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Walter Langbein and the emergence of scientific hydrology

James C. I. Dooge
Centre for Water Resources Research, University College Dublin, Ireland

Abstract. Walter Langbein (1907–1982) contributed to the growth of scientific hydrology in a number of ways. His research publications introduced original concepts of both theoretical interest and practical importance. He served on a number of committees of the American Geophysical Union and played a key role in promoting new approaches in hydrological thinking. He played a major role in the launching of the International Hydrological Decade of 1965–1974 and in the establishment of the International Association of Hydrological Sciences Committee on Mathematical Models in Hydrology in 1967. He was a source of inspiration to many young hydrologists who have since made their own important individual contributions to that discipline. It is timely and useful to look back at his personal contribution to hydrology and to draw lessons on it for our future work.

1. Career Outline

A recital of the bare outline of the career of Walter Langbein (1907–1982; Figure 1) would not leave one with the impression that he was a key figure in the development of hydrology during a critical period in the development of that subject as a discipline firmly based on rational theory and optimal measurement. In 1931, he graduated with a degree of Bachelor of Civil Engineering from Cooper Union; between 1931 and 1935 he worked for the Rosoff Construction Company, where his first contact with hydrology was the control of groundwater by pumping during subway excavations in New York, and from 1935 to 1969 he worked in the U.S. Geological Survey, starting with traditional work on hydrometric surveys and going on to develop a number of major research interests.

The simple structure of his career outlined above inadequately represents his career, as is borne out by the number of prestigious awards he received honoring his work as a research hydrologist. In 1963 he received the J. C. Stevens Award of the American Society of Civil Engineers. In 1969 he received the Bowie Medal, the highest award of the American Geophysical Union (AGU), "for fundamental contributions to geophysics and unselfish cooperation in research." In the same year he received the Warren Prize of the National Academy of Sciences, "for the significant advancement of hydrology and fluviatile geology through geophysics and mathematics." In 1982 he received the International Prize in Hydrology awarded by the International Association for Hydrological Sciences (IAHS) in conjunction with UNESCO and the World Meteorological Organization (WMO).

Langbein himself wrote an outline of the development of hydrologic research within the U.S. Geological Survey (USGS) and thus provided us with a description of the context in which his important work was carried out. In this account [*Langbein*, 1981] he reviewed the significance of the work of the USGS in the hydrological field during four periods, which he characterized as follows: (1) the exploration years from 1880 to 1920, (2) the sideline years from 1920 to 1950, (3) the Sputnik years from 1950 to 1970, and (4) the post-Sputnik years of increasing demands for research results combined with a limitation of funds. The contributions of the USGS during the exploratory years were important in the development of a scientific basis for hydrology. Classical publications include reports and papers on measurement of free surface flow [*Horton*, 1907], on the theory of groundwater flow [*Slichter*, 1899], on the physics of sediment transport [*Gilbert*, 1914], and on the effect of waste disposal on water quality [*Rafter*, 1897].

The sideline years (1920–1950) were characterized by a lack of funds and of a critical mass of research workers so that research remained an adjunct and support to field measurements rather than an activity in its own right. Nevertheless, this

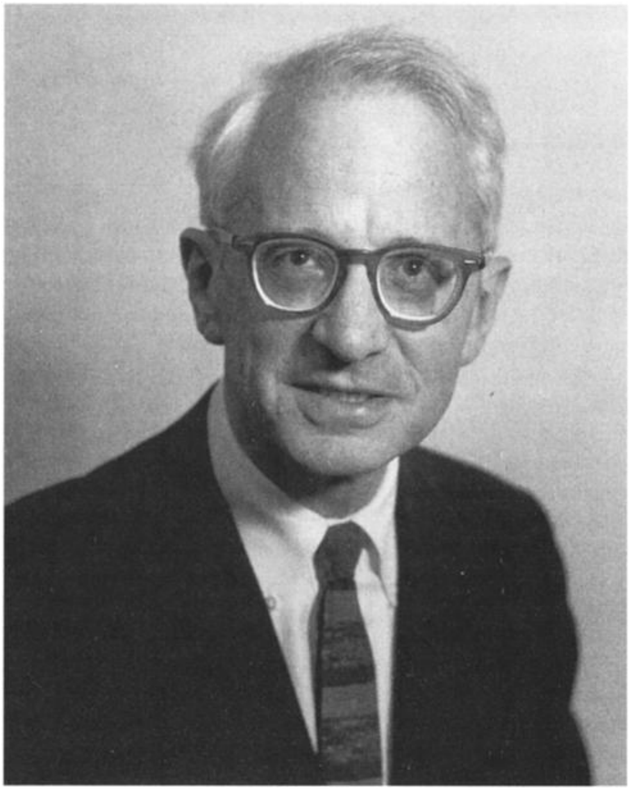

Figure 1. Walter Langbein (1907–1982).

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period saw the emergence from the work of the USGS of milestone publications on groundwater hydrology [*Meinzer*, 1923], on rainfall-runoff relationships [*Hoyt et al.*, 1936], and on flood frequency methods [*Jarvis et al.*, 1936]. All three of these classical works should be required reading for all teachers of hydrology and all who plan careers in hydrologic research. The USGS water supply paper by Hoyt and his colleagues was my own first introduction to the unit hydrograph approach and thus to the systems approach in hydrology. It contained an extensive study of empirical unit hydrographs carried out during the short few years since the introduction of the concept by *Sherman* [1932, 1933].

During the Sputnik years (1950–1970), Langbein, with ten years of research experience behind him, was a key figure. He was either an author or acknowledged as a contributor in the remarkable series of professional papers on geomorphology that emerged from the Water Resources Division of the USGS during that period. These included the reports on the hydraulic geometry of stream channels [*Leopold and Maddock*, 1953], on entropy and landscape [*Leopold and Langbein*, 1962], general systems theory applied to river systems [*Chorley*, 1962], channel geometry [*Langbein*, 1964a], probability concepts in river networks [*Scheidegger and Langbein*, 1966] and river meanders [*Langbein and Leopold*, 1966, 1968]. During the post-Sputnik years, Langbein was officially in retirement but continued to exercise an important influence on the work of the USGS and on hydrology generally through his continued research and publications and through his personal influence in stimulating the innovative work of a younger generation of hydrologists.

2. The Context of AGU

It is impossible to evaluate the career of Walter Langbein or the development of scientific hydrology over the past 60 years without considering the preeminent role of the hydrology section of the American Geophysical Union. When Langbein commenced his research career, the meetings of the hydrology section of AGU represented the major contact opportunity for the research hydrologists scattered throughout the country, and *Transactions, American Geophysical Union*, represented the main outlet for the publication of research papers in hydrology, both for the United States and increasingly for hydrologists from other countries. If we look at the contents of the Transactions for the year 1938, in which Langbein first published in that journal, we can appreciate the importance of AGU in the field of hydrology. Of the 685 pages in the volume for 1938, 68 were devoted to Union activities and 617 to section activities. Of the latter 617 pages, some 431 pages, or 70%, were devoted to the section of hydrology and the remaining 30% to the other five sections.

During the 1930s and 1940s there were virtually no monographs or textbooks in hydrology. To someone like myself, who graduated in 1942, the *Transactions, American Geophysical Union*, formed the basic element of one's self-education in hydrology. This may be illustrated by recalling some of the classical papers that appeared in the Transactions during these years. The developing understanding of the relationship between the elements of the hydrological cycle is reflected in such classical papers as those on infiltration by *Horton* [1933], on discharge recession curves by *Barnes* [1939], on plot experiments of surface runoff by *Sharp and Holtan* [1940], on evaporation by *Holzman* [1941], and on overland flow by *Keulegon* [1944] and *Izzard* [1944]. AGU papers on groundwater that represented key advances in this area were those on nonequilibrium flow in aquifers by *Theis* [1935] and on the behavior of elastic aquifers by *Jacob* [1940]. Important papers on flood formation included those by *Snyder* [1938] on synthetic unit hydrographs, by *Linsley* [1943] on runoff from snowmelt, and by *Bernard* [1949] on the relation between precipitation and runoff. As will be seen later, many of Langbein's own key papers, particularly those on the elements of the catchment water balance, were published in the Transactions.

Apart from papers detailing the results of measurement and of analysis, the Transactions of the AGU contained important reports of research committees. During this critical period, Langbein played an important part in a number of these committees and as a result was in contact with the leading research workers in all fields of hydrology. Thus in 1943 he was chairman of the subcommittee on infiltration in relation to runoff, of the AGU Research Committee on Infiltration. The other members of this subcommittee (H. L. Cook, G. A. Hathaway, R. A. Hertzler, and W. W. Horner) were experts in various aspects of the question of infiltration and well known for their contributions to the subject. In 1946, Langbein was a member of the subcommittee on permeability of the AGU Permanent Research Committee on Groundwater. This brought him in contact with a number of leading figures in hydraulic and hydrologic research, namely B. A. Bakhmeteff (open channel flow), M. K. Hubbert (groundwater hydraulics), O. W. Israelson (irrigation), C. E. Jacob (pumping tests), O. E. Meinzer (groundwater), M. Muskat (flow in porous media), L. A. Richards (flow in the unsaturated zone) and L. K. Wenzel (pumping tests).

Langbein was chairman of the subcommittee on publications format of the AGU in the mid-1950s. In the following decade he was a leading figure in the launching of *Water Resources Research* as "a journal of the sciences of water" and was joint editor in the critical starting period 1965–1969.

Langbein was also at this time Chairman of the Panel on Hydrology of the Federal Council on Science and Technology, which was organized through AGU. The 1961 progress report of this panel stressed four important points that are still vital principles for the organization and advancement of hydrology today. The panel stressed that "hydrology is the examination of the whole continuum of the water cycle conceived as a circle made up of numerous arcs, some of which traverse the domains of other related Earth sciences" [*Panel on Hydrology*, 1961, p. 94]. The view reflected in this statement had an important influence on subsequent developments both nationally and internationally. Equally important was the stressing of the principle that "man is a hydrological agent" (p. 95), which has been widely accepted only in recent years, over a quarter of a century after this particular report. Two other deficiencies that have since been remedied to some extent were also stressed in the report. Thus it states that "deficiencies in hydrologic research may be linked to the deficiencies in formal training facilities in the hydrology as we defined it" (p. 96). There has been improvement in this respect, but the point is still relevant. The link between the efficiency and productivity of research and the nature of formal training is still not universally or adequately recognized. The final principle of importance, that "most hydrologic inquiry in this country, as elsewhere, has been provincial" (p. 96), has largely been overcome, and Langbein was himself influential in producing an improvement in this regard.

Langbein, together with L. Leopold and R. Nace, his colleagues in the Water Resources Division of the USGS, played a leading role in the discussions leading up to the establishment by UNESCO of the International Hydrological Decade of 1965–1974 and the subsequent succession of international hydrological programs which have done so much to encourage international cooperation in data gathering and in research in hydrology. Langbein also played a key role in the formation in 1967 of the Committee on Mathematical Models in Hydrology of the International Association of Scientific Hydrology (IASH; the name was changed to International Association of Hydrological Sciences in 1971 on Langbein's recommendation) when he acted as chairman of a special ad hoc group which recommended to the Berne General Assembly of IASH the establishment of such a committee. I can testify personally that without his support and influence, this initiative which I undertook to provide a bridge between research workers in Eastern Europe and the West on new approaches in hydrology would have had great difficulty in becoming firmly established.

3. Elements of the Hydrological Cycle

The earliest paper by Langbein available to me is a study entitled "Some channel-storage studies and their application to the determination of infiltration" [*Langbein*, 1938]. In this early paper, Langbein was concerned to apply the ideas of R. Horton on the role of infiltration in the hydrological cycle to measured flows in the Ohio River in January 1937. The paper compares six empirical methods for determining the duration of significant rainfall such that the division of the total infiltration by this duration will yield the correct value of the infiltration capacity and satisfy the requirement that the total rainfall in excess of the infiltration capacity be equal to surface runoff.

In another paper 2 years later, *Langbein* [1940] concentrated on the channel phase of the rainfall-runoff relationship. This study was related to the Muskingum method of flood routing recently introduced by *McCarthy* [1938] (cited by *Linsley et al.* [1949, p. 502]). It is of interest to note that in the case of one of the two examples shown (the North Platte River between Bridgeport and Lisco in Nebraska), the flood movement along the 28-mile reach conforms closely to uniformly progressive flow. Langbein commented that the data indicate the reach is too long for the direct application of the Muskingum method and split the reach into two sections for further analysis. The plotted data indicate a value of the weighting factor of $x = 0.47$. This real world example of a close approximation of uniformly progressive flow [*Langbein*, 1940, p. 623] has been very widely used to illustrate flood wave translation, typically by *Linsley et al.* [1949, p. 48, and subsequent editions]. In this paper, Langbein also commented that the lag interval in unit hydrograph studies should be defined as the lag between the center of mass of effective rainfall and the centre of mass of direct runoff, and he presented an average S hydrograph in terms of a dimensionless time based on a lag defined in this way.

Later papers by Langbein on elements of the hydrological cycle contain further original concepts. Typical of these is his paper on "Monthly evapo-transpiration losses from natural drainage-basins" [*Langbein*, 1942a], in which he dealt with the problem of estimating monthly evapotranspiration at the catchment scale. He suggested that in the absence of basin-wide direct measurements of evaporation and transpiration and of field moisture, an estimate of the monthly evapotranspiration can be made on the basis of the following three assumptions: (1) the rate of evapotranspiration of loss is proportional to the evaporating power of the atmosphere, (2) the rate of losses is directly related to the volume of field moisture (including water on the ground and vegetal surfaces) existing at a given time, and (3) the volume of field moisture is related to the rate of base flow. The combination of these first two assumptions is equivalent to the Budyko bucket used in the early attempts to incorporate the influence of the land surface in global climate models [e.g., *Manabe*, 1969]. The paper represents early attempts at a conceptual model linking subsurface storage with land surface fluxes and subsurface outflow. Another interesting example of new concepts due to Langbein is his paper on "Computing soil temperatures" [*Langbein*, 1949a], which, by analogy with flow estimation, treats the variation in temperature in temperature at given depths in the soil as a response to the variation in surface temperature.

Langbein showed an early interest in flood flows and the factors responsible for their magnitude and variation, including the now fashionable topic of climate change. In a joint paper with W. G. Hoyt, "Some general observations of physiographic and climatic influences on floods" [*Hoyt and Langbein*, 1939], flood events are analyzed with respect to three fundamental factors: (1) the precipitation in the form of rain or snow which may depend on temperature and physiographic features, (2) the soil conditions in the basin, and (3) basin characteristics and channel characteristics. Hoyt and Langbein pointed out that each of these factors is influenced by both climate and physiography. In a later paper on "The yield of streams as a measure of climatic fluctuations" [*Hoyt and Langbein*, 1944] the same authors present the results of the analysis of more than 4000 station year records in North America for the period 1911 to 1942. The decrease of annual stream flow in the Pacific Northwest between 1895 and 1945 was studied by *McDonald and Langbein* [1948]. In their paper, the application of correlation techniques indicates the dependence of annual runoff on both the short-term weighted precipitation and the long-term weighted precipitation, indicating substantial storage effects in the region.

The compilation of "Topographic characteristics of drainage basins" carried out by *Langbein et al.* [1947] under the U.S. Federal Works Progress Administration (WPA) between 1939 and 1941 is reported in a paper (prepared in 1941 but not published until after World War II) which has been heavily drawn on since its publication. Prior to this study, there had been only a few sporadic attempts to link runoff and basin characteristics based on small data sets. The WPA study was notable for its comprehensive coverage and careful design. Selected topographic features for 340 drainage basins in the northeastern United States, varying in extent from 1.64 to 7797 square miles (4.25–20,194 km^2) were compiled. The features listed are basin area, stream density, area-distance distribution, length of basin, land slope, channel slope, area-altitude distribution, and area of water surfaces. The rationale behind the choice of each characteristic and the method of measurement are systematically discussed in the paper [*Langbein et al.*, 1947, pp. 133–142].

The publication "Annual runoff in the United States" [*Langbein et al.*, 1949], which is also often cited in later work, contains a map of runoff isograms for the United States for the 25-year period 1921–1945. Also included in this publication is a figure relating the mean annual runoff to the mean annual precipitation for various values of mean annual temperature.

This chart was later used to provide the basis of one of the earliest estimates of the effect of climate change on catchment runoff [*Revelle and Waggoner*, 1983]. In another paper [*Langbein*, 1950] the relationships between long-term changes in water supplies and changes in climate are discussed. In a particular study of the eastern United States, *Langbein* [1950] concluded that the instrumental records of precipitation and temperature since about 1850 indicate substantial variation and a clear trend, whereas the records of the stream flow since 1863 show a slight relative lowering with respect to climatic factors. It is concluded that this problem can only be resolved by the establishment of "key gauging stations on the natural streams, carefully operated with a view to maintaining consistent longterm records of stream flow as independent as possible from any influences of man" [*Langbein*, 1950, p. 814]. Langbein's concern for the careful planning of data networks as vital both for the evaluation of theoretical speculation and for the efficient design of water resource projects is evident in this as in many other of his papers. Later papers deal with elements of the hydrological cycle related to paleoclimate and floods [*Langbein*, 1964a] and with groundwater [*Langbein*, 1968].

4. Hydrology and Water Resources

One of Langbein's strengths in his approach to hydrologic problems was that he was conscious of the link between theory and practice and alert to the need for interaction between them. This is well illustrated by his remarkable two and a half page paper on "Annual floods and the partial-duration flood series" [*Langbein*, 1949b]. This paper uses the result from pure mathematics [*Hardy*, 1945, pp. 410–411]

$$\operatorname*{Limit}_{n\to\infty}\left[1-\frac{\varepsilon}{n}\right]^{n}=\exp\left[-\varepsilon\right] \tag{1}$$

to provide an asymptotic relationship between (1) the probability of a flood of a given magnitude being an annual flood and (2) the expectancy of a flood of this magnitude among all floods in the partial duration series. A number of actual cases are plotted that reveal the predicted approximation of the two values for higher recurrence intervals, the validity of the calculated relationship as a bounding value at smaller recurrence intervals, and the slight effect of persistence in giving somewhat higher values for the recurrence interval in the annual flood series compared with that predicted from the partial duration series. In a discussion of this paper, *Chow* [1950] pointed out that on this hypothesis the extreme value distribution of *Gumbel* [1941] would correspond to a single exponential distribution for the partial duration series and consequently the relationship between discharge and recurrence interval in the partial duration series would plot as a straight line on semilogarithmic paper. The *Langbein* [1949b] paper is notable as an example of a penetrating analysis based on a search for simplicity that justified the use of annual series for the study of infrequent events and could serve as a model for hydrologic researches today.

Langbein was interested not only in the measurement of hydrologic data and the understanding of the hydrologic processes but also in the application of hydrologic knowledge to real problems. In this he emphasized the need for a balance between theory and application and the importance of the interaction between them both. Thus one can consider together two papers of his published during the first half of the Water Year 1958–1959 dealing with problems of reservoir storage and stream flow. Langbein had published an earlier paper in the *Journal of the American Water Works Association* on "Municipal water use in the United States" dealing with the problem from a classical point of view [*Langbein*, 1949c]. Nine years later he published a paper on "Queuing theory and water storage" [*Langbein*, 1958a] that suggested the replacement of the classical mass diagram method of analysis due to *Rippl* [1883] by techniques based on queuing theory as used in operations research and thus extended the classical work on the theory of storage by the Australian statistician *Moran* [1954]. It is interesting to note in passing that Moran stimulated and interacted with Australian engineers such as B. W. Gould and C. H. Munro who were primarily interested in water resources development.

Langbein [1958a] established clearly the analogues in the reservoir control problem of the operations research factors of arrival rate, queue discipline, service function, and attrition rate. He illustrated the approach by four examples: (1) a simple analytical solution for a normally distributed inflow and a linear relationship between discharge and storage, including the effect of nonrandom distribution of inflows in increasing storage requirements, (2) solution by probability routing for a case of nonnormal distribution of inflows and an irregular service function, (3) the reworking of example 2 to incorporate upper and lower bounds to the storage, and (4) the incorporation of seasonal effects by a simultaneous solution of the 12 separate sets of monthly queuing equations.

In a parallel paper [*Langbein*, 1959], he studied the relation between storage capacity and reservoir regulation for a representative set of actual reservoirs with detention periods (ratio of usable capacity to mean annual flow) ranging from 0.01 to 21.8 years. The corresponding ratios of regulated flow to mean annual flow range respectively from 6%, which approximates run-of-the-river conditions, to 91%, which is almost certainly higher than the economic optimum for storage development. Figures are tabulated for the detention period in years and for the mean annual regulation (the amount of water that is stored or released in a year) and the ratio of the mean annual regulation to both the reservoir capacity and to the mean annual flow. The plots of the regulation/capacity ratio against detention period and of the regulation/flow against the detention period both indicate well-defined relationships despite the significant differences in the regime of the streams involved and the manner of operation of the reservoirs. The data for the detention period as a function of the regulation/flow ratio are fitted by an equation of the form based on the analogy with queuing theory discussed in the previous paper [*Langbein*, 1958a]. On the basis of the plotted results, Langbein estimated that reservoirs with capacities of about 0.17 of a year's flow would have their full capacity utilized about once each year on the average. For smaller capacities, the storage would be used more than once a year. The results are applied to estimating the amount of storage required in the United States for purposes other than flood control per se. They concluded that a considerable increase in useful water supply could be attained in the eastern United States but that some drainage basins in the western United States may already have been approaching the limit in which the benefits of additional storage are offset by increased evaporation.

Langbein's work at this period was not confined to studies of quantitative hydrology but also concerned itself with questions of water quality. His interest in reservoir capacity and in the effect of climatic change on water resources development is reflected in the paper "Yield of sediment in relation to mean annual precipitation" [*Langbein and Schumm*, 1958]. This paper is a good example of the benefits to be derived from a skillful organization of data to reveal dominant relationships in contrast to the automatic use of a software routine. The annual sediment loads from about 100 sediment gauging stations were plotted against effective precipitation, i.e., the amount of precipitation required to produce the known amount of runoff. The previous work of *Langbein et al.* [1949] linking precipitation, runoff, and temperature was used to standardize the data to effective precipitation based on a reference temperature of 50°F (10°C). The variation of annual sediment yield with effective precipitation obtained in this way was then compared with that obtained by relating annual sediment yield to effective precipitation on the basis of records of deposition of sediment in reservoirs. The resulting curve was quite similar in shape to that obtained from the records of suspended sediment measured at river stations, and the values for reservoir deposits were in general about twice as large. This difference was attributed to the omission of bed load from the figures for sediment gauging stations and the fact that most reservoirs are built in terrain with steep slopes, which would give higher rates of net erosion. Both plottings show a maximum sediment yield at an annual effective precipitation of about 12 inches (305 mm) which recedes to a uniform yield from areas with more than 40 inches (1016 mm) of effective precipitation. The authors suggested that the variation is the result of the interplay of two factors: (1) increased precipitation has a direct impact in soil erosion and also generates runoff with a further capacity for erosion and transportation, and (2) vegetation, which retards erosion, tends to increase with increased effective annual precipitation. An attempt is made to derive an empirical relationship based on power law representation of each of these two factors. At the present, when there is a good deal of discussion on the question of the effect of climate change on water resources without reference to the effect of vegetation, it would be timely to revisit this paper.

Other aspects of water quality with hydrologic and climatic implications were also of interest to Langbein. *Langbein* [1961] discussed the variation of the salinity of closed lakes and possible mechanisms for the loss of salt dissolved in the lake which offset the hydrologic processes of lake inflow and lake evaporation that tend to build up the salt content. Langbein typically prefaced his own opinions by a survey of key speculations and contributions from the literature and in this instance quotes *Halley* [1715], *Gilbert* [1890], and *Hutchinson* [1937]. The question is examined as to whether the historical fluctuation in lake levels due to climatic and hydrologic variability is matched by an analogous fluctuation in salinity rather than a continual increase in salinity. Evidence is quoted for the record of Devil's Lake in North Dakota between 1899 and 1948 and for Lake Eyre in South Australia, which suffered a catastrophic decline and drying out between 1950 and 1952. In each case, the mass of salts in solution appears to decrease with contraction in lake and volume. Typically, Langbein determined the appropriate scale at which to analyze the problem and sought an empirical relationship based on his data as a basis for further study of the problem.

A later paper by *Langbein and Dawdy* [1964] supplements this work and deals with the relationship of dissolved solids and the distinction between the three elements of the dissolved load in streams, the suspended load in streams, and the lake constituents. Langbein probably came closest to dealing with the relationship between water quantity and water quality in a joint paper on "The aeration capacity of streams" [*Langbein and Durum*, 1967].

Langbein was one of the first hydrologists to emphasize the importance of socioeconomic impacts of hydrologic phenomena. In an early paper on "Flood insurance" [*Langbein*, 1953] he pointed out that floods are almost the sole natural hazard not insurable by the industrialist or the home owner, and there is a need for the problem to be subjected to adequate analysis based on sound hydrologic principles and sound actuarial principles. He called for a pilot experiment carefully designed to explore whether there is a potential market, whether the method of determining risks can be simplified, and whether politics could be kept out of the process. This paper [*Langbein*, 1953] discussed such key problems as the amount of flood damages in the United States in the first half of this century, the actuarial problem of evaluating the risk on the basis of flood magnitude and flood frequency, the reliability of flood frequency estimates, and the relative advantages of private and government insurance. This was followed by a book coauthored by W. G. Hoyt which surveyed the whole problem of floods and was addressed to all sectors of the community who should be concerned in the matter [*Hoyt and Langbein*, 1955]. He maintained his interest in this general topic in a short monograph on the actual operation of the Erie Canal [*Langbein*, 1976] and his coauthorship of a USGS publication on flood insurance [*Edelen et al.*, 1979]. His choice of the Erie Canal as an enterprise for the study of actual operation was apparently due to his wish to avoid criticism that might be hurtful to living persons.

5. Research on Channel Geometry

Some of Langbein's the most comprehensive and influential research work was on the linkages between hydrology and geomorphology. His papers in this area cover a period of almost 40 years. They include work on hydraulic criteria for sand waves [*Langbein*, 1942b], the yield of sediment [*Langbein and Schumm*, 1958], his cooperation with L. Leopold in the classic monograph on entropy and landscale evolution [*Leopold and Langbein*, 1962], the hydraulic geometry of shallow estuaries [*Langbein*, 1963], a chapter with Leopold on association and indeterminacy in geomorphology [*Langbein and Leopold*, 1964], his classic work on the geometry of river channels [*Langbein*, 1964b, c], his theory of minimum variance applied to river meanders [*Langbein and Leopold*, 1966a, b], his work with A. Scheidegger on probability concepts in geomorphology [*Scheidegger and Langbein*, 1966a, b], on a random-walk approach to hydraulic friction [*Langbein*, 1966], and on the theory of kinematic waves applied to river bars and dunes [*Langbein*, 1968]. To discuss all of these would not be possible within the compass of a single publication, and accordingly, his approach will be illustrated by a discussion of his 1964 paper on the geometry of river channels.

Langbein's [1964c] paper on the geometry of river channels, supplemented by his closure to the discussion [*Langbein*, 1965a], illustrates his original approach to the problems of fluvial geomorphology based on the theory of self-regulating systems. He starts from the approach of hydraulic geometry of channels introduced by *Leopold and Maddock* [1953], which assumes relationships between channel properties and bankful discharge Q of the following type

Average velocity $$v \propto Q^m \qquad (2a)$$

Average depth $y \propto Q^f$ (2b)

Average width $w \propto Q^b$ (2c)

Average slope $S \propto Q^z$ (2d)

in which the exponents, m, f, b, and z are determined from systematic data. The requirement of continuity is basic so that

$$m + f + b = 1 \tag{3}$$

For the solution of any problem of channel formation, it is necessary to postulate other equations based on the dynamics of that particular problem. Langbein did this by applying the principle of equable action, i.e., by minimizing the variance of a number of dynamic variables. Because these indices approximate to the coefficient of variation of the respective factors under near equilibrium conditions, Langbein used the exponents themselves rather than these coefficients of variation in his analysis. The dynamic variables used are

Boundary shear $(\gamma y S) \propto Q^{f+z}$ (4a)

Friction factor (Chezy)

$$\left(\frac{gyS}{v^2}\right) \propto Q^{f+z-2m} \tag{4b}$$

Friction factor (Manning)

$$\left(\frac{gy^{4/3}S}{v^2}\right) \propto Q^{(4/3)f+z-2m} \tag{4c}$$

and five measures of stream power (per unit length, per unit volume, per unit bed area, per unit discharge, per unit time of stream travel). Langbein applied this approach to a number of cases, with extremely interesting results. In the present account, attention will be concentrated on three of these cases: (1) flow in a two-dimensional flume, (2) flow in a canal regime, and (3) flow in a graded river.

In the case of a two-dimensional flume the continuity constraint of equation (3) reduces to

$$m + f = 1 \tag{5}$$

and one further condition is required to determine the values of m and f. If the hypothesis is made that the dynamic adjustment involves only the velocity and the depth of flow, then from (2a) and (2b) and the simplification of replacing the variance by the exponent, we have the condition

$$m^2 + f^2 = \text{minimum} \tag{6}$$

Substitution from (5) into (6) gives us a minimization problem in terms of a single variable as follows:

$$m^2 + (1 - m)^2 = \text{minimum} \tag{7}$$

which is easily shown to have a solution $m = 0.5$ and consequently $f = 0.5$ from (5).

This simple analysis thus gives the aesthetically pleasing result of equipartition of variance between the velocity and the depth of flow. When compared with the classic flume studies in the literature [e.g., *Simons et al.*, 1961], this result is seen to give a close but not entirely satisfactory prediction, since these comprehensive series of studies give the results

$$0.45 < m < 0.48 \tag{8a}$$

$$0.52 < f < 0.59 \tag{8b}$$

If the hypothesis is now modified to include a simultaneous minimization of boundary shear and of the friction factor, it is necessary to express these factors in a fashion similar to (2). This is done by introducing the standard dynamic relationships for shear τ and for the Manning friction factor M

$$\tau \propto Q^{f+z} \tag{9a}$$

$$M \propto Q^{(4/3)f+z-2m} \tag{9b}$$

When these factors are included, the requirement of minimum variance accordingly becomes for the case of a constant flume experiment (i.e., $b = 0$ and $z = 0$)

$$m^2 + f^2 + f^2 + (\tfrac{4}{3}f - 2m)^2 = \text{minimum} \tag{10a}$$

Substitution from (5) into (10a) gives us the equivalent dynamic requirement

$$\frac{127}{9}m^2 - \frac{116m}{9} + \frac{34}{9} = \text{minimum} \tag{10b}$$

which is easily solved to give $m = 0.457$ and, consequently, $f = 0.543$. The latter two values are seen to fall within the range found from the classical flume data indicated in (8) above.

In contrast to the case of two-dimensional flow in a flume of fixed slope where both the width and the slope are constrained (i.e., $b = 0$ and $z = 0$), the width is self-adjusting in the case of canals in regime [*Lacey*, 1930] and of graded rivers [*Mackin*, 1948]. The freedom of the slope to vary means that some further property is required. The constraint of continuity takes the full form of equation (3), and two further equations or conditions are required to solve the problem in contrast to the single extra condition in the case of a flume of constant width and constant slope. Langbein postulated that one should be a minimization of the variance of stream power. However, he pointed out that there are five aspects of stream power: stream power per unit length, stream power per unit volume, stream power per unit bed area, stream power per unit discharge, and stream power per unit time of stream travel. He suggested that all five be considered and that the minimization of the total variances be applied.

For the case of canals in regime he used the constraint of uniform sediment concentration in the form

$$f = 2m \tag{11}$$

and combined this with the requirement of minimization of the variance in boundary shear τ from (4a) and a Chezy friction factor from (4b) which takes the form

$$(f + z)^2 + (f + z - 2m)^2 = \text{minimum} \tag{12}$$

Substitution from the constraint of uniform sediment concentration represented by (11) into the slope adjustment condition of (12) gives

$$(2m + z)^2 + z^2 = \text{minimum} \tag{13}$$

which has the solution $z = -m$ appropriate to the equipartition solution for the case of two variables. The cross-sectional adjustment is assumed to depend on the five aspects of stream power, which gives us the requirement

$$(1 + z)^2 + (m + z)^2 + (m + f + z)^2 + z^2 + (1 + m + z)^2 = \text{minimum} \tag{14a}$$

or from (11)

$$(1 + z)^2 + (m + z)^2 + (3m + z)^2 + z^2 + (1 + m + z)^2 = \text{minimum} \quad (14b)$$

Substitution of the result $z = -m$ for the solution of (13) into (14b) gives the single relationship for the exponent m as

$$6m^2 - 2m + 2 = \text{minimum} \quad (15)$$

which can be easily solved to give $m = 1/6$ and consequently $f = 1/3$ and $z = -1/6$. Substitution of the latter values for m and f in the continuity constraint given by (3) gives us the final value $b = 1/2$. There is a long tradition in the study of regime canals in homogeneous noncoherent materials. The values of the exponents derived by the techniques of statistical mechanics using the above assumptions correspond exactly to those found empirically in the canal measurements in India and elsewhere and recommended for use in canal design [*Lacey*, 1930, 1958].

In the third case of a graded river, both the width and the slope are self-adjusting. In this case, Langbein suggested two sediment assumptions: (1) that load per unit width is proportional to the cube of the velocity [*Colby*, 1964] and (2) that load per unit volume is proportional to the fourth root of the channel slope. These combine to give the sediment constraint [*Leopold and Langbein*, 1962]

$$f = 2m - z/4 \quad (16)$$

which is used in conjunction with the full form of the continuity constraint of (3) and the same constraint of equable action in relation to stream power used in the case of the regime canal and given by (14). The values of the exponents m, f, and b obtained by this analysis correspond closely to those suggested by *Leopold and Maddock* [1953] based on data for rivers assumed to be graded. Thus for velocity the analysis gives $m = 0.123$ for the velocity exponent compared with 0.10 for the data. Analysis gives an exponent of 0.383 for the depth, compared with 0.40, and 0.494 for the width, compared with 0.50. *Leopold and Maddock* [1953] found the value of the slope exponent z to vary between −0.49 and −0.95 compared with *Langbein*'s [1964c] theoretical value of $z = -0.553$.

6. Data Networks

In view of his work on stream gauging in the beginning of his career with the USGS, it is no surprise that Langbein maintained an interest in data networks throughout his career, and equally it is no surprise that his approach to the problem broadened and deepened during that time. In 1954 he presented two papers on this topic, one on the general topic of stream gauging networks at the Rome General Assembly of the International Association for Scientific Hydrology [*Langbein*, 1954a] and the second on the topic "How long should gauging stations be operated?" at the Western Snow Survey Conference [*Langbein*, 1954b]. In a 1958 paper at the American Society of Civil Engineers, he stressed the need for a proper division of effort between the collection of data on the one hand and the correct analysis and use of data on the other. He ended this paper saying [*Langbein*, 1958b, 1809-6]

> "We have seen that the early appeals for collection of basic data by massive attack as the sole means for solving problems were a matter of concern as early as 1867. It must be clear that the usefulness of extensive programmes for the collection of basic data depends on correct and timely interpretation of the data. The matter appears to be one of emphasis. An equally eloquent plea can be made for more analyses of principles and for more sensitive data. A basic-data programme can go wrong when there is an imbalance on either side.

This concern for balance recurs in many of his later writings on this general topic. In 1959 he once again collaborated with W. G. Hoyt to bring these considerations to a wider public [*Langbein and Hoyt*, 1959]. In the introduction to this work they pose as a focus of the study the three leading questions:

1. Do the existing basic data programs provide information fast enough and efficiently enough?
2. Is the grasp of relationship keeping up with the amassing of the facts? Is routine fact gathering being overstressed at the expense of research that might lead to programs of better design?
3. Is the best use being made of what is already known, or "old" data? For instance, are they being critically reviewed for what they might reveal about water behavior? Is water development going ahead without using all the information available?

The book itself is divided into two parts. The first describes the origins and the present usefulness of data programs in the field of hydrology under the heading of "Gathering Data" and the second part deals with how data are used to solve water problems under the heading of "Data in Action."

Following his retirement from the U.S. Geological Survey, Langbein continued to interest himself and to publish in the field of data networks. In 1965 he presented the opening general statement on "National networks of hydrological data" to the first international symposium on the subject of network design [*Langbein*, 1965b]. He opened this statement by describing the collection of basic data as an attribute of intelligent sovereignty and suggests that the new countries of the world could learn a good deal in this respect from the experience of older countries. He went on to stress three important lessons: (1) that programs of basic data are profitable and essential for the promotion of sound development, (2) that organizational problems such as the linking of basic data are more effectively carried out in organizations that have no responsibility in water development because of such factors of unconscious bias in data policy and competing concerns at critical times, and (3) that maximum information can be attained for the available investment of time and money if the network is efficiently designed and efficiently operated. He discussed each of these problems in some detail.

In a later paper written on the occasion of the Jubilee of IAHS [*Langbein*, 1972b] he stresses impartiality, relevance, and continuity as the three intrinsic properties of water data providing a link with the past and a sound basis for future action. He defines impartiality as freedom from influence by prior constraint or accuracy in the sense of truth rather than precision, defines relevance as utility in relation to some present or prospective purpose or problem of society, and stresses continuity as important because a hiatus in the program breaks the timescale of water which is a flow resource. The paper goes on to discuss these three attributes of a basic data program in the light of organizational influences and in relation to major classes of use of the data. In 1971 he was joint author of a paper on the important topic of linking design of data networks and modeling [*Matalas and Langbein*, 1976].

A year later, he is again encountered addressing an international audience as the senior author of "A note on costs of collecting hydrometric flow data in the United States" [*Langbein and Harbeck*, 1974]. The purpose of this note was stated as being to provide a general indication of the levels of cost for hydrometric work in the United States with a view to inducing greater attention to the factors of cost and to promote reaction to them when they appear out of line. The data, based on four of the forty-seven district offices of the USGS, give figures of installation costs and publication costs.

Ten years after his retirement he was still stressing many of these same points in an "Overview of conference on hydrologic data networks" [*Langbein*, 1979]. In this overview, Langbein once more demonstrated his powers of synthesis, which are also apparent in many of his closures to discussions when he absorbed the contributions of others and deepened his final thinking on the topic. Once more he stressed the need for network design to broaden its perspective rather than concentrate efforts on the deeper penetration of topics more relevant to past problems. He wrote of (1) the importance of strategy rather than tactics, (2) the gap between research and application as being as dangerous as the lack of information, with the possibility of economics as a bridge between the supplier and the users of data, and (3) the effect of the departure of hydrologic systems from a natural condition, and many others. Among his recommendations is the auditing of existing networks to see how well they fulfill their objectives as originally stated and as now perceived. He suggested that an outline of such an audit might be (1) description of the network and its financing and identification of its uses, (2) definition of the network objectives as perceived over time, (3) assessment of the errors of estimate of parameters as applied in the use of the data, (4) analysis of the results, efficiency of network, redundancies and gaps, and use of data transfer, and (5) a study of the implications of the network for public policy and the effectiveness of water programs, including the validity of claims of lack of data.

7. Conclusion

The career of Walter Langbein illustrates many of the elements that characterized the immense contribution of U.S. hydrologists and of the American Geophysical Union to the emergence of hydrology as a discipline based on scientific principles. This was supplemented by initiatives in regard to international cooperation, both formal and informal. As we move toward a further consolidation of that process, it is instructive to review the history of that period. The development of computer technology has not removed the necessity for theoretical studies based on insight and aimed at deeper understanding, or for data networks that are well planned and well maintained. Indeed, such developments often tempt us to ignore these essentials in favor of multiparameter models of doubtful provenance and relevance. A retrospective contemplation of the careers of Langbein and his contemporaries is useful in reminding us of certain first principles in seeking to make fundamental advances in our discipline. If we can contribute even a fraction of what Walter Langbein contributed in his time to that discipline, we will have done well.

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J. C. I. Dooge, Department of Civil Engineering, Earlsfort Terrace, University College Dublin, Dublin 2, Ireland.

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