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## A view from the watershed

### Institute of Hydrology Report No. 20, June 1973

On 9th May 1973, the Institute of Hydrology arranged a one-day Symposium to mark the opening of the Institute's new building, named after the late D J Maclean, Deputy Secretary of the Natural Environment Research Council from 1965-1971. The Symposium followed a short opening ceremony performed by Lord Jellicoe, the Lord Privy Seal.

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### The catchment area of the Institute: the achievement and future research plans for the Institute

H.L. Penman, FRS  
Chairman, IH Advisory Committee

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Happily, we are here today still as a unit of the Natural Environment Research Council, and can start the hydrological cycle in another NERC unit — the National Institute of Oceanography. NIO has some concern with ocean/atmosphere exchanges, and particularly with the mammoth world-wide distillation process that produces all the world's fresh water (and no charge for the energy needed). It always seems a bit odd to me that desalination should be considered as an alternative way of getting fresh water: what other way is there?

At this stage we have to hand over to the Meteorological Office, to get the water up into the atmosphere, to move the atmosphere round, and then to re-precipitate the water. The erratic elements in this, both in time and space, are, of course, the sources of most of our water problems, but with at least one compensation. Most of the water falls where some trapping device can hold it at maximum potential energy, for later release either as a resource for use, or as a method of river regulation. It can be a matter for debate as to how far we should want any degree of control over the erratic income, but all, I'm sure, will want to stop a long way short of putting the Director-General of the Meteorological Office in the position of Elijah and being able to say: "There shall not be dew nor rain these years, but according to my word".

Having delivered the goods the meteorologist could say "There, I've done my job: the rest is up to you, to answer the What, How and Why questions in the later history of the water". This, though it would be a very foolish arrangement, could work; for British hydrology *could* get along — somehow — with no more from the Meteorological Office than information about rainfall, and, in fact, it is not such a long time ago since this was almost the situation in Britain. The very much better position we are in to-day was reached partly because

meteorologists, both inside and outside the Office, showed a willingness to help in the study of what happens to the rain, and partly because the hydrologists — as scientists and as engineers — were willing to invite and encourage this interest, and even to do some homework to understand the principles on which meteorological expertise is based. But please note the order here. Meteorology is part of hydrology, and this new building that will formally come into existence later to-day is a solid demonstration of public recognition — governmental and non-governmental — that hydrology is now an independent science, taking its place within the geophysical sciences that include oceanography, meteorology and geology.

How has this come about? There was a time when, I suspect, the only committee in this country that called itself a 'Hydrology Committee' was that of the Royal Society, as a sub-committee of the British National Committee of the International Union of Geodesy and Geophysics. I think I am correct in suggesting that it was this committee that started to haul British hydrology out of the appalling depression that it had got into about 1952, and in the course of the next ten years all sorts of people began to show interest and, in varied groupings, started to look at national water problems. In all, they were drawn from professional engineers concerned with rivers, water supply and land drainage; Government Departments; Research Councils; the Meteorological Office; Research Units; Research Associations; Universities; Learned Societies; and Professional Institutions. There was a lot of talk, of course, but out of it there emerged a clear conviction that to ensure rational management of Britain's water resources some 20 or more years ahead there was immediate need of new research effort into the scientific aspects of the hydrological cycle in Britain. Eventually this was approved by Government — in parallel with other activity that led to the setting up of the Water Resources Board — and what started as a small Hydrological Research Unit within DSIR (with Professor Nash as its first Head) became the Institute of Hydrology within NERC, but still on the site provided by DSIR alongside the Hydraulics Research Station, and only as tenants in somewhat makeshift accommodation. Now — today — the Institute has a home of its own and, speaking from the outside, I can see nothing to deplore in the fact that the geographical translation is very short. I'm sure that both the Institute and the Research Station will benefit from being close neighbours.

Before looking at what the Institute is expected to do, it is desirable to see what the Unit was expected to do when it was set up. For this purpose I'd like to read most of a two-page document I prepared ten years ago: at the end I'll put it into context in explaining why I indulge in self-quotation at such length. It is headed *Hydrological Research in Britain*.

#### HYDROLOGICAL RESEARCH IN BRITAIN

Almost every nation in the world is concerned about its water resources, and Britain is no exception. Within recent years the Central Advisory Water Committee has surveyed the resources, and probable future needs for domestic use, for industry and for agriculture. Over the country as a whole there is no danger yet, but the warning light is there to suggest that now is the time to study how best to manage our catchment areas to produce the optimum water harvest. The optimum is not necessarily the maximum, and is very unlikely to be, because water yield must be considered in relation to other factors such as water quality, flood control, erosion control, economic value of crops grown in the catchment, amenity and so on.

Behind this problem of catchment management there is a wide variety of technical problems associated with rainfall measurement, stream gauging and deep percolation, among others, but all of these have somebody or some research organisation working on them. Until very recently, however, the biggest problem of all was nobody's business. Put briefly it is: *If the existing vegetation on a catchment is replaced by another type, how will the water balance of the catchment be affected?* At the moment there is no agreement on the kind of answer to be given, because there are major differences in ideas among those who would reason their way to an answer, and major conflicts in the field evidence from experiments in other countries. The problem is too important to be left unresolved, and hence one of the first objectives of the Hydrology Research Committee, set up under DSIR, has been to bring into being a Research Unit to work on the problem.

Guided by a Steering Group appointed by the Research Committee, the philosophy of the Unit can be summarised as follows. We need two 'identical' catchments side by side, C and M say. After a few years of gauging to make sure that they are equivalent hydrologically, the vegetation on one, M, will be modified, and the gauging will 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. At the very least, and it is a pessimistic minimum, some of the empirical information about any differences between C and M should be applicable to other British catchments in similar climates. But the real hope is that by putting in good equipment it may be possible to account completely for the behaviour of each of the catchments individually, for periods that may range from an hour to a year or more. Success at this level would make it possible to predict the hydrological behaviour of catchments elsewhere, given relevant information about geology, soil and plant cover, and weather (and any other factors that working experience may show to be important). For the first attempt it was decided that the contrast should be between forest and grassland, for two reasons. First, this is the

most common source of clashes of opinion on catchment management; and second, in the light of current ideas, it is the contrast most likely to reveal any differences of behaviour.

Reconnaissance parties have tried to locate suitable catchments and soon found that there were few sites that satisfied the *technical* specification (social problems follow). Briefly, the catchments had to be accessible, but not popular public playgrounds: they had to be reasonably representative of upland catchments: they had to be free from topographic features that would make adequate rain gauging impossible: the climate must be such that at least once in ten years there should be a dry summer: the soil and climate must be suitable for proper growth of trees: and, very important, the catchments must be water-tight, or at least not suspect.

The social problem is simply stated. Wherever the Unit works — as guest, as tenant, or as owner — it wants the approval and, where possible, the co-operation of local interest and particularly of those who have a jealous concern for the preservation of natural beauty and amenity. Although the experiment may alter it will not mar the beauty of the countryside, and apart from some necessary protection of instruments at ground level, it need not affect amenity value and access.

The Government seems to be willing to spend a fair amount of taxpayer's money over a long period, in the belief that the experiment will help to improve the efficiency of use of upland catchment areas throughout the country, i.e. the experiment will become a national scientific asset.

The reconnaissance parties I've referred to spent a lot of time before they found a suitable site and, with very valuable help from the Nature Conservancy, got a long way on with problems of getting access to the site. By December 1962 matters had got to the stage at which a party from the Unit's Steering Group went to meet a representative delegation of the local Conservation Trust, a meeting at which I was pushed into the chair and in which we discussed in full the implications of the proposed experiment. It was a very friendly discussion, and very successful, for the Trust representatives became as enthusiastic about the experiment as we were: but there was a sting in the tail. The whole Trust had to be satisfied, and please would the Chairman supply them with a short paper setting out what was behind the proposals scientifically? My heartless companions thought this an excellent idea, so I did my best, and the result was what I have just read to you. It cannot have been too bad, because some weeks later the full Conservation Trust not only welcomed the idea but offered collaboration too. Then, for the most stupid of reasons, the whole thing collapsed on the verge of success, and the Hydrological Research Unit had to start all over again to find a site and get access to it. The choice was Plynlimon, and though this has its story of problems in getting access, it is not my story. Enough that it was achieved, and successive Annual Reports have shown the developments in this the primary task of the Unit (and now of the Institute).

Now I come back to what the Institute is expected to do. Here I think it relevant to note that between the Green and White Papers on "Framework for Government Research and Development" the only significant change anywhere concerned

the future of the Institute. Paragraph 57 of the White Paper reads:

“There will be no change in the status of the Institute of Hydrology within the Natural Environment Research Council, though some applied research may in future be funded by Customer Departments. When final decisions have been taken on future arrangements for the management of the country’s water resources, it will be necessary to work out a comprehensive research programme, taking account of the whole capability in this area of which the Institute is an important part”.

I am not in serious dissent with any of this, but a comprehensive programme already exists, and many of you here spent a lot of time in thrashing it out. Dr. McCulloch, limited then in both staff and facilities, took as much as he dared into his five year programme for 1966 onward, not without some trepidation, as he states in his most recent annual report. I will not join Mark Anthony in asserting that ambition is ‘a grievous fault’ but will say that, in a research unit, timidity is. I hope there will be very little timid thinking in this new building.

Staying with the White Paper, one very important aspect of the decision is that the work of the Institute is recognised as being of Research Council type. I won’t waste time here by explaining in detail what I mean by that — there will be a hint later, and most of you know, anyway — but will make the shortest possible statement about what I consider the Institute’s job is. It is not intended to be exclusive in any way.

The task of the Institute is to seek knowledge and understanding of the hydrological cycle in ways that will lead to safer exploitation, more reliable prediction and more effective control of water and water resources.

In discussion you may wish to add to my three outlets — please do so — but as I am sure that no-one wants any of the three removed, I move to a little discussion of the inlets. ‘Knowledge’ and ‘Understanding’. Except to be deliberately and unnecessarily provocative no-one will deny that both are needed, but there can be, and are, reasonable differences of opinion about which is the more important. In terms of your two speakers this morning I think Professor Nash would cheerfully assert that he is a ‘Knowledge’ man: I, equally cheerfully, assert that I am an ‘Understanding’ man, fortified in this, first by Leonardo’s dictum that “When you know the reason, you have no need of the relation”, and second by the fact that I know it works. Leonardo, of course, needs a bit of qualification: a vague idea of the relation in advance often helps toward identification of a reason: some knowledge of a reason or reasons can be very helpful in deciding how a relation should be sought, how it can be checked, and how it can be applied in a field situation. Here, for a while, I would like to digress, to comment on “how it can be checked”. Coming as I do from Rothamsted, I am not unaware of the great contribution statistics has made to agricultural research and farming practice — R.A. Fisher started it at Rothamsted — but there are two aspects of statistical statements, not equally attractive to me. The first is little better than soothsaying, in the spirit of the casino and the racecourse, but using slightly more elegant

language: the second is scientific when — dare I say only when? — the statement can be checked by experiment or observation. Ignoring possible absurdity in the numbers I use, here are two statements. First, as soothsaying. “With a probability of 1 in 100,000 there will be  $k$  or more inches of rain here tomorrow”. Second, as science “On at least one day in the next 30 years there will be  $k$  or more inches of rain here”. This second statement can be checked: the first cannot. At the moment there is no weather service in the world able to make absolute forecasts and, very rightly, they refuse to do so, but it is worth noting in passing that our own Meteorological Office is getting close to it for tomorrow’s rainfall — one of the most exciting breaks-through there has ever been in meteorology. Today, however, there are many, in this audience and elsewhere, who have to be their own soothsayers, making decisions today against the contingencies of tomorrow.

How far ahead is tomorrow? I hope that you, Mr. Chairman, might allow a little time for discussion of this point, always important, and doubly so at present in the middle of the Doomsday debate. It would help the Institute to have your opinion, and that of others, on the sort of time scale needed in creative forward thinking about water problems. More than 10 years — yes. Less than 1000 years — yes. But where in between? The longer the time scale the more relevant it becomes to the work of the Institute, but there will always be short-term bread-and-butter problems from those who have to handle water, in or out of control. As the already considerable expertise of the Institute in this sort of job grows, I wonder if we can dream ahead to a National Hydrological Advisory Service that would compound the work of the Institute, the Water Research Association, the Water Pollution Research Laboratory, the Meteorological Office and the Hydraulics Research Station? Agriculture has had one for a long time and it has earned its keep. Why not something similar for water?

Waking up, and ending the digression, most of the problems past, present and future take one of two forms. Knowing the facts as they are now, what will the facts be some (specified) time ahead: (a) if I do nothing; or (b) if I do something, possibly with a range of options in what I might do? In the history of hydrology the use of the mathematical model has had a long and not unsuccessful history, mainly in the first form, in trying to extrapolate into the future the experience of the past, hopefully assuming that the boundary conditions governing the behaviour of the system will remain unchanged. For a wide range of problems ‘hope’ is no more than good sense, because it must be assumed that climate, geology (surface and solid) and geomorphology will be the same, and that a mathematical model will work without any major injection of physics. Those of us who have had recent contact with international discussions of problems shared by the world have found that priorities seem to settle round flood problems, and the interaction of human activity and the hydrological cycle. Flood studies almost inevitably fit into my (a) group, and I have no doubt that the report of the Institute’s Flood Study Group, due next year, will be an impeccable display of first class statistical analysis, matching the skill and enthusiasm that has been put into the job, stimulated by Mr. Nixon as Chairman of the Steering Group. But inside the report, I optimistically hope to find that some parts are simpler, more precise and more accurate because a little physics has been squeezed in to guide the method of

analysis. We will see.

In contrast, the physical model is relatively new and it is still fighting for some sort of general recognition. One of the first to use it as a basis for thinking about and designing catchment experiments is Dr Pereira, who will be talking to us this afternoon. He set up catchment experiments in East Africa to measure the effects of contrasting land use on water supplies, soil stability and so on (with a strong element of social science thrown in). Dr McCulloch was a colleague in this work, and they based their experimental design — what to measure, how to measure it, and where, and when — on what they then knew of the relevant physics of the atmosphere, of the trees and other crops, and of the soil. When Dr Pereira moved further south in Africa, Dr McCulloch took over direction of the experiments, and continued to do so until he was appointed to his present post. So, to some extent, the history of the Institute has a start in darkest Africa, with a Director who has the wet feet and dirty hands experience in the kind of work that the original unit was set up to do. The experiments he left behind would fit easily into my specification of what I have called ‘Research Council’ activity: within about *J* years enough reliable scientific information had emerged to permit clear answers to the initial technical problems posed about the sites of the experiments, and policy decisions about future management could be taken confidently. But there was much more to it than just this possibility of exploiting local experience to meet local needs. The way in which the job was done — and continues to be done — taught the rest of the world a lot about how to do good catchment experiments, and put some valuable new ideas and information into the world pool. It is very gratifying to know that in spite of political changes in East Africa the Institute is still very closely associated with these catchment experiments and is helping to run them in co-operation with the East African Agricultural and Forestry Research Organisation. It is part of the Institute’s achievement that it prevented the collapse of the African work, and on two of the catchments has been able to improve on already good measurement techniques. Most of us would welcome this simply as a demonstration of desirable British aid to developing countries, but the taxpayer gets a very good return too. In the modelling of hydrological processes — whether it be physical or mathematical — it is invaluable to have available reliable records from widely different climates and for soils carrying very different vegetation. When the reliability from Central Wales matches that from Equatorial Africa, McCulloch’s modellers will have a grand time. I envy them.

A moment ago, I said “When”. From a start in 1967, Dr. McCulloch was able to report that the basic instrument network was completed in 1970, but quality control on the first results showed shortcomings, and the work in 1971 was necessarily concerned with tracking down the sources of uncertainty, diagnosing causes, and attempting cures. Most of us know this sort of thing as an occupational hazard in field work, and don’t fret about it. However, not all the work is affected by these particular uncertainties, and there is excitement in the discoveries made about the nature of the surface and sub-surface flow whereby water reaches the streams. To have had this sort of information over 20 years ago could have helped a Technical Panel in its task of advising the Central Advisory Water Committee on whether river floods are made more severe or

more frequent because of the extension of land drainage. There are two or three in the audience who were members of the Panel, and I think they will agree that the 20 pages of report boiled down to: “We don’t know, the available evidence is conflicting, and some good experiments are needed”. I hope that when the Institute’s knowledge of the hydraulics of the natural drainage process is more complete that it might be possible to tuck in an experiment on the effect of moorland gripping, or some other form of unnatural drainage. To me, this would be in keeping with the Director’s statement that he wants the catchments to serve as outdoor laboratories for a number of projects, each designed to investigate a certain phase of the hydrological cycle.

So far, the story of Plynlimon is prologue and the main tale is just starting. As it unfolds one important set of observations may turn out to be very significant. Among the necessary auxiliary weather records taken, there is a measure of solar radiation, and I have been astonished to discover that monthly and annual totals on Plynlimon differ very little from those at Wallingford. We know that energy income is a dominant component in determining the evaporation term in the water balance, and it may well turn out that Plynlimon rates will not be very much less than those at Wallingford.

Whatever comes out of the measured contrasts between the grass Wye catchment and the forest Severn catchment will need interpretation in terms of ideas that cannot possibly be explored — in measurements — sufficiently intensively on the two sites. So the other major enterprise of the Institute, in Thetford Forest, is in some ways a complement to the catchment work (including sites other than Plynlimon), but it stands as good and desirable in its own right. However, maintaining the unnecessary link for ease in presentation here, we know as the result of 25 years successful application of a physical model to agricultural crops that we have got enough viable ideas to explain the greater part of the inter-relations of the energy and water balances of short crops, such as the grass of the Wye catchment, in terms of the physics and plant physiology of the soil–plant–atmosphere continuum in which the crops grow. As knowledge and understanding in the agricultural problem deepened (with exploitation, prediction and control exercised to give a handsome economic farming return) it became obvious that both for forestry and for forest hydrology similar fundamental experiments were needed for tree crops. Relatively, what we did, and are doing, for farm crops is easy: there are few instruments on our field site that I cannot reach on tiptoe, but going from a 1 or 2 metre crop to a 20 or 30 metre crop means that meteorological physics has to become engineering, and, as was correctly predicted, some of the measurement techniques need a precision and accuracy many would consider unattainable. Granting the desirability of the experiment, who should pay for it, and do it? Ignoring other options, my answer, without qualification, is a Research Council, both paying and doing. It is an expensive experiment, it is a one-off job that must be right from the very start, it is a job for full-time career professionals in research. At the start the Institute did not possess all the expertise it needed and, happily, the Director General, Meteorological Office, seconded one of his research staff to work full time on the project. Scientifically this seems to be working well, to the benefit of both parties. The Institute is getting the help it needs, and the

Office is getting desirable information on the meteorological physics of boundary layer processes over forested land that it could obtain in no other way. More recently, Dr. Thorn of the Department of Meteorology, Edinburgh University, has been brought in as a consultant, and with his expertise added there has started what I am ready to defend as the only necessary outcome of the work, namely, a series of scientific papers of high quality taking honourable places in reputable scientific journals. I trust that the Research Council shares, and will continue to share, this viewpoint, while being just as keen as I am on having some bonuses thrown in. And they'll get them, of course. I have already referred to a feed-back into meteorology: someday — but not soon! — the research team in the Office working on quantitative rainfall forecasts may want to put in a more precise 'surface cover' factor into the bottom of the ten layer model of the atmosphere they are using. Plynlimon and Thetford results, together, will help. There is also a feed-back into our agricultural hydrology: the brief annual reports on the Thetford experiment always provoke some challenge among my colleagues and a little bit of fresh thinking. On the more direct outlets, in forestry or forest hydrology, I do no soothsaying; for two reasons. First, it is the people on the job who must do this forward projection; and second, at the corresponding stage in my own work I had only the vaguest ideas about possible exploitation. I was happy to have solved — up to a point! — an intellectual problem. But in dodging making a positive forecasting statement I do want to add a negative back-casting statement. One of the results of living intensively with an experiment such as the Thetford project is that of being able to give completely disinterested technical advice, and it may happen — perhaps only once in a career — that this advice stops some expensive nonsense at source, without ever getting into any financial balance sheet, with no mention in any report, no public reference to it, and probably no private reference to it either. I won't labour the point: some of you will know what I mean, either as advisors or advised.

Although there is more of the Institute's work I would like to talk about, I will finish with a sweep-up of where I have got to now. In the metaphor of my title I have looked at four kinds of sub-catchments within the Institute's hydrological boundaries. One — very small in terms of time and effort — is the international work. It is good to know of the arrangements for collaboration in the East African work; good to know that the Floods Report will be much more worthwhile because, thanks to splendid co-operation from Professor Nash's fellow countrymen, the Report will be for the British Isles as a geographical unit: good to know that the size of the staff is now great enough to undertake overseas missions without major disturbance to home activity (giving valuable experience to those who undertake the missions); and good to know that in terms of paper production associated with international hydrology Dr. McCulloch, acting for H.M. Government, is doing his best to cut it down, and Dr. Rodda, in effect acting for the Royal Society, is doing his best to increase it.

The second sub-catchment is the practical work, represented by the activity of the Floods task. Neither the Hydrology Committee of the Council, nor the Advisory Committee that succeeded it, had or has any feeling of excessive virtue because this problem was accepted as a fair charge on the Institute's resources. The requirement was to study the

factors affecting major floods, particularly with respect to the safety of reservoirs and the flooding of land and urban communities. To this, NAFR added a most important rider. The information is needed to meet "the demands of the professional engineer and others for sound information on which to base their proposals". From this I suspect that we could probably agree on relative responsibility within the customer/contractor principle: The customer specifies the problem — as a problem, but it is the contractor who decides what research is needed and how it shall be done. The contractor then reports on the work in a way that makes the results most relevant to the nature of the problem, but it is the customer who decides how the results shall be used. To establish a principle I have made the boundaries hard: in practice, with sensible people on both sides, they can be much smoother.

The third sub-catchment is that part concerned with what the International Hydrological Decade programme calls 'inventories and balances', and may be tackled either in Representative Basins, of which Plynlimon is a good example, or in Experimental Basins of which Coalburn, and Ray are conventional examples, and Milton Keynes is an important unconventional example. Here the facts are important, and their accumulation may be a justifiable end in itself, but one always hopes that with increasing knowledge there will be some interpretive deepening of understanding, even for the one-off kind of job represented by the monitoring of the hydrological effects of establishing a new town. In essence, the Inventories and Balances problem is: Where is the water now? and in what form? How did it get there, and where did it come from? How long will it stay? Where and when will it go and in what form? To every one of these questions the Institute has to add another: "Why?", and be prepared to tackle the problems on a very wide range of scale in space and in time. To do so it may be forced into two very contrasted kinds of activity. Notwithstanding the jargon of every annual report from any place, facts are not data: somebody has to sweat, shiver or get soaked to collect the facts and needs adequate instruments to do it, so the Institute must be able and ready to undertake instrument design and development where there is no instrument available, or the best available is not good enough. The Wallingford Soil Moisture meter and the automatic weather station represent successful efforts of this kind, with a utility that goes beyond the particular needs of the Institute.

The other in the pair of contrasts is, in fact, the fourth sub-catchment, represented in what I have said by the Thetford work, but equally likely to appear as part of the work on mathematical modelling. This is the fundamental research and, as I have already indicated, the test of success here is not in the group opinion of an assembly even as erudite as you are, nor of an Advisory Committee, nor of the Research Council: the judgement is to be that of the research workers peers, and for some of the more abstruse research there may be very few capable of exercising such judgement. But even at my purest, where I am ready to urge government support for science as a cultural activity, I don't want to see any of the Institute's work slipping into the category: 'Much admired. Never used'. If there is to be any development after the research there may be need for some education first, to be maintained later alongside the development. It is good to note that the Director has already given some thought to this problem — and some action. He

might reasonably claim that to-day's exercise is part of the educational programme and, while he deplores the waste of time so far, feels as confident as I do that the next three speakers will have something to tell you that you didn't know already, and something you ought to hear.

## Real hydrology

J.E. Nash

University College Galway

When some months ago I received Dr McCulloch's invitation to take part in these proceedings I was very pleased indeed. He did mention that I should be expected to deliver an address of some sort, but somehow this requirement seemed less formidable at a distance of some months.

As a sort of distant country cousin of the British Hydrological Community, I was particularly pleased to receive the invitation and I very much welcomed the opportunity of honouring the late Mr Maclean for whose integrity, and whose selfish promotion of hydrology, I have had great respect over many years and whose pleasant informal manner and sense of humour I much enjoyed.

It is fitting that Mr Maclean's memory should be honoured not only on account of his work in recent years in NERC, work which made possible the extraordinary growth of the Institute of Hydrology, but also on account of his earlier association with urban hydrology at the Road Research Laboratory.

In honouring Mr Maclean thus, we of course do not detract from the role of Dr McCulloch. Throughout this Institute can be seen the mark of his design. It is of course ironic that in proportion to his success in building up one of the most impressive hydrological organisations of its kind in the world, he has inevitably found less and less time to engage in personal research in his chosen field.

I have previously suggested to him that his role is now analogous to that of a conductor of an orchestra. The greatest of the musical instruments is the orchestra itself and he who plays the whole orchestra is a more important musician than the player of any one of the component instruments. I think this analogy is valid and if I were the director of a large research organisation I would take comfort in it. We must however remember that the analogy is with the conductor of the orchestra not with the business manager.

The hydrological orchestra is difficult to direct because of its size and complexity. It ranges from the sounding brass to the tinkling cymbal — though perhaps we ought not to press this analogy any further. Because of this variety it is possible that some sections may get less than their due share of attention and I would like today to make a plea for special attention for that part of the orchestra concerned with what I have dared to call 'Real Hydrology'. I use this term for that part of our studies and endeavour which cannot be said to belong to any other discipline — physics, chemistry, statistics, etc.

Moral theologians use the expression 'a perfect society' to describe one which is 'supreme in its own domain', that is

one which has a field of responsibility in which it alone is authoritative. Within this field there is no appeal to a higher authority. I think the same concept may be applied to a *profession* which might be defined as a field of knowledge or endeavour whose practitioners are supreme or authoritative in their own domain. This of course would not exclude say a physician from depending upon or even being corrected by, for example, a chemist. But if there existed no region of knowledge or practice, within which the physician *qua* physician, constituted the highest authority, then the practice of medicine would not constitute a profession in the sense I have defined.

It is in this sense also that I associate the term 'real hydrology' with that region — if any — in which the hydrologist is supreme. That there is such a region may perhaps be illustrated by an apocryphal story which I would like to tell.

When the architect first conceived this delightful building, he no doubt considered how inconvenient, and indeed embarrassing, it would be if during its lifetime it was inundated by a flood in the Thames.

We might imagine he decided to consult a suitable authority and knowing, like all of us, that physics is the truly basic science, he approached a well known physicist, working in a government establishment and enquired from him, "What would be a safe level for the floor of the new building?". The physicist, however, explained that this question was wrongly posed, in fact that it was quite the wrong question. If the architect was prepared to rephrase it, he the physicist would be glad to explain to him the laws governing the movement of water in porous media, the laws governing the flow of water in open channels, or even the subtleties of the processes of evaporation and transpiration. But really, one could not expect a physicist to be concerned with specific cases; after all, the whole business of physics was abstraction and generalisation.

The architect replied that he was quite willing to abstract and generalise his problem and, perhaps after going out and coming back in again, he asked "How would one, with the aid of modern science, compute a level for the floor of a building to ensure that the building would be safe from inundation by a near-by river?" I imagine our physicist reiterated much of his earlier discourse on the nature of physical science and 'the scientific method' and, perhaps in haste to be rid of this importunate enquirer, suggested the possibility of consulting a climatologist.

The next day the architect made his way to the Government Bureau of Climatology where he was affably received by the Head Climatologist. This gentleman, who was a geographer by profession, assured the architect that he appreciated his problem and recognised its solution as a legitimate scientific aim. His own experience and responsibility however did not quite include this field and he felt unable to go further than mentioning the possibility of rainfall frequency studies and the computation of maximum possible precipitation. The architect clutching hopefully at the straw, asked if the rainfall frequency analysis could be made to provide frequency estimates of flood levels in the Thames.

The head climatologist was doubtful. He had heard of some obscure groups, whose description escaped him at the moment, who were concerned with studying the process of conversion of rainfall into discharge. He did not really know how much

progress they had made but promised to make enquiries. The next day he sent a letter to the architect to say that such persons were known as hydrologists and while they would scarcely be indexed in the scientific registers, he understood there were some cells of them throughout the country and in some of the lesser known universities. He could not however recollect ever having actually met one, and in any case felt that the architect would probably be better employed consulting a reliable statistician.

This the architect proceeded to do, and was pleased to find that the statistician recognised his problem as being that of associating with each level an expression for the frequency of its exceedence by the Thames in flood. The statistician hastened to point out that this could not be done merely by counting the frequency of exceedence of such levels in the historic records and that it was quite possible, that even in the coming year, before the building would be completed, a flood would occur which was substantially higher than any which had previously occurred in the period of record.

The architect, duly chastened and impressed, asked if the statistician could help him solve his problem. The statistician replied that of course he could. Had not a colleague of his own, a Mr Gumble, calculated the probability of a man living to be a million years old, despite the fact that no such case was recorded. And really, when one thought about it, this was a very similar problem. Indeed, on the assumption that there were many flood events in each year and that the architect would settle for a statement about the highest such event in any year, not only would the statistician be able to supply an estimate of the relationship between water level and frequency of occurrence but he would also be able to provide confidence intervals for these estimates. The architect would be required only to produce the records of the highest levels reached in the Thames in each year as far back as records extended.

The architect retired delighted. He wasn't quite sure how this trick was to be performed. Nor was he quite sure what was meant by the term 'confidence interval' but he had the layman's deep faith in mathematicians and, all the way home, marvelled that so much could be produced from so little.

From a mere handful of historic flood levels, no one of which had reached the level of the field upon which the building was to be made, this almost omniscient person had promised not only to estimate the frequency with which such higher levels could occur, but also to provide fiducial limits or confidence intervals associated with each such estimate. The architect saw clearly that, with such information available, it would be a mere book keeping exercise to compare the cost of raising the floor level with the reduced risk of being flooded, and so arrive at the optimum design.

For many days the architect continued to marvel at the skill of the statistician but eventually his curiosity overcame him and, having prepared himself by reading Moroney's introduction, he again approached the statistician and asked for details on how this seemingly magic trick could be performed. The statistician stated that he would assume a model for the distribution of annual maxima and would estimate the values of the parameters of the distribution from the sample data. That is, he would choose those values for the parameters of the distribution which gave the highest likelihood of occurrence to the actual sample provided by the historical

record. Obtaining the confidence intervals, explained the statistician, required a somewhat more sophisticated trick. Obviously if one knew the actual or population values of the parameters one could compute the probability of obtaining any given sample and hence any given estimate of these same parameters. A very good trick, indeed, would be to invert this calculation and obtain a probability statement about the population values from an examination of the sample values. This, however, was not quite on, but a probability statement could be made about the amount of error associated with a single sample and due to the genius of a Dublin Brewer this statement could be made using only information contained within the sample itself, that is, it would not require any population values. Such a statement could almost certainly be relied upon to confound all but the initiated and would be accepted, almost universally, in lieu of the required probability statement concerning population values.

The architect was somewhat disappointed by this new information but not too much. Even if the confidence intervals did not mean exactly what he had hoped, still they represented errors associated with stated probabilities and by choosing conservatively he might still achieve a high degree of safety without actually putting the building up on stilts. However he was still a little bit doubtful about the model and, encouraged by his readings of Moroney, he enquired from the statistician how he knew the form of the distribution of the annual maximum flood levels. The statistician launched into a long and learned discourse on assumptions, the stability postulate and the double exponential distribution. In the end, however, he admitted that really he did not know what was the appropriate distribution. On further questioning it emerged that this ignorance was not reflected in the confidence intervals which were based entirely on the assumption of a particular distribution and reflected only sampling errors.

"In other words", said the architect, growing bolder, "we have here an elaborate computation based on a single sample, wherein the parameters are estimated under the assumption of a particular distribution and the confidence intervals likewise are computed under this assumption. But no allowance is made, in either computation, for the possibility of the chosen distribution being wrong. We have an elaborate calculation of part of the error and the complete neglect of what is probably the most significant part".

The statistician somewhat reluctantly agreed, but defended his position by stating that if the architect was dissatisfied with the assumption concerning the model he, the statistician, had a colleague down the hall, a Mr. Bayes actually, who claimed to be able to resolve this sort of difficulty, though he added confidentially, that because of some recent indications concerning the probable absence of life on Mars, he, Mr. Bayes, was at the moment somewhat in disfavour with the top management.

The architect politely declined to be taken further and somewhat sadly made his way home, musing to himself how strange it was that all the scientists whom he had consulted had ignored his problem and instead had devised methods of solution for problems of their own specification. The architect finally resolved his problem by consulting an experienced engineer on the staff of the Water Resources Board who told him to put the floor in at 175 feet OD.



Like all good stories this one has a moral and the moral is that the basic sciences on which hydrology depends do not, of themselves, provide the solutions to real hydrological problems. If we accept that problems such as the one we have been discussing are within the legitimate business of science then there is also, at least potentially, a scientific field of investigation in hydrology which is different from, though dependent on, basic sciences. It is my contention that this field constitutes the particular domain of the professional hydrologist and constitutes what I have called 'real hydrology'.

There will always be a role intermediate between those of the scientist and the practical engineer (or architect). This is not merely the role of interpreter though the need for this too can arise. There is a whole field of endeavour in providing solutions to practical problems through the application of physical and mathematical laws where appropriate, but also, when this is impractical, through the scientific analysis of experience. It is not possible on this occasion to define the limits or likely progress of this science. The prophet whose predictions are sufficiently vague has a much better chance of surviving with honour than the one who is rash enough to be specific.

The *objective*, however, certainly includes the forecasting of hydrological behaviour in real time and the prediction of the stochastic properties of hydrological variables, including prediction of the effects of man-made changes in a catchment.

The *method* of the science, while necessarily confined within the general scientific method, must be applied on a macro scale. The behaviour of the catchment as a whole must be studied rather than the component parts. Manifestations of this behaviour must be compared with previous manifestations and with corresponding manifestations on other catchments. General models, both of a stochastic and deterministic nature, must be found and the parameter values related to recognisable characteristics of the catchments.

The incentive for this work comes from the customer — the engineer concerned with water resources development. The model concepts will derive from the work of the physicists and the micro-hydrologists and the analysis will depend on the skills of the statistician and the mathematician. The synthesis of the concept, and the analysis and the prior definition of the problem, are not specifically in any of these fields but belong to the domain of the hydrologist.

The specific role of the hydrologist will remain until a model of a hydrological process, such as the conversion of rainfall into discharge, can be built up purely on physical laws and measurements of catchment characteristics and to this model can be applied the actual boundary conditions in all their complexity.

This role will include the synthesis of the macro-model or hypothesis in a form in which it can be tested on available observations using of course, where appropriate, the tools of statistical analysis of experiments.

The methods of analysis themselves and the observations available will in turn influence the structure of the hypothesis of macro-model. Due regard must be paid to the principle of William of Ockham concerning unnecessary complexity, both to achieve elegance in the model and for ease of recognition of parameter values.

Perhaps it would not be over bold to draw an analogy here

with the relation between modern atomic physics and classical mechanics. Referring to mechanical theories in modern physics, Linsley and Margenau in *Foundations of Modern Physics* states:

“These are important and well-established theories and appear to justify our faith in the essentially mechanical concepts which are so closely-related to our intuitive notions of space and time. Nevertheless, the attempt to use these concepts in framing hypotheses for theories of atomic structure has by no means been so successful. So the necessity has arisen for seeking postulates outside the fold of mechanics. What have we here to guide us? We still have a considerable background to call upon, but the results of modern research show that free mathematical construction has a great place after all, and that postulates which appear to have little connection with anything anybody has ever experienced in space and time may prove remarkably apposite in the formulation of theories”.

Again the analogy must not be pushed too far but if the atomic physicist allows himself this freedom in forming conceptual models, surely the micro-hydrologist will allow a comparable freedom to the macro-hydrologist.

I have every confidence that under Dr. McCulloch's wise guidance (and on the advice of his Advisory Committee under Dr. Penman's chairmanship) due attention will be paid to this important aspect of the work of the Institute. Dr. McCulloch has always shown appreciation of the practical aspects of his work; the government's White Paper *Framework for Government Research and Development* has emphasised this aspect by insisting on the concept of a customer for research, and the Institute has recently undertaken the extremely practical exercise of the Floods Project already referred to.

I have one concern, however, deriving from the fact that the Floods Team has a term to its work. I think it very desirable that, initially, some such term should be applied in order that within a couple of years as much as is readily available can be ascertained and made available to the practical engineers. However, one must not expect that within such a short period all practical problems of Flood Hydrology will be solved. A team capable of doing this, where so many in the past have failed, would indeed be worthy of indefinite continuance; therefore, while, conceivably, the Flood Team might, perhaps, be disbanded because of failure to achieve success, their disbandment for the contrary reason would be very shortsighted. The developing world, according to a recent UNESCO document, is more in need of applied hydrologists than of any other profession. In the face of this need it would indeed be reprehensible if the expert team which Dr. Sutcliffe has carefully gathered and developed over the past three years should at the height of their efficiency be disbanded. I cannot believe that such would be the case.

I would like to conclude with a word of caution. I read some time ago the suggestion that because Satanic manifestations were more common in the Middle Ages than at present, it would seem that the Devil's present *modus operandi* is to persuade the world that he doesn't exist. I found that a spine-chilling hypothesis. In the case of real hydrology, however, our *modus vivendi* must be the opposite. If we fail to persuade the world that we exist then we won't exist for long.

It has always been a great pleasure for me to come to the

Institute of Hydrology once or twice a year over the last ten years, and I am grateful to Dr. McCulloch for this further opportunity of meeting so many old friends and colleagues.

## Research progress to watershed management

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The long time-lag between research and development is of major concern in many other sciences. In hydrology our concern is reversed. Viewed from the watershed, there is sometimes no lead at all, so that important water developments have to be undertaken on a semi-empirical basis because the research has not yet been done. Even more important, in the long term, is that major decisions on land use, in Britain as in other parts of the world, have been undertaken without any knowledge of, or even any concern for, their effects on the hydrology of the areas under development. I believe that this situation has come about because the vast growth of science over the past century has taken place in high-latitude communities in a temperate climate with a stable tradition of land-use. In the well-watered contentment of these green pastures our communities developed a complacency about the ability of the civil engineers to supply enough water as long as we raised enough money. In our stable patterns of land-use the question of the hydrological effects of development did not reach the level of public discussion except over local incidences of flood or drought.

Had the world's scientific history continued to develop in those semi-arid lands which gave us our algebra, I am certain that hydrology would have been a major preoccupation of the learned societies. In contrast, we have neglected the subject to the extent that, even today, hydrology is struggling to gain respectability in the professional councils of the Civil Engineers.

A harsher climate would have led to far earlier study of the physics and biology of evaporation processes and to the chemistry of water pollution. It would thus, I believe, have brought us some 50 years earlier from our concentration on the variability of streamflow to the study of the hydrological cycle.

Because our temperate zone streamflows are continuous and provide the output which the water authorities want to know about, hydrologists have until recent years paid almost exclusive attention to the study and analysis of streamflow and the probabilities of its variation.

### WATERSHED EXPERIMENTS

We have only just begun to recognise and to study on an adequate scale the complex routes by which water gets into a river. The interceptions, the storage, the evaporation and seepage losses *en route* are all liable to be altered when we change the land use, particularly if we start, as usual, by

removing the vegetation.

Half a century of watershed studies in the USA has led to major doubts as to whether the watershed is a practical unit for research. It is certainly a difficult enterprise in Britain's crowded islands, whose stream source basins lie under a formidable complex of ownership and legislative control. The question now is whether, having learned the complexity and size of the job, we should continue to instrument complete catchments for the study of the hydrology of stream source areas.

This is the question which I want to examine briefly this afternoon.

For the early stages of watershed research, and many of the records on which hydrology is built, we owe a great deal to our foresters, who took an interest at a time when the learned academies showed none. In Britain, public officials were appointed soon after the Norman Conquest to look after forests, although the object was to safeguard the royal game rather than the streamflow. The foresters of Europe, appointed for similar reasons, sought to guard trees against both farmers and townsmen and found their stream source situation to be a trumpcard. They roundly claimed the rainfall as well as the streamflow for the credit of their forests, and believed implicitly in their own hypotheses. In support of these claims, foresters in Moravia, now Czechoslovakia, began stream gauging more than 200 years ago.

The pioneer attempt to compare stream flow from valleys of different land-use was begun at the turn of the century by a Swiss forester, Hans Berger, in the famous Emmental and Rappental Valleys. Ten years later, the pioneer attempt to find out what happens to streamflow when land-use in a valley is changed was made, also by the foresters, Bates and Henry, in the USA.

One-third of that vast land is still under forest, largely as the result of its precipitate history. While the new American community of high technology was spreading rapidly westwards into virgin lands there were, inevitably, serious mistakes, which resulted in soil-laden floods. The US Forest Service was authorised and funded by an Act of Congress in 1891 to protect forested watersheds: the foresters of both Federal and State services now guard land which produces three-quarters of the streamflow of the country.

Active watershed research still continues on a larger scale in the USA than anywhere else in the world, although it has made slow initial progress. This was because both engineers and foresters concentrated on long-term comparisons of streamflow. They made the basic assumption that the hydrological complexities of a natural valley are too great for measurement or analysis and that the only effective form of hydrological integration must be that of the streamflow itself. In 1934 the US Forest Service set up the world's largest outdoor hydrological laboratory at Coweeta in the southern Appalachian Mountains, where streams from 30 small valleys were gauged. I visited Coweeta in 1957, when it had been running for 23 years, and found excellent river gauging, rather sparse rain gauging, and no attempt whatever to measure the third major component of the hydrological cycle, the evaporation rates. There was neither evaporation pan, sunshine recorder, nor any other form of energy measurement, except for the air temperature in the meteorological screen.

## EXPERIMENTS ON CLEAR-FELLING OF FORESTS

The first step in most forms of land development in a forested stream source valley is the clear-felling of the forest. This is the simplest and most drastic land-use change and the effects of such treatments have now been widely studied for 40 years. Much good data have been published and we should by now be able to answer with confidence two important questions: *Firstly*, can we repeat the same vegetation change in the same valley and expect to get the same results? *Secondly*, can we repeat the same treatment on the same type of forest in another valley and get the same result?

Hewitt, from Coweeta, answered the first question convincingly at the International Symposium on Forest Hydrology at Pennsylvania State University six years ago. After only three years of initial comparison of monthly water yields for calibration, the pine forest on one of a pair of valleys was clear-felled. The increase in water yield was prompt, and this increase dwindled away as the pine forest regrew. After 25 years the water flow was back to normal. It was then felled again and the response in water yield was almost identical.

On the second question, Lull and Soper also presented very impressive evidence to the same meeting. They summarised 17 years of results for 28 experimental watersheds and compared them with routine measurements on 137 watersheds, each of less than 100 square miles. These lay in an area bounded by 600 miles of the New England coast and extending 300 miles inland. The watersheds were grouped by proximity and geographical similarity, but even within the groups there was a disturbing lack of agreement in average annual yields. Fourteen variables were studied, including annual and seasonal precipitation, return periods for 24-hour intensities, latitude, altitude, channel slope, area of forest, etc. These were reduced by successive multiple regression analyses, progressively eliminating the least effective.

The results were disappointing, in that they failed to produce any effective predictions for other watersheds not included in the analyses.

Leakage through the floors of the catchment basins is the major source of error, and the comparisons of rainfall and of streamflow, however elaborate the analysis, can give no effective check on leakage.

Thus, for the well-watered eastern USA, the answer to my first question on repeatability in the same valley is "yes", but to my second question it must be a qualified "no". The qualification is that while the experiments rely only on the comparisons of rainfalls and streamflows, without any attempt to estimate water storage and water loss by evaporation, then the prospects of transferring the results are poor.

It is not surprising that when Hewitt assembled a comparison of published results of 39 forest-felling experiments from east and west of the USA, from both East Africa and South Africa, and from Japan, he obtained a wide scatter when the observations are plotted in the form of depth of extra water yielded by the catchment over the area cleared of forest. Some extreme values came from entirely different climates in tropical Africa and Eastern America but both showed a maximum of 435 mm of water saved over the area cleared.

## BUDGET FOR BOTH WATER AND ENERGY

The water-surplus climate of the eastern USA, with about 100 mm of precipitation in every month of the year, does not help at all in the detailed investigation of water penetration, storage and transpiration.

Leakages cannot be detected by the streamflow comparison method because all of the losses are pooled in the  $R - Q$  difference, which is then the only estimate of the third major component of the hydrological cycle. Over much of the world this is a bigger term than the streamflow, but it was not measured because the botanists misled their engineer colleagues for more than a century by their hypothesis that for each plant species a different 'transpiration ratio' prevailed, so that measurements on a watershed scale would be impossible.

## THE COMBINATION OF THE ENERGY AND WATER BUDGET

Progress was not possible until Dr Howard Penman sorted this out for us at Rothamsted in 1948, demonstrating the dominance of the weather and the uniformity of evaporation from different green crops; Professor Thornethwaite demonstrated the same conclusion from North American data in the same year. Penman's solution was based on first principles and has stood the test of transfer to other climates. Thornethwaite's method has empirical simplicity and is excellent for the continental area from which the constants were derived, but elsewhere it has proved a trap for unwary geographers.

In 1960 Penman was able to show that the main catchments of the British Isles behave as if they were continuously covered with well-watered vegetation, an impression which any air-journey confirms. I was privileged to spend a few weeks at Rothamsted at the end of the war and went to East Africa in 1946 armed with a stencilled advance copy of Dr Penman's 1948 paper. We were able to confirm quite quickly in East Africa that the equation applied to an open water surface near to the equator at 5000 ft above sea level.

The high altitude tropics have immense geographical advantages for hydrology and also experience large-scale land-use changes under some degree of Government control. They were therefore ideal places to check the possibility of measuring the third major component to enable us to find out whether a watershed was leaking.

We could use seasonal storage changes in the deep stone-free soils as an additional quantitative component, and our reliable dry seasons gave reproducible depletion curves for groundwater. Using Penman's energy budget we were able to show that leakage was serious in two cases and negligible in four cases out of the first six valleys which we equipped. Although expensive, this is far cheaper than carrying on for many years of uncertainty, with no check on the final outcome.

Major policy problems for the land-use of the precious forested watershed areas of Kenya were in dispute. For study of such land-use changes we found that the device of comparing evaporation from plant canopies with that from open water, the  $E_t/E_o$  ratio, to have substantial advantages for watershed work, although Penman has been able to discard it for comparisons of farm crops.

Using this  $E_t/E_o$  comparison it has been possible to confirm

in two different types of tropical forest, with different temperature and rainfall regimes, the basic hypothesis that complete canopies of tree foliage of different types, in well-watered situations, can be substituted over whole valleys without long-term change in the water yield. In one such change, from bamboo forest to pine plantations, it was shown that as soon as the new tree canopy has closed, the water use returns to its original rate; further, that if the land-use change is skilful, even the stream pattern need not be altered.

In the case of clearing forest for tea gardens, where bulldozers were used and the land stripped clean, the pattern was violently changed — peak floods were four times as high — but again the restoration of a full canopy of tea bushes, very different from the tropical forest which it replaced, gave the same water use after five years.

We thus obtained direct experimental evidence, in less than 10 years, and at very slight cost, of the hydrological results of a land-use change about which both professional and political controversy had raged for the previous 20 years. Much more important, we had answered the second of my two questions today about watersheds, i.e. do the results of one experiment apply elsewhere. Penman's results from a 4 foot tank at Rothamsted had applied equally to a 100 acres of montane bamboo forest and 1000 acres of tall rain forest, both changed to entirely different forms of continuous canopy of well-watered vegetation. We can therefore answer "Yes" to both questions if we use adequate research methods.

#### CAN WE YET ASSEMBLE THE HYDROLOGICAL CYCLE BY THE COMPUTER INSTEAD OF BY A WATERSHED?

Knowing that a balance is possible, can we do it more cheaply with a computer? The answer is that we might do so if we knew enough about characteristic internal workings of watersheds to write a sound model. At present, computer models of watershed functions are still very crude approximations. The quality of the data is steadily improving as we learn more about how to measure inputs, such as rainfall, streamflow, evaporation, soil moisture storage, rainfall infiltration, percolation rates, root ranges and other variables.

A strong watershed study team in the USA under Dr Holtan worked at Beltsville for five years on the assembly of research results for the storage and movement of water through soils, and for estimates of rainfall, evaporation and transpiration. When, eventually, they produced a model in 1970, there was no independent set of watershed readings comprehensive enough to test it. They therefore had to use a simplified model on the very well documented 60-ton lysimeters at Coshooton Soil Conservation Station in Ohio. They first studied a four-year crop rotation as a calibration run, and then predicted the results for a second four-year rotation, using only rainfall, pan evaporation and the known soil moisture storage characteristics, all with a remarkable degree of success for such a very simple and restricted example.

We still await a successfully verified example of full-scale watershed modelling, but the water resource authorities are making increasing use of computer modelling of flow studies of river systems, incorporating reservoir storages and water-supply extractions. More accurate simulation of both overland

and subsurface flow from the watersheds can be incorporated as they are achieved by research. There is therefore little doubt that we shall eventually be able to use the computer to assemble our separate measurements of many factors in order to predict the results of land-use change.

#### DO WE THEREFORE NEED MORE WATERSHED EXPERIMENTS?

My answer would be that we need very few indeed in the highly developed countries and that these should be very fully equipped studies applied only to land-use changes of high economic and social importance.

In developing countries, where large areas of virgin lands are being invaded by the rising tide of human population, there is a need for simpler, pilot-scale land-use changes on a watershed basis.

Looking first at the highly developed countries, this new building today is evidence of national enterprise in this field; we see the scale of staff and facilities needed to undertake major multi-disciplinary experiments. These need the long-term continuity, assured staffing and technical servicing that is made possible by such a base with the backing of a Research Council and its parent Ministry. I believe it is important that they should offer facilities as focal points for the many other interests concerned, particularly for university teams doing shorter-term component studies of watershed work.

What we do not need is a lot of small, inadequately developed watershed studies, which cannot be staffed or equipped sufficiently to achieve a water and energy balance. Such studies are not capable of estimating leakage and are therefore liable to give arbitrary and equivocal results.

Major land-use experiments are difficult to organise in our crowded islands and we need only a few very good ones, applied to major issues, of which afforestation is still one, in spite of all the stream-comparison efforts over decades, while I suggest that urbanisation must surely be the other major change which is important on a national scale.

#### WHAT ARE THE MAJOR SCIENTIFIC ISSUES REMAINING TO BE TACKLED?

We have two important technical fields to conquer. Firstly, the measurement of the hydrological effects of advective energy, which is of dominant importance in semi-arid lands. The Australians and Americans are working hard at it, since their major irrigation areas are surrounded by desert. We are approaching the problem from the reverse direction in Britain, by which I refer to the work done by the hydrometeorology team at the Institute of Hydrology's powerfully-equipped study of forest water use at Thetford. They are demonstrating that, from wet forest canopies under British conditions, evaporation is in excess of that explicable by the incoming solar energy; the additional energy is extracted from the air stream and from the forest.

Secondly, the water and energy balance of a *permeable* catchment basin must be a major objective. A great deal of Britain's water supplies come from underground aquifers, but our technology is barely capable, as yet, of advancing from the water-tight valley to the combined study of surface and

underground waters of a permeable valley. This is clearly a joint task for the hydrologists and the hydro-geologists in the study of our complex water resources.

These two problems represent sharp technical challenges for which, at last, Britain is becoming well-equipped. The graphs of water-supply and public demand suggest that there is not too much time in hand for such difficult studies.

Finally, the hydrological problems of land-use changes overseas are larger in scale and no less urgent. The problem area of humanity is the subsistence agriculture of the tropical and sub-tropical developing countries. FAO forecasts that of the huge new crop of human beings, who will double our numbers in the last quarter of this century, 6 out of 7 will be born on watersheds under subsistence agriculture in which population pressure and unskilled cultivation and grazing are already damaging the hydrological controls.

Here all the threats to the stability of agriculture are exaggerated. Erratic rainfall, with intense, erosive storms, high evaporation rates, frail Kaolinitic clays exposed by overgrazing, all contribute to acceleration of soil erosion.

We already know the soil conservation methods necessary to put this right, but even when we do restore an organised water regime, it is useful to do it on a watershed basis and to verify the hydrological outcome by simple measurements.

Here the Institute of Hydrology can contribute materially to the science and practice of a major world problem. I wish them good luck in their many important tasks.

## The contribution of hydrology to river basin management

Marshall Nixon, CBE  
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### THE NEW SCENE – A NEW IMPETUS

The concept of river basin management has now been generally accepted and is the basis of the Government's proposals for the reorganisation of water services in the United Kingdom. These are now sufficiently advanced to forecast with some confidence the shape of the future administrative framework in England and Wales, Scotland and Northern Ireland. Already in Ireland the functions of water supply, sewerage and sewage disposal, land drainage and flood control have been centralised. On the 1st April 1974, these functions will be the responsibility of nine new Regional Water Authorities in England and the Welsh National Water Authority in Wales. The reorganisation in Scotland is timed for 1975. The present proposals do not follow those for England and Wales or Northern Ireland as water supply and sewerage and sewage disposal are to be the responsibilities of local government. The logic of this is questionable and there are some who hope that the proposals may yet be changed.

The Regional Water Authorities in England and Wales will be multipurpose bodies responsible within their river basin areas for:

- Water resource development
- Water supply
- Sewerage and sewage disposal
- Land drainage and flood control
- Fisheries
- Recreational and amenity use of water space
- Prevention of pollution
- Research
- Hydrometry and flood forecasting

The aim of the new authorities will be to control the water resources of their area for the benefit of mankind. They will achieve this only if they are able to plan and integrate their various functions towards this common objective. This process of integration has become known as river basin management. Central to this concept is the production and execution of a water development plan to meet the future demands for all users of water. Areas deficient of water resources will need to make provision in their plans for the importation of water from other areas where surpluses exist. This process requires a degree of national planning which will be done by a Central Planning Unit. Other central functions will be the responsibility of the National Water Council. Although regional water authorities may do their own research, most of the research required by the industry will be undertaken by a Water Research Centre which is to be established on the foundation of the existing Water Research Association and the Water Pollution Research Laboratory and will incorporate the technology division of the existing Water Resources Board.

There will be a need for a close link to be maintained between the new Research Centre and the Institute of Hydrology which lies outside these proposed arrangements. The institutional framework which will be provided by the new legislation for water will be the most advanced in the world. Engineers and scientists working in this field will no longer be restrained by the limitations of an inadequate legal system. This opportunity must be exploited fully. The law makers provide the system; the technologists must make it work.

### HYDROLOGY AND RIVER MANAGEMENT

Water is made available through the natural hydrological cycle. It is distributed naturally on the surface through a river system and in the ground by porous strata. The amount of water available is determined by the incidence of precipitation and lost by evaporation. Left to itself, this system would not meet the demands for water in this highly populated country. The net rainfall (precipitation less evaporation) is highly seasonal and its distribution by the rivers and aquifers is unrelated to the spatial pattern of the demands. In other words the system provides in the wrong places either too much water or not enough. Man must, therefore, for his own convenience adjust the natural hydrological cycle both in time and in space. If we are to practise this surgery with confidence we need to understand the anatomy of the system. The engineer has the role of the surgeon; the hydrologist the role of the anatomist. Neither can do without the other.

Water users fall into two classes. There are those who wish to abstract water from the system for some purpose and those who wish to use the water within the system. The main uses

can be so classified:

*Abstractive uses*

- Irrigation
- Domestic and industrial water supply
- Electric power

*In situ uses*

- Navigation
- Waste disposal
- Fisheries
- Recreation

Each user will generate a demand for water and the water development plan will provide measures for meeting these demands. In addition to these user elements the plan will contain provisions for the drainage of the land surfaces, flood control, reclamation and re-use of water and, perhaps in arid areas, for weather modification.

Meeting the demand for water in quantity terms only will not satisfy the needs of the users so an essential part of the plan is the control of the quality of the water to standards required by each use. The quality factor will be a new dimension to many hydrologists. In short, the aim is to provide the right quantity of water of the right quality at the right time.

It is by the measures required to achieve this objective that changes to the natural hydrological cycle will be made. For example, surface storage reservoirs effect a delay in the natural rate of run-off and a change in the temporal distribution of water. Groundwater abstraction and artificial recharge alter the natural drainage rate and the rate of replenishment of aquifers. Sea water desalination short-circuits the whole cycle and provides potable water independently of rainfall. Flood control works alter the spatial distribution of water. In all these components of the development plan hydrology has a part. Indeed, none of the purposes of the new regional water authorities is without some element of hydrology.

#### THE CONCEPT OF RISK

In most cases the deliberate adjustment of the hydrological cycle will be made by the construction of engineering works. The effectiveness of these works is usually expressed in hydrological terms. Obvious examples are the yield of a surface storage reservoir, the yield of a groundwater development scheme and the size of the flood contained by flood control works. Generally the selection of these and similar design parameters involves an assessment of the frequency and the risk of failure. In current practice most water resource development works are designed to fail on average twice in every hundred years; this means that the yield of the works will fall short of the design yield or in extreme cases a storage reservoir will be empty. Flood control works are now being built to provide, in an urban environment, protection against a flood which can occur once in every hundred years. These matters require subjective engineering judgement. These judgements are based upon hydrological data. It is, therefore, vital that the hydrologist who provides the data must indicate to the engineer the degree of accuracy of his information. It seems possible that, particularly since the development of

powerful computers, engineers and hydrologists are manipulating data and drawing conclusions from the results without considering the quality and the accuracy of the original measurements. It is important, therefore, that hydrologists assisting engineers to reach judgements state clearly the limits of accuracy of their advice. It is also equally important to improve upon the accuracy of measurements of fundamental data such as river flows, rainfall and evaporation.

In the design process it will not be sufficient merely to answer the question: "What will these engineering works achieve?" It will also be necessary to ask: "What will be the effect of these works?" The hydrologist must, therefore, be able to forecast the changes in the hydrological system due to engineering works and, in addition, to forecast the effect of one engineering work upon another. This must be a continuing process as circumstances in the catchment area change. For instance, urbanisation by its effect on flood frequencies can diminish the degree of protection provided by flood control measures and changes in land use can affect the yield of water resource works. Allied to this process, although it may have a lesser content of hydrology, is the need to examine from time to time the degree of risk inherent in the design of works as a risk of failure acceptable today may not be acceptable in 20 years time or even less. Changes in the operation of an existing resources works or proposals for conjunctive use of resources will also require extensive hydrological studies.

#### THE ENGINEER AND THE HYDROLOGIST - A TEACHING ROLE

Because of the interdependence of hydrology and engineering in the design and operation of water resource works, there is a need for a close relationship between the hydrologist and the engineer. Hydrology is a comparatively new science in its own right and has, like other new sciences, tended to develop along theoretical and academic lines while the engineer has continued to use an empirical approach. As a consequence there has been a lack of liaison between the two disciplines and a failure to interchange knowledge. A positive effort is needed to overcome this deficiency and to foster the interchange of knowledge. Two approaches to this problem may be possible. Firstly, hydrologists must learn to express themselves in a manner which can be understood by practising engineers. There is an increasing output of hydrological literature which is incomprehensible to the engineer. This is not because the engineer is stupid but merely because he has not the time to devote to the subject nor has he the depth of knowledge to be selective in his reading. There must, therefore, be many advances in hydrological knowledge in the last 20 years which have still not reached the stage of practical application — why else is the Bilham formula still widely used?

The second approach is for research institutions to deliberately assume a teaching role. This can be easily done by providing residential courses for practising engineers in the application of hydrology. Such courses will promote an interchange of views which will be of mutual benefit to both the teacher and the student and may help to identify new research topics. This might well be the manner by which the results of the work of the Institute of Hydrology on floods should be disseminated. The future role of the Institute is

primarily to fill the gaps in our present knowledge but this is not in itself enough. It must also see that its store of knowledge is used and applied. The publication of a series of manuals or alternatively, a series of state-of-the-art papers, may well be desirable.

#### THE COORDINATION OF HYDROLOGICAL RESEARCH IN THE FUTURE

The Government has suggested that expenditure on water services in England and Wales will exceed £600 million a year and that the new Water Research Centre may have a budget of £4 million per year. This latter figure does not include expenditure by many research agencies who are contributing to hydrological research either wholly or as part of their other work, neither does it include the contribution of the Institute of Hydrology or the Meteorological Office. It may also be assumed that the new regional water authorities will wish to do some research and development directly on their own projects.

Every project requires some research, some design and some operational experience. With the present shortage of suitably qualified manpower it will be important to achieve the optimum allocation of resources between the three elements. It seems improbable that the ideal balance could ever be achieved. However, a little progress could be made towards this ideal if the hydrological research being carried out by the numerous agencies, the water authorities and the universities is in some way co-ordinated.

No-one at present is attempting this co-ordination and it seems unlikely that it could be achieved by legislation. Perhaps it could be attempted voluntarily by a National Hydrological Committee. Something will be necessary but whatever form it takes it must be compatible with the growing importance of the science of hydrology and recognise the combination that hydrologists can make to the management of water resource systems.