This area embraces the assessment and prediction of benefits in ecological quality which arise from management, and also their socio-economic valuation. It includes also the appraisal and basis of tools such as RHS, SERCON, RIVPACS and general quality indices in catchment management.

2. The impact and management of disturbances in catchment ecosystems.

This includes the assessment and prediction of effects by diffuse versus point-source discharges, from episodic versus chronic discharges, from pollutants in mixtures, and the linkage between ecotoxicology and real system response. It includes also improved understanding of flow and sedimentary regimes, understanding links between the terrestrial and aquatic features of catchment ecosystems, and of understanding and modifying features which influence sensitivity to change. It also implies improved understanding of deterministic influences on important ecological features and processes, and how important these are relative to background variation.

We return to these priority areas in the subsequent chapters (see Table 5.1, Chapters 6, 7 and 8).

Table 3.3 Overall priorities (High (H), Medium (M) or Low (L)) for management outputs in specific topic areas.

(1) Scientific and economic basis for environmental quality objectives. (H)
(2) Assessing impact of, and recovery from, point/diffuse, episodic/chronic pollution. (H)
(3) How to measure impact and manage eutrophication and pesticide contamination. (H)
(4) How to manage the physical habitat for fish and other species. (M)
(5) How to model and manage the link between land-use (including agrochemical applications) and contaminant cycling and transport in catchments. (H)
(6) Means of rendering ecosystems less sensitive to pollution. (M)
(7) How to design and restore habitats. (L)
(8) Measures of conservation quality and value. (L)
(9) Measuring and objectively defining 'allowable damage' to ecosystems. (H)
(10) How to detect community change. (M)
(11) Offering new/improved ecological indicators. (L)

4.0 REVIEW OF CATCHMENT-BASED RESEARCH PROGRAMMES: ARE CURRENT APPROACHES ENOUGH?

In this chapter we present the results of our survey of present research programmes on freshwaters both in the UK and abroad. In the light of a perceived mismatch between the capabilities of science (Chapter 2) and the needs of end users (Chapter 3) we concentrated on the spatiotemporal scale of research and on whether it was multi-disciplinary in nature. We also briefly consider other British research initiatives of various kinds, including previous Community (Thematic) Programmes from Research Councils, to ensure maximum complementarity and minimum overlap in any future research initiative.

4.1. UK Studies

4.1.1 Responses to Standard Letter

From the UK higher education establishments we received notices of some 82 separate 'projects', of which only nine dealt with scales of the whole catchments or above and dealt with both biological and physicochemical elements of the system (see Table 4.1). Of the 38 projects at various institutes, 7 were large scale and 'multidisciplinary'.

Table 4.1 **The focus of freshwater research in the UK: Higher education (Institutes)**

Focus of interest	Geographical Scale	
	Catchment or above	Sub-catchment or below
Biological and physico-chemical	9 (7)	12 (6)
Either biological or physico-chemical	16 (6)	45 (19)

Even those projects which do address the scale of the catchment (merely defined as focusing on a whole waterway plus giving some attention to processes or inputs from the terrestrial part of the ecosystem) mainly dealt with small or rather special catchments. Further, no projects address, in an integrated manner, the full range of ecosystem components (Table 4.2). Not surprisingly, and with the marked exceptions of a very few projects based at research institutes, nearly all British freshwater research is relatively small-scale and relatively short term (Table 4.3).

Table 4.2 'Targets' of UK research.

Research area	HE establishments (%)	Institutes (%)
Physico-chemistry and Biology	25.6	34.2
Physico-chemistry only	28.1	18.4
Biology only	46.3	47.4
Total Physico-chemistry (i.e. Physico-chemistry and Biology + Physico-chemistry only)	**53.7**	**52.6**
Percentage of Total Physico-chemistry studies which include		
nutrients	19.5	7.9
hydrology/hydraulics	13.4	13.2
sedimentology	11.0	7.9
Total Biology (i.e. Physico-chemistry and Biology + Biology only)	**72.0**	**81.6**
Percentage of Total Biology studies which are multi-group (2 or more of the following groups)	29.3	18.4
Percentage of Total Biology studies which include		
microbes	12.2	2.6
phytoplankton/algae	11.0	13.2
macrophytes	22.0	5.3
zooplankton	4.9	2.6
invertebrates	34.1	18.4
fish	17.1	42.1
other vertebrates	3.7	2.6

Notes: Data recorded as percentage of UK higher education establishments n = 82; Institutes n = 38.

Table 4.3 Timescales of UK studies.

Timescale of study (years)	Percentage of all studies HE establishments (%)	 Institutes (%)
≤ 1	14.6	7.9
> 1 - ≤ 2	4.9	5.3
> 2 - ≤ 3	18.3	10.5
> 3 - ≤ 4	4.9	5.3
> 4 - ≤ 5	1.2	0
> 5 - ≤ 10	4.9	15.8
> 10 - ≤ 20	6.1	18.4
> 20	2.4	15.8
Unspecified	42.7	21.0

Notes: Data recorded as percentage of all studies: UK higher education establishments n = 82; Institutes n = 38.

4.1.2 Present experimental catchments in the UK

A few long-term, experimental catchment studies have been set up in the UK such as those of the Institute of Hydrology at Plynlimon and Llanbrynmair in mid-Wales, Coalburn in northern England and Balquhidder in central Scotland (e.g. Johnson and Law 1992, Kirby *et al* 1991, NERC 1993). Research at Plynlimon has been carried out since 1966, at Coalburn for more than 25 years and at the Balquhidder catchments (Kirkton and Monachyle) since 1981. All these studies are, however, based on small headwater catchments and, like Coweeta, the Andrews and Hubbard Brook experimental catchments in the United States (see Section 4.2), concentrate primarily on the hydrological effects of forestry. Effects of forestry have also been the objectives of stream water chemistry monitoring investigations undertaken on small catchments in Beddgelert Forest since 1983.

Research undertaken since 1980 on Loch Dee, Scotland, again focuses on an upland catchment; in this case examining the combined and separate effects of afforestation and acidification. Similarly, studies carried out since 1984 on Loch Fleet (southwest Galloway, Scotland) to explore the effects of liming to counter acidification, involve an upland catchment.

The Windermere catchment has received ongoing study since the 1930s but studies were originally unformalised. Individual study components have been directed towards a variety of targets and timescales range from 3 to 40 years.

Records for Slapton Ley NNR, Devon extend back at least 50 years and the lake and its catchment have been the subject of intensive study since at least the late 1960s. The main objectives are long-term monitoring and management-related research (the greatest management problem is eutrophication). However, the focus of the research has varied over the years towards a wide range of targets.

At Llyn Brianne, research involved examining interactions between land use, acid deposition, soil processes, stream chemistry and biology through a wide range of interacting scientific disciplines (Edwards *et al* 1994). It was unusual among catchment experiments in the UK in achieving some replication at the catchment scale (e.g. Rundle *et al*, 1995). It represents an interesting model for other studies because the scientific programme was undertaken by academics and by staff from the National Rivers Authority. In turn, project management involved senior University staff, NRA managers, representatives from government departments, Welsh Office Agriculture Department and Forestry Commission. The project is still continuing in a scaled down form, so that some data sets span 10-12 years.

4.1.3 Related UK Research Initiatives

UK research initiatives include the following:

JAEP (The Joint Agriculture and Environment Programme)
JAEP was one of the first community programmes between NERC, ESRC and AFRC and focused on the impact of modern agricultural practices on the natural environment.

Each Council took lead responsibility in a particular area:
☐ NERC - The ecology of farmland.
☐ ESRC - Changing farm economies and their environmental relationships
☐ AFRC - Herbivore/plant interactions and their vegetation dynamics.
However, the programme was relatively small and **had no significant freshwater component.**

TIGER (Terrestrial Initiative in Global Environmental Research)
Some of the scientists we consulted received support from TIGER. As the title implies, the focus is again, on terrestrial systems (freshwater studies form a minor component of some areas but these are largely concerned with physical systems and processes with only limited ecological research) and issues are linked to global scale processes. Some links between the present catchment ecosystem research initiative and TIGER lie in the carbon budgets in upland soils.

NELUP (NERC/ESRC Land Use Programme)
The objective of NELUP is to bring together the results of research in the fields of agricultural economics, hydrology and ecology that are relevant to decisions about land use and to make them accessible to decision makers. Topics include
☐ distribution of organic wastes and nitrates in groundwater
☐ acidification of water catchments
☐ distribution of flora and fauna
☐ population distribution and availability of labour
☐ policy issues, e.g. National Parks and SSSIs
☐ road networks
☐ financial/economic constraints.
It, therefore, has some complementarity with a small part of the present proposal (in relation to the early phases of utilising existing information) but does not have the underpinning catchment-based research necessary for understanding the ecological processes. This is essential for further development in this area.

LOIS (Land-Ocean Interaction Study)
Several of the scientists we consulted reported their involvement with the LOIS study. Detailed descriptions of the study are provided in the Science Plan (NERC 1992) and the

Implementation Plan (NERC 1994). The overall objective of the programme is to provide the scientific basis for the development of predictive models of the response of the coastal zone of the UK to changes in human activities, climate and sea level. LOIS has a major component on river basins, atmosphere and coasts and estuaries (RACS) where objectives include a) quantifying and identifying the chemical and biological transformation processes within river basins, and b) observations and modelling of 'how changes in land use ... affect riverine ecosystems'. The major emphasis of LOIS, however, concerns river basins as they determine delivery of materials and energy to coastal ecosystems. **LOIS does not focus upon catchment ecosystems in their own right** nor on their wide use and management but new initiatives in UK catchment research should seek to complement LOIS and to utilise relevant information from this programme. The NRA is contributing to this study.

ECN (Environmental Change Network)
The Environmental Change Network now has both terrestrial and freshwater sites such as the rivers Exe, Wye and Tweed (Sykes *et al*, (1994). The sites do not consist of whole catchments and the aim of this network is to collect and collate environmental information from a broad spectrum of UK sites over an extended timescale (decades) so that long-term environmental changes can be detected against a background of local and regional effects. Again, this is an important UK resource and one which will strengthen the present initiative by providing a framework within which the more focused studies of particular catchments can be placed.

Environmental Diagnostics
This is a three-year research initiative due to commence in 1995/96. The primary objective is the development of diagnostic and predictive models making use of knowledge and understanding of processes. It is intended that this will provide a firmer scientific basis for environmental clean-up and remediation of landfill, for example. This initiative will mainly comprise processes, environmental impacts, critical loads, pollution chemistry, biotransformation and ecotoxicology.

Testable Models in Aquatic Systems
This is a NERC Special Topic running over three years and providing almost £1 million in new grants. Its main objective is to stimulate new interactions between empirical aquatic (both marine and freshwater) ecologists and mathematical modellers. Most of the awards were to marine projects and none was for work at the catchment scale. It could be useful in identifying suitable modelling expertise for the new catchment programme.

Large-scale processes in Ecology and Hydrology
This Special Topic is a three-year, £1.74 million, collaborative undertaking between NERC, DoE and SOAFD. Its objectives are to focus on the integration of ecological and hydrochemical research and spatial and temporal processes, and to generate both new theory and results of practical significance. It is envisaged that 5-6 projects will be undertaken and proposals have been invited for innovative studies in the following categories: Spatial and temporal population dynamics; community assembly and ecosystem structure and biogeochemical cycles and hydrology. At present, the extent of the aquatic contribution to the Special Topic is unknown. The research is intended to be undertaken by consortia from Universities and other research institutes. Although projects are focussed towards practical outputs, it does not appear that managers are to be involved in the research process.

4.2 Overseas Studies

4.2.1 Responses to Standard Letter

From overseas establishments we received notices of some 61 separate 'projects'. Tables 4.4, 4.5 and 4.6 provide comparisons with Tables 4.1, 4.2 and 4.3 respectively. (The corresponding data for freshwater research in the UK).

Despite the current paucity of UK catchment research programmes, there are important, large-scale, multi- and interdisciplinary initiatives in North America, Europe, Australia and New Zealand. Such initiatives include Coweeta and the H.J. Andrews and Hubbard Brook experimental forests (United States), the Canadian Experimental Lakes Area, and the rivers Rhine, Danube, Elbe, Murray and St. Lawrence. Members of the Steering Group for the present initiative are in regular contact with overseas workers in this field and there are good opportunities for international links and collaboration thereby focusing international efforts back to the UK. Despite these efforts, even in the US, the recent Freshwater Imperative (Naiman 1995) has found inadequacies in the nation's ability to manage fresh waters on a sustainable basis. The report calls for further long-term, interdisciplinary research programmes to answer future requirements for models, information and expertise and argues that funding and infrastructure for freshwater sciences have suffered while government expends significant resources on ineffective management activities that have a poor scientific foundation. This scoping study has found similarities in the UK and further exacerbation from the intensity of anthropogenic pressures on UK catchments. The solution to this problem is to be found through long-term, multi-scale research, in order to provide the generic, predictive models which are the ultimate 'tools' required by managers (Chapter 8).

Table 4.4 The focus of freshwater research overseas

Focus of interest	Geographical Scale	
	Catchment or above	Sub-catchment or below
Biological <u>and</u> physico-chemical	15	30
<u>Either</u> biological <u>or</u> physico-chemical	0	16

Table 4.5 'Targets' of overseas research.

Research area	Overseas establishments (%)
Physico-chemistry and Biology	73.8
Physico-chemistry only	11.5
Biology only	14.8
Total Physico-chemistry (i.e. Physico-chemistry and Biology + Physico-chemistry only)	**85.2**
Percentage of Total Physico-chemistry studies which include	
nutrients	18.0
hydrology/hydraulics	41.0
sedimentology	19.7
Total Biology (i.e. Physico-chemistry and Biology + Biology only)	**88.5**
Percentage of Total Biology studies which are multi-group (2 or more of the following groups)	57.4
Percentage of Total Biology studies which include	
microbes	13.1
phytoplankton/algae	24.6
macrophytes	16.4
zooplankton	14.8
invertebrates	57.4
fish	36.1
other vertebrates	9.8

Notes: Data recorded as percentage of studies n = 61

Table 4.6 **Timescales of Overseas studies.**

Timescale of study (years)	Overseas establishments (%)
≤ 1	13.1
> 1 - ≤ 2	11.5
> 2 - ≤ 3	8.2
> 3 - ≤ 4	6.6
> 4 - ≤ 5	8.2
> 5 - ≤ 10	9.8
> 10 - ≤ 20	4.9
> 20	8.2
Unspecified	29.5

Notes: Data recorded as percentage of overseas studies n = 61.

5.0 AN OVERVIEW OF OBJECTIVES AND OPTIONS FOR CATCHMENT ECOSYSTEM RESEARCH AND DEVELOPMENT.

Earlier chapters set out the results of our surveys of the 'Science landscape'(p. 11), key questions in catchment ecosystem management (p. 25), and of present initiatives and research programmes (p. 38). In this chapter we

i) review the objectives of managers and scientists in the field of catchment ecosystems,
ii) examine the match between management ('user-led') uncertainties and scientific ('science-led') interests,
iii) outline two elements (Research and Development) that together make up a range of options for future progress.

5.1 Objectives of managers and scientists

A common, overall objective of scientists and managers is to achieve a better understanding of catchment ecosystems to allow their sustainable management. Through an iterative series of consultations and assessments we have identified a series of key scientific questions and themes that attract widespread interest in the freshwater community.

The single, key scientific uncertainty, identified throughout the review, relates to interactions between the (mainly small) scales at which phenomena or processes are well known and the larger scale patterns and events at which we need prediction for both science and management purposes. In our view, this scientific uncertainty about the large-scale ecology of catchment ecosystems undermines attempts at a better symbiosis between science and management. It is only likely to be ameliorated by large-scale, longer term research. The list of key science questions arrived at by our review process was prioritized in Chapter 2 by criteria of 'interest', 'feasibility', and 'ability' i.e. judgement as to whether the question was identified as scientifically interesting, modified by considerations of the likelihood of success ('feasibility') and whether adequate expertise is available in the UK community ('ability'). It is the object of science-led research to progress these questions in the short- to long-term.

Key management questions were arrived at by the iterative consultations described in Chapter 3. This arrived at a list of 11 specific target outputs required as the highest priority of managers. We now look for opportunities to match science and end-user interests to mutual benefit.

5.2 Matching science questions and user interests to prioritize and target research

In this section we look for research opportunities to answer the 15 key scientific questions identified and particularly those which coincide with user interests. Table 5.1 presents prioritized science issues alongside user priorities and shows cases where targetted research would be mainly science- or user-led or where there is some match. The latter occurs where both science issues and user interests are categorised as at least medium priority. This yields seven areas where targetted research has support of both science and user interests (Table 5.1). Not surprisingly, these are areas where management outputs could be expected in the short to medium term (up to 10 years). They are also mainly areas where there is ongoing effort in the current NRA R&D portfolio. These areas identified as predominantly science-led concern broader, more fundamental questions where answers would have extreme user interest but where progress cannot be expected at short to medium timescales (up to 10 years).

5.3 A range of options

Having identified priorities and areas of overlapping interest we turn to the question of future progress. Our consultation, and particularly the Cardiff workshop, revealed two separable elements of any response to the challenge ahead. 'Development' would involve more effective transfer of research findings and knowledge, improved training initiatives (many now already in hand) and better communications between scientists and end-users. Much can be done in this area and can be achieved mainly by initiatives in the user community. 'Research' will involve new scientific initiatives in the key areas where there is a match between science and end-user interests, plus research in areas where interest is mainly science-led if appropriate science funding can be found. The potential mutualism between end-user and scientist should not be underestimated. Adequate science funding should be encouraged, even if not directly provided, by end-users since it can be used to promote longer term fundamental and strategic research of great potential interest to them in the longer term.

In the next chapter we look briefly at possible strategies for new/improved Development (Chapter 6).

In Chapter 7 we then consider a range of options in this area. They are made up of a series of mixtures of the two elements 'Development' and 'Research'. These options are:

i) 'Do nothing'. This would involve present levels and focus of R&D in the user community.
ii) 'Do minimum'. This option involves no new research but a much more active and targetted development programme (see Section 7.3.2, below).
iii) 'Do minimum plus extra research'. Extra development as in (ii) plus a modest programme of better targetted, site-specific or problem-orientated applied research.
iv) A Catchment Ecosystem Research Initiative. Extra development efforts (as in (ii)) plus a coordinated, larger-scale programme of research between the science and user communities targetted at a small range of 'demonstration' catchments.
v) A Catchment Ecosystem Research Initiative (as (iv)) but aimed at a comprehensive range of catchments representing all the main conditions represented in UK rivers.

Table 5.1/1 Matching Key Science Issues and Management Priorities. Science Issues have been prioritized (High, Medium, Low) as in Chapter 2.0 (p. 24) and present management interest (High, Medium, Low) as in Chapter 3.0 (p. 37). The overall management priorities arrived at in Chapter 3 (p. 37) have, in some instances been modified in the light of what is likely to emerge from research into each of the 15 science issues. For instance, the overall management interest in an issue might be reduced in parts of this Table if it is judged that the output from research on a specific science issue might be only partly relevant. The probable timing (Long, ≥ 10 y; Medium ≥ 5 y; Short 0-5 y) and the nature of management outputs are also given. Any links with existing NRA R&D is also indicated. The final column indicates whether new, targetted research should be either Science (S) or User (U)-led, or whether there is a match of interests (U&S, S&U).

Science Issues	Science Priority (H,M or L)	Present User Priority (H,M or L)	Timing Management Output	Management Output	Subject of Existing R&D?	Science Led/User Led (S,U, S&U)
1. Temporal and spatial characteristics of sediment transport in catchments, along with their wider ecosystem effects.	M	M	Long	How to model and manage the link between land-use (including agrochemical applications) and contaminant cycling and transport in catchments. [part] (5)	Studies of the natural erosion processes and rates from mixed aggregate built roads in upland forests and the impacts of heavy vehicles, in order to identify impact on water quality.	S&U
2. Direct and indirect effects of flows and sediment transport on:- • flow, substratum stability and channel forms. • processes of mixing and retention in rivers, from the micro- to the reach scale, including interactions with water quality. • ground water/river interactions Flood plain/river interactions.	M	H	Medium +	Means of rendering ecosystems less sensitive to pollution. (6) How to design and restore habitats. (7) Measures of conservation quality and value.	Field studies and monitoring of sediment and gravel bed transportation at selected sites to improve management practice.	U&S

Table 5.1/2

Science Issues	Science Priority (H,M or L)	Present User Priority (H,M or L)	Timing Management Output	Management Output	Subject of Existing R&D?	Science Led/User Led (S,U, S&U)
3. Knowledge of basic biogeochemical processes is insufficient for a generally applicable, catchment scale model incorporating routes, flows and transformations of materials in catchments (including soils, riparian zones, hyporheic zones, biofilms and water column).	M	H	Medium +	How to model and manage the link between land-use (including agrochemical applications) and contaminant cycling and transport in catchments. (5)	Joint nutrient study (JoNuS): To understand the scale, trends and processes of nutrient cycling in estuaries and coastal waters. Determination of metal speciation in rivers and estuaries. Measures for protecting upland water quality: Development of management practices required for practical implementation of Forest and Water Guidelines, e.g. the optimisation of buffer strip width in forest planting.	U&S
4. Freshwater biodiversity:- • poorly known elements (biofilms, *meiofauna*). • biodiversity and scale in catchment ecosystems.	H	L	Long	Measures of conservation quality and value. [part](8) Offering new/improved ecological indicators. [part] (11)	-	S

Table 5.1/3

Science Issues	Science Priority (H,M or L)	Present User Priority (H,M or L)	Timing Management Output	Management Output	Subject of Existing R&D?	Science Led/User Led (S,U, S&U)
5. Fully quantitative, long-term data in population ecology, is usually insufficient for modelling purposes:- • particularly for non-salmonids, for young or 'difficult' stages/species (eggs, adult insects, meiofauna). • interactions between deterministic and stochastic processes, particularly in relation to the physicochemical environment and to disturbance.	H	L	Long	Measures of conservation quality and value. [part] (8)	Assessment of elver stocks in the Severn Estuary together with elver exploitation and implications for river stocks. Review and evaluation of current knowledge, research and stock assessment capability in relation to sea trout and the design of a cost effective programme of investigations for effective, sustainable management of sea trout stocks. Assessment of the impact of introductions of non-native crayfish and outbreaks of crayfish plague on freshwater ecosystems and formulation of a strategy for the conservation of the native species. Determination of the present status of rare fish in certain lakes of England and Wales, and compilation of related information on the ecology and genetic variation of these species which is necessary to safeguard their population. Installation, operation and evaluation of a hydroacoustic fish counter in order to produce reliable data for salmon stock management.	S&U
6. Spatial characteristics of freshwater populations in relation to the 'nested', physical hierarchy of fluvial systems, for instance:- • most existing studies are small scale (and short term). • do metapopulation dynamics apply? • the role of patchiness and physical heterogeneity in evolution and population dynamics.	H	M	Medium +	How to manage the physical habitat for fish and other species.[part](4) Means of rendering ecosystems less sensitive to pollution. (6) How to design and restore habitats. (7)	Assessment of the conservation value of headwater streams and macroinvertebrates and their contribution to catchment macroinvertebrate richness, determination of agricultural impacts upon them and devise proposals for a conservation strategy.	S&U

Table 5.1/4

Science Issues	Science Priority (H,M or L)	Present User Priority (H,M or L)	Timing Management Output	Management Output	Subject of Existing R&D?	Science Led/User Led (S,U, S&U)
7. Models applying to freshwater communities over a range of spatio-temporal scales:- • 'spatially explicit' models (e.g. patch dynamics, probability refugia, random patchiness and others). • role of disturbances of various spatial, and temporal characteristics, physical refugia, source-sink populations.	M	L	Medium +	How to manage the physical habitat for fish and other species. [part] (4) How to design and restore habitats. (7)	-	S
8. Persistence and change in communities:- • natural variation, natural 'baselines'. • responses to sustained, environmental change (including resilience/resistance across different scales).	H	H	Long	Measuring and objectively defining 'allowable damage' to ecosystems. (9) How to detect community change. (10)	-	S&U
9. Pattern and process in freshwater food webs in relation to environmental characteristics.	L	L	Long	Offering new/improved ecological indicators. [part] (11) How to detect community change. [part](10)	-	S

Table 5.1/5

Science Issues	Science Priority (H,M or L)	Present User Priority (H,M or L)	Timing Management Output	Management Output	Subject of Existing R&D?	Science Led/User Led (S,U, S&U)
10. The importance of relatively well known small-scale processes for large-scale, persistent patterns and processes.	H	L	Long	Science-based management.	-	S
11. The role of species and of biodiversity in ecosystem processes.	M	L	Long	Measures of conservation quality and value. [part] (8)	-	S
12. There are few catchment-scale models able to forecast the impacts of environmental change (including human-related impacts). Some <u>within</u> discipline models exist but the integration of models has not yet been achieved.	L	H	Long	Predictive catchment-based models.	Investigation of the impact of liming treatments and land use change on streams and refining models for predicting deposition impacts and land use changes in the aquatic environment. (Llyn Brianne project). Development of a nitrogen process model for MAGIC (acidification model) and application of the model to investigate increasing nitrate in atmospheric deposition.	U
13. The need for a credible, widely accepted assessment of the economic value of ecosystem "goods and services"; and the costs of restoration/ rehabilitation work <u>and</u> an objective ecological basis for environmental 'targets' and standards relating to thresholds and system resilience.	M	H	Medium +	Scientific and economic basis for environmental quality objectives. (1) Measuring and objectively defining 'allowable damage' to ecosystems. (9)	Development of an economic benefit methodology for evaluating enviromental benefits resulting from changes in water quality stemming from improvements in effluent quality. Development of environmental quality standards for substances of concern to the NRA.	U&S

Table 5.1/6

Science Issues	Science Priority (H,M or L)	Present User Priority (H,M or L)	Timing Management Output	Management Output	Subject of Existing R&D?	Science Led/User Led (S,U, S&U)
14. Ecological effects of the nature and temporal and spatial characteristics of chemical perturbations, for instance:- • additive/synergistic effects. • repeated episodes. • multiple point sources throughout a catchment. • indirect effects of chemistry.	L	H	Short +	Assessing impact of, and recovery from, point/diffuse, episodic/ chronic pollution. (2) How to measure impact and manage eutrophication and pesticide contamination. (3)	Development and assessment of toxicity-based criteria in order to assess the general quality of receiving waters. Development of internationally standardised toxicity tests for use with sediments contaminated with sparingly water-soluble substances. Development of management practices required for practical implementation of Forest and Water Guidelines, e.g. the optimisation of buffer strip width in forest planting. Assessment of the impact of different pesticides on the structure and functioning of riverine ecosystems. Total impact assessment of pollutants in rivers: i.e. investigation of the pollution of streams draining agricultural catchments and specifically, development of a simple model of the movement of pesticides from the point of application to streams.	U

(and transfer of knowledge)

6.0 DEVELOPMENT: OPPORTUNITIES FOR SCIENCE TRANSFER, TRAINING AND COMMUNICATIONS

good links between ~~the~~ scientists and managers

In addition to new research, a potentially important element in addressing management problems and improving the effectiveness of environmental regulatory organisations arises in the uptake of new and existing knowledge. Development (i.e. the 'D' in 'R & D') in this case represents optimising the transfer of science into management for maximum benefit relative to costs.

Development as defined for public sector research (see NRA Annual R&D Review, or Govt. forward look

The Leicester conference (Harper and Ferguson, 1995), Cardiff workshop (Hutchinson, Hildrew and Ormerod, 1995) and consultations with NRA staff (Annex 3) have all identified the importance of ~~this issue to which~~ the NRA has already, in part, responded by developments in its training programme (NRA R&D Committee paper (95)8). The organisation's own initiatives in this sphere aim to create a culture of professional excellence in the application of science and technology, plus a working environment that encourages innovative and exciting thinking. These areas are seen as pivotal in the run up to the new Environment~~al~~ Agency in April 1996. The development of a Professional and Technical Training Programme is ongoing, and is being expanded to address the priority areas for the development of knowledge, understanding and competence required by staff in all functions. An overall strategy for Science and Technology training is still being developed, and we reiterate here some of the key elements to emerge from the Cardiff workshop to advise this development process:

6.1 Outputs from the Cardiff workshop: the 'how' of science transfer.

Outputs from the Cardiff Workshop (Hutchinson, Hildrew and Ormerod, 1995), and consultations with NRA staff have been in close agreement over potential routes forward. Both reveal the recognition that the creation of new opportunities for science transfer and development has two central elements:

i) what science needs transferring ?

and

ii) how will transfer be achieved ?

The report of the Cardiff workshop discussed the second of these areas in most detail, and options are outlined here along with additional possibilities that have arisen during the scoping study. Most stress or imply the value of broader links with the Science and Technology community outside the NRA and the Environment~~al~~ Agency that will take on its duties. Among them, 6.1.1, 6.1.3, 6.1.8 and 6.1.9 will have low costs; 6.1.2, 6.1.4, 6.1.6 and 6.1.7 will have medium costs (perhaps £10,000-50,000 per project), while 6.1.5 will have costs varying between low and medium depending on the scale of activity chosen.

"Development" is application of science and development of tools etc, ~~and~~ Development (i.e. technology transfer) of the science, not simply development of staff.

6.1.1 Working behaviour and standing orders

? Title

Some of the simplest solutions to problems of science transfer are incumbent on the manager and scientist in their everyday roles. Firstly, the manager, before taking management action, might ask whether better science is available to guide a given action, whether s/he can access it or use it, and whether s/he is abreast of scientific development. Equally, the scientist might ask whether his or her scientific outputs are being used fully, and if not how can outputs be better suited to management needs.

Specific areas of working behaviour which involve both the NRA and the external science community include functional links via project working groups, and regional links through local catchment studies.

6.1.2 Training courses and seminars

Training courses and seminars can use many formats in the classroom, field, office, laboratory and at distance, using many media including direct contact, video, CD Rom, hard literature and software. Training might involve time allocated in blocks (e.g. for MSc courses), day release, or ongoing seminar programmes. In the context of this report, it is important that training initiative should be jointly advised by science and management needs, while being aimed to inform scientists about management needs, or managers about science developments. On the one hand, this might mean practitioners having input to the development of university courses, and on the other, scientists providing more direct input to the design, provision and content of training in the NRA and its sister bodies. In other instances, 'hands on' training might arise in new operations, tools and technologies. Recent examples in the NRA include courses designed specifically around the new River Habitat Survey.

Training courses are liable to be of the utmost importance in the NRA's Professional and Technical Training Programme, and central to the development of a culture of professional excellence. For this reason, we make specific recommendations in Section 6.2 about priority areas for development. At the same time, this area is likely to require more detailed examination about how links between science in theory and practice can best be forged. In our opinion, differences between the cultures of the academic sciences and river catchment managers will be thrown into sharp relief when course content and training needs are discussed in detail.

We can provide examples from our own experience with MSc and undergraduate professional training courses that involve out-posting students into NRA laboratories for periods of project work. Students often receive distinctly different advice from NRA and academic supervisors over the scope, design and interpretation of their work. As an example, the NRA supervisor, driven by the needs of cost-effectiveness, pragmatism, policy and established practice typically will ignore replication in field sampling, approach problems with a site-specific focus, and interpret data in the light of professional judgement, expectation and experience. Meanwhile, the academic supervisors, from a theoretical and often impractical viewpoint, will reveal statistical and logical flaws in the resulting work. We make no case for the correctness of either approach (and clearly both extremes have been exaggerated for the purposes of our argument), but suggest that it illustrates potential challenges to the future development of scientifically robust river catchment management. It also illustrates a danger that established practice in the NRA can resist new ideals.

Our concept of the needs of training courses is to close this gap, aptly termed the 'turbulent boundary between water science and water management' (Cullen 1990), so that both academic and practising communities recognise each other's needs, and recognise a common set of values in the aims of scientific training.

6.1.3 Two-way workshops, conferences and professional institutions.

Any programmes involving discussion meetings and workshops would clearly benefit from the different perspectives of scientists and managers. In the case of conferences, rolling programmes on an annual or biennial time step might benefit from being aimed at maintaining dialogue through general themes. The Leicester conference (Harper and Ferguson, 1995) provides a useful prototype. Regional meetings of professional institutions already exist, and involve speakers from academic institutions, but tend to attract participation from EITHER the academic OR regulatory sector. We see value in enlarged joint participation.

Emphasise

6.1.4 Science manuals and reviews

Possible areas for the development of manuals (e.g. the current 'Rivers and Wildlife Handbook') and reviews might be led by basic science, by disciplinary or functional issues, by applied issues, by new science developments or by geographical units, such as individual river catchments. Output media might vary from reports, books, videos or reviews in scientific journals. Concern was expressed at the Cardiff workshop that these should be readily understandable by managers, applicable to their needs, and not overly academic in tone.

6.1.5 Staff exchanges and shadowing schemes

Staff exchanges, secondments and shadowing schemes are possible between the user community, the institutes and the universities.

6.1.6 Demonstration exercises

Where jointly staffed by practitioners and scientists, demonstration exercises might provide the opportunity for outdoor workshops. For example, field courses on experimental design and sampling might simultaneously take the form of small research campaigns geared to advising a particular management problem.

6.1.7 CASE studentships and fellowships

The NRA has had a programme of fellowships which have provided science outputs, at least in academic terms, although the number of individuals involved has been small. There would be value to both academic institutions and the regulatory bodies in viewing such projects in the future as an important means of integrating activities across the science/management frontier.

6.1.8 Institutional developments

Important routes for knowledge transfer might arise from institutional developments. They might include committees modelled on the JNCC 'Think Tanks', which meet on an *ad hoc* basis to confront key issues, or science review panels which examine particular areas of operation. 'Science Advisory' committees, standing alongside the RRACs, FACs, FDCs in the NRA regions, are also an option.

6.1.9 Circulating information

Key routes through which information, reports, scientific papers and outputs can be circulated between academic and regulatory institutions require development. There are currently few examples where academic scientists invite peer review and comment from regulators, and vice versa.

6.2 The 'what' of science transfer

Clearly, there is a large array of topics within which better science transfer could support catchment management (Hutchinson, Hildrew and Ormerod, 1995). In part, this reflects the different perspectives from different areas of academic expertise, different NRA functions, and different NRA regions. Under these circumstances, there is need for firm prioritization, but also a need for R & D to be crafted to the suit the particular situations in each NRA region. This need is recognised within the NRA. A further important element, however, is that any issues of science transfer and development should have a large degree of generic value when implemented in any location or function. We suggest that two key needs (6.2.1 and 6.6.6, below) satisfy these criteria and are important priorities for training. We also recognise, however, that a further area for potential training lies in the economic evaluation of the environment.

?

Title?

technology transfer

6.2.1 Improvements in the statistical analysis of data and the design of investigations.

Major areas of the NRA's responsibility involve detecting effects following degradation, or recovery, in catchment ecosystems. Among these, the measurement of recovery will be paramount as catchment management plans shift to action plans which specify targets and the means to achieve them. The measurements to detect such patterns can be chemical physical or biological, the geographical scales can be from reaches to whole river systems, and the time scales from hours in the case of pollution incidents, to decades in the case of long term change through acidification, eutrophication or changing habitat structure. Intensive or extensive field investigations are involved in all these instances, linked sometimes with laboratory studies, so that there is a clear need to assess observed patterns in relation to background variability of the types outlined in Section 8.1. This is bound to be the case, because the measurement of any environmental parameter - whether it be a quality index, a biological community, a chemical determinand, or a measure of flow - will be subject to variation in space, time, or due to error. This is illustrated as the 'uncertainty' box on Figure 1.1.. Under these circumstances, there is a challenge to detect whether effects due to a supposed source (e.g. a polluting discharge, a flood defence programme, a conservation enhancement scheme) is greater than that from other sources. We need to ascribe change accurately to our successful managerial interventions in river ecosystems, to attach blame accurately where problems arise, and correctly detect adverse or positive trends where they occur over a wide range of timescales.

Yet the detection of such effects is riddled with difficulties that confound attempts involving intuition alone, or sometimes even detailed studies. Professional and academic ecologists have not escaped problems, and a large percentage of field investigations published in scientific journals are likely to be characterised by errors in design or statistical analysis (e.g. Hurlbert, 1984). The failure to replicate correctly is common, and is endemic when an investigator is faced with assessing problems in just one location (e.g. a point source, a single river catchment subject to deforestation or afforestation). This is, of course, a key problem in the NRA since many investigations are of this type. The use of RIVPACS, where patterns at single sites are compared with expected patterns from many sites, has been a frequent strategy which might overcome this problem. However, while there is a tendency on the part of operators to view differences between observed and predicted faunas in RIVPACS as indicative of impact, there has been increasing recognition that chance elements also affect faunal change, recolonisation, and persistence through time (e.g. Weatherley and Ormerod, 1990; Wright, 1995; Rundle, Weatherley and Ormerod, 1995). As a result, therefore, this approach does not escape the need for the sound design of sampling regimes (Underwood, 1994).

Given that many scientific investigations by academic ecologists have themselves been subjected to criticism (e.g. Hurlbert, 1984), it is unsurprising that operational activities by regulatory bodies have themselves come under scrutiny. Here, practice is still governed as much by pragmatism and tradition as by the rigours of sound design (e.g. Norris *et al.* 1992; Underwood, 1994). In the USA, where pressures of pursuing or avoiding litigation are strong, basic design flaws in field investigations by regulators and others have sometimes reached the law courts (e.g. Underwood, 1994). In what can be highly patchy and stochastic river environments, failures to account for all possible sources of variation, error, change and causation, for example upstream and downstream of polluting discharges, mean that statistical loopholes can be exploited by attorneys. Typical deficiencies in surveillance, monitoring and investigation programmes include:

i) sampling with insufficient replicates to give suitable precision;

ii) a tendency to concentrate only on mean values for determinands, whereas disturbances are equally likely to affect variances in space and time;

iii) sampling for an insufficient duration prior to planned disturbances to characterise background variation;

iv) mis-using statistical tests due to non-independent, auto-correlated or non-normally distributed data;

v) incorrectly ascribing, or failing to ascribe, disturbance effects to human activity through inappropriate replication;

vi) failing to build appropriate reference locations into field investigations;

vii) failing to use any statistics at all, for example in 'eye-balling' time-series data.

While organisations with restricted budgets will always have to operate with a degree of pragmatism, we recommend that the NRA pays close scrutiny to the design of its investigations, and to the needs to improve practice.

To maintain mutual recognition between the needs of the NRA and the needs of robust approaches, and in the spirit of developing shared values (e.g. Section 6.1.5), we suggest that training in this area might involve:

i) Initial in-service time spent by academic course leaders in NRA establishments to assess need;
ii) a formal course element at a training centre (e.g. a University); this would run concurrently with
iii) practical training involving the guided use of computer teaching facilities, software, and worked examples;
iv) a further in-service evaluation period involving a second visit by course leaders to course participants.

Items (ii) and (iii) together are liable to involve 10 days in two blocks.

An outline syllabus might be:

1. Outline and recognition of problems in current approaches

2. The appropriate design of field investigations

3. The analysis of data, and illustration of important patterns (illustrated with exercises).

    3.0 Hypothesis testing
    3.1 Means, variances, standard deviations and errors, power.
    3.2 Parametric and non-parametric approaches
    3.2 Comparing samples: t-tests, U tests.
    3.3 Comparing more samples: ANOVA
    3.4 Regression
    3.5 Multivariate extensions: multi-factor ANOVA, multiple regression, principal components.

3.6 Ordination, classification

4. Putting statistics into practice.

6.2.2 The ecological basis of river catchment management: a cross functional and interdisciplinary view.

While the research and development programmes that underpin the work of the NRA have responded well to some issues (e.g. the needs of nature conservation and biological classification to detect common forms of pollution; Wright *et al.* 1993; Boon *et al.* 1994; Boon and Howell, 1996), the needs of river management have meant a continual need to update available knowledge. Increasingly, management needs have focussed on forms of pollution in addition to sewage (e.g. Harper, 1992; Ormerod and Tyler, 1994; Hildrew and Ormerod, 1995; Hendriks, 1995; Gower *et al.* 1995) which affect rivers through a complex mix of chronic and episodic discharges (e.g. Weatherley and Ormerod, 1991), mixtures of varying complexity (e.g. McCarty *et al.* 1992), and point or diffuse sources (e.g. Parr, 1994). Equally important, management has increasingly required an integrated perspective of the physical (e.g. Brookes, 1994; 1995; Petts and Maddock, 1994; Armitage, 1995), biological (Wade, 1995) and energetic (e.g. Calow, 1992) environment of rivers in the face of demand for water resources, flood defence, fisheries, conservation, recreation and navigation (e.g. Karr, 1991; Calow and Petts, 1994; Harper and Ferguson, 1995; Boon and Howells, 1996). Science-based information must thus inform management over a wide range of needs (e.g. pollution detection and prevention, habitat management, fisheries enhancement, abstraction, assessment of conservation importance) and over a wide range of temporal and spatial scales (short- term/habitat specific to long-term/whole catchment). Linked strongly to the changing needs of management, and often driving them, are a range of important legislative and policy concerns at UK, European and global levels. Among these, the EU Directive on the Ecological Quality of Surface Waters, currently in draft (Mandl, 1992) is currently paramount. Additionally, global conventions (e.g. UNCED Convention on Biological Diversity, Heywood, 1995) have prompted UK initiatives which emphasise riverine biodiversity in general, and the distribution of particular scarce species (e.g. the shads, otter, pearl mussel). Also, wider policy issues challenge us to define, measure and manage rivers to the ends of sustainability, ecosystem health and ecological integrity.

Under these circumstances, examples of the uses of knowledge to meet the business needs of the NRA and Environmental Agency will include:

(i) The formalisation of chemical, biological and physical measurements into typologies, quality indices and quality standards;

(ii) The need to identify important resources in river systems at a range scales from reaches to whole catchments. This might include areas with important fish stocks (e.g. Elliott, 1995), or high nature conservation value (e.g. Boon, 1991; Boon *et al.* 1994; Ormerod *et al.* 1996; Raven *et al.* 1996 in Boon and Howells, 1996)

(iii) The need to detect increasingly difficult environmental problems, such as pollution or habitat degradation (e.g. Wright, 1995);

Needs to link
to tools NRA has
under devt.

(iv) The need to diagnose their causes;

(v) The need to give warnings where problems might arise (e.g. Calow, 1995);

(vi) The need to predict with confidence the likely success or failure of alternative management actions at a range or scales. Biological classification has figured strongly in the development of empirical models used for this purpose (e.g. Ormerod *et al.* 1988; Armitage, 1994);

(vii) The need to evaluate the effects of remedial action or regulatory programmes in post-project appraisal (e.g. Karr, 1991; Rundle, Weatherley and Ormerod, 1995);

(viii) The need to indicate the endpoints of system recovery from planned or uncontrolled disturbance (e.g. Milner, 1994)

Advising the NRA and Environmental agency on all of these fronts is central to our conceptualisation of a generic catchment ecosystem research initiative described in Chapter 8. Here, the above needs for management are placed alongside the importance of recognising that catchments are characterised by variations in disturbance regimes, and in resilience and resistance against them; by physical heterogeneity and patchiness; by the need to recognise the budgets of natural and anthropogenic substances; and by the need to evaluate resources and, if possible, give them economic valuations.

All of this should, of course, operate from the soundest science base possible, and hence should take account of ecological advances. Relevant recent theoretical developments in ecology include the concepts of ecosystem disturbance, resilience and resistance to change, disturbance, ecological scale and hierarchy, fragmentation and meta-populations, river-floodplain linkages, downstream linkages, patch dynamics, and concepts of the habitat-template through which river habitat conditions select species traits, and hence species communities.

But some information already exists from which the NRA can be better advised. In this sphere, our recommendation is for the development of a cross-functional and interdisciplinary training course or initiative which rolls from year-to-year and exposes regulatory staff to current science and new developments. Its content should be conceptual and broad based, equally applicable to all NRA regions, and to Scottish and Northern Irish river catchments. Inputs should be sought from key academics in the physical, chemical, biological and socio-economic sciences with knowledge and specialism at the catchment scale. It should air management problems, as much as basic science issues.

6.2.2.1 A suggested course structure

The exact content of this training course should be subject to further dialogue with the NRA, and the Environmental Agency which succeeds it, in order to agree specific training needs. We suggest that key areas would include:

1. The socio-economic, legal and policy framework of catchment management;
2. Current advances of catchment physical systems: flow, sediment dynamics, approaches to the appraisal and classification of channel structure.
3. Chemical dynamics in catchment ecosystems: budgets, interactions and the importance of land use.
4. Current developments in catchment ecology, including theory; the ecology of species and communities; processes, food webs and energetics.
5. The quest for a holistic view: linking 1-4 in a management context.

Parts 1-4 would involve formal lectures and set texts, while part 5 would be advanced through directed scenario-setting in a discussion and workshop format.

6.3 A final comment: science transfer as a two-way process

To a large extent, the transfer of information or concepts between the management and scientific spheres will benefit if it is a two way process. New and existing science will flow to advise management, while managerial problems and actions will provide a context for the development and testing of new scientific theory. A past example of this two-way process, interesting also because it carries an explicit illustration of both geographical and temporal scale, is provided in Table 6.1 (from Hildrew and Ormerod, 1995):

Table 6.1 **Scales of approach to the management of acidification (From Hildrew and Ormerod 1995)**

Spatial scale	Option	Time scale (years)	
		Implementation	Effectiveness
Supra-catchment	Reduce deposition	10-100	10 upwards
Catchment	Manage land use	1-10	1-10
Sub-catchment	Liming	1-10	1-10
Riparian	Buffer strips	1-10	?
Habitat	Channel morphology	1-10	?
All scales	Do nothing	Environmental cost?	

It incorporates suggestions about management solutions available to combat surface water acidification; in this table are illustrations of instances where management recommendations have resulted as a result of ecological surveys (e.g. about forest cover at the catchment scale), experiments (liming at the sub-catchment scale) and models (about deposition reduction). At the same time, potentially new management solutions have been proposed to challenges ecological science (e.g. manipulations of stream morphology to provide alkalizing environments). Also, commonly held management beliefs - that bankside 'buffer strips' would protect streams against acid inputs - were tested and found wanting (Ormerod *et al.* 1993). In the instance of supra-catchment action to reduce acid deposition, the only advice to management could arise from the pragmatic development of long-term projections and models, because the response of affected systems would be too long to allow management action by trial and error. In this context, new hypotheses and model predictions are now being tested through management action, but shortfalls between predicted and actual recovery have guided new fundamental hypotheses about why such shortfalls should occur (Rundle, Weatherley and Ormerod, 1995).

In this example, then, managerial and scientific progress has occurred simultaneously to mutual benefit.

7.0 ASSESSMENT OF THE OPTIONS

This chapter sets out the future options for meeting management needs and/or science interest.

7.1 What is needed?

The prioritization process in Chapter 3 arrived at a list of eleven key questions of interest to end-users in catchment management and these were matched with fifteen questions or gaps of science interest in Chapter 5. This process yielded three categories of issues and questions, a) those in which there is a match between scientific interest and end-user requirement (seven issues), b) those in which user interests clearly predominate, and c) those in which science interests lead those of users. Recall that these are specific issues and are additional to the general need to promote science-based management and to provide holistic and predictive models of whole catchment ecosystems. These are the 'needs' of the end-user and of the science community and there is an encouraging overlap between them. Even where there is no clear match between the two there remain strong links and commonalities in most cases.

Areas in which science interests are presently paramount would all be of great end-user interest in the long term if scientific success was achieved. Several of these issues (numbers refer to these in Table 5.1 p. 48) are presently:

i) rather speculative and/or likely to have rather long lead times into end-user uptake (Science Issues 10, 11, 7, 9)

ii) already the subject of a good deal of site-specific research by the user community (Science Issue 5) (which may have reduced the perception of need by end-users)

iii) deal with areas in which management 'tools' already exist (Science Issue 4)

These considerations reduce the perception of immediate 'need' by end-users, although the strategic interest is strong.

Areas in which user interests predominate are also of very considerable scientific interest but are of somewhat lower priority for scientific funding because they are already in part the subject of considerable applied research (Science Issue 14), or are areas in which scientific progress may be extremely difficult (Science Issue 12).

The greatest scope, therefore, is for effort to be concentrated on those areas of maximum overlap between science priority and end-users' need: we believe this scope exists in the economic valuation of ecosystems (issue 13); basic biogeochemical cycles (issue 3); the dynamics and effects of flow and sediment transport (issues 1, 2, 15); long-term population ecology (issue 5); the ecological and managerial relevance of nested catchment hierarchies (issue 6); persistence and change in community composition (issue 8). In developing the concepts of our favoured option in chapter 8, we resolve these linked issues into four related sub-themes (see Table 8.1). It is important to recognise here, however, that the greatest end-user needs will be met by the R&D options which either increase efficiency and best practice in management operations, or which result in real cost savings in management. We expand this theme in the next section.

7.2 Costs of Environmental Management

In this section we try to establish the quantities and pattern of expenditure on environmental management associated with catchment ecosystems. It is by making savings against these costs that the various options for action may be judged. Savings could be made by enabling managers to achieve higher standards for the same expenditure or to achieve present standards at lower cost.

The real costs of environmental management are difficult to estimate but are incurred in:-

a) improving water quality
b) environmental clean-up operations
c) low flow alleviation
d) river rehabilitation
e) conservation ehancement works
f) flood protection
g) management and notification of SSSIs
h) meeting all the directives listed in Text Box 2
i) implementing catchment action plans to meet their various targets
j) environmental monitoring and surveillance for all these purposes

The private sector water supply and sewerage companies in England and Wales invested over £7 billion (10^9) in the three years from 1989 and present plans for the 10 years 1989-2000 take the total to £30 billion, mainly in improvements to drinking water quality and wastewater treatment works (OFWAT 1992). Annual capital expenditure on sewage treatment and sewage management for the water service companies in England and Wales in 1992/93 was about £1 billion. OFWAT (1992) present estimates of two scenarios for the sewerage service from 1995/96 - 1999/00 and 2000/01 - 2004/05. The scenarios are named 'Progress maintained' (which includes current key improvements plus assumed enhancements) and 'Pure and green' (which envisages 'an enhanced set of new and potential obligations') (Table 7.1).

Thus, costs of the sewerage service in England and Wales over the next decade will lie between about £7 and £8 billion, depending mainly upon our obligations and implementation of the Urban Wastewater Treatment Directive. The figures and their basis have been challenged by the NRA (1993j) but the sums required are bound to be large.

Statzner and Sperling (1993) quote figures of about £43 billion in new construction and repairs relating to wastewater treatment in Germany (including a special programme in the former DDR) over the ten years from 1993. Adding operating costs, plus stream restoration measures in Germany, they estimate that expenditure on aquatic resources will be limited (!) to about £12.5 billion y^{-1} (assuming £1 $\approx$ 1.6 \$US). They project that about £0.6 trillion (10^{12}) would be required in the European Union to bring standards everywhere up to new guidelines, assuming conventional means of compliance.

Table 7.1 Projected investment in the sewage service (OFWAT 1992) (£ millions)

	'Progress Maintained' (plus assumed enhancements)	'Pure & Green'	
	2000	2150	Capital costs
1995/96-1999/00	1520	1560	Operating costs
	3520	3710	Total costs
	1600	2100	Capital costs
2000/01-2004/05	1920	2020	Operating costs
	3520	4120	Total costs

Expenditure by the NRA is partly met by recouping costs from various charging schemes and partly by Government Grant-in-Aid. In 1993/4 the NRA spent over £440 million. Expenditure (£ millions) on the following core functions at the year end 31st March 1994 was: Water Resources (78.1), Water Quality (83.4), Flood Defence (229.1), Fisheries (25.1) Recreation and Conservation (7.4), Navigation (9.8).

Environmental management in the NRA is organised at the catchment level and is to be achieved by the (partially complete) process of drawing up catchment management plans and their subsequent implementation. Information made available to us by the NRA indicates the average cost of writing a CMP is about £72k, whereas implementation over a 5 year period or more is obviously highly variable. Six recent examples are given in Table 7.2.

The increased cost of meeting environmental quality objectives, and how much of this cost can be passed on to customers, has led to conflict of the regulators with the private sector. The Chairman of the Water Services Association (Courtney 1992) said:

> 'the drive of the NRA, other UK quality regulators and the EC for more and more improvements often reflects too much enthusiasm and too little science and cost benefit analysis'.

He went on to argue that the 'law of diminishing returns' applies to the environment. That is, that 'we shall be spending more and more to get less and less improvement'. The argument is, therefore, that there must be a well founded objective and scientific (including socioeconomic) basis to justify the expenditure of large sums of money on environmental protection. Of course there is a clear, firmly founded basis (not least based on human health) for protection of inland waters from pollution and other forms of environmental insult, and in no sense could it be argued that statutory bodies, should escape their obligations. However, as has already been detailed in this report, the definition of endpoints in restoration and the guidance of managers in ensuring sustainability, are by no means so clear.

Table 7.2 **Estimates of costs of implementing Catchment Management Plans by the NRA and others. (£k). Timescales 1-5 years plus future.**

Function	River Cam Action Plan April 1993	Louth Coastal Final Report July 1993	Gipping/ Stour Final Plan December 1993	Ely Ouse Final Plan January 1994	River Medway Action Plan July 1993	River Test Action Plan July 1993
Water Quality	1,250+	650+ - 1,760+	58+	112+ - 1,205+		
Water Resources	720	2,350+ - 2,550+	70+	1,340	20,000	23,190+
Flood Defence	4,245 - 4,345	45,200	1,925	6,370	1,892	
Fisheries	62.5	70	5+	130		740
Recreation				100		
Conservation	525	+ ?	90	254		
Navigation	43	7.000	60	700		
Land Use		+ ?		+ ?		
Other			69			
Estimated Total	6,845.5+ to 6,945.5+	55,270+ to 56,580+	2,277	9,006+ to 10,099+	21,892	23,930+

There are clear cost savings to be made by the better application of ecological knowledge and by the acquisition of new knowledge. Costs of uncertainty in science and of potential errors can be illustrated by three examples (Statzner & Sperling 1993).

Eg. a) Varying standards for effluents from sewage treatment plants in Europe.
Until the imposition of common standards in the EU, standards for some determinands in effluent have been as specified in Table 7.3. It can be argued that the large differences in standards among countries are not based on objective knowledge of the ecology of catchment ecosystems. For instance, Danish streams are not five times more sensitive to NH_4-N than German ones, neither is there a five-fold difference in wealth between Denmark and Germany. Either, one country is being needlessly cautious (Denmark) or the other is risking ecological damage (Germany). Clearly a scientific basis for standards is required.

Eg. b) common standards, varying conditions
The general risk of imposing a global limiting value on effluents throughout the community can also be demonstrated by considering NH_4 emissions. NH_4 does ecological damage because it is progressively converted to non-ionized NH_3 when pH and temperature rise. Thus NH_3 is toxic to freshwater fish above about 0.03 mg NH_3-N l^{-1} as 17 °C and 100%

Table 7.3 **Current standards for effluents plants in various European countries (Statzner and Sperling 1993).**

Country	BOD (mg l^{-1})	NH_4-N (mg l^{-1})	Total N (mg l^{-1})	Total P (mg l^{-1})
Belgium	15-50	ND	ND	ND
Denmark	15	2	8	1.5
Germany	15-40	10	ND	1-2
Italy	40	10	15	0.5-10
Netherlands	10-20	ND	10-15	1-2
Portugal	40	10	15	2-10
UK	15-50	10-25	ND	ND

ND, not defined

oxygen saturation. Statzner and Sperling (1993) take Denmark as their example and point out that streams in S.W. Denmark, because of geological conditions, are more acid than those elsewhere. Thus the critical value of NH_4-N with respect to ammonia's toxicity to fish is very different, (by as much as five-fold) in acid versus basic stream water and shady (cool) versus non-shady streams. Thus, a single value for NH_4-N for Denmark (let alone the whole EU) ignores what we already know of the system and risks ecological damage or unnecessary cost.

Eg. c) reduction in BOD and the response of bioindicators

It is well-established that the relationship between investment in sewage-treatment plants and technical performance is non-linear. To reduce the final 5 mg of BOD is almost 35 times more expensive than the first 5 mg. Similarly, the ecological responses of bioindicators are also non-linear. A modest increase in oxygen concentration in polluted waters produces an obvious shift in bioindicators. In water already fairly clean, bioindicators change rather little for a similar improvement. Thus, improvements from good to very good are costly. Further, removing organic pollution as a stress reinstates the previous, natural limiting factors. If the stream in question is a lowland, sluggish stream it will never be shown as really top quality by some older indicator systems. In such circumstances, money could better be spent on some other, less-traditional restoration options. It is possible, that greater environmental benefits could accrue by application of new ecological knowledge rather than by conventional, advanced tertiary treatment. Research could avoid the risk of missing these benefits.

This last example illustrates the clear role of non-linearities in ecological systems. Statzner *et al* (in press) have recently extended this logic to look at the optimal investment strategies in environmental improvement using three separate measures: waste water treatment, stream restoration through the provision of buffer strips, and the specification of minimum flow requirements. If each is applied through the normal practices of imposing inflexible threshold or limiting values, environmental gains are made more slowly (and in fact may never accrue in practice) than if the environmental benefits of each 'slice' of the total investment were assessed continuously. For instance, managers might focus first on measures that relate to the limiting values for which legislation places the greatest constraint; in practice this is usually waste water treatment. Only after standards set for waste water treatment are achieved throughout a river basin, therefore, will investment be made in the next kind of measure. Because the budget may be consumed entirely by waste water treatment, there may be very little available for other measures. This kind of investment strategy will achieve lesser benefits than if a mix of available measures were applied, optimally, at each stage of the investment process. Such considerations establish the need for new approaches and measures in the science and practice of catchment management. They argue powerfully for blends of natural sciences and environmental economics to produce optional strategies for the sustainable management of catchments.

Finally, Statzner *et al.* (in press) provide figures for the percentage of total expenditure on 200 projects in freshwater resource management reported worldwide in 1994 (Table 7.4). The total cost was almost US$675 billion. Less than one tenth of one percent was spent on freshwater research and assessment. Even if as little as 1 or 2% of the costs of management could be saved by better research and science application, therefore, a clear economic benefit will be gained.

Table 7.4 Proportion of world-wide investments (reported in 1994) in completed, current and planned projects in freshwater resource management (Statzner *et al.*, in press).

	%
Improvement of the ecological quality of surface waters (primarily restoration of running waters)	39.5
Waste water treatment	38.8
Drinking water supply and irrigation	6.2
Reservoirs (multiple use)	5.8
Miscellaneous	9.6
Freshwater research	0.1

Since decisions over the management of river catchments incur costs of this type, there is clearly a need to weigh alternative management strategies, and to propose R & D options which optimise benefits relative costs. At present the methods for directly weighing such costs and benefits for this purpose are insufficiently developed. Thus, our assessment of the future options in the text that follows is governed by qualitative considerations of costs and benefits. However, we point out two particularly strong features of our preferred option (7.3.4) which are that

i) it emphasises the development of valuation methods, in both economic and environmental terms, that will improve cost-benefit procedures to aid management decisions in the future; and

ii) it promotes a holistic understanding of catchment ecosystems as a general aim, and in particularly emphasises the development of models to predict with confidence the likely success or failure of alternative management actions at a range or scales. The comparison of outcomes from alternative strategies will have clear implications for optimising benefits. In this, the financial savings relative to the costs outlined above are potentially large.

7.3 A range of options

A number of options can now be considered and these were first identified in Section 5.3 (p. 47). They begin with a 'do nothing' alternative. This entails taking no further action other than continuing the present scale of R&D in the user community along with the National effort in basic research in Institutes and Higher Education Institutions. The remaining options involve, in addition, various blends of further Development (see Chapter 6) and new Research.

i) 'Do nothing'. This would involve present levels and focus of R&D in the user community.
ii) 'Do minimum'. This option involves no new research but a much more active and targeted development programme (see Section 7.3.2 below).
iii) 'Do minimum plus extra research'. Extra development as in (ii) plus a modest programme of better targeted, site-specific or problem-orientated applied research.
iv) A Catchment Ecosystem Research Initiative. Extra development efforts (as in (ii)) plus a coordinated, larger-scale programme of research shared jointly between the science and user communities and targetted at a small range of 'demonstration' catchments.
v) A Catchment Ecosystem Research Initiative (as (iv)) but aimed at a comprehensive range of catchments representing all the main conditions represented in UK rivers.

We now identify, for each of these options, a series of associated Costs, Benefits, Constraints and Risks/Uncertainties.

7.3.1 Option (i) 'Do nothing'

Costs The monetary cost of the NRA's R&D programme (93/94) was about £4.9 million. Some further costs to management are unavoidable, such as the EU's Directives on nitrates and waste water treatment (see Section 7.2).

Benefits

Modest progress in meeting some of the user needs identified in Chapter 5. This progress will be site -and/or problem specific and will not increase generic understanding that is 'transportable'. User issues progressed[1] will be specific aspects of:

a) User output 5 - Land-use, contaminent cycling and transport in catchments

b) User output 2 - Impact and recovery from point/diffuse, episodic/chronic pollution

c) User output 3 - Measure and manage eutrophication and pesticide contamination

d) User output 1 - Scientific and economic bases for EQOs

e) User output 9 - Measuring/defining 'allowable damage to ecosystem'

f) User output 4 - Managing physical habitat for fish

g) User output 8 - Measures of conservation quality and value

(This list reflects the present R&D portfolio of the NRA)

Constraints

Uptake of science by the user community is presently inadequate and would remain so. There would be a continuing scale mis-match between science understanding and management needs. The present fund of scientific knowledge and understanding would be increased only slowly and modestly.

Risks and Uncertainties

There would be a failure to focus both existing investments and initiatives already underway within the user community (e.g. The Environment Agency is charged with working to the best available scientific knowledge), and in the national research agenda (e.g. the OST Technology Foresight). The Technology Foresight Panel on Agriculture, Natural Resources & Environment identified 'More widely integrated environmental research programmes' as one of its recommendations for generic areas needing investment. A further need was for 'soundly based legislation, training and advice', while a key constraint was 'Supply of trained science, engineering and technology graduates and postgraduates'. The ANR & E Panel also stated that scientific disciplines had become isolated, whereas many of the problems in attaining a sustainable environment 'require a multidisciplinary approach'.

Uncertainties in how sustainably to manage catchment ecosystems (including uncertainties as to their value) would persist at the risk of their large-scale failure). There would also be the risk of needless expenditure through the

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[1] Numbers refer to those in Table 5.1

operation of the precautionary principle.

No

Its more focussed on completing the tools w/o extra research.

allow whats ~ the pipel to come throug

7.3.2 Option (ii) 'Do minimum'

The increment of effort in this option involves adoption of some or all the initiatives in science transfer, training and communications outlined in Chapter 6.

Costs	Monetary costs associated with 'Do nothing' are still incurred, plus modest extra Development costs of new training, science transfer and communication initiatives (perhaps an extra £2 million y^{-1} depending on the size of the programme).
Benefits	As in 'Do nothing' plus some improvement in currently available best practice. There would also be a modest strengthening of the freshwater community through increased communication between scientists and end-users.
Constraints	As for 'Do nothing' except the constraint of an inadequate science uptake would be removed.
Risks and Uncertainties	Broadly as for the 'Do nothing' option. Scientific uncertainties would persist, we would forego much new knowledge with the risk that inappropriate models will be applied at high economic costs and unknown environmental risk.

7.3.3 Option (iii) 'Do minimum plus extra research'

The development initiatives under Option (ii) are adopted plus a modest programme of extra research, undertaken by the user community alone. This research would be strictly targeted, and site- or problem-specific, as is the present R&D Programme of the NRA, but would be expanded in intensity and/or coverage. Research would be focussed on existing management approaches and initiatives (i.e. on use-led interests, (U), and on questions with joint science (S) and user interests in Table 5.1. of Chapter 5, p. 48). Further, an 'Ecological Assessment Group' could be formed, that would be charged with 'phenomenological' research on the effect of specific works or incidents, wherever/whenever they occur. This would eventually establish a 'case law' of such effects that might subsequently be of predictive value.

Costs	Monetary costs will be as for the previous Option (ii) 'Do minimum', plus the costs of the extra research effort that perhaps would require a doubling of the Users' R&D budget, depending on the size of the programme.
Benefits	These include the benefits accruing to the previous Options (i) and (ii). Two further kinds of benefits would accrue. First, we could expect progress with specific aspects of a further group of the user priorities identified in Table 5.1 (p. 48). These might be:

a) User output 7 - How to design and restore habitats

and/or
b) User output 10 - Detection of community change
c) User output 6 - Rendering ecosystems less sensitive to pollution.

Secondly, further (i.e. additional) site-specific aspects of User priorities 1-5, 8 and 9 (see Option (i) above) could be progressed, depending on the size of the enhanced programme.

Constraints: Outputs would be targeted to user priorities, so advance in scientific understanding would be relatively small. There would be little/no progress with the problem of scale. Generic scientific understanding would not be substantially advanced.

Risks and Uncertainties: These remain as in Option (ii), above. Failure by the user and science communities to collaborate in a large-scale thematic programme on catchment ecosystems will lose the opportunity for generic understanding. Tools and models will remain largely empirical, with the risk that environmental changes or failures will be unpredictable. Sustainable use (i.e. good husbandry of the resource base) cannot be guaranteed.

7.3.4 Option (iv) A Catchment Ecosystem Research Initiative (CERI)

This would involve, first, the Development (transfer, training and communication) initiatives adopted under Options (ii) and (iii). Additional development opportunities, however, would arise by the partnership of users and scientists in a large-scale, thematic programme. These would be partly by the participation of user staff in research modules and their joint ownership of it.

Research would involve a large, thematic programme, undertaken jointly and collaboratively by the user and science communities. It would involve multi-scale research and have clearly targeted objectives and outputs. A research strategy would be adopted of a single ('demonstration') catchment, plus several (say 5) comparative catchments.

Costs: A proposal to NERC has been costed at about £13.5 million over 5 years to the Research Council. In addition, the socioeconomic aspects (ESRC might be a source) would cost an additional £2-3 million. The user community would provide support in kind (sites, labour, transport and facilities) plus cash of between £5-6 million over five years.

Benefits: The real needs are to advance science-based catchment management to obtain a holistic understanding of catchment ecosystems. This option is the first of those considered to achieve that. Research would attain a 'critical mass' sufficient to answer large-scale questions. Cost benefits to users accrue through collaboration and common cause, and particularly in the mutualistic use of user and science funds. Benefits follow from the increased contacts of scientists and users.

Progress in understanding, in improved models and user 'tools' in all of:-

(a) Areas where there is a match between science and user interests (Table 5.1, p. 48).
(b) Science-led questions of a basic or strategic nature.
(c) User-led priorities.

This progress would be less problem- or site-specific and there is a reasonable expectation of generic (or 'transportable') understanding and prediction. Greatly improved best practice could be anticipated, promoted initially by more effective science transfer and communication but, subsequently, through new scientific understanding.

Cost savings would accrue via better advised investment strategies (i.e. more environmental benefit per pound spent) and more objective environmental targets (i.e. advice when to relax or tighten regulations and constraints). Technology Foresight Panel recommendations would be addressed.

Constraints The main constraint is in the ability of the Freshwater Science Community to respond to the challenge of large-scale research. Supply of young scientists may initially be inadequate.

Risks and Uncertainties The main risks are with management and targeting of a large, collaborative programme. Scientific progress can never be guaranteed, but fundamental effort in freshwater ecology in the UK is presently small and the benefit accrued for new expenditure should, from this low base, be substantial. A further technical risk is that the single demonstration catchment (plus five comparative catchments) will provide insufficient replication of conditions.

7.3.5 Option (v) A Multi-Catchment Ecosystem Research Initiative

This would be similar to Option (iv) (CERI) but would be both more extensive and intensive. Rather than a single demonstration catchment and five comparative catchments (as in CERI), a programme of multi-scale research would be directed equally at each of a sample (at least five) of substantial river catchments in the UK. In Option (iv) CERI this level of research wold be applied only to the single, demonstration, catchment.

Costs The costs of CERI (in the order of £21 million, total) would be added to by, perhaps £8-10 million per catchment (economies would be obtained for further catchments), giving a total for five catchments of between £50-60 million.

Benefits A wider range of conditions would be studied and all/most UK regions could be represented. Replication is more assured and greater certainty achieved.

Constraints These are financial and in expertise and manpower. The UK does not have the resources to mount this level of effort in the freshwater sciences. (It might be achievable and justifiable in a European context).

Risks and Uncertainties

There would be great risks in the management of such a large programme. Data Stewardship would be very complex indeed - with associated risks to the output.

7.3.6 Which Option?

The main need for the user community is to increase certainty in science-based catchment management. Enormous investments are being made in environmental management and savings even of 1% in these, through improved science-uptake and/or scientific knowledge, will be cost beneficial.

In our view only Options (iv) and (v) provide the increased scale of scientific certainty (including holistic catchment science) required. Option (v) is too costly and ambitious for a national level of effort in the UK. Option (iv) (CERI) also has the advantage for the user of better focussing the efforts of the science community to the needs of the user community. This is entirely consistent with the OST's policy for science in the UK and with the Technology Foresight Panel's report on Agriculture, Natural Resources and Environment.

In the final chapter of this report, therefore, we present a more detailed plan for CERI and where/when specific outputs/deliverables can be expected.

Must get a better angle on this

Show where gaps in science are causing problems

- lack of targeting
- lack of supporting data

8.0 THE CATCHMENT ECOSYSTEM RESEARCH INITIATIVE

Previous sections of this report have formulated and prioritised science questions (2.0), identified key end-user issues (3.0), and compared these two to produce three lists of topics that have some match between the interests of Scientists and User (S&U or U&S), or are predominantly Science (S) or User (U) led. A consideration of options (7.0) then concluded that the most beneficial option would be for a programme of Development (improved transfer, training and communication as specified in Section 6) plus a collaborative programme of multi-disciplinary research undertaken through a partnership of scientists and users. The research programme has been named CERI, the Catchment Ecosystem Research Initiative. In this section we describe CERI more fully, including the science programme, suggestions for scientific approach and location, plus costs, timetabling and a possible management structure.

8.1 Themes and Science Questions in CERI

While this feasibility and scoping study was being undertaken the Steering Committee put forward a proposal for NERC support of a Thematic Programme (CERI) of research. This was a bid for science funds, that might subsequently attract some measure of matching funding from other sources, including other Research Councils (such as ESRC) and, crucially, the user community, thus forming the desired science/user partnership. The bid to NERC is bound in this report as Appendix 2. This Section borrows from the NERC proposal but differs from it in being able, for reasons of space, to give a somewhat more detailed description of the Science programme and of the anticipated User outputs, while avoiding repeating the background.

The NERC Thematic Proposal was born out of work carried out during this feasibility/scoping study and addresses the key science issues identified. The central idea is that there is a need for multi-scale research to clarify linkages between patterns and processes at different spatiotemporal scales and, thereby, to bridge the present gap between 'small-scale' scientific understanding and 'large scale' management questions. The scientific themes and questions described in the NERC proposal, however, were a reformulation of those given in the earlier parts of this Report and we need, therefore, to demonstrate how CERI will address the fifteen key science issues and produce the desired end-user outputs identified.

CERI takes 'Scale and Linkage in the Catchment Hierarchy', as its overarching theme, with a single, key scientific question.

- How are patterns and processes at any scale in the catchment hierarchy linked with those at neighbouring scales?

There are four related subthemes, each with associated questions:-

a) *Disturbance, resilience and resistance*

- What determines the sensitivity of freshwater ecosystems to perturbations of different spatiotemporal characteristics?
- Can we predict or influence system recovery?

b) *Physical heterogeneity and patchiness*

- Does the division and heterogeneity of fresh waters in catchment ecosystems control ecological and genetic diversity in the biota?
- At what spatial scales in the physical hierarchy are ecological and community dynamics stabilised?

c) *Budgets and transport*

- What are the key ecosystem linkages in catchments, for instance between land use and/or atmospheric depositions and water quality?
- What are the dominant processes in material cycling and river transport and how is the latter regulated?

d) *Evaluation and valuation*

- How do environmental indicators relate to the underlying ecological function of systems and how do these indicators respond to specific perturbations?
- Can we establish widely accepted, credible economic values for ecological processes?

Table 8.1 provides a 'translation' of these CERI themes and subthemes in terms of the key science questions and user outputs identified in this Feasibility and Scoping Study (Sections 2 and 3).

8.2 Scientific Approach

A single, moderately large river catchment will be studied intensively, plus a group of five 'comparative' catchments, each of which will be subjected to a restricted sub-set of the intensive programme. These comparative catchments will provide replication at the greatest scale, ensure a wider range of conditions than is represented in any single catchment (for instance, very impacted tributaries), and will increase the generality of models/concepts.

Secondary studies should also take advantage of opportunistic events to study specific phenomena as they arise. Such events might include engineering impacts, flood alleviation schemes, sewage treatment works, acute pollution spillages, appraisal of river restoration schemes, etc.

Research will be organised around the physical catchment hierarchy (Table 8.2) and will involve three approaches (i) a sampling programme with a nested, hierarchical design, (ii) manipulations at various scales in field and laboratory, (iii) modelling. Modellers must be involved at the outset of data gathering and experimentation to encourage the development of testable and validated models relevant to the problems of end users.

Table 8.1 Relating the CERI Theme and Sub-themes (Column 1) to the Key Science Questions identified in Chapter 2 (see Table 2.1) and User outputs from Chapter 3 (see p. 37) in Columns 2 and 3, respectively.

Themes and Science Questions in CERI. Scale and Linkage in the Catchment Hierarchy	**Key Science Questions in the Feasibility/Scoping Study**	**Management Outputs**
■ How are patterns and processes at any scale in the catchment hierarchy linked to those at neighbouring scales?	(10) ..small scale...large scale...patterns	Science-based management.
	(12) ..catchment-scale models...	Predictive catchment-based models.
a) *Disturbance, resilience and resistance*		
• What determines the sensitivity of freshwater ecosystems to perturbations of different spatiotemporal characteristics?	(14) ..ecological effects of...chemical perturbations...	Assessing impact of, and recovery from, point/diffuse, episodic/chronic pollution. (2) How to measure impact and manage eutrophication and pesticide contamination. (3)
	(15) ..effects of flows...on organisms...	How to manage the physical habitat for fish and other species. [part] (4) How to design and restore habitats. (7).
• Can we predict or influence system recovery?	(8) ..persistence and change in freshwater communities...	Measuring and objectively defining 'allowable damage' to ecosystems. (9) How to detect community change. (10)
b) *Physical heterogeneity and patchiness*		
• Does the division and heterogeneity of fresh waters in catchment ecosystems control ecological and genetic diversity in the biota?	(4) ..freshwater biodiversity...	Measures of conservation quality and value. [part](8) Offering new/improved ecological indicators. [part] (11)
	(6) ..spatial characteristics of freshwater populations...	How to manage the physical habitat for fish and other species.[part](4) Means of rendering ecosystems less sensitive to pollution. (6) How to design and restore habitats. (7)
	(7) ..models applying to freshwater communities...	How to manage the physical habitat for fish and other species. [part] (4) How to design and restore habitats. (7)
• At what spatial scales in the physical hierarchy are ecological and community dynamics stabilised?	(5) ..quantitative, long-term population ecology...	Measures of conservation quality and value. [part] (8)
	(9) ..patterns in freshwater food webs...	Offering new/improved ecological indicators. [part] (11) How to detect community change. [part](10)

c) Budgets and transport • What are the key ecosystem linkages in catchments, for instance between land use and/or atmospheric depositions and water quality?	(3) ..basic biogeochemical processes...	How to model and manage the link between land-use (including agrochemical applications) and contaminant cycling and transport in catchments. (5)
• What are the dominant processes in material cycling and river transport and how is the latter regulated?	(1) ..temporal and spatial characteristics of sediment transport... (2) ..effects of flows and sediment transport...	How to model and manage the link between land-use (including agrochemical applications) and contaminant cycling and transport in catchments. [part] (5) Means of rendering ecosystems less sensitive to pollution. (6) How to design and restore habitats. (7) Measures of conservation quality and value.
d) Evaluation and valuation • How do environmental indicators relate to the underlying ecological function of systems and how do these indicators respond to specific perturbations?	(11) ..role of species...in ecosystems...	Measures of conservation quality and value. [part] (8)
• Can we establish widely accepted, credible economic values for ecological processes?	(13) ..assessment of...economic value...	Scientific and economic basis for environmental quality objectives. (1) Measuring and objectively defining 'allowable damage' to ecosystems. (9)

Table 8.2 The physical hierarchy and 'descriptive/survey' and 'experimental' approaches feasible at each scale

Description/Survey* of pattern and process	Experimentation† and manipulative process studies
The whole river system and its catchment ☐ within a broader regional/national framework (applying broad or regional scale techniques from remote sensing, GIS, and regional economic models).	
Replicated tributaries ☐ reflecting categories of solid geology (base poor/rich) and land use both in the river corridor and in the general catchment (e.g. arable, forestry).	'natural' experiments with factors such as geology, soil and land use.
Replicated river reaches (1-10 km) ☐ nested within tributaries	manipulations at the reach scale (e.g. nutrient additions, retention manipulations using woody debris).
Macro-habitat features ☐ riffles, pools, dead zones, replicated within reaches	manipulations in replicated stream-side channels (with nutrients, contaminants, predators, etc.)
Meso-habitat features ☐ vertical (within stream bed) and lateral (across channel into riparian) dimensions, replicated within macro-habitats.	manipulations in in-stream channels, enclosures and exclosures (with predators, competitors, food and nutrients, for instance).
Micro-habitat features ☐ replicated micro-habitat units, such as stones, leaf packs.	small scale experiments at the substratum particle scale (leaching substrates, stone turning, leaf packs etc). Laboratory microcosms.

* Descriptive/survey efforts will be directed at nested, hierarchical sampling of patterns and processes involving:

- ☐ biotic components (fish, other vertebrates, macroinvertebrates, macrophytes, epilithon, plankton, meiofauna, hyporheos)
- ☐ chemical components (nutrients, major ions, metals, etc)
- ☐ physical components (hydraulic variables, substratum particles and sediment yields, storage zones, debris/detritus, light, temperature, etc).
- ☐ socio-economic components of the system.
- ☐ whole system features.

† The 'targets' of experimental/process studies will similarly address the living, physico-chemical and socio-economic components of the system. Experimental facilities would include a large scale, fixed facility of replicated channels, plus sets of mobile channels that could be operated at any secure stream or riverside site.

8.3 Addressing the Themes

Here we describe the research emphasis for each of the four CERI Subthemes and specify research modules that would fall under each of them. Activities described under each Subtheme would answer the key ecological questions, and provide the key management outputs, indicated in Table 8.1.. Additional Scientific and Management outputs (specific to each module) are indicated in Table 8.3 below.

8.4 Locations and Experimental Facilities

The primary catchment will have the following characteristics:-

i) a varied but not too complex solid geology, incorporating base-poor and base-rich components.
ii) a varied relief with upland and lowland courses, including some functional flood plain.
iii) a range of land uses.
iv) a variety of environmental impacts (but not extensively degraded).
v) a background of previous research and management knowledge with a good, existing data-base.
vi) be of national economic and conservation importance.
vii) a strategic position for the provision of training facilities for students and environmental managers.

The main candidates are the Wye, Severn and Trent. The five secondary catchments would be drawn from the two rejected from the primary list plus the Exe, Thames, Tweed and Yorkshire Ouse (Table 8.4).

Provision of new, national experimental facilities for lotic research will be an essential element of the programme. These would include large-scale, replicated off-stream channels plus sets of smaller, transportable, channels. The active support of the NRA in providing infrastructure, facilities and technical expertise in such a venture (and in the project in general) is a crucial and strong feature of this project.

8.5 Costs and Resources Required

This section concerns the Research element of CERI (i.e. in addition to Development costs). the four Subthemes would each be undertaken through a mixture of 'core' research and 'special topics'. Core research establishes the central theme of the catchment hierarchy and its sampling, central methodologies and facilities, quality control and data analysis and modelling. Special topics give somewhat greater flexibility to researchers involved to set their own targets and methodologies within a carefully directed and managed overall programme. It is also possible to distinguish the Modules in CERI (see Table 8.3) of main interest to the user community, the science community, or of mutual interest. We recommend that user funds are directed primarily (though not necessarily solely) at modules with the highest or clearest management priority, while more basic aspects be earmarked for science funding. It should be stressed that this strategy does not offer a way of partitioning or dividing resources or researchers into separate 'camps'. The whole programme proposes a partnership that achieves intellectual coherence only by the interdependence of the parts. Table 8.5 is a two-way classification of the research modules in CERI along categorical axes

Table 8.3 The CERI Research Programme - Description of Sub-themes and modules. 'Scientific Outputs' refers to key scientific questions (by number) from Chapter 2 (see Table 2.1) plus a short further description. 'Management outputs' refers to key management issues from Chapter 3 (see p. 37) plus further descriptions. 'Functions benefitting' are present NRA functions. Final column is an assessment of whether activity should be primarily Science (S) or User (U) led or whether there is a match between the two.

SUBTHEME A - DISTURBANCE RESILIENCE AND RESISTANCE

Research will address fluvial features enhancing ecosystem resilience and resistance (e.g. woody debris, transient storage ('dead') zones, refuges and riparian vegetation. Experimental studies, at the reach scale or in stream-side channels, will impose disturbances (including chemical and flow episodes) on intact systems. Rate of recovery and trajectories after disturbance will be studied.

Examples:

Module	Activities	Scientific outputs	Management outputs	Functions benefitting	U, S, 'Match'
DR&R(i)	Experimental studies with known chemical perturbations versus the structure of communities and the performance of presently available tools. Thus, detectability of impact using low concentrations of pollutants, repeated pulses and/or chronic conditions could be undertaken in natural reaches, large-scale experimental facilities and/or in mobile channels (thus with varying background water quality and with varying background biological communities).	(14) An increased understanding of disturbance.	(2), (3) Improved impact and risk assessment. Improved understanding of the performance of tools presently in use.	WQ, F, C.	U
DR&R(ii)	Either reach-scale or stream-side fixed channels could be used for long-term experiments with flow manipulations and their ecological impact. Replicated channels can be subjected to enhanced/reduced, stable/fluctuating flows and the ecological impact assessed. Long-term field experiments could be undertaken and the results compared with the output of presently available 'tools'. Natural channels could be manipulated by addition of large, woody debris and the ecological/fluvial morphological impacts assessed. Experimental results could be compared with survey results throughout the catchment hierarchy.	(15) Understanding of the physical environmental constraints on population/community ecology and ecosystem processes would be improved.	(4), (7) Increased predictability of the effects of flow management on population/community ecology and ecosystem processes. Testing of presently available tools Knowledge of the role of woody debris in managing rivers/streams (i.e. how much to leave/put in for specific purposes).	WR, F, C.	U

DR&R(iii)	Experimental, descriptive and theoretical studies of statistical sampling designs to detect change against a naturally varying background, using different 'systems' (epilithic algae, macroinvertebrates, meiofauna *et al*). These would combine the establishment of 'long-term' natural baselines, the assessment of the performance of various sampling efforts, and the experimental imposition of environmental and community changes (in natural reaches and/or experimental channels).	(8) Enhancement of our understanding of the scale-dependence and degree of persistence.	The rigorous design and improvement of monitoring efforts.	WQ, WR, F, C, C-F.	Match

SUBTHEME B - PHYSICAL HETEROGENEITY AND PATCHINESS

Research will investigate how biodiversity changes with spatial scale and sample size in the catchment hierarchy. Genetic markers will elucidate population structure in relation to patchiness. Experimental studies will investigate species interaction strengths and elemental/energy flow through food webs. Population dynamics and dispersal at explicit spatial scales will be addressed.

Examples:

Module	Activities	Scientific outputs	Management outputs	Functions benefitting	U, S, 'Match'
PH&P(i)	This would be a core module of nested, multi-scale sampling of many elements of the biota aimed at questions of scaling of biodiversity in the catchment hierarchy. Molecular genetics of patchy, divided populations would also be included.	(4), (6), (10) Role of scale in the ecology of catchment ecosystems.	(4), (6), (7) Guidance to the management of physical habitat and for conservation	C, WR, F	S
PH&P(ii)	Present knowledge of several, specific trout populations (including their long-term dynamics and growth models) provides some of the surest science in freshwater ecology. This knowledge now needs to be placed in a wider, spatial context to be of maximum benefit to management. A genetic analysis of fish throughout the whole catchment would be undertaken, to establish the existence and distribution of distinct sub-populations. The environmental characteristics associated with each sub-population would be studied, along with population characteristics (density, persistence, growth and survival) of fish in replicate streams for each population.	(6), (7) Knowledge of trout at greater scales than hitherto.	(4), (6), (7) How to apply appropriate management techniques to particular circumstances. How to modify/manage habitats for fish. How to predict consequences for fish of local and catchment-wide environmental change.	F	Match
PH&P(iii)	The patterns and processes in freshwater food webs are only partly explored scientifically and have not been used for management purposes. Research could be undertaken to reveal major energetic pathways (by use of stable isotopes, for instance), connectance of webs, strength of interactions in webs, spatial and temporal relatedness of webs in the whole catchment hierarchy.	(9) Understanding the relationships between such web-features and the environmental context (flows, riparian land-use, position in the catchment, anthropogenic influences, etc).	Understanding of the structure of river ecosystems. Potential new markers of environmental change Prediction of impact of new catchment uses. How to ensure management is sustainable.	F, C, C-F	S

PH&P(iv)	New approaches to the measurement of whole-stream metabolism could assess heterotrophy/autotrophy at a variety of scales throughout the primary catchment. These metabolic features of riverine ecosystems can be related to energy inputs (riparian vegetation, organic wastes, light) and to environmental features (geology, land use, aspect).	(9) Understanding of rates of 'self-purification' can be assessed in relation to channel-form, for instance.	(11), (1) Integration of research with socio-economics could balance the costs of physical restoration, flood-plain restoration and other measures against the benefits from an enhanced ability to incorporate, and/or mineralise organic wastes and thus aid management decision-making.	WQ, F, C, C-F	Match

SUBTHEME C - BUDGETS AND TRANSPORT

Multi-scale assessments of cycles of plant nutrients, carbon and contaminants will be part of the programme. Transport across boundaries ('airshed'/catchment; riparian/channel; tributaries/mainstem; hyporheos/superficial) will be addressed. New, automated methods of assessing sediment transport, mixing and flow forces will be incorporated in the programme. Whole stream measures of metabolism and stable isotopes to investigate carbon and nutrient flow will be adopted.

Examples:

Module	Activities	Scientific outputs	Management outputs	Functions benefitting	U. S. 'Match'
B&T(i)	Devising (or modifying from the oceanographic sciences) new equipment to facilitate remote, continuous, long-term measurements of near-bed flow forces and sediment transport.	(1), (2) Understanding of the spatio-temporal patterns in the physical environment (linked with species ecology)	(5), (6), (7) Methods for predicting transport of sediment and sediment-bound pesticides. Easier prediction of impacts of flow modification on particular populations.	WQ, WR, FD, F, C.	Match
B&T(ii)	Multiple-scale assessment of geochemical cycles of plant nutrients and carbon would form a core part of the programme. This would have to stress interactions across system boundaries (e.g. catchment/riparian, riparian/channel, upstream/downstream, hyporheos/water column etc). Such interactions determine nutrient/material spiralling and, ultimately, water quality. Small-scale (microcosm) to large-scale (mass transport) approaches will be necessary.	(3) Understanding of scale-dependent control of spiralling.	(5) Increased knowledge of the fundamental basis of water quality.	WQ	Match
	Interactions between water quality and the physical environment could be assessed by coordinating experiments under this module with those under DR&R(ii), for example. Thus, nutrient spiralling in channels with and without woody debris would be studied. These kinds of interactions will have additional science and management outputs.			WQ, F, C, C-F	
B&T(iii)	Empirical and modelling studies of mixing and retention in river channels at all scales in the catchment hierarchy. Studies on the ecosystem effects of the physical nature of the fluvial system.	(1), (2) Linking the physical environment with the ecosystem and its persistence.	(5), (6), (7) Habitat design for conservation and sustainability.	WR, C, F	Match

SUBTHEME D - EVALUATION AND VALUATION

Current indicators of ecosystem state will be tested under known regimes of perturbation. Multidisciplinary teams will investigate the relationship between economic policy (regional to local), ecosystem response and the economic value of ecosystems and their 'integrity'.

Example:

Module	Activities	Scientific outputs	Management outputs	Functions benefitting	U, S, 'Match'
E&V(i)	Economic valuation of ecosystem 'goods and services'. Multidisciplinary appraisal of the economic performance of natural ecosystems via 'self-cleansing', nutrient interception etc and its integration into economic policy.	(11), (13) Linking ecology and economics objectively.	(8), (1), (9) Objective assessment of EQOs and cost/benefit analysis of the environment.	WQ, WR, FD, F, C, C-F	Match
E&V(ii)	An ecological and socio-economic assessment of salmonid fisheries could be undertaken. Fisheries could be improved by the incorporation of riparian buffer strips of deciduous trees at an optimum density, addition of large woody debris, increased channel heterogeneity, restoration of seasonally flooded areas, etc. Values of such environmental enhancement (from fisheries and other benefits) can be balanced against lost land and agricultural production. Such work demands cross-disciplinary efforts of ecologists, environmental scientists and economists.	(13) Improved understanding of the habitat requirements of salmonids.	(1), (9) Development of techniques for improving management of salmonid fisheries. Integration of ecological research with socio-economics would facilitate development of protocols/techniques for improved decision-making.	WQ, FD, F, C, C-F.	Match

Table 8.4 Rivers short-listed as suitable primary/secondary catchments

River	Link with LOIS	Link with ECN	NRA CMP Consultation Report produced
Wye	-	Yes	Yes
Trent	Yes	-	Dove to Humber due 1997/8 or later Upper Trent due 1997/8 or later
Severn	-	-	Upstream of Perry due 1994/5 Estuary due 1996/7 Perry to Teme due 1997/8 or later
Exe	-	Yes	Due 1994/5
Great Ouse	-	-	Ely Ouse - Yes Bedford Ouse due 1994/5 Upper Ouse due 1995/6
Thames	-	-	Upper Thames due 1994/5 Benson to Hurley due 1995/6 Tideway and estuary due 1995/6 Buscot to Eynsham due 1996/7 Hurley to Teddington due 1996/7 Eynsham to Benson due 1997/8 or later.
Tweed	Yes	Yes	-
Yorkshire Ouse	Yes	-	Yes

of i) priority for end-users/scientists and ii) into core science or special topic modes. It suggests, for instance, that end-user funding should be concentrated on modules in the Disturbance, Resilience and Resistance Subthemes, and be used to support the Core Science in this area plus two Special Topics.

Table 8.5 **CERI modules classified according to i) end-user/science priorities and ii) funding mode.** End-user/science priorities are in three levels, following Table 8.3: A. user-led modules, B. modules where there is a match but where user interests are particularly strong, and C. primarily science-led modules. Funding mode is either, as part of the Core programme or, as a Special Topic. Subtheme names: DR&R - Disturbance, resilience and resistance; PH&P - Physical heterogeneity and patchiness; B&T - Budgets and transport; E&V - Evaluation and valuation. For Module numbers see Table 8.3 p. 82.

Funding Modes	**Funding Priorities**		
	A	B	C
Core	DR&R(i)(part) DR&R(ii)(part)	B&T(ii) E&V(i) E&V (ii)	PH&P(i) PH&P(ii)
Special Topics	DR&R(i)(part) DR&R(ii)(part)	B&T(i) B&T(iii)	PH&P(iii) PH&P(iv)

The Thematic Programme proposal to NERC specified a total cost to the Research Council of £13.45 million, and we here recommend user funding of a further £5.5 million over five years (in addition to support 'in kind') plus a contribution from ESRC of £2-3 million, mainly to support the Evaluation and Valuation Subtheme and to integrate socioeconomic sciences in the other modules. The financial summary in the CERI Thematic Programme proposal is included in Table 8.6 below, to which has been added the proposed contribution from end-user sources and ESRC. Most, though not all, of their contributions are envisaged as going towards Core Science and Special Topics. End-user funding would also contribute, for instance, to the early establishment of experimental facilities.

8.6 Timetable and Management

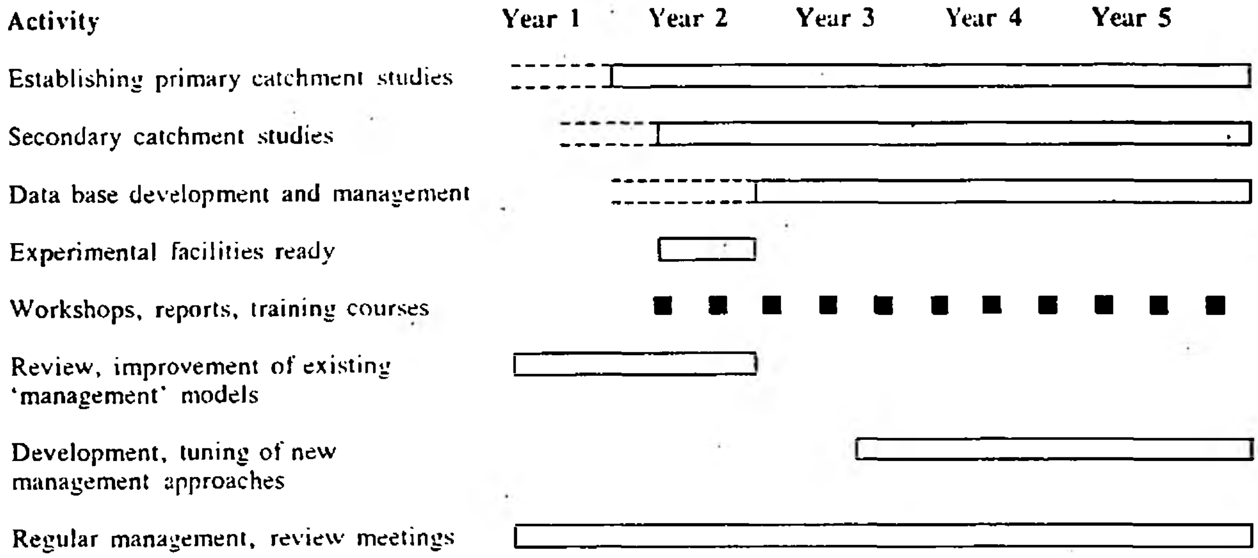
We envisage a series of basic, strategic and applied science outputs from this research. Despite dealing with long term issues, results relevant to management can be achieved with this 5-year project. Each sub-theme a)-d), alone or in concert with the others, will yield new information, new tests of theory at broader scales, and new and improved models. We have specified above the management outputs generated for each of the CERI models.

Table 8.6 **The financial profile of CERI (figures in £k cash).** Support requested from NERC (as in Thematic Programme Proposal) in plain text, contributions under each heading from end-users in italics, and from ESRC in parenthesis. Grand totals are in bold.

			Year			
Activity	1	2	3	4	5	Totals
Core programme of hierarchical sampling and manipulation	2000	2000	1500	300	300	6100
	-	*350*	*800*	*800*	*400*	*2350*
	(400)	(400)	(400)	(400)	(400)	(2000)
Special topics (supporting sub-themes)	500	2000	1600	300	-	4400
	-	*500*	*500*	*500*	*500*	*2000*
	(100)	(100)	(100)	(100)	-	(400)
Central Services (GIS/Remote Sensing/ Stable Isotopes)	300	300	300	300	100	1300
	40	*40*	*40*	*40*	*40*	*200*
	(-)	(-)	(-)	(-)	(-)	(-)
Establishing experimental facilities	400	400	-	-	-	800
	250	*250*	-	-	-	*500*
	(-)	(-)	(-)	(-)	(-)	(-)
Information managment	50	50	50	50	50	250
	20	*20*	*20*	*20*	*20*	*100*
	(10)	(10)	(10)	(10)	(10)	(50)
Project management	100	100	100	100	100	500
	50	*50*	*50*	*50*	*50*	*250*
	(10)	(10)	(10)	(10)	(10)	(50)
Workshops/conferences	20	20	20	20	20	100
	20	*20*	*20*	*20*	*20*	*100*
	(-)	(-)	(-)	(-)	(-)	(-)
Totals	3370	4870	3570	1070	570	13450
	380	*1230*	*1430*	*1430*	*1030*	*5500*
	(520)	(520)	(520)	(520)	(420)	(2500)
	£4270	**£6620**	**£5520**	**£3020**	**£2020**	**£21450**

Success can be judged by our ability to translate scientific outputs into clear generic frameworks of use to managers. Initially, outputs will be in the form of tests, modifications and validation of existing empirical 'tools' (schemes for quality assesment e.g. SERCON, RIVPACS; methods for assessing ecologically acceptable flows e.g. PHABSIM). Finally, there will be data bases, which will be placed in the long-term stewardship of one or more Institutes, and new experimental facilities for river research. We will aim at the schedule of outputs and targets indicated in Table 8.7.

Table 8.7 **Likely timescale for the various component activities of the Catchment Ecosystem Research Initiative**



Achieving these outputs will require clear, effective management and we recommend that end-user investment be protected by using some of the resource to find an independent manager/liaison officer for the project charged with co-ordinating the progress of the science and its uptake into their activities.

A management scheme for CERI is presented in Figure 8.1.

- **The Senior Management Group** will include representatives from the funding bodies, senior members of the Project Management Group and independent scientific peers (from academia and from industry) and will have overall responsibility for the science policy and direction of the Initiative.
- **The Project Management Group**, consisting of chairpersons of Subtheme Groups **plus** key members of the Senior Management Group will be responsible for the practical management and administration of the Initiative.
- A series of **Subtheme Groups** will consist of a chairperson plus Work Unit Leaders for

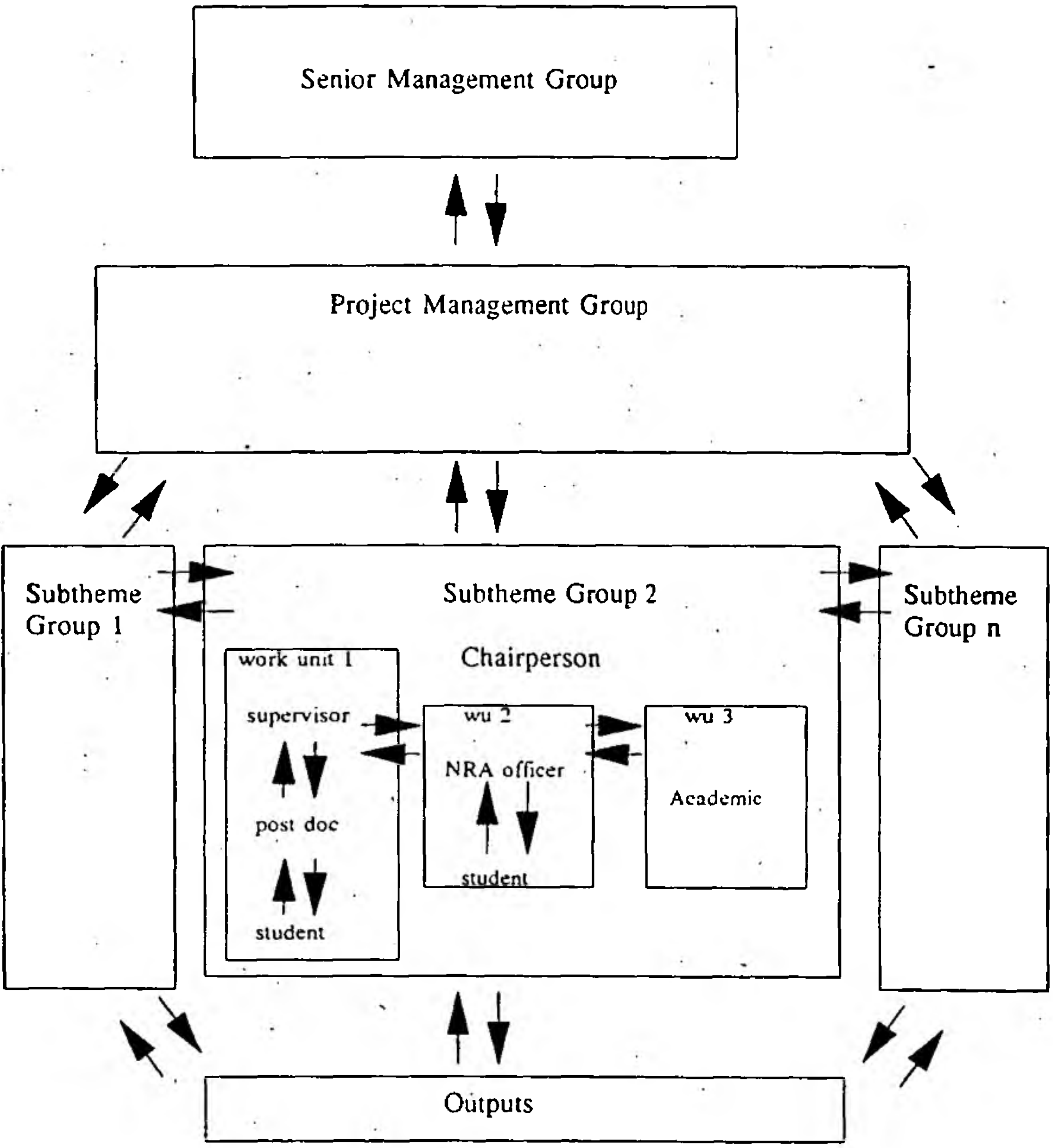


Figure 8.1 Management Scheme for the Catchment Ecosystem Research Initiative

the modules in each Subtheme (see Section 8.3 for details) and will have responsibility for ensuring communication and coordination within each topic.

- Each module may consist of one or more **Work Units** and these form the core of the research programme and may consist of a variety of types (three possible types are shown in the diagram). Targets will be set for each Work Unit and progress will be monitored through supervision, interactions and meetings, where necessary.

RECOMMENDATIONS

To be included once final text has been agreed.

BIBLIOGRAPHY

Anon. (1994) New Environment Agency. *Environmental Law Monthly*, **3(11): 1**-6.

Armitage, P.D. (1994) Prediction of biological response. In: Calow, P. and Petts, G.E. *The Rivers Handbook, Volume 2.* Blackwell Scientific Publications, Oxford, pp 254-276.

Boon, P.J. (1991) The role of Sites of Special Scientific Interest (SSSIs) in the conservation of British rivers. *Freshwater Forum*, **1**: 95-108.

Boon, P.J. and Howell, D.L. (Eds) (1996) *Freshwater Quality: Defining the Indefinable.* HMSO, Edinburgh. In press.

Boon, P.J., Holmes, N.T.H., Maitland, P.S. and Rowell, T.A. (1994) A system for evaluating rivers for conservation (SERCON): an outline of the underlying principles. *Verhandlungen der Internationalen Vereinigung fur theoretische und angewandte Limnologie*, **25**: 1510-1514.

Brookes, A. (1994) River channel change. In: Calow, P. and Petts, G.E. (Eds). *The Rivers Handbook, Volume 2.* Blackwell Scientific Publications, Oxford, pp 55-75.

Brookes, A. (1995) The importance of high flows for riverine environments. In: D.M. Harper and A. Ferguson (Eds). *The Ecological Basis for River Management.* John Wiley, Chichester, pp 33-50.

Brown, A.E. and Howell, D.L.. (1992) Conservation of rivers in Scotland: Legislative and organizational limitations. In: *River Conservation and Management.* P.J. Boon, P. Calow and G.E. Petts (Eds). John Wiley and Sons, Chichester. pp. 407-424.

Calow, P. (1992) Energy Budgets. In: Calow, P. and Petts, G.E. *The Rivers Handbook, Volume 1.* Blackwell Scientific Publications, Oxford, pp 370-378.

Calow, P. (1995) Methods to assess the effects of chemicals on fresh waters. In: Linthurst, R.A., Bordeau, P. and Tardiff, R.G. (Eds). *Methods to assess the effects of chemicals on ecosystems.* Scope 53. John Wiley & Sons, Chichester, pp 113-125.

Calow, P. and Petts, G.E. (Eds) (1992) *The Rivers Handbook, Vol 1.* Blackwell Science, Oxford.

Calow, P. and Petts, G.E. (Eds) (1994) *The Rivers Handbook, Vol 2.* Blackwell Science, Oxford.

Countryside Commission (1991) *Countryside Stewardship.* Countryside Commission, Cheltenham, England.

Courtney, W. (1992) *Improving the water environment - and the cost.* Water Services Association, Water Information WSA/S37, 1-18.

Cullen, P. (1990) The turbulent boundary between water science and water management. *Freshwater Biology*, **29:** 313-342.

Edwards, P.J., May, R.M. and Webb, N.R. (1994) *Large Scale Ecology and Conservation Biology*. Symposium of the British Ecological Society, Blackwell Science, Oxford.

Elliott, J.M. (1995) The ecological basis for the management of fish stocks in rivers. In: D.M. Harper and A. Ferguson (Eds). *The Ecological Basis for River Management.* John Wiley, Chichester, pp 323-338.

Giller, P.S., Hildrew, A.G. and Raffaelli, D.G. (Eds) (1994) *Aquatic Ecology: scale, pattern and process.* Symposium of the British Ecological Society. Blackwell Science, Oxford.

Gower, A.M., Myers, G., Kent, M. and Foulkes, M.E. (1995) The use of macroinvertebrate assemblages in metal contaminated streams. In: D.M. Harper and A. Ferguson, (Eds). *The Ecological Basis for River Management.* John Wiley, Chichester, pp 181-192.

Harper, D. (1992) *Eutrophication of Freshwaters.* Chapman & Hall, London.

Harper, D.M. and Ferguson, A.J.D. (Eds) (1995) *The Ecological Basis for River Management.* Wiley, Chichester.

Hendriks, A.J. (1995) Bioaccumulation of pollutants and its consequences. In: D.M. Harper and A. Ferguson (Eds). *The Ecological Basis for River Management.* John Wiley, Chichester, pp 175-180.

Heywood, V.H. (1995) *Global Biodiversity Assessment.* Cambridge University Press, 1140 pp.

Hildrew, A.G. (1993) Freshwater ecology in Britain - a case of decline? *Freshwater Forum*, **3(3):** 237-242.

Hildrew, A.G. and Ormerod, S.J. (1995) Managing the effects of acidification in upland rivers. In: *The Ecological Basis for River Management.* D.M. Harper and A.J.D. Ferguson (Eds). Wiley, Chichester. 147-160.

Hurlbert, S.J. (1984) Pseudoreplication and the design of ecological field experiments. *Ecological Monographs*, **54:** 187-211.

Hutchinson, J.D., Hildrew, A.G. and Ormerod, S.J. (Eds) (1995) *Catchment Ecosystem Research. Report of a Workshop held on 14-15 September 1994, Cardiff.* Prepared for NRA/NERC/English Nature/ESRC at QMW, London.

Johnson, R.C. and Law, J.T. (1992) *The Physical Nature of the Balquhidder Catchments.* Institute of Hydrology, Wallingford and Lochearnhead. 16 pp.

Karr, J.R. (1991) Biological integrity: a long neglected aspect of water resource management. *Ecological Applications*, **1:** 66-84.

Kirby, C., Newson, M.D. and Gilman, K. (eds) (1991) *Plynlimon research: The First Two Decades.* IH Report No 109. NERC Institute of Hydrology, Wallingford. 188 pp.

Likens, G.E. (1992) The Ecosystem Approach: its use and abuse. *Excellence in Ecology* **3**, Ecology Institute, Oldendorf/Luhe, Germany.

Mackay, D.W. (1994) Pollution Control. In: *The Freshwaters of Scotland: A National Resource of International Significance.* P.S. Maitland, P.J. Boon and D.S. McLusky (eds). John Wiley and Sons Ltd., Chichester. pp. 517-529.

Mandl, V. (1992) Draft EC Directive the Ecological Quality of Surface Water. In: P.J. Newman, M.A. Pivaux and R.A. Sweeting (Eds). *River Water Quality - Ecological Assessment and Control.* CEC, Brussels.

McCarty, L.S., Ozburn, G.W., Smith, A.D. and Dixon, D.G. (1992) Toxicokinetic modelling of mixtures of organic chemicals. *Environmental Toxicology and Chemistry*, **11:** 1037-1047.

Milner, A.M. (1994) System recovery. In: Calow, P. and Petts, G.E. (Eds) *The Rivers Handbook, Volume 2.* Blackwell Scientific Publications, Oxford, pp 76-100.

Naiman, R.J. (Ed.) (1995) *Watershed management: balancing sustainability and environmental change.* Springer-Verlag, New York.

Naiman, R.J., Magnuson, J.T., McKnight, D.M., Stanford, J.A. *et al* (Eds) (1995) *The Freshwater Imperative: a research agenda.* Island Press, Washington DC.

NERC (1992) *Land-Ocean Interaction Study (LOIS). Science Plan for a Community Research Project.* February 1992. NERC, Swindon. 31 pp.

NERC (1993) *Report of the Institute of Hydrology 1992/1993.* NERC, 11-13.

NERC (1994) *Land-Ocean Interaction Study (LOIS). Implementation Plan for a Community Research Project.* July 1994. NERC, Swindon. 61 pp.

Norris, R.H. (1995) Biological monitoring: the dilemma of data analysis. *Journal of the North American Benthological Society*, **14:** 440-450.

Norris, R.H., McElravy, E.P. and Resh, V.H. (1992) The sampling problem. In: In: P. Calow & G. Petts (Eds). *The Rivers Handbook, Volume 1.* Blackwell Scientific Publications, Oxford, pp 282-308.

NRA (1993a) *Catchment Management Planning Guidelines. August 1993.* National Rivers Authority. 11 pp.

NRA (1993b) *NRA Conservation Strategy.* NRA, Bristol. 20 pp.

NRA (1993c) *NRA Fisheries Strategy.* NRA, Bristol. 20 pp.

NRA (1993d) *NRA Flood Defence Strategy.* NRA, Bristol. 24 pp.

NRA (1993e) *NRA Navigation Strategy.* NRA, Bristol. 16 pp.

NRA (1993f) *NRA R&D Strategy.* NRA, Bristol. 20 pp.

NRA (1993g) *NRA Recreation Strategy.* NRA, Bristol. 16 pp.

NRA (1993h) *NRA Water Quality Strategy.* NRA, Bristol. 20 pp.

NRA (1993i) *NRA Water Resources Strategy.* NRA, Bristol. 22 pp.

NRA (1993j) *News Release: NRA challenges 'Cost of Environmental Improvement Debate'.* July 1993.

NRA (1994a) *NRA Corporate Strategy.* NRA, Bristol. 26 pp.

NRA (1994b) *Corporate Plan 1994/95. Catchment Management Planning. 5 year programme and timetable.* NRA Head Office, Corporate Planning Section, Bristol. 22 pp.

OFWAT (1992) *The Cost of Quality: a strategic assessment of the prospects for future water bills.* Office of Water Services, Birmingham. 1-25.

O'Riordan, T. (1993) The politics of sustainability. In: R. Kerry Turner (Ed) *Sustainable Environmental Economics and Management: Principles and Practice.* pp 37-69. Belhaven, London.

Ormerod, S.J. and Tyler, S.J. (1994) Inter- and intra-annual variation in the occurrence of organochlorine pesticides, PCB congeners and mercury in the eggs of a river passerine. *Archives of Environmental Contamination and Toxicology*, **26:** 7-12

Ormerod, S.J. Weatherley, N.S., Varallo, P.V. and Whitehead, P. (1988) Preliminary empirical models of the historical and future impact of acidification on the ecology of Welsh streams. *Freshwater Biology*, **20:** 127-140.

Ormerod, S.J., Baral, H.S., Brewin, P.A., Buckton, S.T., Juttner, I., Rothfritz, H, and Suren A.M. (1996) River Habitat Surveys and Biodiversity in the Nepal Himalaya. In: P.J. Boon and D.L. Howell (Eds) *Freshwater Quality: Defining the Indefinable.* HMSO, Edinburgh. In press.

Parr, W. (1994) Water-quality monitoring. In: P. Calow & G.E. Petts (Eds). *The Rivers Handbook, Volume 2.* Blackwell Scientific Publications, Oxford, pp 124-143.

Petts, G.E. and Maddock, I. (1994) Flow allocation for in-river needs. In: P. Calow & G.E. Petts (Eds). *The Rivers Handbook, Volume 2.* Blackwell Scientific Publications, Oxford, pp 289-307.

Rundle, S.D., Weatherley, N.S. and Ormerod, S.J. (1995) The effects of catchment liming on the chemistry and biology of upland streams: testing model predictions. *Freshwater Biology*, 34: 165-175.

Schindler, D.W. (1994) Linking species and communities to ecosystem management: a perspective from the experimental lakes experience. In: *Linking Species and Ecosystems.* C.G. Jones and J.H. Lawton (Eds). Chapman and Hall, London pp 313-325..

Slater, S., Marvin, S. and Newson, M. (1993) *Land Use Planning and the Water Sector: A Review of Development Plans and Catchment Management Plans.* Working Paper 24. University of Newcastle upon Tyne. 34 pp.

Statzner, B and Sperling, F. (1993) Potential contribution of system-specific knowledge (SSK) to stream-management decisions: ecological and economic aspects. *Freshwater Biology*, **29:** 313-342.

Statzner, B., Capra, H., Higler, L.W.S. and Roux, A.L. (in press) Focusing management budgets on non-linear responses of economic and ecological systems: potentials for rapid environmental improvement. *Ambio.*

Sykes, J.M., Scott, W.A. and Lane, A.M. (1994) *The United Kingdom Environmental Change Network. Progress Report for 1993.* ECN Central Co-ordination Unit, NREC ITE, Merlewood.

Turner, R. Kerry (Ed, 1993) *Sustainable Environmental Economics and Management: Principles and Practice.* Belhaven, London.

Underwood, A.J. (1994) Spatial and temporal problems with monitoring. In: P. Calow & G. Petts (Eds). *The Rivers Handbook, Volume 2.* Blackwell Scientific Publications, Oxford, pp 101-123.

Wade, P.M. (1995) The management of riverine vegetation. In: D.M. Harper and A. Ferguson, (Eds). *The Ecological Basis for River Management.* John Wiley, Chichester, pp 307-314.

Weatherley, N.S. and Ormerod, S.J. (1990) The constancy of invertebrate assemblages in soft-water streams: implications for the prediction and detection of environmental change. *Journal of Applied Ecology*, **27:** 952-964.

Weatherley, N.S. and Ormerod, S.J. (1991) The importance of acid episodes in determining faunal distributions in Welsh streams. *Freshwater Biology*, **25:** 71-84.

Wright, J.F. (1995) Development and use of a system for predicting the macroinvertebrate fauna in flowing waters. *Australian Journal of Ecology*, **20:** 181-197.

Appendix 1	Terms of Reference
Appendix 2	Proposal to NERC for a New Thematic Programme.

These will be bound into the final document.