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Hydrology in Scotland: towards a scientific basis for the sustainable management of freshwater resources—foreword to thematic issue

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Abstract

The physical background to hydrology in Scotland is briefly reviewed. The main scientific events associated with understanding the science of hydrology in Scotland are summarized and major contemporary research themes are outlined. A brief overview of each paper in the current volume is given. © 2002 Published by Elsevier Science B.V.

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1. Introduction

The collection of papers published in this volume provides an overview of Scottish hydrology at the start of the 21st century. The papers originated from invited keynote presentations given at a symposium held at the University of Dundee in 2000 which was titled 'Hydrology in Scotland; an agenda for the 21st century'. Taken together, the papers provide a representative cross-section of the diverse range of research themes that hydrologists in Scotland are actively engaged with. Individually, each paper provides a summation of the current understanding of particular issues and highlights the main research questions that need addressing in that specific field. The themes covered will be familiar to water scientists and managers in both developed and developing countries, as societies attempt to harness the resources of the hydrological cycle in a more sustainable manner (Gleick, 1993; Naiman et al., 1995). This requires: increasing interdisciplinarity in freshwater research; improved technologies for data collection and modelling; improved communication between scientists, managers and policy makers; and increasing stakeholder involvement in water resource planning and management (HELP Task Force, 1999). Thus, although there is necessarily a Scottish focus, many of the themes and issues covered by the papers are generic.

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This volume of *Science of the Total Environment* follows a series of other recent overviews of the interdisciplinary science base that is required to underpin the sustainable management of freshwater resources in northern temperate environments such as the UK (Neal et al., 1997, 1998, 2000). Moreover, the emphasis in this volume is on the hydrological context of freshwater resource issues, a conceptual framework that is sometimes under-utilised in understanding and managing water pollution and freshwater ecosystems (Law, 2000). This emphasis on hydrology and environmental change also dictates that this volume provides a complimentary companion to the recent Special Issue of *Science of the Total Environment* which focused on 'Environmental change, land use and water quality in Scotland' (Langan et al., 2001). This foreword seeks to provide an introduction to the volume. A brief outline of the unique characteristics of the Scottish environment is given, both in terms of the natural environment and the institutional framework for water resource management. A brief historical background to Scottish hydrology is provided to show how contemporary themes and concerns have evolved in a rapid and dynamic manner over the last decade or two. These current themes are then explored through a brief overview of the papers that follow.

2. The Scottish context

2.1. Physical environment

A detailed overview of the Scottish environment, and its influence on water resources, has recently been provided by Langan and Soulsby (2001) and only salient details follow here. As a country of some 78 130 km^2, Scotland shows some remarkable hydrological diversity, compared with other European countries of comparable size (e.g. Ireland, 70 280 km^2; Austria, 83 850 km^2). This diversity in part derives from striking geological contrasts and the climatic conditions arising from Scotland's topography and its location on the north-west margin of Europe. In terms of geology, Scotland has some of Europe's oldest rocks, with Lewisian gneiss making up much of the Hebridean Islands, and highly resistant schists and granites forming much of the highest mountain areas in the north-west of the mainland. A simplified geological map of Scotland is illustrated in Fig. 1. Here, altitudes exceed 1300 m and provide a barrier to the dominant westerly airflow from the Atlantic Ocean. Mean annual precipitation values exceed 4000 mm in some of the highest western areas. The Scottish mountains have been extensively glaciated with associated landforms of over-steepened slopes, over-deepened valleys and complex suites of glacial and periglacial drift deposits. By contrast, around much of the east coast, gently undulating lowland landscapes are found, supporting arable and pastoral agriculture, with mean annual precipitation values as low as 600 mm (Marsh and Lees, 1998). Actual evapotranspiration rates are typically in the 350–400 mm year^{-1} range (Robins, 1990), with high wind speeds a major controlling factor in the uplands. Soil characteristics are strongly influenced by altitude and climate. A simplified soil map of Scotland is illustrated in Fig. 2a. In the uplands, thin alpine soils on the highest mountains (above 1000 m) grade to peats and podzolic soils which characterise much of the Scottish uplands (Langan and Soulsby, 2001). These soils have limited available storage and are usually highly responsive to hydrological events. Moreover, the soils are generally thin and highly leached, resulting in an inherent sensitivity to acid deposition and other forms of atmospheric pollution. Furthermore, snow accounts for as much as 30% of mean annual precipitation in some upland areas (Johnson, 1995; Soulsby et al., 1997), but forms highly transitory snowpacks that exert strong influences on flow regimes in some areas. Increased winter temperatures in many areas result in concerns that snowpack influence on spring and summer flows may be less evident in future (Dunn et al., 2001). At lower altitudes, the hydrogeological effects of fluvio-glacial drift and permeable (sedimentary) geologies also impact on hydrological characteristics, and lead to more subdued hydrological regimes and create considerable challenges in modelling low flow behaviour (Gustard et al., 1992). The localities of the main aquifiers in Scotland are given in Fig. 2b. As the subsequent contributions to this volume

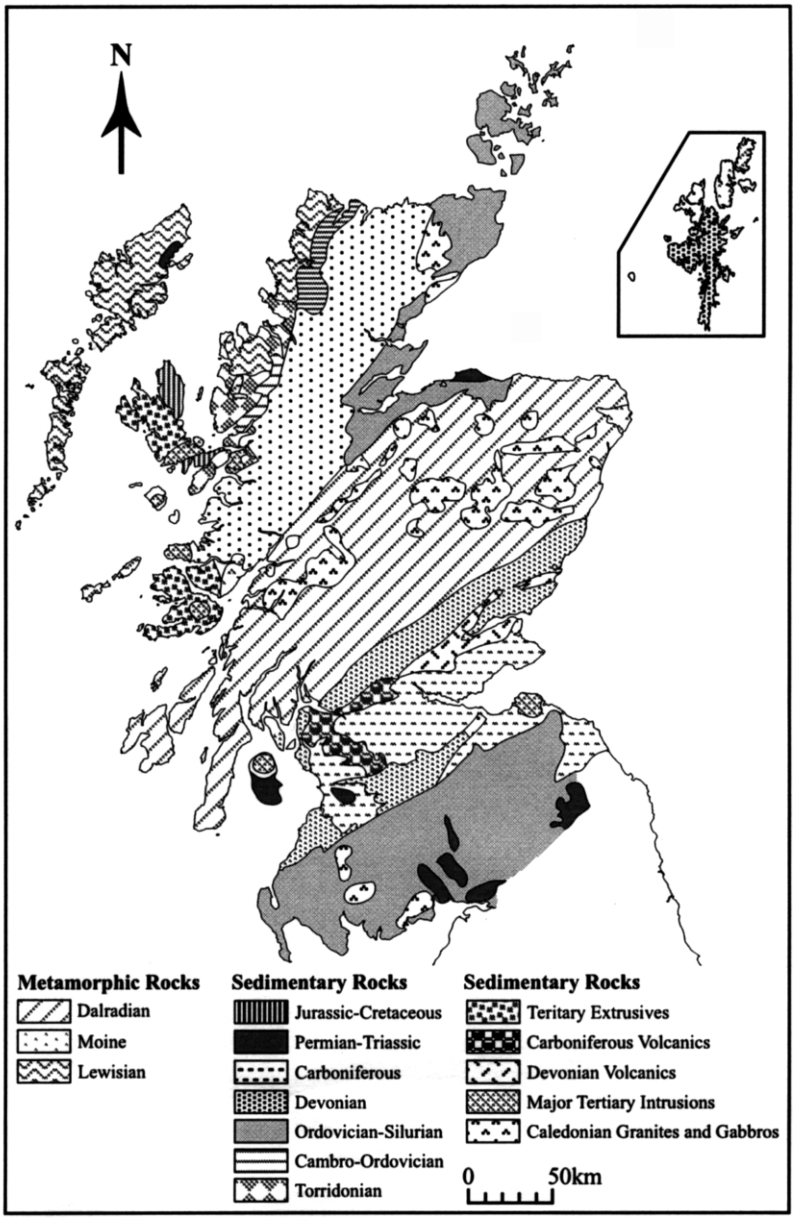

Fig. 1. Simplified geology map of Scotland.

demonstrate, these many dimensions of physical and hydrological complexity establish Scotland as a challenging country in which to undertake the research and monitoring necessary to support a sustainable system of freshwater management.

2.2. Management of Scotland's water resources: an evolving regulatory framework

Water resource planning in Scotland has often been characterised as being concerned with sur-

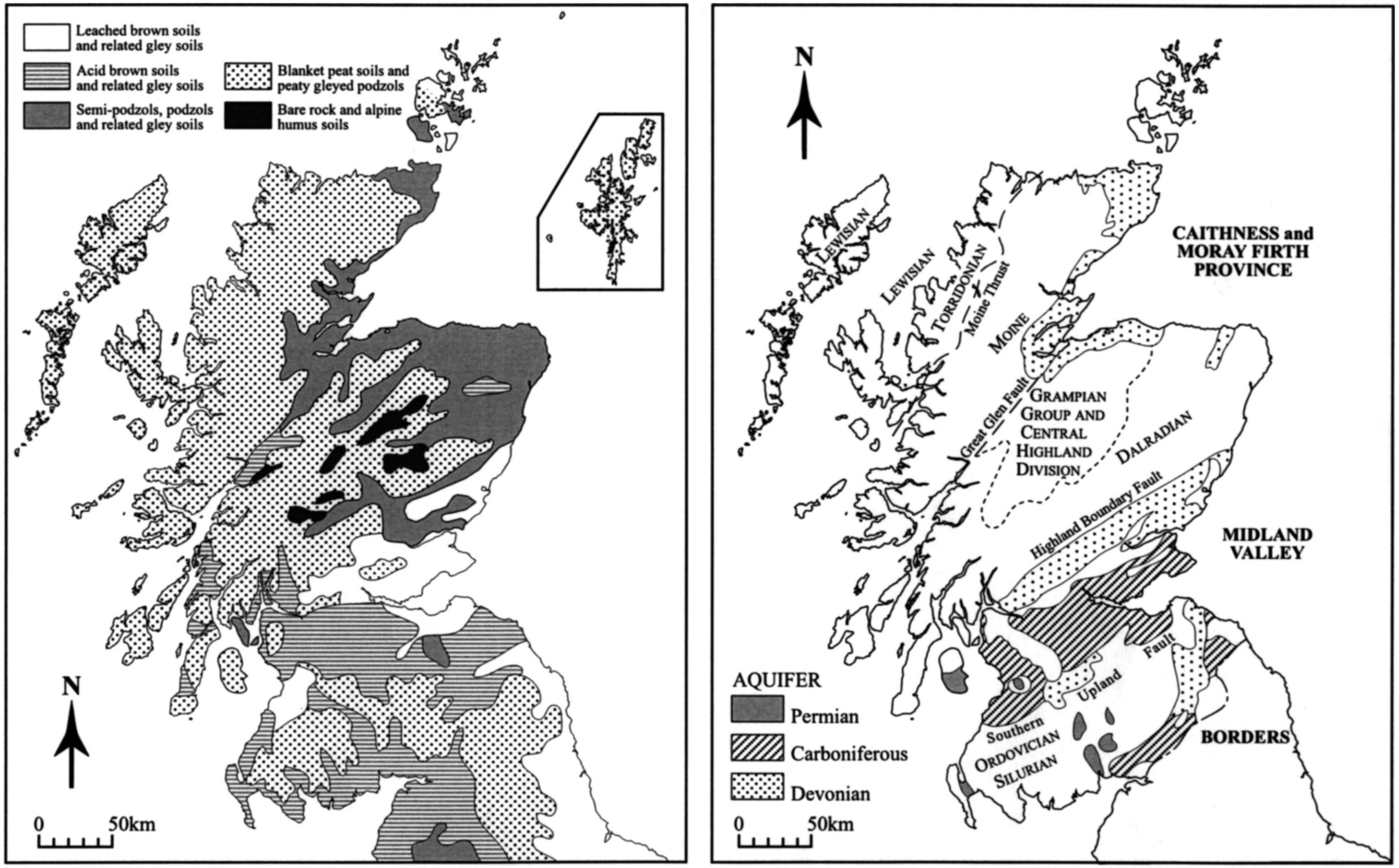

Fig. 2. (a) Simplified soils map of Scotland; and (b) main aquifer locations (after Robins, 1990).

pluses: UK hydrology texts often draw contrasts between overall water scarcity in the south-east of England when compared with abundance in Scotland (e.g. Shaw, 1994). Indeed, only 1% of the available resource, 97% of which comes from surface sources, is used for supply (Scottish Office Environment Department, 1995). However, in Scotland as elsewhere, resource distribution in space and time is of critical importance. The principal traditional water uses are for: public supply; hydro-power generation; agriculture (especially for spray irrigation); industry; effluent disposal; and recreation. Notwithstanding the relative abundance of the resource in many areas, demands on water can cause conflicts in all areas, especially in relation to current or predicted adverse ecological impacts (particularly in relation to salmonid fisheries or species protected under conservation laws) arising from water management activities, such as abstraction and hydro-power generation (Leighton, 1996).

Partly in response to such conflicts, but also related to marked political change, the institutional framework for water resource management in Scotland has been, and remains, in a state of rapid change. A major change in the main agencies involved in water management occurred in 1995 when a new regulatory authority, the Scottish Environment Protection Agency (SEPA), was established together with three regional water authorities which remained as public utilities. This, together with devolution and the establishment of a Scottish parliament in 1999, have resulted in changes in how water resources are managed, and created a higher profile for water-related issues.

The institutional framework that currently exists for the management of water and related activities in Scotland is notoriously fragmented, with overlapping responsibilities spread over a number of different agencies (see Howell, 1994). Briefly, three public sector water authorities currently provide supply and sewerage services; SEPA regulates point and diffuse sources of pollution, originates flood warnings and assesses water resources; Scottish Natural Heritage (SNH) exercises a conservation and recreation remit for freshwaters; District Salmon Fisheries Boards (DSFBs) carry powers for fisheries conservation on Scotland's salmon rivers, while 32 local government authorities are each responsible for local biodiversity action plans and flood defence. These diverse and complex institutional arrangements are, therefore, not readily suited to the integrated catchment-centred approach to the management of freshwater resources that is being advocated both nationally and internationally (Werritty, 1995; Leighton, 1996). Despite this, many of the organisations involved often explicitly recognise the benefits of such an approach, and the implementation of the European Union's Water Framework Directive will drive organisations towards more integrated, catchment-based management approaches in the future (Walker et al., 2000; Scottish Executive, 2001).

3. Hydrological research and Scottish freshwaters

3.1. Historical background

Historically, Scottish hydrology had been rooted in its distinguished engineering tradition. This is perhaps most clearly reflected in the remarkable engineering feats that planned and implemented schemes to provide water supplies to the main population centres of Edinburgh and Glasgow (Smout, 2001) and exploit the extensive hydroelectric power resource throughout much of the central highlands (Hill, 1984; Payne, 1988). It is not surprising that the first major symposium on Scottish water resources reflected this tradition and was strongly focused on the concerns of water supply engineers (Anon., 1961). However, increasing scientific interest in physical hydrology and new technological developments, which allowed the measurement and modelling of physical processes, followed in the 1960s and 1970s. This, together with subsequent interest in the chemical interactions that occur in the terrestrial phase of the hydrological cycle in the 1980s, dictated that the 1986 'Hydrology in Scotland Conference' held at the Royal Society of Edinburgh reflected a more diverse and mature discipline. Increasing involvement in a much wider range of environmental management issues such as: land use change impacts; acidification research; and wetland conservation reflected the emergence of hydrologists who had trained in the environmental sciences, rather than engineering (Royal Society of Edinburgh, 1987).

In many ways, the proceedings of the Edinburgh symposium provided a land mark in Scottish hydrology and the foundation for many of the themes developed in the present volume are clearly evident in 1986. However, following on from that meeting, the first major survey of the hydrogeology of Scotland was only published recently by the British Geological Survey (Robins, 1990). Moreover, other freshwater scientists in Scotland also produced a seminal volume to mark the 25th anniversary of the ecologically-based Scottish Freshwater Group (Maitland et al., 1994). Despite the wealth of knowledge and expertise in Scottish freshwater science, it was clear from this publication that hydrology was not as well integrated with related disciplines, though this situation is rapidly changing. This was evident in a symposium held by Scottish Natural Heritage in 1995 which brought together a wide range of freshwater scientists with physical, chemical and biological interests to debate the statement 'Freshwater quality—defining the indefinable?' (Boon and Howell, 1997).

3.2. Contemporary themes

The scientific papers presented at the Hydrology in Scotland 2000 Conference centred on four main themes: (i) water resource assessment; (ii) water quality issues; (iii) hydrology and the natural heritage; and (iv) the re-evaluation of traditional water resource management concerns. These themes are represented by the papers presented here and reflect three discernible trends in Scottish hydrology. Firstly, the discipline is evolving in a manner that is causing the traditional engineering and scientific approaches to the subject to increasingly overlap; secondly, that hydrologists are increasingly involved with other environmental scientists in interdisciplinary research that is problem-centred on issues such as water quality management; this partly reflects the third main trend of hydrological research being increasingly policy orientated, which calls for improved communication between scientists and managers as well as wider society.

The first two papers in the volume explore the themes of water resources and the ways in which they might be affected by climate change. Marsh and Anderson (2002) show how the physical characteristics and contrasts outlined above provide formidable challenges to basic hydrological assessments in Scotland. Environmental heterogeneity dictates that measurement of the most basic water balance components of precipitation and runoff are extremely difficult. Moreover, funding limitations and logistical difficulties dictate that the basic hydrological monitoring network of the country is somewhat skeletal, raising concerns over the quality of the information resource available to assess the likely impact of future pressures such as climate change.

Nevertheless, Werritty (2002) makes use of the best long-term data sets that are available to examine recent trends in precipitation and runoff. Contrasting trends are found in different parts of Scotland, showing patterns of increasing wetness in the north and west and a shift to drier conditions along the east coast. Thus the distribution of water availability is changing, and Werritty describes how the best available climate change predictions indicate that problems of water excesses and deficits will probably increase in future. The likely far-reaching, but uncertain, implications of these changes for the management of the freshwater environment is also considered.

The following four papers underline the importance of water quality issues in contemporary hydrology and emphasise the close links between water fluxes and chemical transfers in the hydrological cycle. Robins (2002) highlights the hydrochemical characteristics of Scottish groundwater, which despite providing only 3% of public water supplies, strongly influence the quantity and quality of surface waters. Despite this obvious importance of groundwater, an alarming paucity of water quality data is highlighted, probably reflecting the overwhelming utilisation of surface water sources. Nevertheless, recent problems such as acid mine drainage (Younger, 2001) and nitrate pollution of water supplies (Vinten and Dunn, 2001) have indicated that ignorance of groundwater issues in

Scotland have resulted in serious environmental degradation in some areas.

More optimistically, Ferrier and Edwards (2002) show how in the context of surface waters, environmental managers in Scotland have been responsive to pollution problems, once they have been recognised. Improvements in surface water quality, from point source pollution control in urban and industrial areas, have been notable. However, the authors show how diffuse pollutants represent a major challenge, both in terms of their understanding (through monitoring and modelling) and practical management. In particular, the nature of pollution reversibility and ecosystem recovery are two areas characterised by major knowledge gaps that need to be addressed through empirical and modelling studies. Given the moves towards more ecologically-based targets for water quality improvements, these gaps constitute important research themes.

Following on from the over view of Ferrier and Edwards (2002), Soulsby et al. (2002a) and Petry et al. (2002) focus upon surface water quality issues in the uplands and lowlands, respectively. In the case of the former, Soulsby et al. (2002a) show how in a mountainous country like Scotland, marked rainfall gradients, steep topography and hydrologically responsive soils dictate that water quality in the uplands exerts a strong influence on downstream resources (Langan et al., 1997). Despite this, threats to water quality from global environmental change (e.g. atmospheric deposition and climatic change) and local changes in land use occur. The authors show that despite the popular image of the 'pristine' Scottish highlands, a wide range of potential pollutants adversely affect water resources in remote areas for which limited data exists. The need to understand and model the hydrological processes, which route such pollutants through catchment systems, is stressed. Petry et al. (2002) consider the more obvious water quality concerns of nutrient enrichment in lowland streams. The importance of hydrological events in delivering nutrient-rich soil waters into stream channels is highlighted in the context of marked changes in lowland catchment hydrology (e.g. under drainage, channelization, etc.). The extent of such hydrological modification is stressed and the real difficulties that this will cause in attempting to manage diffuse agricultural pollutants are considered.

The three subsequent papers consider the importance of hydrology to the understanding and management of the conservation and natural heritage value of Scottish freshwaters. This increased interest in hydroecology in the 1990s probably represents one of the main areas of growth in the hydrological sciences not just in Scotland, but internationally (Law, 2000). This follows on from foci on water quality issues in the 1980s and physical process studies in the 1970s. Bragg (2002) highlights the reciprocal nature of hydrological influences on peat formation, and in turn, the influence of Scotland's extensive coverage of peat-dominated wetlands on catchment hydrology.

The influence of catchment hydrology and water resource management on the biodiversity of riverine ecosystems, is examined in detail in the subsequent paper by Gilvear et al. (2002). These authors use economically important salmonid fish species to show how the natural hydrological and geomorphological processes in Scottish river systems contribute to the provision of habitats exploited by salmonids. Nevertheless, the long history of human exploitation of Scotland's rivers results in many systems now having highly modified flow regimes and channel characteristics. These can be a consequence of management for hydro-electric power production and flood control, respectively. The need to adapt water resource management objectives to try and maintain the biodiversity of freshwater resources is a major challenge facing scientists globally, not just in Scotland (Naiman and Bilby, 2000).

Johnson and Thompson (2002), like Soulsby et al., 2002a, stress the important and reciprocal relationship between hydrology and the Scottish mountains. The vulnerability of mountain ecosystems to changing climate and land use are discussed, and their impact on the downstream hydrology, water quality and ecology of river systems are considered. In particular, the transitional nature of the Scottish climate is stressed, and concerns over the impact of less marked and more transient snowpacks on river systems in many parts of the Scottish highlands is discussed.

The final three thematic papers examine more traditional aspects of applied hydrology in water resource management, in terms of flood risk assessment, reservoir management and abstraction control. The importance of developing new assessment methods and management techniques in the face of changing climate, increased societal pressures and a rapidly evolving policy agenda are common themes to each paper. The first of these, by Black and Burns (2002), examines assessment of flood risk. The increased awareness of climatic variability and change raises serious questions over the assumption of climatic stationarity that flood risk assessments have been traditionally been based upon. The use of long-term climate records provides the basis for use in hydrological models which have allowed the identification of unprecedented 'flood rich' periods in Scotland during 1980s and 1990s. This highlights how societal perceptions of such environmental hazards need to be changed and policy objectives need to rapidly evolve in a framework that recognises the complexities and uncertainties of flood hydrology.

Climate change and variability also impacts on water supplies, and Jowitt and Hay-Smith (2002) show how the water yield assessment for most major Scottish sources is based on dated traditional engineering methods. The need for contemporary modelling to re-appraise operating rules, notably with respect to drought management, is stressed. Moreover, increased awareness of the need to develop ecologically acceptable compensation flows on regulated river systems emphasises that the simple aims of traditional water supply schemes need to be modified in the context of broader environmental objectives.

This move towards multi-objective management goals is also stressed in the paper by Fox and Walker (2002) which examines how traditional riparian rights in Scotland have resulted in limited powers for regulators to control river abstractions. The imminent move to a scheme for abstraction licensing within the context of broader catchment management is viewed as a prerequisite to sustainable approaches which can ensure that objectives of different interest groups concerned with Scotland's rivers can be achieved in a balanced manner. This reflects a world-wide move to give much fuller recognition to the importance of stakeholder views as rivers become more fully managed.

This final paper by Soulsby et al. (2002b) attempts to take stock of hydrology as an environmental science in Scotland. The paper summarises some of the main research themes that are most likely to occupy Scottish hydrologists over the coming decade. The current strengths and weaknesses of the discipline, which will determine the contribution it will make to solving the significant problems that society faces in moving towards more sustainable approaches to freshwater resource management, are critically considered.

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