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Dramatic growth of hydrological science in the UK in the 1960s and early 1970s

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ABSTRACT

The mid-1960s to early 1970s were a formative stage in hydrology in the UK. This was a period of a major increase in government funding for science. Establishing hydrology as an environmental science to compete for a share in this boost in funding with well-recognised subjects such as geology, ecology and oceanography depended on the work of enthusiastic scientists influencing the Natural Environment Research Council (NERC). Progress was made by key individuals not only by their own research contributions but also by their influential work within the government, exemplified by the roles of five physicists. In attempting to accelerate hydrological science, mistakes were made but, in this period, a major research institute was founded, large field catchment experiments were set up and research and training within UK universities increased significantly. The research is based on participant observation and examination of contemporary committee papers held in the UK National Archives, Kew and in the Science Museum Archive, Wroughton.

Key words: hydrological science, Institute of Hydrology, Natural Environment Research Council, Rothschild report, social history of hydrology

HIGHLIGHTS

- The social history of scientific hydrology in its formative years in the UK reveals complex relations between scientists and government.
- Five physicists played leading roles.
- An expensive laboratory catchment study failed.
- Hydrological science was defended against demand for precipitate applicability.

INTRODUCTION

Since the publication of Thomas Kuhn's (1962) influential essay on 'The structure of scientific revolutions', simplistic chronologies of the growth of scientific knowledge have been supplemented by analyses of the circumstances under which new discoveries emerge including the 'institutional bases of power in knowledge production' also 'the special characteristics of the groups that create and use it' (Kuhn 1962, p 210). A vibrant new sociological literature on Science, Technology and Society has developed. Using some of these insights, a formative period of hydrology during the 1960s and early 1970s in Britain is analysed to illuminate how rapid growth was achieved, its institutional context and the role of a network of scientists determined to promote investigations into the causes of hydrological phenomena. The interplay of these selected scientists, working through and with government, made funding decisions which shaped the hydrological research agenda.

This period, 1965–1974, was significant because the UK Government's desire for more prudent management of water resources was accompanied by realisation of a need for an improved knowledge base to guide decision-making. Knowledge of hydrology was found to be inadequate to explain, and to fully utilise, a growing number of empirical measurements of rainfall and runoff. Additional pressure on the government to invest in more research came from developments in international science with the launch of an International Hydrological Decade in 1965. The relative weakness of UK's research effort was exposed to view on a world stage.

This is an account based on participant observation by the author, who served as a Senior Scientific Officer in the NERC Headquarters 1967–1974 and study of contemporary committee papers held in the National Archives at Kew and the Science

Museum Archives held at Wroughton[1]. Emphasis in this account will be given to an interlinked group of scientists, who influenced both the extent of funding for hydrology and its scientific agenda. For more traditional historical accounts, more inclusive of all the scientists involved, see Rodda & Robinson (2015) and Mather (2004).

UK GOVERNMENT SUPPORT OF HYDROLOGY IN THE 1940S AND 1950S

Before investigating the reasons behind a sudden expansion of hydrological science in the 1960s, the prior conditions of relative neglect during the 1940s and 1950s will be considered.

(a) Support for hydrology nationally

During the Second World War, governance of water supply was the responsibility of the Ministry of Health because drinking water and sewage treatment were dominant issues. After the 1945 Water Act, responsibility for water resources passed from the Ministry of Health to the Ministry of Housing and Local Government (MHLG). Rising standards of living, a growing urban population and increasing demand for water from manufacturing industry led to concern that water supply might be threatened, especially during droughts. Many rivers and estuaries were becoming severely polluted, reducing availability of treatable water for supply (Porter 1978).

Rodda (2006) claims 'in Britain in the early 1950s, hydrology was not recognised as a separate science and no one was employed specifically as a hydrologist or hydrogeologist'. A few disparate scientists and engineers worked individually, or in very small teams, on problems involving freshwater in engineering firms, in the Rothamsted Agricultural Research Station, the Nature Conservancy, the Meteorological Office, the Geological Survey of Great Britain, the Road Research Laboratory or in university departments. Formal teaching of hydrology was not available in Britain prior to 1955 when a short-lived Post-Graduate Diploma course in Engineering Hydrology was led by Professor Peter Wolf at Imperial College. Elsewhere, aspects of hydrology formed only part of training in some engineering, physics, agriculture, geography, and geology university courses.

In a post-war UK where, until 1953, food was still rationed, and famines were reported from parts of the diminishing British Empire, improving food production was an inspiration for the following four British scientists, who became colleagues and friends: Howard Penman, Charles Pereira, Jim McCulloch and John Monteith. Their pioneering research on water and crops would influence the subsequent growth of hydrology. Even more remarkable, their enthusiastic advocacy of the value of fundamental studies during their involvement in the governance of hydrological research ensured increased investment of the necessary resources. In this, they were aided by a fifth physicist/hydrologist, Donald Maclean, Deputy Secretary of the NERC.

First, I shall introduce the dominant leader of UK hydrology in this period, Dr Howard Penman, Order of the British Empire (OBE) and Fellow of the Royal Society (FRS) (1909–1984), who was a physicist working at Rothamsted Agricultural Station (Monteith 1986). He studied moisture requirements of crops and evaporation loss by linking energy balances with water balances. Penman published a much-cited paper on evaporation which enabled estimations to be made using meteorological data (Penman 1948). Open water evaporation could be calculated using Penman's equation from standard meteorological measurements of air temperature and humidity, wind speed and either incoming energy or sunshine hours (Sutcliffe, 2004). His acknowledged contribution to science, his enthusiasm for promoting hydrology, and his dry wit, led to Penman being appointed to serve on many hydrology and meteorological committees throughout this period. He chaired a British National Committee on Hydrology[2], keeping discussion of scientific hydrology alive during the 1950s, even though hydrology was then only a supporting, subsidiary subject to other sciences. He was elected to the Fellowship of the Royal Society in 1963 and he led UK's contribution to the International Hydrological Decade (1965–1975). He served on the Hydrology Committees of the two major government funders, the Department of Science and Industrial Research (DSIR) followed by the NERC. Later, on the Advisory Committee of the Institute of Hydrology (IH), he guided the progress of the new research institute.

[1] NERC Committee papers of this period were not open to public inspection until the 1990s, by which time the majority had been destroyed. However, the National Archives hold papers of the Water Resources Board and some collections of individual scientists who sent their copies of the agenda papers for conservation. Hydrology Committee papers may be found at WRB AT3/49-55. The Science Museum Archive holds agenda papers of meetings of the Committee on Hydrological Research of DSIR and early NERC Hydrology Committee papers 1959–1968.

[2] The Royal Society is the UK's national academy of science which set up National Committees in many branches of science to foster and encourage science in Britain and act as the voice of British science abroad.

Penman described the early 1950s as a period of ‘appalling depression’ for hydrology. Yet concern about water resources led to the setting up of a Central Advisory Water Committee in 1955 with a sub-committee on Information in Water Resources, which reported to the MHLG that it recognised a need for ‘*additional investigation into hydrological relationships and for further inquiry into the use of hydrological information*’.

A severe summer drought in 1959 threatened the closure of major industrial plant in Teesside and confirmed the seriousness of water resource problems in Britain. A lack of any central hydrological information and research organisation, comparable to the British Geological Survey or the Meteorological Office, was deplored in the scientific press (Balchin 1959).

(b) UK support of hydrological research internationally 1950s and early 1960s

The apparent slow start to the development of hydrology within Britain was not the whole picture. Before the 1960s, hydrology was a neglected subject in the UK, perhaps because there was a complacency about sufficiency of water supply at the national level. Interruptions tended to be localised and episodic. Agriculture was largely rainfed, industrial needs were met by small dams and reservoirs in local upland river valleys feeding water under gravity to industrial consumers on the coasts. Groundwater was a major resource, particularly in the drier south-eastern part of the country.

To the UK government, the need for water and for hydrological research was far more apparent in semi-arid tropical regions where Britain had colonial or post-colonial interests. Increasing food supply within Kenya, to alleviate famine and unrest among the Kikuyu and other indigenous peoples and to increase productivity of export crops such as coffee and tea, was a priority for the Colonial Office. The disastrous failure of the Groundnut Scheme (1946–1951) in what was then called Tanganyika (Wood 1950) was convincing evidence that agricultural development should be preceded by research.

A major agricultural research station at Muguga near Nairobi was opened in 1952 by the Secretary of State for the Colonies, Rt. Hon. James Griffiths. The Colonial Office provided the whole of the capital costs and half the running costs (Pereira 1997). Within this organisation, worked two of the five physicists highlighted in this account. The Physics Division was headed by H.C. (Perry) Pereira (1913–2004) (later Sir Charles Pereira, FRS). He was trained in mathematics and physics, partly at Rothamsted with Penman, and he led catchment studies to record and understand the effects of changes in land use in the headwaters of major rivers which provided vital water for farming downstream (McCulloch 2008, 249–251). Starting a decade before the major home-based catchment studies at Plynlimon, Pereira and colleagues, including Dr J.S.G. (Jim) McCulloch, who was later to play a major role in developing UK hydrological research, were already reporting results based on 5 years of recording (Pereira *et al.* 1962, 1973, 1997).

After a period as Director of the Agricultural Research Council (ARC) of Rhodesia and Nyasaland, Pereira visited 30 countries studying catchment management on behalf of the Council of the International Hydrological Decade. He returned to UK in 1969 as Director of East Malling Research Station, was elected a FRS and then, in 1972, Deputy Secretary and Chief Scientist of the Ministry of Agriculture and Forestry. He served on the Council of NERC 1971–1977 and chaired the Advisory Committee of the IH. A belief in the value of scientific hydrology and research institutes was brought back from the colonies to the mother country.

EARLY DAYS OF UK HYDROLOGICAL SCIENCE 1960–1965

Hydrological science had an unusual birth in the UK: government-funded science in a dedicated research institute preceded its development in the universities. A few universities were supporting hydrology and those that were had no funds for ambitious, long-term catchment studies. Whereas the 1963 Trend report on the organisation of Civil Science claimed that ‘Science in the universities is the ultimate foundation on which all scientific effort rests’ (Trend 1963, p 67), when the need for developing a co-ordinated hydrological approach to water resource assessment based on catchment studies was called for by a DSIR Committee on Hydrological Research in 1961, rather than choosing to invest in universities, the response was to set up a small Hydrological Research Unit (HRU) within its major Hydraulics Research Station.

In 1962, the HRU started with seven staff in Howbery Park, Wallingford, where Eamonn Nash (1927–2000), an Irish engineer, had set up a pioneering field experiment on a small clay catchment at Grendon Underwood in the headwaters of the River Ray in Buckinghamshire to explore the discharge hydrograph (Nash 1958; NERC/HRU 1968; Rodda & Robinson 2015, p 4).

INFLUENTIAL INDIVIDUALS WORKING WITHIN INSTITUTIONS TO PROMOTE AND GUIDE HYDROLOGICAL SCIENCE

The expansion of hydrology in the late 1960 s followed increased investment of public funds. This was a period of peak nationalisation of science in the UK. Two scientists were persuasive that hydrology was a science worthy of stimulus by Government: Penman and Pereira. They both came to hydrology by the application of physics to agriculture and paved the way for wider recognition of hydrology as a science.

Two younger men were greatly influenced by Penman and Pereira. Both Jim McCulloch (1928–2014) Head of the HRU and Director of the IH, 1964–1987) and John Monteith (1929–2012) FRS, NERC Hydrology Research Grants and Training Awards committee member 1968–1972, later Council Member, 1980–1984, graduated from Edinburgh University in physics in 1950 and 1951, respectively, inspired by the meteorologist James Paton. Later, both men completed Meteorology diplomas at Imperial College London and studied under Penman, at the Rothamsted Agricultural Research Station.

McCulloch, after completing his doctorate on soil water and temperature and 2 years of National Service as a Royal Air Force officer working on atomic weapons research, in 1955, he joined Pereira and colleagues in Muguga, Kenya, running catchment studies, researching an extension of Penman evaporation estimation to high altitudes in low latitudes, also the effect of shade trees in coffee plantations. Hydrological experimentation on changing land use in Kenya at that time was helped by the availability of land and plentiful cheap labour. By the mid-1960s, Kenyan independence curtailed positions held by Europeans but an expansion of hydrology in the UK in 1964 provided an opportunity for McCulloch to lead the HRU and later the IH, at Wallingford (Oliver 2015) .

As McCulloch left Rothamsted, Monteith arrived as a Scientific Officer. Penman's studies of the rate of evaporation from wet surfaces did not consider the complicating effects that vegetation imposed on water loss. Monteith, by harnessing the analogy of electrical resistance, showed how to account for surface conductance of water and later produced the Penman–Monteith equation that more accurately accounted for wind and surface effects (Monteith 1965; Dolman *et al.* 2014). After 17 years at Rothamsted, Monteith continued his hydrological (agricultural physics) career working in the University of Nottingham, which he felt gave him more freedom to develop his own ideas.

A fifth physicist, little known academically, helped the growth of hydrology within the NERC by advising on preparation of successful bids for funding during the crucial years when embryonic scientific hydrology was competing for support with well-established sciences, including oceanography and geology. This was Donald J. Maclean, known as Mac, Deputy Secretary of the NERC, in charge of scientific research from 1965 until his sudden death in 1970. In his previous career in the Road Research Laboratory, he researched soil compaction, ran small catchment studies and was very aware of the potential of hydrology to improve design of culverts and bridges. The 1970 IH Maclean Building was dedicated to his memory.

These five physicists proved influential in both the quantity and quality of hydrology funded after the expansion beginning in 1964. Engineers, geographers and geologists were also involved in hydrology but the interest of physicists in trying to find the basic causes of hydrological processes enhanced the status of hydrology as a science. Without a core of recognised hydrological scientists, the subsequent, rapid expansion of hydrology in the UK would have been unlikely.

Penman (Pereira 1962, p 127) expressed the scientific ambition which enthused each of these scientists. He wrote:

> *Among the earth sciences, hydrology is far behind the others in the evolution of a set of first principles. Too much of the textbook material is expressed in statistical relations unsupported by scientific reasons … and the conclusions drawn from the relations are frequently no more than opinions. These opinions are usually quite sound in their own context, but some of the attempts to extrapolate them to other environments have failed because elementary principles in meteorology, plant growth or soil science were unknown or ignored. Perhaps because of these failures there is a strong philosophy of despair among attitudes to catchment hydrology, expressed in the belief that every catchment is unique, and its problems must be solved on the spot, without importation of experience from outside, and with no hope of being able to export any newly acquired experience.*

He was convinced that hydrology can be treated as a science. From the start, Penman and his disciples had ambitions for research that went beyond ad hoc empirical answers to specific problems to discovering scientific principles.

THE MID-LATE 1960S: A FORMATIVE PERIOD IN UK HYDROLOGY

Funding by the government, directly or indirectly, was crucial to the growth of hydrology, alongside other environmental sciences, from the mid-1960s. This was a high point for nationalisation of the sciences in the UK. For the first time, hydrologists were supported in setting an innovative and synoptic agenda to seek the reasons for the occurrence of various phases of water, as a gas, liquid or solid and movement of water through the hydrological cycle. A major expansion of investment in hydrology was boosted by the formation of a non-departmental governmental body, the NERC, in 1965.

Funding of hydrology by this Research Council was governed by committees, with members appointed[3] rather than democratically-elected, supported by salaried staff. The Research Councils:

- increased investment of public funds in scientific personnel and research facilities by bidding to Central Government with convincing arguments,
- selected research topics,
- promoted an interdisciplinary approach,
- determined the scale and duration of field investigations,
- accounted for all expenditure and planned future budgets.

Research was supported both in research institutes, where staff had terms and conditions of employment on equivalent terms to the civil service, and in universities by means of research grants and training awards which supplemented the core funding of universities by the University Grants Committee (see Table 1).

Synchronously in the 1960s, governance of water resources progressed. The Water Resources Act 1963, created River Authorities for management of water resources regionally, and a Water Resources Board for planning the engineering of water on a national basis in England and Wales (McCulloch 2009). Increased funding was made available for hydrological measurements and simple catchment studies by River Authorities.

Table 1 | Hydrology and hydrogeology research support

Research institute	University
Long-term research and monitoring	Project-based, usually 3-year span; lack of continuity of lead scientists and assistants.
Large teams may tackle ambitious projects. Team spirit	Critically dependent on individuals working with one or two research assistants or students with little experience: Difficult to build teams.
Branding attracts outside funders. Reputation for reliability and customer care from team-based pools of expertise.	Communication with customers often difficult, Continuity often affected by staff movements.
Prepared to advise government, often at short notice.	More difficult for government to locate expertise.
Individual scientists confined to imposed research programme may dampen innovation	More freedom to develop own ideas and to respond quickly to new research opportunities.
Good for promoting inter-disciplinarity with staff on same site.	Staff recruited according to teaching requirements. Often little collaboration with other departments in the university.
Most staff full-time	Staff with teaching responsibilities may only research part-time.
Publications may be dominated by internal reports, reports for clients	Open publication in peer-reviewed journals the norm
Staff may become too comfortable and immobile.	Continual supply of young recruits. Staff mobility between research and teaching
Expensive for a Research Council which bears all staff costs, including pensions.	Research costs shared with university. Core funding by the University Grants Commission, research councils only pay supplementary costs

Arguments over the best investment of NERC funds whether in a research institute or in a university under discussion in the late 1960 s, recalled by the author.

[3] The method of private soundings, recommendations by officers and ratification by Council was traditional.

THE NERC AND THE EXPANSION OF HYDROLOGY 1965–1973

The 1965 Science and Technology Act proposed two new Research Councils and continuation of two existing Research Councils. The Science Research Council and the Natural Environment Research Council were new. The Nature Conservancy was incorporated within the NERC and both the ARC and the Medical Research Council were continued. The Research Councils bid for funding from the Department of Education and Science but were allowed some autonomy from central government, guided by a belief that science was best guided by other scientists. The environmental sciences earned their own Research Council because of their neglect under the previous funding body, the DSIR. Rather than being under direct rule of a government department, each Research Council was made up of learned people invited to serve, without additional remuneration apart from expenses and, sometimes, attendance allowances.

Hydrology as a subject was fortunate to be assigned to the newly-created NERC. This allowed development of hydrology as a science rather than being tied directly to utilitarian ends demanding quick approximations. Had hydrology been linked to engineering and come under the remit of the Science Research Council (later named the Science and Engineering Research Council) or the ARC, the chance of gaining so much support would have been much less, making it unlikely that a new research institute dedicated to hydrology would have been set up. A further option would have been to fund hydrology outside the Science budget as part of the work of the Water Resources Board. Each of these options would have guided British hydrology in different ways, perhaps allowing only an incomplete study of the whole hydrological cycle or with less emphasis on studies requiring long-term data collection.

Hydrology within the NERC might have been allocated to the established research institutes which it had incorporated, such as the Geological Survey later named the Institute of Geological Sciences (IGS) or the Nature Conservancy, which would have limited the remit of the subject.

Instead, hydrology was recognised as one of the founding subjects of a Research Council anxious to promote embryonic environmental sciences. At its First Meeting in June 1965, the Council decided to develop the small HRU with seven (1965) staff into a multi-disciplinary research IH aiming for a staff complement of 95 by 1971, to work in association with an expanded Hydrogeological Department of the IGS with a target of 36 staff.

Competing for funding in a Research Council arena meant that priority needed to be given to scientific hydrology. Support of physicists awarded prestigious Fellowships of the Royal Society (FRS) was influential. With hydrology's scientific credentials validated, one of the first and most important decisions of the NERC was to set up a Hydrology Committee to oversee hydrology and the foundation of a new research institute, with a sub-committee on Hydrology Research Grants and Training Awards to encourage expansion of hydrology within the universities.

The first Chairman of the Hydrology Committee was Norman Rowntree (later Sir Norman) the Director of the newly-formed Water Resources Board, which had a research programme of its own on resource development. Up to 26 members, all men: Water Resources Board (2); MHLG (1); Ministry of Agriculture Fisheries and Food (1); Scottish Development Department (1); Ministry of Development Northern Ireland (1); Meteorological Office (1); Cabinet Office (1); HRU (2); Geological Survey (1); Water Pollution Research Laboratory (1); ARC (1); Nature Conservancy (1); Water Research Association (1); Freshwater Biological Association (1); Royal Society (1); Universities (1); Institution of Civil Engineers (1); Institution of Water Engineers (1), plus a secretariat of five men, deliberated on how to encourage and co-ordinate hydrology research. Note the long list of organisations wishing to have a say in agendas for hydrology and the small representation of universities. The budget allocation for 1965/66 was £57,100 with £44,000 of this allocated to HRU, the rest for universities.

At the first meeting of the Hydrology Committee, a paper written by the Head of HRU, Jim McCulloch, revealed an aim of finding and instrumenting two hydrologically-identical catchments, then modifying the land use on one of the pair:

> *the real hope is that by putting in good enough ideas and equipment it may be possible to account completely for the hydrological behaviour of catchments elsewhere …. the gauging would be continued until the amount of new information becomes so small as to be valueless, which may be* ***two or three decades after the start of the experiment****. (Hydrology Committee First Meeting) (Author's emphasis)*

Such ambitious, long-term research, with delayed payback, required commitment of funding for more than the usual 3 or 4 years for project funding in universities. The attempt to 'account completely' for hydrological behaviour in catchments also required development of more accurate instruments. These two types of research, large-scale field experimentation together with development of the tools of the science, aimed to produce outcomes to further the science generally. The expense and length of such projects were unlikely to appeal to a single customer or beneficiary. For both activities, a research institute appeared to be the most suitable environment. The considerations governing whether investment in hydrological science should be directed towards a research institute or to universities are shown in Table 1.

HYDROLOGY COMMITTEE INFLUENCES THE RESEARCH AGENDA OF THE IH

The agenda papers reveal boundary disputes between the many organisations represented on the Hydrology Committee. Overlap of research was frowned upon and territorial claims affected the scope of the IH, particularly in the early years. These territorial disputes are problematic in a subject like hydrology because the connectivity of all phases of the hydrological cycle lay at its heart. Territoriality resulted in awkward decisions: IH was not allowed to invest in water chemistry laboratories in the first 5 years because of fears of overlap with the Water Pollution Research Laboratory; hydrogeology was deemed to be the province of the IGS and only a limited programme of groundwater hydrology was allowed at the IH. Collaboration with the Soil Survey was impeded by its control by the ARC rather than the NERC.

As well as responsibility for IH, the Hydrology Committee invested funds in the universities to promote hydrology. Sometimes. instead of reinforcing agenda boundaries, the Committee brokered collaborations such as over the study of evapotranspiration. This was funded by seconding staff from the Meteorological Office to IH. Also, the Committee endorsed research collaboration with Professor Jack Rutter of the Department of Botany at Imperial College and other linkages between university research and the work of the research institute.

GROWTH OF THE IH

The rapid expansion of the HRU into the IH had several effects: the recruitment of many, mostly young, people to the Institute gave each an unusual degree of responsibility for their research. People from a variety of backgrounds in physics, mathematics, engineering, geography, and geology were brought together in teams. This allowed innovation and new approaches to problem solving. Jim McCulloch was inspired to write:

> *One of the features of the Hydrological Research Unit is the way in which specialists in different disciplines collaborate in a joint project or in solving a difficult problem which lies within the purview of another section. It is a pleasure to record the amount of cross benefit which has accrued to the Unit as a whole because of the willingness of staff to co-operate in this way. (McCulloch et al. 1968)*

Jim McCulloch reduced the potential disbenefits of a research institute as listed in Table 1 by encouraging staff to undertake applied work as consultants for short periods to extend their skills and to bring in extra funding to the Institute; conferences were organised; overseas visitors were offered facilities; post-graduate students came to study; collaborations were arranged with Universities and some staff were seconded overseas for continuing catchment research in Kenya and for contract research in various parts of the world. A new purpose-built building, officially opened in 1971, won a prize for its design, which provided comfortable accommodation, laboratories, workshops, library and conference facilities.

One downside to this rapid formation was a need for many committee meetings to gain approval of research agendas, to develop collaborations, disseminate research findings and to account for financial expenditure. The Head/Director chaired or was a member of at least five NERC committees or sub-committees, represented the UK on several IHD meetings, recruitment boards and negotiations with potential customers. In addition, lengthy negotiations with the architects of the new building were necessary because the new Research Council had not yet developed the administrative backup later considered essential to relieve scientists of many managerial tasks.

SUPPORT FOR HYDROLOGY IN UNIVERSITIES 1965–1973

The investment of most funds for hydrology in IH provoked criticism. Several editorials were published in the magazine Nature: Anon (1969a, 1969b) reports the House of Commons Select Committee on Science and Technology as ‘particularly exercised by the problems of university hydrology’; Anon (1970) criticises the small proportion of NERC funds (around 15%) invested in universities. Ray Beverton, the Secretary of the NERC, defended its position explaining that the Research Councils only paid part of the cost of university projects while research in institutes was wholly-funded, also the NERC budget included very expensive research vessels (Beverton 1970).

However, investment in the universities was not straightforward. Research in universities by staff with teaching responsibilities meant that there were no teams of researchers able to undertake synoptic, long-term, multi-disciplinary catchment studies like those being set up by the IH. Instead, 2- to 4-year, project funding was the norm.

RESEARCH GRANTS

Within the NERC, university research grant applications were considered by a sub-committee of the Hydrology Committee, the Research Grants and Training Awards Committee. First, chaired by Norman Rowntree then succeeded by Professor Peter Wolf. In anticipation of a large demand for funds, this Committee decided on a selective approach: only 40% of the funds sought should be granted. But the response from universities was disappointing. At its First Meeting, only four applications were considered. At the Second Meeting, there was only one application, and this was rejected! The following year, the Committee decided that it would need to be pro-active in attracting universities to make more applications: 'the Committee might suggest to universities the kind of investigation for which grant applications would be welcomed' (Hydrology Research Grants and Training Awards Committee 2 May 1966).

While investment in HRU/IH grew by 49% from £57,000 in 1965/66 to £86,000 in 1966/67 by attracting not only funding from the NERC but also payment for consultancy work, the university hydrologists, in Penman's words 'the part-time amateurs' as opposed to the 'full-time professionals' in the research institutes, received relatively little.

Impatience with the expensive and slow progress of field observations and talk of answers to be reached in decades rather than in years led Council to hope that physical modelling would lead to speedier understanding of hydrological relationships. At the time, mainframe computing time was scarce, slow, and extraordinarily expensive. Hydrologists ran up bills of thousands of pounds in computing time. Punched cards and data logging tapes were in use. In 1968, the IH reported 'Cards and paper tapes have been punched for all data recorded on the catchments, 50,000 cards and 90,000 feet of paper tape! (AT3/55 Report IH NERC/H68/2(5) p 14–15)'. Computing was at a too early stage of development to enable complex catchment models.

Council members agitated for more rapid progress in hydrology. If computer models were not yet attainable, surely the experimental methods of physical scientists could be adapted to hydrology? Council became pro-active. To redress the balance between investment in the research institute, IH, and the universities and in hope of a breakthrough in hydrology, a leading university was invited to apply for a laboratory experiment in hydrology in 1967. Its Civil Engineering Department rose to the occasion and applied for a huge, unprecedented amount £76,758 (£1.3 m in today's money) over 4 years. This was by far the largest grant ever awarded by the NERC at that time. To give an idea of its size, the other grants awarded by the Hydrology Research Grants and Training Awards Committee 1968–1969 were £675 supplement to £5,354 to Dr E. White, Zoology, University of Liverpool to study the 'Physical, chemical and biological consequences of impounding water'; £10,000 over 3 years to Professor J.L. Monteith, School of Agriculture, University of Nottingham, for 'Evaporation from a catchment in relation to climate and plant cover', and to Dr K. Smith, Geography, University of Durham 'Thermal characteristics and related low flow hydrology of upland catchments' £3,240 over 2.5 years.

The laboratory project promised rapid progress in understanding hydrological relationships without the slow messiness of field studies. Laboratory experiments with accurate measurements appeared to be more rigorous and deserving of investment. The application met with 'very strong support' from the Hydrology Research Grants and Training Awards Committee.

A large experimental catchment, with a 'raised reinforced concrete tank measuring 36 ft (11.0 m) by 23 ft (7.0 m) by 5 ft (1.5 m) deep' was constructed with the topography of river catchments shaped in concrete and with water sprays from the ceiling to simulate rainfall.

> *A pattern of 16 pipes cast into the sides of the tank and 96 drains in the floor will permit the control of groundwater flows once a permeable medium has been introduced, and the control of channel flow for special studies of 'sub-catchments'. (Hall & Wolf 1967)*

When the experimental laboratory was completed, the Hydrology Research Grants and Training Awards Committee sent a Visiting Group led by Penman to inspect. This was a disaster! Some of the rainfall sprays failed to operate and worst of all, the

Visiting Group could not be convinced that scaling effects could be overcome. The conclusion was that the laboratory experiment would not produce results which had any relevance to natural catchments. The visitors recommended that the experiment be wound up immediately. This major investment resulted in training for one research assistant, who was awarded a doctorate for his work on designing rainfall nozzles.

With this problematic shortcut route to hydrological prediction of rainfall/runoff relationships abandoned by the NERC, the expansion of hydrology continued with further investment in the IH and more, but smaller, research grants to universities. Investment in the IH had a snowball effect: recognition of its ability to recruit and support a significant team and its prowess in multi-disciplinary hydrology led to award of a major grant for Flood Studies, as promoted by the Institution of Civil Engineers.

TRAINING AWARDS

Hydrology teaching was extended in universities and by 1965, new advanced courses, all set in civil engineering or geology departments, were launched at the Universities of Birmingham, Newcastle and University College London, and the Engineering Hydrology course at Imperial College was revived. An increase in advanced course and research studentships, and Research Assistants produced rapid growth in trained hydrologists and hydrogeologists[4]. NERC recognition of an advanced course was important for a course's accreditation and prestige and students with other funding, including many from overseas, were attracted to these courses Table 2.

SUSPICION OF GEOGRAPHY

The NERC aimed to tackle environmental problems which demanded work in the field and measurements of natural phenomena under difficult and variable conditions. Other factors could not be kept equal while one factor was changed as could be done within a laboratory experiment. In hydrology, weather and climatic variability, variations in soils and geology and in vegetation compounded the difficulties. The scale of the phenomena was great, making extrapolations and generalisations difficult. Few catchments, if any, were in a natural state and the effect of human intervention, historic and contemporary, had to be considered. The challenge of field work and the interplay of landscape and humanity appealed to geographers trained with some knowledge of geology, soil science, climatology, biogeography, agriculture and forestry.

Despite these methodological challenges which demanded multi-disciplinary approaches, for which physical geographers appeared suited, physicists and engineers with training in higher mathematics suspected that geographers' knowledge was superficial. A quota limit was placed on the number of studentships which could be awarded to Geography Departments. Yet there was a quandary, geographers had enthusiasm and the numbers needed for the expansion in hydrology desired by Council. Indeed, two of the four hydrologists staffing the HRU at its inception came from a geographical background, Dr John Sutcliffe and Dr John Rodda, and had proved their ability to contribute to hydrology. When hydrological projects

Table 2 | NERC funding of post-graduate training of hydrologists in universities

		Awards	
University department	**Advanced MSc course**	**1965**	**1973**
Birmingham Civil Engineering	Water Resources Technology	2	9
Birmingham Geological Sciences	Hydrogeology	2	5
Imperial College Civil Engineering	Engineering hydrology	2	4
University College London Geology	Hydrology and groundwater resources	2	2
Newcastle Civil Engineering	Engineering Hydrology	0	7
Newcastle Civil Engineering	Water Resources	0	1
Total		8	28

Note an absence of advanced courses in departments of Geography.

[4] By 2013, the number of 'career hydrologists' has been estimated as 'about 2,000' (Rodda & Robinson 2015 p 5).

were surveyed in 1967, university geography departments reported as many projects as did civil engineering departments and twice as many as those reported from natural science departments. (McCulloch 1970). A textbook on hydrology had been written by a geographer Ward (1967) and significant publications were authored by geographers: for example, Kirkby 1969; Weyman (1970); Smith (1965).

In 1970, Council invited leading physical geographers from universities to make presentations on their work, to stimulate discussion of their methods and the potential of their training for furtherance of environmental science. In the subsequent discussion, the geographers were told that their students should be provided with 'adequate specialist training'. 'Complicated mathematics' was needed for meteorology, for example. The focus of environmental science should be on quantitative understanding of physical and dynamic mechanisms. While the training of geographers might be useful for 'synoptic studies interpreting measurements in a regional context', preference would be given to those with specialist training. This NERC judgement had a lasting effect on geography, encouraging physical geography to become increasingly quantitative, specialised and separated from human geography, a trend which was already happening in the United States. For hydrology, a wider agenda, less physics/engineering-based, was now deemed suitable to be considered for funding. A further result was that a geographer, Professor Keith Clayton, was appointed to serve on the Council.

LORD ROTHSCHILD'S REPORT 1971 THREATENS BASIC RESEARCH

The freedom of the NERC to define scientific hydrology for study at IH was threatened by the Rothschild report 1971 (Rothschild 1971). This was written in very blunt terms:

a major part of the NERC is applied. But this work had and has no customer to commission and approve it. This is wrong. However distinguished, intelligent, and practical scientists may be, they cannot be so well qualified to decide what the needs of the nation are, and their priorities, as those responsible for ensuring that those needs are met. This is why applied R&D must have a customer. (Rothschild 1971, p 4)

Even though the priorities for the IH had been set largely as fundamental scientific research, there was a danger that the whole of hydrology would be classified as applied with aims set by users. Also, in the appendix, there was an even more disappointing recommendation:

Exceptionally the Institute of Hydrology should be physically transferred, together with its staff, to the Department of the Environment, where it should be fused with the Department of the Environment's contiguous Hydraulics Research Station. (Rothschild 1971, p 22)

This would mean loss of status of hydrology as an environmental science, distance from the links forged within the NERC and a narrow remit dominated by engineers and focused on providing ready answers for customers.

The IH Director, Jim McCulloch, protested:

Hydrology is a science that has been applied before the scientific principles have been fully understood. Solutions to particular problems have been given without a basic knowledge of the functioning of the hydrological process involved and with only a qualitative understanding of the operation of hydrological systems. Fundamental problems have been bypassed in favour of assumptions that are adequate as design criteria only if a large enough margin of error can be tolerated …. To answer (basic questions) is the only way to improve the methods fundamental to applied hydrology, such as water resource studies or the design of hydraulic structures on which civilisation depends. (McCulloch 1972a)

Notwithstanding the Rothschild report, hydrology is as much an environmental science as oceanography and geology. (McCulloch 1972b)

This was a time when friends in high places were needed. How discussions behind the scenes progressed will never be known but having three hydrologists wedded to scientific hydrology in the Royal Society (Penman, Pereira and Monteith) and Pereira newly-appointed as Chief Scientist in the Ministry of Agriculture, Fisheries and Food must have made a difference. Another factor which stood the IH in good favour was that consultancy work and outreach to users had been part of the agenda of the research institute from its beginning.

The recommendation in the Rothschild report about transferring the IH was dropped. Scientific hydrology continued to have a focus of expertise in the research institute for both fundamental and applied research, albeit with greater input into the research agenda from Government Departments.

CONCLUSIONS

Examination of a formative period in the growth of hydrology during the 1960s and early 1970s in the UK has demonstrated the influence of a network of scientists determined to foster investigations into the causes of hydrological phenomena. Working through government-funded institutions, mainly the NERC, these enthusiastic scientists influenced the research agenda and persuaded the UK Treasury to make significant investments.

Progress was not a simple trajectory. Successes included a dedicated research institute; increased funding for university research and training; agendas led by hydrologists as well as by users; recognition of the value of field measurements; improved instrumentation; long-term catchment studies funded (Robinson *et al.* 2013); growth of inter-disciplinarity between engineers, physicists, geologists, geographers and botanists and greater participation of the UK in international science.

Mistakes were made in trying to accelerate the science through investment in a laboratory catchment. Agendas were negatively influenced by territorial disputes between institutions limiting some investigations, especially delaying study of water chemistry as integral to hydrology. A lack of diversity among the membership of funding committees at first constrained investment in some aspects of hydrology but a presentation by leading geographers resulted in a broadening of the hydrological agenda. The Rothschild report threatened a return of the IH to pre-1965 funding by users but advocacy by scientists retained the position of hydrology within the NERC.

While history never repeats itself, the successes and failures experienced during this period do have resonance today: the problem of 'weighing ideas in gold'[5] remains a challenge. Also, provision of environments conducive to stimulating creativity and to foster progress in hydrology is still a matter of debate.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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[5] A pithy aphorism used by Penman to describe the hard task of committees choosing which research ideas to support.

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