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The Emergence of Scientific Hydrology in the Twentieth Century°

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Abstract: The general growth of the scientific basis for hydrology is reviewed through reference to outstanding publications which in the opinion of the author represent landmarks in that process. The discussion is organised on the basis of four periods each with a special feature. These are (a) the period of empiricism (1900-1930), (b) the period of rationalisation (1930-1950), (c) the period of theorisation (1950-1975) and (d) the period of computerisation (1975-2000)

Key words: twentieth century; hydrology; development; empiricism; rationalisatiion; theorisation; computerisation

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1 Introduction

To master any subject in science or technology a knowledge of its past history is of great assistance. Accordingly, it is useful before confronting the present-day problems of extending our knowledge of hydrology to look briefly backwards in time in order to survey past efforts at establishing hydrology on a firm scientific basis. To do so within the scope of a single paper is difficult and must of necessity be subjective in its treatment. Accordingly, the following is essentially a personal view-others might present a list differing in several respects.

The period selected for review is the past century and it reflects the interests of the author who has studied and practised several aspects of hydrology since 1943. Those interested in a longer time span and in developments in China are well served by the relevant material in the monumental work of Joseph Needham who has made westerners aware of so many aspects of Chinese Civilisation (Needham 1971). Those interested in more detail of developments relevant to China over the past decade are well served by the contents of this journal on Advances in Water Science during that period.

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Biography: James C. I. Dooge, professor, Centre for Water Resources Research University Dublin, Ireland, Member of the Royal lriah Academy, President of International Association of Hydrological Science (1975- 1979). Famous Hydrogist, Honoray Professor of Hohai University Nanjing.

The present discussion has been grouped on the basis of the categorisation used by Ven Te Chow in his influential Handbook of Applied Hydrology (Chow 1964 pp 1-7 to 1-10). This scheme, slightly modified by the present author, divides the twentieth century into four eras: (1) the period of empiricism (1900-1930); (2) the period of rationalistation (1930-1950); (3) the period of theorisation (1950-1975); and (4) the period of computerisation. Within each period attention will be given to a few outstanding developments in relation to the following classical divisions of hydrology: (a) precipitation, (b) evaporation, (c) infiltration, (d) groundwater, (e) streamflow, (f) sediment transport, (g) catchment hydrology, and (h) regional water balance.

2 Period of Empiricism (1900- 1930)

This period was characterised by solid work in the field aimed improving the basis of the design of works in hydraulic engineering. The progress made in these early years can be judged by examining the published works of D. W. Mead (1904, 1919) and of A. F. Meyer (1917). It is significant that no important new texts on hydrology were published until the late 1940's Nevertheless, important steps in the development of hydrology did occur in relation to isolated topics.

The annual official publications of rainfall data became of increasing importance and were supplemented by a few special publications for individual regions such as Salter (1921). In the case of evaporation, a significant step in going beyond empirical formulae was the first formulation of the Bowen ratio linking the latent heat of the evaporation flux with the sensible heat of the energy flux (Bowen 1926).

The theoretical foundation for the scientific study of unsaturated subsurface flow was laid by Buckingham (1907) who introduced the concept of capillary potential now known (with an opposite sign) as the matric potential of soil water. At the end of this period of empiricism, Richards (1931) introduced the basic equation governing the isothermal transport of water through unsaturated soil, proposed a method for measuring the matric potential in soil samples, and discussed the hysteresis between wetting and drying conditions. The knowledge of groundwater hydrology at the opening of this period is well covered by the monograph of C. S. Slichter published as part of the Annual Report of the U. S. Geological Survey (Slichter 1899). The progress in the first twenty years of the century is equally well reflected by Meinzer (1923a. 1923b) in his two U. S. Geological Survey Papers of that year.

The practices of the hydrometric measurement of river flow using current meters are covered by the classical text of J. C. Hoyt and N. C. Grover which the author found of inestimable value as an introduction to the topic when he was first engaged on hydrometric survey work forty years later (Hoyt and Grover 1907). The results of such measurements were published in systematic form and compared with historical records. From time to time, these were the subject of regional or national publications such as that for Britain by Glasspoole and Brookes (1928).

The gradual development in the application of satistical methods is seen in the use of plotting on probability paper (Hazen 1914) and in the later emphasis on the skewness of hydrologic extrems (Foster 1924). These developments are well discussed in the book on Flood Flows written by Hazen at the end of this period of empiricism (Hazen 1930).

The early work of the U. S. Geological Survey on sediment transport and his own important researches are described by G. K. Gilbert in a monograph of 263 pages (Gilbert 1914). The first extension of the equation of continuity to cover the case of a movable bed also dates from this period (Exner 1920). There was a beginning of interest in the problems of fluvial geomorphology (Davis 1913). A number of the important early papers in this field are reprinted in Schumm (1972) and in Schumm and Mosley (1972).

3 Period of Rationalisation (1930– 1950)

The next twenty years proved to be a most fruitful period advances in theoretical hydrology. This was particularly true in the United States where the publications and meetings of the American Geophysical Union were important factors. The framework for this development is reflected in the important paper by Horton on the science of hydrology published by the AGU (Horton 1931). The progress made during this twenty year period is well surveyed in the comprehensive work on Applied Hydrology by Linsley, Kohler and Paulhus which became the first book on hydrology to have a worldwide circulation (Linsley et al 1945). The important publications on streamflow measurement in the first half of the century are listed in the comprehensive bibliography by Kolupaila (1961).

Most of the advances in this period were in relation to hydrology at the catchment scale. Early in the period there is a good survey of the state of knowledge of the elements of the hydrological cycle in a presentation to the International Association of Scientific Hydrology by Sherman and Horton (1934). The transition from the empirical to the rational in relation to land surface fluxes was characterised by the introduction of the concept of infiltration by Robert Horton (1933), the improved estimation of evaporation by Thornthwaite (1935, 1948) and the estimation of transpiration (e. g. Blaney and Criddle 1950). A key step, which was to be the basis of the future treatment of evaporation, was the introduction by H. L. Penman of the concept of potential evaporation and the use of the combination formula to estimate it (Penman 1948). In the same year, Budyko published the first of his important series of papers on evaporation (Budyko 1948).

The most significant developments in groundwater hydrology were those on non-equilibrium flow in aquifers by C. V. Theis (1935), the reformulation of the basic theory of groundwater flow by M. K. Hubbert (1940), and the behaviour of elastic aquifers by C. E. Jacob (1946). Shortly after the end of this period Polubarinova-Kochina (1952) published a text contaning substantial contributions to groundwater studies by herself and other Russian writers.

In relation to streamflow, major advances were made in the area of replacing empirical formulae by statistcal analysis in the estimation of flood flows. In this area, an extensive monograph described the general practice in the United States shortly after the start of this period (Jarvis et al 1936). A key development on this topic was the application of extreme value statistics to flood flows introduced by Gumbel (1941). In the Soviet Union, a generalised form of the gamma distribution was applied to the same problem by Kritskii and Menkel (1934, 1950). These approaches were developed and generalised by others after 1950. The simple relationship between the frequency of the annual maxima and the frequency of a partial duration series (i. e. peaks over threshold) was derived by Walter Langbein (1949) through the application of a simple limit a theorem in pure mathematics. There were also intersting developments in flood routing at the scale of the channel reach. These included the Muskingum method of flood routing (McCarthy 1939), the method of lag and route (Meyer 1941), and the use of the diffusion analogy (Hayami 1951).

In the area of catchment response, a key development was the introduction of the unit hydrograph method of identifiying the rapid response of a catchment to storm rainfall by L. K. Sherman (1932). The experience in applying the method in these early years is described in a substantial monograph by the U. S. Geological Survey (Hoyt et al 1936). In 1945 C. O. Clark suggested that the shape of the unit hydrolograph could be approximated by routing the time-area-concentration curve of the rational method through a single element of storage (Clark 1945). Ten years later, this paper became the starting point for important theoretical developments in relation to the unit hydrograph approach.

In 1945, Robert Horton at the age of 70 produced his landmark paper linking drainage basin morphology with runoff processes. The remarkable laws of drainage composition postulated in this paper (Horton 1945) sparked off a new line of research in both hydrology and geomorphology that has remained vigorous ever since.

4 Period of Theorisation (1950– 1975)

In the subsequent quarter of a century, hydrologists began to build a body of theoretical results based both on internal developments in hydrology and importations from other sciences. Descriptions of the theoretical basis of hydrologic practice are to be found in relevant sections in the Handbook of Applied Hydrology (Chow 1964). This work also contains two chapters reflecting the position at the time of snow and ice hydrology. Garska on Snow Survey (Chow 1964, Chapter 10, page 10-1 to 10-57) and Meier on Ice and Glaciers (Chow 1964, Chapter 16, pages 16-1 to 16-37). A thorough science-based discussion of processes in physical hydrology is to be found in the book on Dynamic Hydrology by Eagleson (1969). In the area of unsaturated flow, the main advance during this period was the classical theoretical work of Philip (1957, 1969) in relation to ponded infiltration. In some areas no substantial theoretical advance of practical importance was made. Thus, an intensive, careful and detailed study of evaporation from Lake Hefner in the United States using sophisticated instruments and complex physical formulae failed to produce any improvement in prediction over existing empirical formulae based on measurements of vapour pressure deficit and wind speed (Harbeek et al 1954).

In the area of catchment morphology the deterministic formulation of Horton (1945) was replaced by the stochastic formulation of Shreve (1966). Meanwhile, other new ideas were introduced into the discussion including that of entropy (Leopold and Langbein 1962). Langbein also produced a stimulating discussion on the fluvial characteristics of channel geometry as the outcome of a self-regulating system (Langbein 1964, 1965). The classical papers up to this time on river morphology and slope morphology are reprinted in Schumm (1972) and Schumm and Mosley (1972), respectively.

Finally notice should be taken of the first detailed study of the World Water Balance undertaken as a contribution to the International Hydrological Decade of 1965–1974 by the Soviet Union (Korzun et al 1974).

During this period theoretical advances were accompanied by the beginnings of improvements in computation exemplified by Skibitzke (1960, 1963) in analog simulation and Linsley and Crawford (1960) in digital simulation.

5 Period of Computerisation (1975– 2000)

Between 1950 and 1975 both analog and digital computers were used in the simulation of hydrologic systems but from 1975 onwards digital simulation was dominant. One of the earliest examples of such digital simulation was the original Stanford Model (Linsley and Crawford 1960). The move from lumped models to semi-distributed models is exemplified by TOPMODEL using a compound parameter to characterise local topography (Beven and Kirkby 1975) and by the Xinanjiang Model incorporating a storage-capacity curve for the whole catchment (ECCHE 1977, Zhao 1980, 1992). With further development of larger computers and more complex models involving a profusion of parameters, the danger increased of concentrating on more and more detailed simulation at the expense of greater insight into hydrological phenomena through theoretical advances confirmed by field measurements. Nevertheless there have been some notable advances in the past twenty-five years. A good review is available in a special issue of the the Journal of Hydrology (O'Connell & Todini 1996).

A new development belonging to this period was the introduction of the concept of non-Hortonian surface runoff (Dunne and Black 1970). This period also saw the introduction into hydrologic thinking of research into the effect of vegetation on surface fluxes. Good surveys related to this topic are to be found in Sopper and Lull (1967) and in Monteith 1975).

The area in which greatest progress was made was that of stream flow and catchmrnt response where both deterministic and stochastic approaches were used. In the Soviet Union, G. P. Kalinin and P. I. Milyukov used a simplified form of the St. Venant equation for unsteady flow in an open channel to determine the characteristic length of channel reach for which the routing of an input in a channel would be equivalent to routing through a single linear reservoir and went on to suggest that longer lengths be considered as a superposition of such characteristic lengths (Kalinin and Milyukov 1957). Independently, Nash on the basis of the comparison of limiting relationships for cascades of linear reservoirs with data from 90 storm events in Britain suggested the same model for the unit hydrograph of catchment response (Nash 1958, 1960). At the same time the unit hydrograph approach was linked with the theory of linear time-invariant systems and analysed by separating the process of channel flow into separate elements of pure translation (i. e. linear channels) and concentrated subsidence (i. e. linear reservoirs) (Dooge 1959). Towards the end of the period under review, the results from this deterministic approach were summarised in a substantial monograph by the present author (Dooge 1973). The application of non-linear Volterra Series to catchment response was pioneered by Amorocho and Orlob (1961).

Meanwhile, similar progress had been made using a statistical approach. At the beginning of this period, H. E. Hurst used the substantial data the Nile to demonstrate the presence of long term dependency in the series and then examined the phenomenon in other geophysical series (Hurst 1951). The study of stochastic processes in hydrology was stimulated by Matheron (1965) in France, by Kartvelishvilii (1967) in the Soviet Union, by Kaczmarek (1970) in Poland, and by Thomas and Fiering (1962) and by Yevjevich (1972a, 1972b) in the United States. The application of statistical methods to the problem of reservoir storage was pioneered by P. A. P. Moran (1954) and by Barnes (1954) in Australia and by G. G. Svanidze (1974) in the Soviet Union.

In the area of surface fluxes there was the authoritative book on evaporation by Brutsaert (1982). Apart from this, the main tendency relating to precipitation and evaporation has been to extend the scale of interest so as to study the structure of rainfall fields and to link hydrologic models and atmospheric climate models (Eagleson 1982a)

In the area of groundwater hydrology a principal topic of interest has been the upscaling of the micro-scale equations based on continuum mechanics for the case of non-homogeneous aquifers. Typical of these approaches are the work of Freeze (1975) and Gelhar (1976) ing the United States, Delhomme (1979) and de Marsily (1982) in France, and Dagan (1986) in Israel.

In the area of streamflow and catchment response, progress has been disappointing. The separate developments in deterministic and stochastic methods developed in the period 1950-1975 have not been brought together as would have been hoped. Isolated attempts have been made in this direction by Eagleson (1972) in the United States by Klemes (1978) in Canada, and by Zhu (1985) in China but the general response has been disappointing. An example of the use of a stochastic component as part of an otherwise deterministic model is the storage capacity curve of the Xinanjiang rainfall-runoff model (ECCHE 1977, Zhao et al 1980, Zhao 1992).

In the area of catchment morphology there has been considerable progress. A notable achievement was the linking of the shape of the catchment response to the drainage pattern of the catchment through the concept of the geomorphological unit hydrograph. (Rodriguez-Iturbe and Valdez 1979). The whole field has produced a large number of reseach publications in the last two decades. These are too numerous to review here but there is a general survey of the topic in a recent book by Rodriguez-Iturbe and Rinaldo (1997).

A feature of hydrologic research in the last quarter of the century has been concern with problems of a continental or global scales. There have been further comprehensive estimates of the world water balance at both the beginning (L'vovich 1974, Baumgartner and Reichel 1975) and at the end of the period (Shiklomanov 1997). Of more fundamental significance has been the probing of the dynamics of large scale hydrologic processes including internal feedbacks. The main centre for this research has been the Massachusetts Institute of Technology in the United States. Among this work has been the linking of climate, soils and vegetation (Eagleson 1978), the analysis of ecological optimality in large catchments (Eagleson 1986), and the effect of local re-precipitation of evaporated water on persistence of wetness or dryness (Entekhabi et al 1991). The general progress in this area has been summarised by Eagleson (1994)

6 Main Challenges for the Future

The nature of the main challenges facing hydrological research have been very well formulated in the report on Opportunities in the Hydrological Sciences to the U.S. National Research council (Eagleson et al. 1991). However, it would be appropriate to end this outline with a summary of the views of the present author on three important challenges. Firstly, from a purely scientific point of view, a vital problem is the question of scale (Dooge 1986). A fully complete science of water would need to cover a range of scales from the water molecular (10^{-10} metre to the global 10^{8} metre). Since the continuity equation can be expressed in linear form, it can be upscaled or downscaled without the need for a new estimation or measurement of parameters at the new scale of interest. It thus can provide a fundamental theorem of hydrology at all scales. All of the remaining equations of interest in hydrology are non-linear and thus involve difficult problems of scale and also introduce all the complexity of systems with non-linear feedbacks (Dooge 1997). A thorough and innovative synthesis of deterministic methods and stochastic methods will be required to solve this problem.

Secondly, hydrologic theory will remain speculative unless confirmed by reliable data which is relevant to the problem and the scale of interest. The fascination of more powerful computers and the lure of complexity has led to an under-valuation of hydrologic data in recent decades. Financial pressure has in many countries led to a serious reduction in observation programmes and in the processing of data. This trend must be revised in the interest of both theoretical and applied hydrology (Dooge and Kuusisto 1999 pp 4-7).

Thirdly, progress in both theoretical and applied hydrology depends on adequate communication between hydrologists of all specialities, between research hydrologists and scientists in other disciplines, and between hydrologists and decision makers (Dooge 1998). Good partnerships do not arise or flourish automatically. To be effective, they must be worked at and encouraged. Hydrologists must learn to listen to others, to appreciate their concerns, to recognise differences in language and in concepts and to respect the viewpoints of those from other specialities. If we devote a real effort to improving such communicaltions skills, we have a better chance of developing and financing the observation programmes required, and even of making real progress on the daunting problem of the scaling of hydrologic processes.

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20 世纪科学水文学的崛起°

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摘要: 参阅了水文学发展历程中具有里程碑意义的杰出出版物, 评述了水文科学基础的成长历程。将水文学发展史划分四个时期, 每一个时期各有其特点。这四个时期是: (a) 经验时期 (1900～1930); (b) 推理时期 (1930～1950); (c) 理论化时期 (1950～1975); (d) 计算机化时期 (1975～2000)。

关 键 词: 20 世纪; 水文学; 发展; 经验主义; 推理; 理论化; 计算机化

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