1 Introduction

JOHN C. RODDA[1], MARK ROBINSON[1], JIM MCCULLOCH[2], CHRISTINE MCCULLOCH[3], ALAN JENKINS[1], TERRY MARSH[1], CELIA KIRBY[4], IAN LITTLEWOOD[4], MAX BERAN[2], AND GRAHAM LEEKS[1]

[1]Centre for Ecology and Hydrology, Wallingford, Oxfordshire, UK
[2]Ex-Institute of Hydrology, Wallingford, UK
[3]School of Geography and Environment, University of Oxford, Oxford, UK
[4]British Hydrological Society, UK

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1.1 Starting Point

Hydrology can claim to be one of the *oldest*, yet one of the *youngest* of the natural sciences. Since the start of civilisation it has been applied to control and manage water; yet, hydrology only emerged as a distinct scientific discipline during the latter half of the twentieth century.

This book reviews the development of modern hydrology primarily, but not exclusively, through the experiences of the scientists and engineers at Wallingford, near Oxford, who have been at the forefront of many of the developments in hydrological research over last 50 years. Coming from very differing academic backgrounds, they form an effective multidisciplinary team, one which includes a number of foreign members. Together they describe the results of their scientific research which seeks to improve understanding of the vicissitudes of the hydrological cycle in order to apply knowledge for

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a variety of purposes. These include data collection on the ground and from space, together with the management and application of these data to: prediction and forecasting of extremes, husbanding surface and groundwater water resources and the control of pollution. Initially, this research aimed to answer to just one question – what is the impact of land use on water resources? But as might be expected, seeking this answer raised a host of other questions. Indeed, as time progressed the ambit of Wallingford hydrology has widened immeasurably to the extent that the complexion of research in 2015 includes hues that were not even thought about in 1965. The new knowledge generated by research emanating from Wallingford has acted as a catalyst on the hydrological community in the United Kingdom and internationally, both informally and through specific technology transfer initiatives.

1.2 Setting the Scene

The story of progress in hydrological research at Wallingford (Chapter 1) mirrors that of advances made by similar institutions in several other nations and in the developments achieved at the international level. Essential to tackling practical questions and advancing scientific understanding is the collection of high-quality data on the ground and from space. This necessitated the development of specialised instrumentation, and often their conjunctive use in experimental basins (Chapter 2). An early concern was the study of extreme flows – initially floods – but later droughts – the importance of the variability of the hydrological cycle in space and time was seen as a key issue (Chapter 3). Central to most hydrological processes is the role moisture in the soil, influencing recharge of groundwater, determining the availability of water for plants and generating runoff (Chapter 4). It became apparent that it was not sufficient to observe differences in behaviour between sites and basins, since the reasons 'why' needed to be understood and predicted through process studies (Chapter 5). Although much of the hydrological development work and its application was UK based, there has always been a strong overseas component to the work at Wallingford, especially in water resources (Chapter 6). As hydrological understanding developed and grew, modelling and prediction of the extremes of flow improved (Chapter 7), along with understanding of water quality issues (Chapter 8). There is widening recognition of the importance of an ecosystem approach (Chapter 9). The application of the experience gained is needed to meet the challenges of climate change, where water has a key role (Chapter 10). The generation of large amounts of data need skills in quality control, handling, storage and retrieval (Chapter 11). Finally, Chapter 12 tries to capture the essence of the gain in hydrological understanding and looks to future developments in hydrology and the pressures which generate them.

The United Kingdom shares most of the hydrological problems that affect other nations, excepting those concerned with glaciers, ice and large rivers. It occupies one relatively large island, part of another and a series of smaller islands covering a total area of nearly 250,000 km^2 on the eastern edge of the Atlantic Ocean. Westerly airflows predominate but weather systems can arrive from all points of the compass. Consequently, the generally temperate climate is inherently very variable. Ancient igneous and metamorphic formations elevate the north and west, whereas more recent sedimentary deposits floor the south and east. The drainage patterns across the United Kingdom are largely a response to regional and more local contrasts in geology. Carved into the landscape are almost 1500 discrete river systems draining to the sea through over 100 estuaries. The rivers and streams are major agents of landscape modification and, in turn, their characteristics are greatly influenced by the catchments through which they flow. The diverse patterns of climate, topography, geology and land use make for a rich variety of watercourses and aquatic environments.

The regular passage of Atlantic low-pressure systems ensures that the United Kingdom is one of the wettest countries in Europe. Average annual rainfall totals grade across the country from over 4000 mm in the higher north and west to less than 600 in the lower south and east. The daily maximum recorded rainfall has once reached 280 mm and totals exceeding 100 mm are not uncommon in the western high lands. However, short period rainfall intensities are relatively low on the world scale, but the number of days with rainfall is high. Absolute droughts extending over 45 days or more are rare, but accumulated rainfall deficiencies over periods of six months or more can have substantial impacts on society, particularly in relation to water resources.

On average, rainfall is evenly distributed throughout the year but with a tendency towards a late autumn and early winter maximum. By contrast, evaporation losses are highly seasonal with around 80% of the average annual evaporation normally occurring over the April–September period. Evaporation is a relatively stable variable with annual losses generally in the 400–560 mm range, accounting for around 40% of the annual rainfall at the national scale but rising to over 85% in the driest parts of the country.

The residual rainfall (rainfall minus evaporation) ranges from less than 100 mm a year over much of South East England to over 3500 mm in parts of Scotland and Wales. It is markedly seasonal with the bulk of the annual runoff occurring in the November–March period when fluvial and groundwater flooding is most frequent; in contrast, urban flash flooding is most common following intense summer storms. Annual minimum flows in western and northern rivers generally occur in June or July but, to the east and south, flows are typically at their lowest during the late summer and early autumn – and later in rivers draining some permeable catchments where groundwater, via springs and seepages, is a major component of low flows.

The spatial trend in average runoff across the country is largely the reverse of the distribution of the population; this creates problems of water supply. Indeed, much of South East England can be classed, according to the World Bank criterion (less than 1000 m^3 per head per year of available water), as suffering from serious water stress. This is likely to be exacerbated as the population rises by 10% from a total of 63.7 million in 2012 to a forecast 70 million by 2027, with much of the increase occurring where water resources are under most pressure. New environmental controls are also limiting abstractions. Groundwater from the Chalk is the chief source in the South East, whereas some parts of the Midlands and north of England rely on groundwater from Permian, Triassic and Jurassic formations. The Thames is the principal source of London's drinking water and the river supplies a number of other towns and cities along its course. This pattern is replicated in many other UK rivers. The pattern of multiple abstractions and discharges of treated effluent causes concern over the long-term effects on human health, particularly during droughts when dilution is low. Long-standing problems include high levels of nitrate and phosphate as well as newer challenges such as oestrogens and nanoparticles. Reservoirs in the high rainfall areas of the north and west supply by aqueduct the cities and towns in those parts of the United Kingdom. Usually supplies are more than adequate, but occasional droughts have caused shortages. Problems arose in the1960s and 1970s in these areas because of acid rain – the acid buffering capacity of the soils being very limited. Toxic drainage from abandoned mines occurs in a number of basins, particularly in the north and west. Plans were drawn up in the 1970s for the large-scale transfer of water from the wetter parts of England and Wales to the drier ones, but they were not implemented. Increased interconnectivity of water resources at the regional and local levels has bolstered resilience to drought; however, no new reservoirs have been built for more than 20 years: a few in the south have been extended. Many rivers in the north and west have steep short courses and flows generated by moderate amounts of rain falling on saturated soils can overtop flood defences in a matter of hours. Where rivers in flood reach flatter downstream areas, extensive flooding can occur. Storm surges in coastal areas coupled to river floods have produced some of the worst inundations, although the highest recorded floods in many rivers resulted from heavy rain falling on melting snow in March 1947. Flood forecasts are issued by the Environment Agency (EA), whereas local government emergency bodies provide flood relief to affected localities assisted by the Police. Fortunately, there are few fatalities, but frequently there is considerable property damage and loss of income. Farm land may be flooded for weeks as happened in the winter of 2013–2014. Insurance cover is not universal and where floods are repeated premiums are very high. The Flood and Water Management Act (HMSO, 2010) gave powers to English County Councils to develop, maintain, apply and monitor a flood risk strategy.

Continuation of the recent febrile nature of the climate into the future threatens to alter the variables that affect water resources and the hydrological extremes. Drier summers are predicted for the south and east with rain falling in more intense showers; in contrast, winters are expected to become wetter and milder. The north and west is likely to get wetter with longer periods of rain and less snow. The wetter, warmer atmosphere with its procession of frontal systems moving east across the Atlantic, is interrupted from time to time by periods of high pressure emanating from the east and south. Changes in the balance between the different air masses and the battle between persistence and volatility will continue to characterise the UK weather and climate.

Fifty years ago river and water management was predicated on an assumption that hydrological variability was about a relatively stable long-term mean – rainfall averages were based on a standard 30 year period. This can no longer be taken for granted and the challenge for the future is to build on the firm scientific foundations established at Wallingford and elsewhere to accommodate change, whilst reconciling, the often competing demands on rivers, aquifers and wetlands.

1.3 Early Days at Wallingford

The post-World War II years heralded a period of unprecedented social, political and economic change in the United Kingdom. Industrial production slowly recovered and started to expand, whereas the response to the demand for housing promoted a surge in urban growth. The 'space age' was about to dawn and the technological revolution was beginning to blossom. This was the time when hydrological research at Wallingford made its first impact. The late 1950s saw several ground-breaking papers on predicting runoff from rainfall published by Eamonn Nash, at the then Hydraulics Research Station (HRS) (Nash, 1958, 1960). The advances these papers describe attracted the attention of scientists and engineers, nationally and internationally. To complement his mathematical approach, in 1960, Eamonn launched an experiment on the small clay catchment surrounding the headwaters of the River Ray in Buckinghamshire to determine the factors controlling the flow from the basin. He also developed a novel weighing lysimeter which was installed at Howbery Park. A large cylinder filled with soil floated on a trough of mercury, its changes in level registering the evaporation and rainfall on the grass surface of the lysimeter. This strong scientific base at Wallingford led to the formation of the Hydrological Research Unit (HRU) within HRS in 1962.

The formation of HRU came with an upsurge in the 1960s of UK interest in hydrology (Fig. 1.1). Hitherto hydrology had received little recognition (Rodda, 2006), with the exception of the Postgraduate Course at Imperial College where Peter Wolf was appointed Reader in 1955. Later, courses were launched at Newcastle, Birmingham, University College London and several other universities. At undergraduate level, hydrology became part of the syllabus, mainly in Departments of Geography, such as at Reading, Hull and Aberystwyth. This upsurge was also reflected in several other ways. For example, hydrology gained credibility as a separate profession (Law, 2000), a growing number of scientific papers were published dealing with a wide range of hydrological research topics (Royal Society, 1971) and the Hydrological Discussion Group was started in 1963 at the Institution of Civil Engineers.

As a result of the reorganisation of government science in 1965 (Science & Technology Act, 1965), the Unit was transferred to the newly formed Natural Environment Research Council (NERC). In recognition by the Council of the importance of advancing hydrology, in 1968 it metamorphosed into the Institute of Hydrology (IH). Then on April 1, 2000 the Institute became part of the Wallingford Laboratory of the Centre for Ecology and Hydrology (CEH), just at a time when an ecological approach to river basin management was being widely advocated.

Innovative and perceptive programmes pursued by these bodies placed 'Wallingford' hydrology at the forefront of most national and many international initiatives. Over the last 50 years, the spur of fresh problems facing this 'new' science has carried activities forward to the frontiers of research on a wave of excitement and enthusiasm. This book attempts to capture these sentiments. It highlights what has been achieved and indicates future directions for action (Box 1.1).

1.4 NERC's Role in Promoting Hydrological Research

From its inception in 1965, the Council has, in the words of its first chairman Sir Graham Sutton, 'encouraged and supported research in hydrology and the provision of advice and the dissemination of knowledge' through its component bodies and in the universities. It aimed to promote previously neglected environmental sciences by a dedicated budget separate from the support for the physical, agricultural and medical sciences. Within NERC itself, recognition of hydrology as an embryonic science requiring nurture and shelter from competing established disciplines was achieved with

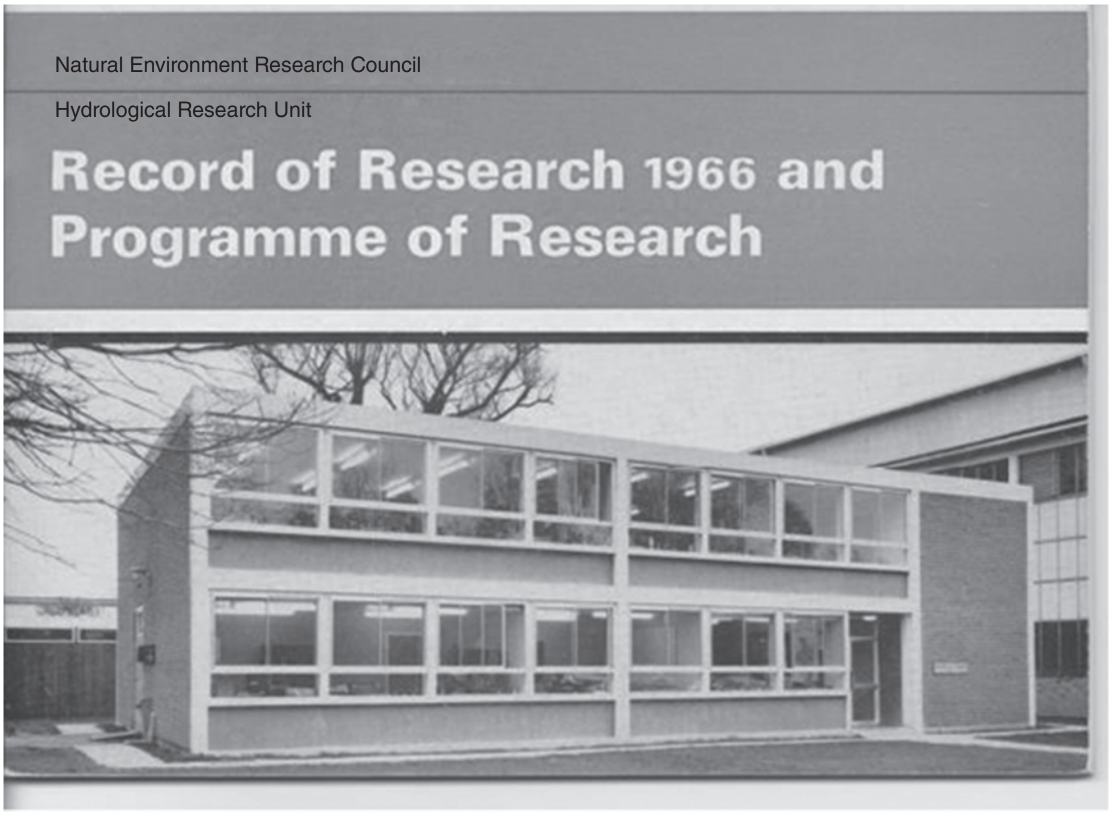

Fig. 1.1 The First HRU Annual Report in 1966. (Source: Reproduced with permission of CEH.)

> **Box 1.1** Scientific research at Howbery Park
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> It may be of interest that the site at Wallingford where HR Wallingford and CEH are located, namely Howbery Park, has been in the forefront of research in the past. Jethro Tull (1674–1741), a pioneer in agricultural research, was the first to introduce mechanical devices, such as the seed drill, to replace hand methods of cultivation. He sowed seeds in rows rather than by broadcasting, and he developed ideas on plant nutrition and soil and plant management. This was at the start of the agricultural revolution.

a struggle. The new entrant had to compete for funds against existing research organisations; a convincing case had to be made for removing the small research unit from an engineering body to create a dedicated hydrology centre, rather than spreading support thinly in the universities. At the same time, NERC encouraged universities to train scientists and to cooperate in advancing the subject. From a time when there were few, if any, practicing hydrologists in Britain and minimal activity involving them, the last 50 years has seen a remarkable growth in the effort invested in the science and a rising number of career hydrologists, estimated in 2013 at about 2000. Of course, the very nature of hydrology with its many faceted interests, demands the involvement of a wide range of disciplines – civil and electronic engineering, physics, geography, geology, ecology, chemistry, mathematics and statistics, to name but a few.

The transformation of a small research unit (Fig. 1.1) into an Institute with significant funding, an interdisciplinary remit and an agenda in both applied and basic scientific research was influential in defining the identity of hydrology, both in the United Kingdom and abroad. Disciplinary barriers had to be broken down, instrumentation and measurement improved and systems analysis developed whilst responding to urgent solutions to practical problems. From small beginnings in the late 1960s, a series of NERC thematic programmes have been mounted involving CEH, the British Geological Survey (BGS) and a considerable number of universities. Current programmes bring together hydrologists with scientists from a range of other disciplines. But NERC has not been the sole source of funds for work at Wallingford: since the days of HRU, there have been multiple sources of income including government departments, public and private organisations, the European Union and the World Bank. Increasingly, important have been the programmes of collaborative research undertaken through the different tranches of European Union's 'Framework Programme'. In addition, a large number of projects have been engaged in with British consulting engineers, often within technical assistance programmes. A number of developments in the UK water industry have taken place during the last 50 years which have influenced the direction of research at Wallingford.

1.5 Countering Water Problems

Human activities over the last 250 years have quickened the pace of global change, a pace unlikely to lessen in the future. The population explosion, leading to deforestation, desertification and urbanisation are amongst the main agents of this change. These coupled with climate change are today among the most pressing issues threatening the fabric of society – issues which cause concern amongst politicians, the public as well as scientists. Water is pivotal factor across all of them. And while floods claim the largest toll of life and cause the greatest damage of all natural disasters, many extensive areas in Asia, the Middle East and Africa currently suffer severe shortages of water. It must be recognised that parts of the developed world also face water scarcity, South East England being one. Allied to these problems is the pollution of surface and groundwater. As the world population climbs towards 10 billion by about 2050 AD and contemporary climate change *moves the hydrological goal posts* in many regions, these shortages will intensify and extend. If only the distribution of the world's water resources were regular and well ordered in space and time. But it is not. That many regions of the globe will suffer severe shortages by about the middle of this century has been predicted for a number of years. For example, the UN Secretary General, Mr Ban Ki Moon, stated recently that by 2030 AD about half the world's population will be facing water scarcity.

Most types of research aim to reduce risk and minimise uncertainty. One of the prime responsibilities of governments is to reduce risks to its citizens and protect them from hazards, especially environmental hazards, so it follows that public funds should be directed to these ends. Most sources of risk in the natural environment need sound environmental data for purposes such as prediction, forecasting, planning and management. These data are required to better comprehend the risks concerned. Capturing reliable and consistent long-term data is vital to establishing the severity of extreme events, together with their frequency, extent and like variables. Then to analyse, apply and disseminate the results aims to minimise loss of life, damage and disruption. This is not an easy task. This unglamorous segment of research is often the subject of cuts in funding because reduced budgets do not have an immediately apparent impact on the public.

1.6 The Beginnings of Experimental Hydrology

In the years immediately after World War II, the water problems facing Britain were remarkably similar to those current during the early years of the twenty-first century. The most severe floods on record swept the country in 1947, and there were several droughts, including an extensive one in 1959. With the resurgence of industrial production, the burgeoning population and the strong post-war demand for housing, there was anxiety in government and in the water industry that the rising consumption of water would soon outstrip the available resource. It was an anxiety reinforced by the results of a small-scale experiment on a stand of conifers, conducted by a highly respected water engineer Frank Law at Stocks Reservoir in Lancashire (Law, 1956, 1957 and 1958). His experiment showed that the trees used about 30% of the water that might have run into Stocks Reservoir, representing an economic loss for the water company. This was at a time when large areas of upland Britain were being planted with conifers by the Forestry Commission as part of government policy.

To investigate this problem, a government committee was established, the Committee on Hydrological Research, with members drawn from various departments and agencies of government and from the water industry. On their recommendation, on April 1, 1962, and with the agreement of the Department of Scientific and Industrial Research's Hydraulics Research Board, the HRU was set up at HRS with Eamonn Nash as its Head. The Unit was charged with the task of confirming or disproving Law's results at a basin scale. However, it first had to search for an experimental site suitable for comparing the water balance of basins in order to answer the question 'Do trees use more water than grass?' After an extensive survey of suitable sites across parts of Scotland, England and Wales, the preferred site was three small south-east-facing basins on the Long Mynd in Shropshire. The geology rendered them watertight, one basin was in coniferous forest and the others in sheep pasture. When the protracted negotiations over access failed, it became necessary to find an alternative site. A new site was found in Central Wales; this was the small basins surrounding the heads of the rivers Wye (upland pasture) and Severn (mostly coniferous forest) on the east flank of Plynlimon. The forested basin was owned by the Forestry Commission, whereas the other landowner was very sympathetic to the aims of the study and agreed access. Despite initial criticism that the area was too wet to distinguish hydrologically between the contrasting short and long vegetation, the Plynlimon Project started on January 1, 1967. Subsequently, it has provided a core project for the Unit and its successors (Robinson *et al*, 2013).

In addition to the primary investigation at Plynlimon and the earlier River Ray, several fresh catchment studies were launched by HRU. These included investigation of the effects of urbanisation (Milton Keynes), afforestation (Coalburn) and, to contrast with the clay River Ray catchment, a study of one mainly composed of chalk (River Cam). Because of the importance of the influence of forests on evaporation, a very detailed micrometeorological study was mounted to measure forest evaporation. This was at Thetford where there is a very extensive area planted with conifers. For Plynlimon, Thetford and other studies, it was soon found that most of the 'off-the-shelf instruments' then available were not 'fit for purpose'. They were not sufficiently robust, they lacked the required accuracy and in some cases, such as for the measurement of soil moisture, new devices needed to be developed, namely the Wallingford neutron probe. Similarly, for a continuous record of rainfall and the meteorological factors governing evaporation, an automatic weather station (AWS) was devised, the data being logged on a multichannel recorder. In the case of the Thetford study where the turbulent structure of the wind flow was investigated, care had to be taken to select and position the sensors correctly. The way these sensors were used, the neutron probe and the AWS were, at the time, in the forefront of instrument development and operation. In 1966, a Digital Equipment PDP 8 computer was acquired by HRU, one of the first computers in the United Kingdom to be dedicated solely to hydrological research. Alongside these fundamental studies, the Unit's interests expanded to include projects conducted abroad in support of British consulting engineers. To cope with this work, staff numbers increased from 26 in 1966 to 54 in 1968 and to 102 in 1972. In recognition of the importance of hydrology, on April 1, 1968 HRU became a full NERC Institute – IH, with Jim McCulloch as Director. Jim had been appointed Head of HRU in1964 and had successfully led the development of the young Unit. In 1972, a notable, modernist, prize-winning concrete building was constructed to house the rapidly growing staff and the powerful computing facilities. It was formally opened by Earl Jellicoe, Leader of the House of Lords, as the Maclean Building in May 1973, an event marked by a Scientific Symposium 'A View from the Watershed' (IH, 1973).

1.7 Fighting Floods

In the 1960s, the methods of flood prediction dating from the 1930s that were being employed by British consulting engineers were desperately in need of updating. In 1968, the Institution of Civil Engineers (ICE) asked for urgent government action to initiate a study of the factors affecting floods, particularly with respect to reservoir safety and the flooding of land and urban communities. In response, a 15 strong Flood Studies Team was established at IH in 1970 to address this need with

Fig. 1.2 The Flood Studies Team in the 1970s. (Source: Reproduced with permission of CEH.)

John Sutcliffe as its leader (Fig. 1.2). For the first time, the flood records collected by a variety of disparate bodies across the United Kingdom (and Ireland) were brought together at a national level for analysis in a consistent manner. The Team was able to amass sufficient data, analyse it and produce a methodology that was published in the 5 volume Flood Studies Report (FSR) in 1975 (NERC, 1975). This methodology largely met the then needs for flood prediction. When the work of the Floods Team finished, its members were absorbed into the Institute.

1.8 Gaining International Recognition

The 'Cold War' was at its height during the 1960s with threats of a nuclear holocaust peaking at the time of the Cuban missile crisis in the autumn of 1962. In stark contrast to the ongoing confrontation between east and west, there was a willingness to cooperate in hydrology at the intergovernmental level across the Iron Curtain! This was aptly demonstrated by the launch of the International Hydrological Decade (IHD) by UNESCO in 1965, in cooperation with the World Meteorological Organization (WMO), together with several other agencies of the United Nations (UN) and with the support of the International Association of Scientific Hydrology (IASH) and several other non-governmental bodies. The Decade, the first of its kind for encouraging international cooperation in the field of water, had a number of aims: the stimulation of research, improving education and training and facilitating the exchange of information. The UK was a strong advocate of the decade. It participated in the IHD programme and it was represented at the meetings of its Co-ordinating Council, whereas IH provided the secretariat for the British National Committee for the IHD. The Decade gave extra weight to the programme of research being carried out at IH.

Indeed, the International Symposium on 'World Water Balance' held at Reading University in July 1970 gave global exposure to the youthful Institute (IASH/UNESCO/WMO, 1972b). The symposium revealed how much more data and interpretation were needed to understand local and planetary water movements. Three other symposia held at the start of the 1970s helped shaped hydrological research at Wallingford and globally. They were convened in Wellington (IASH/UNESCO/WMO, 1972a), Koblenz (IAHS/UNESCO/WMO, 1970) and Warsaw (IAHS/UNESCO/WMO, 1971) and dealt with results from representative and experimental basins, hydrometry and mathematical modelling.

In September 1974, the International Conference on the Results of the IHD was held at UNESCO with 299 delegates from 90 nations, including the UK, together with a large number of non-governmental organisations (NGOs). The Conference agreed to mount the International Hydrological Programme (IHP) as a major UNESCO Programme from 1975 onwards. The tenor of the IHP was to be similar to that of the IHD, but with several additional aims, one being assisting member states in the organisation and development of their national hydrological activities. The IHP was to be executed through successive phases of 6 years duration. At this same Conference, WMO's Operational Hydrology Programme (OHP) was examined. Similar to the IHP in some respects, the OHP was fashioned to support the hydrological services of member states of WMO. Design of hydrological networks, flood forecasting, water resources assessment and other practical aspects of hydrology are the main thrusts of a programme overseen by the Commission for Hydrology (CHy) at its four yearly meetings. IH provided the UK lead for both the IHP and the OHP, a role continued by CEH.

In 1972, following the appointment of John Rodda to the post of Editor of the International Association of Hydrological Sciences (IAHS), Wallingford became the location of the publishing activities of the Association, now known as the IAHS Press (http://www.iahs.info). The Association's famous 'Red Books' and the *Hydrological Sciences Journal* and its other publications carry the name *Wallingford* to the global community of hydrologists.

In 1972, the UK acceded to the European Community, leading to the Institute's participation in the research programme promoted by the Commission's Directorate General XI, more recently DG Research. This brought IH into contact with a variety of hydrological bodies, governmental and quasi-governmental, within the Community, as well as with a number of universities.

1.9 Governmental Turbulence

In November 1971, a government green paper (Command 4814) was published containing the Rothschild and Dainton Reports on the restructuring of government research and development. The Rothschild Report proposed that part of the funding of government research in the research councils should be channelled through executive departments and that the programmes of research institutes should meet their needs on the customer/contractor basis. NERC (NERC, 1972) and the other councils objected strongly to the proposals; their misgivings were shared by much of the scientific community. However, the 'Rothschild Principle' was enacted (Command 5016) across the research councils, with the Department of the Environment (DoE) being the main customer for the transferred portion of NERC's research. Up to 35% of the science budget was to be transferred from the research councils to the relevant department or ministry over a three-year period. In the case of NERC, discussions with the different institutes, including IH, defined the research that was commissioned and the costs. For the Institute, this amounted to about £150 000 initially, but commissioned research also came for the Ministry of Overseas Development, so that by 1975–1976 some 56% of the IH income was derived from sources outside NERC.

The Dainton Report recommended that IH should be physically transferred, together with its staff, to DoE and fused with HRS. Fortunately for the integrity of IH, the proposed transfer was rejected by the government (Command 5016). In 1982, HRS was privatised as Hydraulics Research Station Wallingford Ltd (later renamed HR Wallingford Ltd.).

Turbulence has also characterised the history of the UK water industry since the end of WWII. Its structure has been radically altered a number of times, but with many of the provisions of the successive Acts of Parliament for England and Wales, Scotland and Northern Ireland still applying. Amalgamations of water undertakings in England and Wales reduced their number from about 1100 in 1945 to 286 by 1966. Twenty nine river authorities were established in England and Wales by the 1963 Water Resources Act (HMSO, 1963) along with the Water Resources Board (WRB). The Act promoted hydrometric schemes which led to a large increase in the number of observations of river flow and ground water. The Act's aim to conserve and ensure the proper use of water resources caused the Board to propose a strategy for water resources development in England and Wales to 2000AD and to embark on research to support its remit. IH was involved in certain aspects of this research. But then the 1973 Water Act (HMSO, 1973) dissolved the WRB and completely changed the complexion of the water industry by establishing 10 Regional Water Authorities for England and Wales, together with a National Water Council. This change demonstrated the government's preference for a regionally based policy for water, rather than continuing with a national water policy. The new water authorities were multifunctional with responsibilities ranging from the conservation of water resources, to recreation and to the control of pollution. The latter caused much concern as the authorities were required to regulate themselves – they were, in other words, both poacher and gamekeeper, something that had not happened previously. To replace the Water Resources Board, the Central Water Planning Unit and the Water Data Unit were established, the latter handling the collection, archiving and analysis of the UK's river flow and groundwater data, amongst other things. The water industries in Scotland and Northern Ireland have evolved over the same period in somewhat different ways.

1.10 An Expanding Role

During the 1970s, IH confirmed its place as leader in its field in the UK and as a global centre of excellence, based on the high quality and reach of its research (Anon, 1973). The global dimension prospered through projects conducted with European partners under the aegis of the EU, through international collaborative programmes and by development projects undertaken for technical assistance agencies, such as the World Bank, as well as with British consulting engineers. Cooperation with the British Antarctic Survey in South Georgia provided a new dimension. The Hydrogeology Unit of the then Institute of Geological Sciences (now BGS) moved into the Maclean Building in 1977, opening the potential for fruitful collaboration.

In 1971, an investigation started of trace elements at Plynlimon, the first water quality study performed by IH (Anon, 1993). The results of the annual water balance experiment for the River Ray indicated that the storage and release of soil heat in the catchment accounted for the equivalent of about 100 mm of water. Inclusion of this term closed the water balance – a term usually ignored in such studies (Edwards & Rodda, 1970). Six newly developed AWS went into service at Plynlimon, Coalburn and South Georgia. IH staff numbers increased to about 100 by 1972, including three based abroad and three at Plynlimon. They were supported by a budget of £463,000. The 1971–1972 annual report showed that they published 17 scientific papers covering the 6 areas of the Institute's programme (IH, various years).

A UNIVAC 1100 series computer and various pieces of peripheral equipment were installed in 1973 to meet rising demands for handling large amounts of data and applications of increasingly complex and realistic mathematical models – lumped and distributed catchment models were being developed. Results emerging from Plynlimon showed an evaporation 'loss' of 17% of the annual rainfall for the grassland catchment and 29% forest catchment. To explain the cause of this difference, studies of hydrological *processes* were started at Plynlimon; detailed micrometeorological studies in a forest near Thetford project confirmed the importance of interception, leaf wetness and the biological controls on evaporation. Studies of soil water flow in the saturated and unsaturated zone were underway. In collaboration with the Met Office, the Water Research Centre and several other bodies, work commenced in 1974 to develop an operational flow forecasting system for the River Dee, using real-time data from radar and ground-based sensors. During the late 1950s, a series of East African catchment studies of land use change were initiated by the East Africa Forestry Research Organisation (EAFRO). In the 1970s, they were supported by IH funded by the Overseas Development Ministry (ODM). Instrument networks were upgraded and effort made to analyse the data. The very severe and extensive drought of 1975–1976 across the UK brought IH a project on low flows funded by the DoE increasing the total receipts from outside NERC to over £0.5 million.

Projects undertaken in Northern Oman, Botswana, Iran, India, Ecuador and Brazil contributed to this total, as did a number of consultancies carried out within the UK, such as a study to rationalise the national raingauge network.

Towards the end of the decade staff numbers had increased to over 130: scientific paper were being published in learned journals at a rate of more than 30 a year and 33 commissioned overseas projects had been completed over the previous 5 years. A substantial extension, the North Wing, was made to the Maclean Building in 1980. However, this apparent progress was sullied by the first of a series of cuts in science budget funding, whereas certain members of staff were encouraged to take early retirement. That the UNIVAC 1108 computer was moved from IH to NERC Computing Services at the Rutherford Laboratory did not assist the progress of mathematical modelling of hydrological systems.

1.11 Extending Hydrological Research into the Eighties

Studies of the hydrological consequences of land use change, previously centred on Plynlimon, were extended to Scotland, Scotland being the main area of expansion in the UK forestry industry. Monachyle Glen (heather, bracken and scrub) and Kirkton Glen (part forest) catchments in Perthshire, of similar size and geology were selected for investigation, in cooperation with a number of Scottish bodies. The instrumentation of these catchments completed in the autumn of 1981 was similar to those at Plynlimon, but with water quality monitoring being included from the outset. Meanwhile, hydrological modelling saw the development of more realistic physically based distributed models, namely the Institute of Hydrology Distributed Model (IHDM) and the Système Hydrologique Européen (SHE), both models representing significant advances. Water quality modelling was also progressing through studies of the River Thames and several other rivers, such as the Bedford Ouse, where a real-time forecasting system was developed.

Applications of remote sensing, assessment of evaporation from the Amazon rain forest and studies of the storage and movement of water in the Chalk in southern and eastern England were among the projects underway in the early 1980s. Groundwater studies included recharge estimates, pumping test analyses and modelling saline intrusion. Groundwater consultancies were undertaken in 12 countries, mainly in the Middle East. Recognition of the effects of atmospheric pollution impact on stream ecology through the type of land use and management led to the start of studies of hydrochemical balances at Plynlimon (Fig. 1.3). Land management, including field drainage, is also important to sediment yield, erosion and deposition and in turn to flood protection.

The 1975 Flood Studies Report (NERC, 1975) provided, for the first time, a set of techniques for estimating the flood of a given frequency on any river in the British Isles. The European Community then commissioned a similar study 'the European Flood Study' to provide the same facility for estimating floods across member states. An extension of this study was one on floods for some 33 countries 'the World Flood Study'. A GEC 4000 Series computer was installed at IH in 1983, the turnover rose to £2.5 million, but staff reductions were sought. With the closure of the Water Data Unit, its work of curating the data from the national river flow and groundwater networks was transferred to Wallingford. In 1985, a 6-man international team was established at IH to undertake the UNESCO FREND project (Flow Regimes from Experimental and Network Data), part of the programme for the third Phase of the IHP. The initial idea was to bring together data from the many studies of experimental basins established during the IHD with data from national networks in Western Europe, to develop better understanding of hydrological variability in time and space, through mutual exchange of data, knowledge and techniques at a regional level.

In the mid-1980s, studies of acid rain were initiated at Llyn Brianne and in the Cairngorms, while collaboration with several Brazilian institutes began in the Amazon on the water use of tropical forests. Michael Heseltine, who was at the time the local Member of Parliament and a government minister, inaugurated the IBM 4381/3 mainframe computer in 1986, but early personal computers, more commonly called 'microcomputers' in the UK were deployed at IH from an early date. These included the PET Commodore (1977 USA), Acorn (1978 UK) RM 380Z (1978 UK) and Sinclair ZX 80 (1980 UK) machines. Subsequently, IBM launched their 'Personal Computer' and thereby imposed a standardised architecture which has dominated ever since, Apple aside. Digitising the UK river

Fig. 1.3 The Workshops at Wallingford were essential in the development of novel hydrological instruments. (Source: Reproduced with permission of CEH.)

network at a 1:50,000 scale commenced prior to the development of digital terrain models.

A new instrument called the HYDRA was developed to measure evaporation directly by making high-frequency measurements of the flux of water vapour moving away from the land surface. IH was selected as the principal investigator in the FIFE Project for modelling and observing land–surface–atmosphere interactions on regional and global scales. A new series of year books and reports: Hydrological Data UK was launched, including the first occasional report. Its subject was the 1984 drought.

In 1988, the National Hydrological Monitoring Programme was instigated by IH in cooperation with BGS based on data on river flows, groundwater levels and reservoir levels collected from a variety of sources across the UK. The Hydrological Summary for the United Kingdom, published online monthly, also contains rainfall information from the Met Office and a hydrological outlook for 3 months ahead. It provides an immediate appreciation of the hydrological condition of the nation, valuable to decision makers at all levels, but particularly at times when floods or droughts are occurring. Few other nations produce such a publication.

Towards the end of the decade, work started with the Met Office to improve land surface inputs into global climate models. A separate study of the relationship between climate and hydrology was conducted, both endeavour enlarging the profile of IH research into the area of climate change. This enlargement was enhanced by a funded study of the effects of forest clearance in Brazil to obtain data for the calibration of global circulation models.

Box 1.2 The British Hydrological Society

In response to expressions of interest from professional research and engineering hydrologists, in the 1970s and early 1980s, the British Hydrological Society (BHS) was formed in 1983 – '*to promote interest and scholarship in both the scientific and the applied aspects of hydrology and to foster the involvement of its members in international activities directed to the promotion of such scholarship*' (BHS Statutes). The Institute of Hydrology (IH) and the Institution of Civil Engineers (ICE) together provided the coordination and steering necessary to establish the new Society. They became statutory stakeholders in BHS. Of the 15 BHS Presidents between 1983 and 2013, three were from IH/CEH. BHS is an Associate Society of ICE. The benefits are that membership and other administrative services are provided by ICE. The prestigious conference and meeting facilities at ICE, in Westminster, London are often used by BHS.

BHS has, in 2014, about 1000 members from universities, government departments and agencies and from consultants and practitioners. The National Committee is elected by the members. It includes representatives of the ICE Water Expert Panel, CEH, the UK Committee for IAHS and the Chartered Institution of Water and Environmental Management (CIWEM). There are four regional Sections (Midlands, South East, South West and Welsh). In addition, the north of England is covered by the Pennines Hydrological Group, and Scotland by the Scottish Hydrological Group. They organise regional events. BHS holds biennial National Symposia, with every sixth year being marked by an International Symposium.

Information about BHS, its activities and publication is given on its website (http://www.hydrology.org.uk/). The BHS quarterly Newsletter, *Circulation* provides reports of recent meetings and notices of future meetings. BHS offers an annual undergraduate dissertation prize, organises an annual event for early-career hydrologists (the Peter Wolf series) and administers applications for travel grants from its members seeking financial assistance to attend international conferences.

With the Nordic Association for Hydrology (NHF), Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway and Sweden, in January 2008, *Nordic Hydrology: An International Journal* was relaunched by BHS in cooperation with IWA Publishing as *Hydrology Research: An International Journal* (http://www.iwaponline.com/nh/)

Subsequently, the Italian Hydrological Society (IHS) and the German Hydrological Society (DHG) have adopted *Hydrology Research* as their research journal. *Hydrology Research* has six issues per year. Within this publishing schedule, there are Special Issues from the biennial BHS Symposia and NHF Conferences.

Following the appointment of Jim McCulloch to a post in NERC Headquarters in Swindon, in 1988 Brian Wilkinson took up the position of Director of IH supported by 160 staff and a budget of £5 million, £3.6 million coming from commissioned research. During the two years 1988–1989, over 150 scientific papers and reports were published.

The First Scientific Assembly of the IAHS took place in Exeter University in July 1982 with a strong IH input. This event led to the formation of the British Hydrological Society a year later (Box 1.2).

The 10 regional water authorities in England and Wales were privatised in 1989 (HMSO, 1989 and 1991), and their regulatory role, including pollution control and water resources management, vested in the newly formed National Rivers Authority (NRA). An economic regulator, OFWAT, was created and the Drinking Water Inspectorate established to monitor water safety and quality. The 16 small water supply companies in England and Wales remained in private ownership, whereas the water and sewerage services in Scotland and Northern Ireland continued as public services.

1.12 Into the Nineties

During this decade, many of the research initiatives launched earlier came to fruition. In a number of projects digital data, software advances and transformed communications radically changed the pace and scale of IH research. Computing turned gradually from the mainframe to desktop machines. Several Science Budget Community Research Programmes were commenced as NERC celebrated its twenty-fifth anniversary in 1990 (Sheail, 1992).

The first of these programmes was Terrestrial Initiative in Global Environmental Research (TIGER). With guidance from the NERC Terrestrial and Freshwater Sciences Directorate, the TIGER office at IH was responsible for a spend of £20 million over the seven years of activities from 1990. TIGER comprised four thematic areas of work – carbon cycling through soil and vegetation, biogenic trace greenhouse gas emissions and sinks, energy and water budgets for climate modelling and ecosystem impacts. These were supplemented by several cross-cutting areas concerning: monitoring environmental change, applications of remote sensing, palaeoclimatology via soil sampling (also managed from IH) and researching technical means of establishing sensitivities to carbon dioxide increase, change in drought and ambient temperature regimes, increase in ultraviolet radiation and functional aspects of biodiversity change. The TIGER office led by Max Beran plus a team of convenors supported the work of the top-level steering committee, the working groups for each of the themes and those for each of the cross-cutting topics from announcement of opportunity through project selection to the finalisation or extension of contracts. As well as this basic administration of research proposals, the office also looked after budget maintenance, organisation of meetings and conferences, setting up TIGER's own flagship field sites at Wytham and Moor House (parts of the Environment Change Network), the provision of publicity material, press releases, conference organisation, the TIGER quarterly newsletter and coordination with sister global change programmes with international links.

Studies were spread over more than 60 laboratories and university departments, the programme funding 300 scientists. IH's own expertise was required in many areas such as field monitoring and flux measurement, but most prominently in the energy and water budgets area (Oliver *et al.*, 1999). New insights were gained into how patchy terrain, such as Tiger Bush, could be represented in modelling transports through the soil–vegetation–atmosphere interfaces recognising strong non-linearities. Field measurement sites were set up in Niger and in Amazonia. Other IH activities in this TIGER area were for developing methods for incorporating lateral water movement at the land surface in a way appropriate to the requirements of global climate models.

Another collaborative programme named Land Ocean Interaction Study (LOIS) was carried out from 1992 to 2001, involving three hundred and sixty scientists from eleven research institutes and twenty seven universities. This unique multidisciplinary large-scale research study aimed to make major advances in understanding the processes and fluxes at the margins of continental shelf seas, from catchments and rivers to the coastal seas, and across the continental shelf edge into the deep ocean. The policy issues driving the investment in the LOIS programme were in part the need to further knowledge of the coastal zone in which over 60% of world cities lie. It was also developed at a time when the issues around coastal water quality were contributing to an impression, current in the media, of Britain as the 'Dirty man of Europe'.

The LOIS programme was at the forefront of the scientific efforts to link atmospheric, terrestrial, river and marine environmental systems. This work ran in parallel with similar initiatives at the global (e.g. the International Geosphere and Biosphere Programme), regional (e.g. The European equivalent to LOIS, known as ELOISE) and national levels. The research also received strong support from the water industry and environmental regulators.

The largest component of the LOIS programme considered the exchange of natural and man-made materials between the land and the sea in temperate regions. Chemists, physicists, biologists, mathematicians and engineers collaborated. The study focussed on catchments and estuaries of the UK's east coast, for example the Humber. This river drains a catchment area which is home to more than 20% of the UK population and is the site of a very significant proportion of the UK energy, industrial and agricultural production. Discharges from the estuary have an important impact on the water quality of the North Sea. The adjacent coast line is in rapid retreat and supplies large amounts of sediment. The Tweed estuary, also on the UK east coast, is a much smaller estuary with very little industrial activity within its catchment, providing an important contrasting environment.

The benefits of this large programme exploited the multidisciplinary nature of LOIS and a number of important innovations can be exampled. These include studies of tidal reaches, with their salinity variations, tidal flows and large fluctuations in river inputs. New insights were gained into the role of these regions as buffers between the fluvial and marine environments. In the intertidal region, a wide range of techniques and disciplines were deployed. They produced new process models for the erosion and deposition of fine sediments, incorporating the vital influence of biological activity at the surface. The cross-calibration of chemical measurements from river and marine samples made possible comparable measurements of nutrients from catchments draining into the adjacent North Sea. IH with other CEH institutes also developed new integrated systems for continuous and flow-related monitoring of river water quality and sediment transport, triggered by both level and turbidity thresholds.

The major research findings have been published widely in special volumes of science journals and in a book (Neal *et al.*, 1997, 1998; Leeks and Walling, 1999; Neal *et al.* 2000; Huntley, and Neal *et al.*, 2003).

In 1991, the report on the 'First Two Decades' of research at Plynlimon was published (Kirby *et al.*, 1991). This brought together the results of the catchment investigations to answer the question: '*Do trees use more water than grass?*' The comparison of the water balance between the forested Severn and the Wye in sheep pasture showed that, on an annual basis, runoff from the latter averaged nearly 200 mm more. Studies of the physical processes explained this difference in terms of the differences in the height and aerodynamic roughness of the vegetation, whereas work on water quality highlighted other contrasts between streams draining the different land covers. Several of the mathematical models developed by IH were employed to analyse the Plynlimon data. The results depicted the implications for land use strategy across the UK. Looking to the future, the report saw the Plynlimon catchments continuing as a valuable outdoor laboratory for long-term monitoring, coupled with new studies, such a geochemical cycling, adding a further dimension to the science. Hydrological studies similar to Plynlimon have been underway in different parts of the world, many stimulated by the IHP and other collaborative programmes. But few have portrayed the hydrology of the studied basins in such detail and with such precision as at Plynlimon. Plynlimon data remains the third most requested data set on the CEH online Information Gateway (https://gateway.ceh.ac.uk/home).

New instruments and techniques were developed and existing ones deployed more widely to the extent that IH became a world leader in sampling, sensors, software and satellite usage for hydrology (Fig. 1.4). One example is the capacitance probe (Dean, 1994) built for soil moisture measurement and, with tensiometers, incorporated in an automatic soil water station. Flow and quality sensors were combined in a system with an intelligent logger, whereas the widely used AWS pioneered at Wallingford was upgraded to measure 12 atmospheric variables at a rate of once every 10 seconds. The data recorded by these systems were transmitted by land-based telemetry or through METEOSAT. To support groundwater investigations, drilling techniques were improved and employed for contract work in the UK and abroad and in IH experiments.

Starting in 1994, the 1975 Flood Studies Report was updated in a 4-year project which produced the Flood Estimation Handbook (IH, 1999). Applications of research included a river flow forecasting system for timely warnings of floods. In 1993, IH was one of the 6 founding members of EUAQUA, a European network of freshwater research organisations, set up strengthen cooperation and transfer of knowledge. Later EURAQUA expanded to 22 members. Collaboration in a number of international programmes, such as the International Geosphere Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP), took IH further into studies of global change. The Hydrosphere Atmosphere Potential Evaporation Experiment (HAPEX) in the Sahel and the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) in the Amazon rainforest were two examples of work of this type. Another collaborative programme was the TIGER, a 5-year NERC Community Programme which was run from IH involving 50 different research groups and universities.

Completion of a digital terrain model for England and Wales, a river centre line network and several other developments permitted a flood risk map to be published in 1996 (Morris and Flavin, 1996) under an MAFF commission. The map shows the areas at risk from the 100-year flood, including urban areas; it is the first national map defining flood risk to a consistent standard and return period. A study (HyRAD) was underway in the Brue catchment in Somerset employing imagery from 3 weather radars and the records from over 50 recording raingauges to improve methods of

Fig. 1.4 One of the Chemistry Laboratories for rapid the in-house analyses of water samples. (Source: Reproduced with permission of CEH.)

network design, whereas images from radars and Meteosat were being employed in a rainfall–runoff model to upgrade flood forecasting. Seeking a method for measuring soil moisture over an area, rather than at a point, led to the testing of the European Space Agency's ERS 1 satellite's synthetic aperture radar.

Results from the study of the Coalburn catchment (Robinson *et al.*, 1998), into the long-term effects of establishing a forest, showed that ploughing prior to planting increased annual total flow and enhanced storm peaks. In contrast, the subsequent growth of trees reduced total flow, base flow and peak flows, while water chemistry (Fig. 1.5) was affected in a number of ways.

In 1994, IH was grouped with three other NERC institutes into the Centre for Ecology & Hydrology (CEH) to 'promote closer collaboration and to reinforce university links'. Brian Wilkinson was appointed CEH Director and Tony Debney became Director of IH. The previous year, a new wing was added to the Maclean Building (Fig. 1.5). By 1995, staff numbers had grown to some 200 (Fig. 1.6), with a budget of nearly £8 million, about £2 million coming from ODA, around £2.5 million from NERC and lesser amounts from other government departments and the EU. They contributed 126 papers to the scientific literature and produced 140 commissioned reports for clients. However, the IH income declined in the last years of the decade to less than £7 million. In 1997, Jim Wallace became Director of IH in place of Tony Debney who retired, then Brian Wilkinson retired in 1998 and was replaced by Mike Roberts as Director of CEH. In 1999, Lord Sainsbury, Minister for Science and Innovation, opened a new West Wing

Fig. 1.5 The library. (Source: Reproduced with permission of CEH.)

and the remodelled front of the Maclean Building in the mid-1990s there was uncertainty about the future of IH due to the review of Government research establishments carried out under the 'Prior Options' initiative. There were threats of splitting the Institute and privatising parts of it, but nothing came of these moves.

In parallel to changes in NERC, on April 1, 1996 the EA came into existence, taking over the role of the NRA, Her Majesty's Inspectorate of Pollution (HMIP) and a number of other bodies mostly concerned with waste disposal (HMSO, 1995). Within a budget of over £1 billion, more than half is spent on water, including flood defences and the task of issuing flood warnings. Scotland and Northern Ireland established bodies equivalent to the EA. In 1999, 'An agenda for land surface hydrology research and a call for the Second International Hydrological Decade' was made by Enteyhabi *et al.* (1999) which possibly led to the IAHS PUB Programme (Prediction in Ungauged Basins) a few years later.

1.13 Moving into the New Millennium

Further *consolidation* within NERC took place in 2000 AD when the Institute lost its separate identity and was designated part of CEH Wallingford, one of then 9 CEH sites. Chosen as the principal site for expansion within CEH and the location of the Headquarters, during the early years of the new millennium, the hydrologists at the Wallingford Laboratory were joined by ecologists with wide-ranging expertise from several of the other former institutes as they closed. As a result, Wallingford became a scientifically richer environment able to address a wider range

Fig. 1.6 Staff picture Institute of Hydrology in the 1990s. (Source: Reproduced with permission of CEH.)

of environmental problems than in the past. In terms of expertise, it could be argued that the strengthened linkage of hydrology and ecology complemented the long-standing links between hydrology and civil engineering. Further enlargement of the Maclean Building from the middle of the decade provided new accommodation for scientists and administrators from sites which closed as CEH was restructured to 4 laboratories, following adoption of a business plan in March 2006 (CEH, various years). Jim Wallace left CEH in March 2003 and Alan Jenkins became Water Science Director for the whole of CEH in the following September. The European Union's Water Framework Directive (WFD) came into force in 2000 requiring member states to establish targets for water quality in rivers and lakes (EU, 2000). It was to be implemented in stages over a period of 20 years, influencing the trend in certain aspects of CEH research. In 2001, CEH became a Partner in PEER (Partnership in European Environmental Research) with 7 other large environmental research centres. PEER aims to follow a joint strategy in the environmental sciences to enhance research in all fields of the environment.

At the start of the decade, there was a growing concern in government and the water industry about steroid oestrogens disrupting fish hormonal systems and the likely effects on humans. A model was developed to predict the impact of these substances, assessing the human excretion of oestrogens, together with their transformations in the sewer and waste water treatment plant (WWTP). The model was used by the EA and water companies to provide concentrations throughout catchments, based on the distribution of the population and the number and location of WWTPs. A study of water fluxes in residential areas using a unique data set showed that if roof runoff were collected, depending on the rainfall of the locality, it would be sufficient to meet the grey water needs of the average household. This would reduce the demand for water and lessen domestic water charges. The 2003 Water Act (HMSO, 2003) seeks to improve water conservation, requiring water companies to publish water resources management plans and drought plans.

To complement the attention given to upland catchments, in 2000 a six-year NERC Lowland Catchment Research Programme (LOCAR) was commenced with a budget of over £10 million. A team of 75 scientists, including a number from IH, was established from 14 institutions to work on 12 projects on 3 chalk and sandstone river basins to study and model their hydrology, geology and ecology. The programme was based on the establishment of several data collection systems and a large number of new boreholes to give a valuable picture of how each basin functions. In 2003, IAHS launched PUB (Prediction in Ungauged Basins) aimed at improving understanding of hydrological processes. Members of IH took part in this programme, collaborating with a number of UK universities (O'Connell *et al.*, 2007). PUB continued to 2012 and has been succeeded by *Panta Rhei* ('everything flows') which started in October 2013.

The receipt, processing and display of weather radar products from HyRAD was developed as the interface to improve the EA's flood forecasting system, extending the lead time for flood warnings and improving decision making. Knowledge of soil moisture is important to many facets of hydrology, for example in flood forecasting, so that CEH work to model soil moisture to smaller grid sizes would result in better flood forecasts. Soil moisture was also studied for the Amazon Basin where previous work on rainforests suggested they were not sensitive to soil moisture deficits, but modelling fluxes for the Amazon revealed they react to even modest amounts of depletion. This gives rise to the conclusion that increasing levels of atmospheric CO_2 will alter rainfall patterns over the basin and to the possibility that Amazonia will change from being a sink for CO_2 to a source. There is concern that global warming has serious consequences for communities who depend on glacier-fed rivers for water. At the present rate of glacier recession in the Himalayas, there could be future widespread water shortages in northern India and Pakistan. A hydro-glaciological model predicts how the region will be affected by global warming. Although global warming is expected to bring significant changes to the world's climate, there is uncertainty about the extent of these changes, particularly at a local level and for extreme events. Using hourly rainfall series, a model was used to compare UK floods for the period 1961 to 1990 with those simulated for 2071–2100 in a number of catchments The results indicated that the current 10-year flood would occur once every 4 years by the end of the century.

Since 1985 when the FREND project began, IH has played a pivotal role – in 2006 a global perspective was published reviewing its geographical expansion and its contribution to the IHP (Servat and Demuth, 2006). When FREND started in Wallingford, its initial focus was the data-rich north-west Europe. By 2006, there were 8 regional projects within Flow Regimes from international Experimental and Network Data (FRIEND), including ones in the Hindu Kush Himalayas and the Nile. A Water Poverty Index was developed for DFID to offer a better understanding of the relationship between the extent of water availability, the ease of abstraction and the level of community welfare. Its key components are the physical availability of surface and groundwater taking account of its variability and quality, how easy it is to access this resource. In 2004, BHS celebrated its twenty-first birthday in a one-day symposium in the Institution of Civil Engineers in Westminster (Fig. 1.7).

In 2007, the Water and Global Change (Watch) Programme started as an integrated endeavour funded under the European Union's sixth Framework Programme. It brought together 25 internationally orientated hydrological, climatological and water resources communities from across the EU, headed by CEH. They analysed, quantified and predicted the components of the current and future global water cycle. They evaluated uncertainties and clarified the overall vulnerability of global water resources for key societal and economic sectors to better inform stakeholders and policy makers (Harding and Warnaars, 2011). See http://www.waterandclimatechange.eu/.

Research continued during the second half of the decade to improve the assessment of flood risk; research that became increasingly important with the growth of housing on flood plains. A prototype method based on a 1-km gridded hydrological and routing model resulted from research by the Joint Centre for Hydro-Meteorological Research setup at Wallingford by the Met Office and CEH

Fig. 1.7 BHS twenty-first birthday celebrations in 2004. (Source: Reproduced with permission of BHS.)

Box 1.3 Advancing hydrology

A special issue of Hydrology and Earth System Sciences (HESS) was published in 2007 (Neal and Clarke, 2007) dedicated to McCulloch (2007). It recognised his contribution to the science as an experimental physicist, as the first Director of the Institute of Hydrology and then subsequently as editor of the internationally acclaimed *Journal of Hydrology* and later as editor of Hydrology and Earth System Sciences. The special issue contains nearly 50 papers on contemporary topics grouped under catchment area research, process studies and modelling.

in December 2000. A newly developed cosmic ray soil moisture probe provides spatially integrated assessments of soil water content representative of conditions across a target area of 350 m in radius to a depth of 0.5 m. Deployment of a countrywide network of these probes and their operational use should ensure much improved flood forecasts and the better assessment of the nation's water resources.

Towards the end of the decade, NERC (2009) published a brief report 'Economic Benefits of Environmental Science'. It was based on extensive research by PricewaterhouseCoopers using an approach which developed a value chain for each of 10 case studies, identified a range of qualitative strategic benefits and wherever possible a quantitative benefits assessment. Detailed arguments were provided for assumptions and caveats. One case study was of the Flood Estimation Handbook which cost NERC £100,000 and produced benefits to the UK economy estimated to be between £7 and £34 million a year. By comparison, the summer

2007 floods, which hit a number of areas in England, were estimated by the EA to have cost £3.2 billion.

1.14 Looking Ahead

That the world's water problems will decline in the future is an unlikely scenario. A burgeoning world population, changes in climate and other forcing factors more or less guarantee a greater number in both the developing and the developed regions of the globe. Indeed, the 2014 World Economic Forum in its Global Risks Report (WEF, 2014) rated water crises third after fiscal crises and high unemployment as the most significant risks to humanity, with extreme weather events including floods as sixth. On this basis, the hydrological research conducted at Wallingford must grow in importance and became even more vital to humankind. Water issues will gather increasing complexity and sophistication, with greater interaction between them and they are very likely to be subject to growing social, political and economic pressures. Never before has the need been stronger for independent, multidisciplinary scientific research into water-related issues.

A settled structure for the UK research community with certain funding and little political interference is probably too much to expect. But if such turbulence can be minimised, that will help to maintain capabilities and their continued development to combat the uncertain future for water. Gathering fees for commissioned research and receiving core funding would continue the NERC financial pattern of the last 50 years, although this model is distant from the Haldane Principle of research independence that applied in much of the first part of the twentieth century. But obviously there are a number of factors which will determine the future well-being of hydrological research at Wallingford. The community of hydrologists must maintain those qualities that have sustained the past advances, and those that characterise the present, namely enthusiasm, dedication and commitment.

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