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13

The Nineteenth Century

INTRODUCTION

The rapid increase of knowledge in the field of hydrology during the nineteenth century is indeed remarkable. The experimental methods, that were successfully pioneered by Perrault, Mariotte and Halley in the seventeenth century had already taken firm roots, and, undoubtedly, the major developments during the nineteenth century were in the fields of ground water hydrology and surface water measurements. At the beginning of the century, the French School was still the leading one in the field of hydrology and hydraulics, but it had a rather bad experience due to the French Revolution. The Revolutionary Government suspended the Académie des Sciences in 1793, executed scientists like Lavoisier, Bailly and Cousin, and drove Condorcet to suicide. Fortunately for science, the authorities quickly realized their mistakes. Men like Du Buat, who had to flee from France to save his life, later returned to their native land, and continued to carry on their admirable work.

VELOCITY-DISCHARGE FORMULAE

The Chézy equation remained almost unknown until 1897 the end of the nineteenth century, the prevailing stream-velocity equation was that which had been conceived by Du Buat. The main problems of this period were concerned with the function relationship between velocity (and hence, discharge) and the frictional resistance. Many different theories were advanced and they produced numerous formulae that attempted to relate velocity, hydraulic gradient and the hydraulic radius. Notable among the contributors were Baron Gaspard Clair François Marie Riche De Prony (1755–1839) and Pierre Simon Girard (1765–1836) from France, and Johann Albert Eytelwein (1764–1848) from Germany.

De Prony, born in Chamelet near Lyons, was associated with several engineering works in France and Italy. He was a student of Chézy, and later received an appointment as Director of the Ecole des Ponts et Chaussées. Girard was a native of Caen, and a graduate of the Ecole des Ponts et Chaussées. He took part in Napoleon’s Egyptian campaign, and was later appointed water commissioner of Paris. The German, Eytelwein, was born in Frankfurt. He was connected with the construction of various river regulating works and harbours. He translated many books on hydraulics into German, including that of Du Buat. His book *Handbuch der Mechanik fester Körper und der Hydraulikl*,[1,2] was published in 1801. His later work on hydrostatics,[3] published in 1896, had considerable influence on the hydrologists and hydraulicians of his country. It was accepted as a standard work in that field well into the early part of the twentieth century. The basic theory of all the early nineteenth century discharge formulae was expressed in a paper[4] published in 1800 by Charles Augustin De Coulomb (1736–1806). De Coulomb fastened discs of various sizes onto the lower end of a brass wire, and immersed them into different liquids. The law of resistance was determined from the rate of damping of the rotational oscillation of the discs. From his elaborate experimentation, De Coulomb concluded that the resistance can be represented by a function containing two terms, one of which varied with the first power of the velocity, and the other with its second power.

In 1803, Girard[5] was the first to apply De Coulomb's law of resistance to the flow of water in rivers and channels, but he used the same value of the numerical coefficient for the both powers of the velocity, i.e.,

$$gRS = C(V + V^2).$$

He made only cursory attempts to test the validity of the equation and of the value of the constant C.

The following year, De Prony discussed a series of formulae[6] for evaluating the flow of water in open channels as well as through orifices. He concluded that De Coulomb's law of resistance was a part of the infinite series:

$$C + aV + bV^2 + cV^3 + \dots$$

The mean velocity V was determined from the surface velocity U,

$$V = 0.816458U \text{ (approximately } \tfrac{4}{5}U).$$

De Prony,[7] unlike Girard, used two separate coefficients in his resistance formula:

$$RS = 0.0000444499V + 0.000309314V^2.$$

Another pair of coefficients was suggested in 1818 by Eytelwein:[8]

$$\mathrm{RS} = 0.000024\mathrm{V} + 0\text{-}000366\mathrm{V}^2.$$

Those two coefficients were assumed to be independent of the extent of boundary roughness. While De Prony's coefficients were widely accepted in France, Eytelwein's formula received more favour elsewhere. For higher velocities, the latter can be reduced to the Chézy type by assuming the resistance to be proportional to the square of the velocity, i.e.,

$$V = 50.9\sqrt{RS}$$

The equation, with the coefficient 5o, became quite popular in Italy in the 1830's. There it was known as Tadini formula. Courtois[8] expressed his approval of it in 1850.
Also, in 1845, Lahmeyer[9] tried to provide for the effect of curvature in the channels. For a radius *r* and width *w*, the equation he suggested was:

$$\frac{RS}{V^{3/2}} = 0.0004021 + 0.002881\sqrt{\frac{w}{r}}.$$

For a straight channel r = ∞ ad hence,

$$V = 49.87V^{1/4}R^{1/2}S^{1/2}.$$

The following year De saint-Venant[10] offered another formula with tables for facilitating quick computations:

$$V = 60(RS)^{11/21.}$$

His equation, however, does not seem to have been used very much. Eytelwein analysed the experimental results reported by Leonardo Ximenes (1716–1786) of Italy and those of Christiaan Brünnings (1736–1805) of Holland to obtain velocity distribution profiles – but the results turned out to be contradictory. He finally suggested a linear variation. The velocity *v* at a depth *d* from the water surface was expressed by:

$$V = (1 - 0.0127d)U.$$

Darcy and Bazin

Henry Philibert Gaspard Darcy (1803–1858) was born in Dijon, and was educated in Paris. Several years prior to 1850, Darcy was concerned with the design and the construction of a public water supply system for the municipality of Dijon. The detailed report on the project,[11] published in 1856, contained technical information as well as historical background, legal considerations, and a series of appendices. The venture was so successful that he was later retained by the city of Brussels to advise on a similar project.

Around 1855, a growing nervous disorder made Darcy relinquish everything but his work on hydraulics. He had an able assistant[12] in none other than Henri Emile Bazin (1829–1917). When Bazin had been stationed in Dijon, in 1854, he had requested a transfer to Darcy's staff. Between them, they set up the most elaborate sets of experiments ever to have been conducted in a laboratory up to that time. They were rather fortunate in that the French Second Empire Government sponsored their outstanding work primarily to exhibit their liberal tendencies. Bazin completed the experimental work with remarkable skill in 1860, two years after the death of Darcy. In 1875, he was made an engineer-in-chief, and by 1886 he was promoted to inspector-general. He retired in 1900 when he had become unable to obtain further research funds to carry out his work. He died in 1917.

The book *Recherches hydrauliques*[13] was published in 1865 under the joint authorship of Darcy and Bazin. The velocity distribution profiles for various types of channels as presented therein were obtained by using an improved version of the Pitot tube, made by Darcy. (It was somewhat similar to present models.) Their experiments revealed that the maximum velocity in natural rivers and in wide channels occurred at the surface. In the centre of wide water courses, where side effects are nil, velocity *v* at a depth *d* from the surface (figure 1) was found to be:

$$\frac{V\,\mathrm{max} - v}{Hi} = 20\left(\frac{d}{H}\right)^2,$$

where the linear measurements were expressed in metres. In narrow canals having a width less than five times the depth the maximum velocity was found to occur somewhat below the surface (figure 1). Darcy and Bazin used a 596.5 metre long channel for their experiments. Water for the channel came from the Burgundian canal near Dijon, and it discharged into the river Ouche. The channel had rectangular, trapezoidal, triangular and semicircular sections with various types of linings. They believed that:

'if there exists an analytical law including all cases it must necessarily be very complicated, and the knowledge of the laws of the motion of fluids is too little advanced to allow us to hope for their discovery at present. In the actual state of the science we must limit ourselves to the search for empirical formulae sufficiently accurate for practical purposes and calculations by which are easy.'[13]

From the experiments conducted, they proposed the following relationships:

$$RS = \left(a + \frac{b}{R}\right)V^2.$$

This differed from the De Prony equation which was of the type:

$$RS = \left(a + \frac{b}{V}\right)V^2.$$

The Darcy-Bazin formula attracted considerable attention, but the use of the two variable coefficients limited its practical application. Realizing that difficulty, Bazin proposed[14] in 1897 another equation which contained only one variable coefficient. It is known as the Bazin formula in contradistinction to the previous Darcy-Bazin formula. According to it:

$$C = \frac{157.6}{1 + (1.81\gamma/\sqrt{R})} \text{ (in f.p.s units)}$$

where γ is the rugosity factor which reflects the characteristics of the channel.
Darcy and Bazin also conducted a series of experiments on the flow of water through orifices and conduits. A summary of the development of their various pipe-flow formulae is contained in a series of articles by Davies and White.[15]

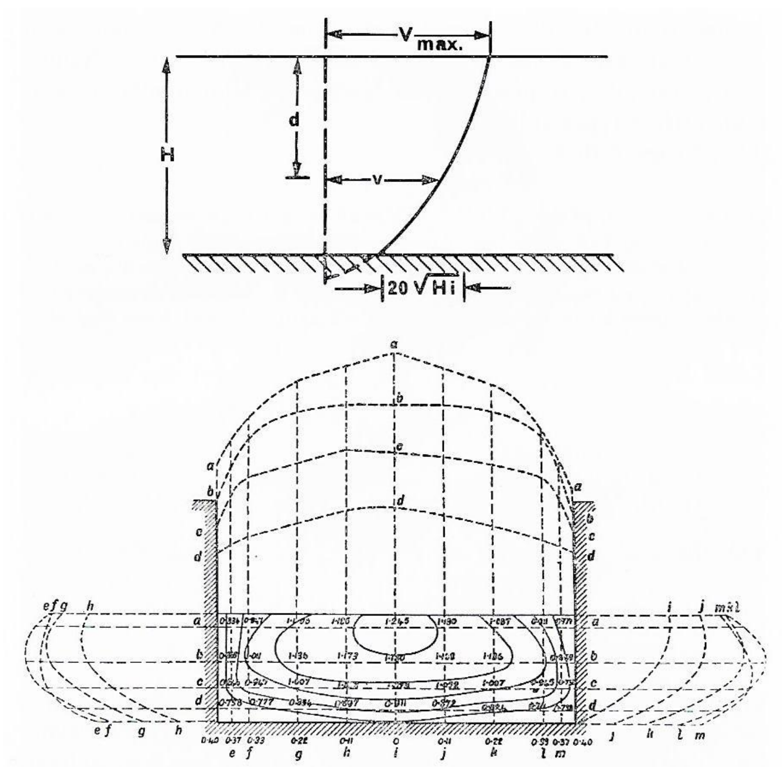

Figure 1. (a) Velocity distribution profile of Bazin. (b) Velocity distribution in narrow channels (from Recherches hydrauliques by Bazin).

Humphreys and Abbot

Andrew Atkinson Humphreys (1810–1883; figure 2) and Henry Larcom Abbot (1831–1927; figure 3) were both graduates of West Point, and were responsible for the Mississippi delta survey of 1851 to 1860. This was by no means the first river survey, but it was certainly the most extensive that had been undertaken up to that time. Humphreys was initially selected to conduct the survey.

Figure 2. Andrew Atkinson Humphreys.

His intense devotion to the project, and the long hours he devoted to the field work caused him to become seriously ill. While recovering there from he was sent to Europe to study developments in water resources field. In 1857, Abbot was appointed as his assistant. Their Report upon the physics and hydraulics of the Mississippi river[16] was published in 1861, and was immediately a ‘best seller’. The monumental Report had 610 pages, and parts of it were soon translated into many languages. Kolupaila[17] has listed 39 reviews and discussions of it, of which 18 were in foreign languages. It contained a review of the state of the art on river hydraulics which, according to the authors were 'partly original and partly compiled' from similar reviews by Rennie, Lombardini, Storrow and others, and from various encyclopedias.[18]

Humphreys and Abbot used double floats almost exclusively for velocity measurements, and found that for the same stages, the discharge could vary as much as 20%, depending on whether the stage was rising or falling. The mean values were selected for presenting stage-discharge relationships. They proposed a rather complicated formula for determining discharge in a water course. It was based on observations from channels as large as that of the mighty Mississippi to the small artificial channels used by Du Buat. The main importance of the formula was that it was the first of a series of formulae supposed to be comprehensive and accurate. The formula did not contain any roughness term. For that and other reasons, it failed to gain much popular acceptance. Undoubtedly, the main significance of the entire project was its thoroughness.

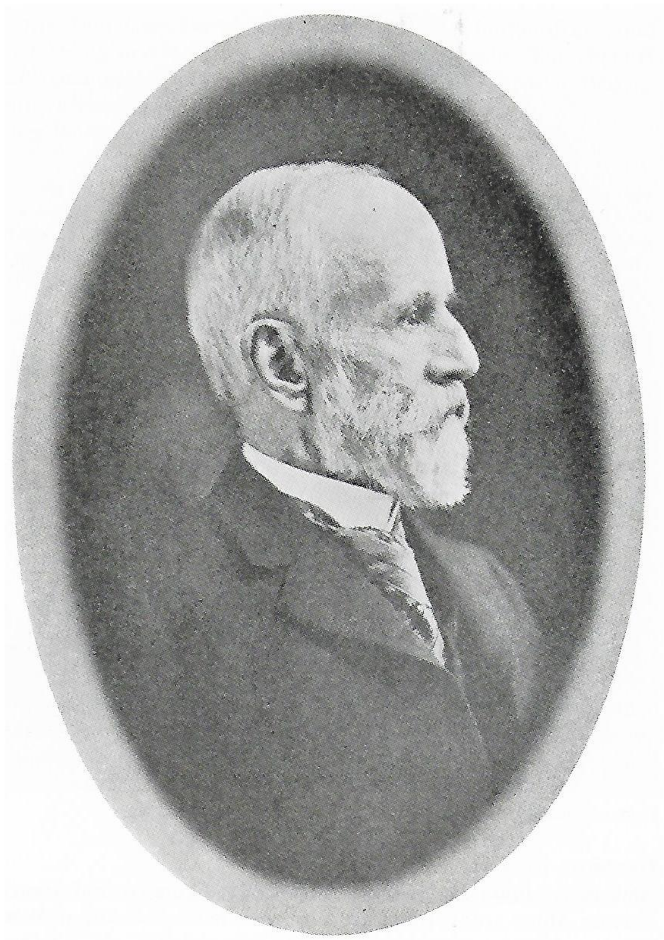

Figure 3. Henry Larcom Abbot.

Ganguillet and Kutter

The two Swiss engineers, Emile Oscar Ganguillet (1818–1894; figure 4) and Wilhelm Rudolph Kutter (1818–1888), were considerably interested in the problems of open channel flow, and carried out a series of experiments in the Swiss mountain streams. Ganguillet was the chief engineer of the Department of Public Works at Berne – Kutter was a member of his staff.

Figure 4. Emile Oscar Ganguillet.

Ganguillet and Kutter were invited by Humphreys and Abbot to check the validity of their (Humphreys' and Abbot's) formula. When they found that it was valid only for streams with gentle slopes, they tried to develop a formula that would apply to the discharge in all types of channels. In doing so they used observations from their own investigations as well as from as many other reliable sources as they could find. On the basis of their analysis, they concluded that:

'The two formulae are equally not entitled to general application. That of Bazin is indeed as inapplicable to the Mississippi as that of Humphreys and Abbot is to channels with steep slopes; but it [Bazin's] contains the basis of a formula which can generally be applied, simply by introducing the effect of slope, while the American formula cannot be thus generalized.'[19]

In f.p.s. units, the expression proposed for the 'C' in the Chézy equation was:

$$\frac{41.65+0.00281/S+1.811/n}{1+(41.65+0.00281/S)\,n/\sqrt{R}}\,.$$

This equation was an immediate success, and the 1869 journal which contained the article was quickly sold out. In 1877, the paper was enlarged and published as a book[19] which was soon translated into several different languages. According to Manning, the English translation of the article, available in 1876, was 'received generally with great favour'.

The complexity of the equation was justified by its originators on the basis that 'any formula that would possess an adequate claim to universal utility must necessarily be very complicated'. Manning was one of the first men to point out the dimensional non-homogeneity of the expression. Later, Forchheimer commented that it would have been more accurate if the early records of the Mississippi river discharge had been excluded when the averages were computed.

In spite of its inherent disadvantages, Ganguillet and Kutter's formula has received a wide acceptance all over the world. In 1905, Merriman considered that,

> 'It is to be regarded as a formula of great value, so that no design for a conduit or channel should be completed without employing it in the investigation, even if the final construction be not based upon it.'[20]

Robert Manning

Robert Manning (1816–1897; figure 5), an Irishman, was born in Normandy, a year after the battle of Waterloo, in which his father had taken part. The first Arterial Drainage Act of Ireland, passed in 1842, stipulated that drainage works should be planned and executed by the employees of the Central Government under the jurisdiction of the Board of Works. The first Commissioner for Drainage was Thomas James Mulvaney. Manning joined the department in January, 1846, as a clerk, and later became Chief Engineer for the Office of Public Works. He was responsible for the planning, design, and construction of various drainage, navigation, and harbour projects.

Manning's papers[21,22] clearly indicate that he considered himself to be a hydrologist. His major contribution to hydrology was the paper *On the flow of water in open channels and pipes*[22] which he presented to the Institution of Civil Engineers of Ireland on 4 December, 1889. Near the beginning of his paper, he gave hydrology a well deserved boost:

> 'Among the numerous subjects a knowledge of which is essential to the practice of the profession of the Civil Engineer, there are none more important than those which range themselves under the comprehensive title of *Hydrology*'[23]

Like Du Buat and Bazin, he also pointed out the imperfection of the existing state of knowledge in hydrology and hydraulics:

‘Even at the present day great differences of opinion exist among writers on the subject, each investigator claiming some excellence over those who preceded him, or roundly stating that the rule proposed by him is the only correct one.’[24]

Figure 5. Robert Manning.

In 1867, 22 years before Manning’s paper was presented, Philippe Gaspard Gauckler (1826–1905), an engineer of the Ponts et Chaussées,[24] proposed[25] the following two general formulae for all types of channels, the choice of which depended on their slope.[25,26]

$$V = \lambda_1 R^{4/3} S \qquad \text{for } S<0.0007$$
$$V = \lambda_2 R^{2/3} S^{1/2} \qquad \text{for } S>0.0007$$

In 1881, Hagen derived[27] a formula very similar to the second one of Gauckler, probably quite independently, but in doing so, he placed no limitation on the Slope.[28] He had derived it from Kutter’s data.

Manning was also probably not aware of the Gauckler formulae when he analysed various available experimental data and announced his belief that the expression $V = CS^{1/2}R^{2/3}$ may be sufficiently accurate. Obviously, this was exactly the same as the second Gauckler formula. Manning used it to determine velocities from 170 experiments comprising the observations of Bazin, Kutter, Revy, Fteley and Stearns, and Humphreys and Abbot, and found that only 25 of them differed from the actual velocities observed by more than 7%. In this regard Manning said:

> ‘Although the formula was independently found by the author in 1885, it is proper to say that Major Allan Cunningham, R.E., states in his paper, ‘Recent Hydraulic Experiments’ (Proceedings of Inst. Civil Engineers, 1882), that the experimental results of Kutter’s work had been recently applied by Dr. Hagen ... [who] ... deduced by the method of least squares $V = CR^{2/3}S^{1/2}$ ‘but the probable errors computed therewith appear enormous’, . . .’[29]

Manning, however, was not too keen about the formula primarily because it was incorrect dimensionally, and fractional powers like 2/3 are too cumbersome for practical use.
Having thus discarded the present-day so-called Manning formula he ventured to propose a new one:

$$V = C\sqrt{SG}\left[R^{\frac{1}{2}} + \frac{0.22}{m^{\frac{1}{2}}}\,(R - 0.15)\right]$$

where C = a coefficient which depends on the nature of the bed (it is not the Chézy C), and m = atmospheric pressure in terms of mercury. Assuming m to be equal to 30 inches of mercury, he reduced the formula to:

$$V = 62\,S^{1/2}\left(R^{1/2} + \frac{R}{7} - 0.05\right) \text{ in ft/sec}$$
$$V = 34\,S^{1/2}\left(R^{1/2} + \frac{R}{4} - 0.07\right) \text{ in m/sec.}$$

The surprising aspect of the proposed formula was the inclusion of the barometric pressure. Manning was very conscious, and rightly so, of the problem of the dimensional homogeneity of any expression describing a physical process, and only by including the term m he could satisfy the necessary condition. Like Du Buat, he concluded that some function which is ‘very small, nearly constant, and a square root’, is generally neglected. Moreover, only by including barometric pressure, could Manning obtain correct discharge values for water passing through pipes of small diameters. (It should be remembered that Manning was seeking a generalized formula for determining the velocity of flow in both pipes and open channels.) In 1890, Flamant saw an advance copy of Manning’s paper, and recommended[30] the use of the simpler formula, $V = CR^{2/3}S^{1/2}$, in his book *Mechanique appliquée – hydraulique,* published in 1891. Willcocks and Holt[31] referred to the equation as the Manning formula in 1899, and that practice was followed by Buckley[32] in 1911. Thus, gradually, the rejected expression became the well-known Manning formula. Manning spent four years in perfecting his universal formula, but, ironically, the formula with which his name is presently associated, is the one that he had previously discarded as not being sufficiently practicable.

RIVER FLOW RECORDS

Even though records of high flood levels of the Nile can be traced back[33] to the dawn of civilization, river flow records prior to the seventeenth century, were, in general, qualitative rather than quantitative. For example, the available brief descriptions of the floods of the Rhone, the Loire, and the Seine rivers for the years 563, 572, and 583 A.D., respectively[34] are primarily about the damage to properties and loss of lives and livestock.

The greatest milestone relating to river flow measurements was undoubtedly Castelli's establishment of the concept that $Q = AV$. With it flows might have been estimated even then with reasonable accuracy, but progress was rather slow. The interest in obtaining regular stage records and analysing them was aroused early in the eighteenth century. For example, the record of stage readings of the river Elbe near Magdeburg from 1727 to 1869, a period of 143 years, was published[35] and analysed by Maass, the Royal Prussian Inspector of Hydraulic Works in 1870.

In 1837, the distinguished German hydrographer, Heinrich Berghaus,[36] published his analysis of the highest, lowest, and the mean gauge readings of the following records:

(1) the river Rhine at Emmerich (Dutch frontier), from 1770 to1835 (66 years);
(2) the river Rhine at Cologne, from 1782 to 1835 (54 years);
(3) the river Elbe at Magdeburg, from 1728 to 1835 (110 years) and
(4) the river Oder at Küstrin, from 1778 to 1835 (58 years).

Later, Wex[37] carried out extensive analyses of river stages of five principal Central European rivers, and 'furnished unassailable proofs' that the discharges of the rivers had continually decreased over a long period of years. He, however, had a comforting thought:

> 'There need probably be no apprehension that the low water-surface of the Danube, Rhine, Elbe, and Vistula will ever go down to their beds, that is, that they will become partially dry, because the first two are partially fed by the ice and snow of the Alps; because the causes which create this decrease will probably not act beyond a certain point, and because the many tributary creeks and rivers which empty into these streams generally have their highest and lowest stages at different periods of time.'[37]

It is difficult to understand how the last factor came into the picture because variations of flow in all tributaries will always take place. Later, efforts to analyse the data, by applying systematic corrections to the gauge heights, invalidated Wex's theory of progressive reduction of discharge.

Jarvis presented the minimum and the maximum flow levels of the Nile as recorded by the Roda nilometer in graphical form for the period 622 to 1926 A.D. The data is reasonably complete – except for parts of the sixteenth and seventeenth centuries. It indicated an average sedimentation rate of about 10 to 15 centimeters per century.[34]

Kolupaila[38] attempted to reduce the stage records of the Memel river at Schmalleningken from the observations made by the Lithuanian Hydrometric Bureau from 1812 to 1930.[39] Details of stage measurements of the eighteenth and the nineteenth centuries have been listed by Kolupaila[40] and by the Miami Conservancy District.[41] Systematic computation of discharge was started around the beginning of the nineteenth century. Notable among them are the observations of Hans Conrad Escher von der Linth (1767–1823) for the Upper Rhine, near Basel, from 1809-1821; Antoine Joseph Chrétien Defontaine (1785–1856) for the Rhine and its tributaries from 1820 to 1833; Giuseppe Venturoli (1768–1846) for the Tiber at Rome from 1825 to 1836; and André Gustave Adolphe Baumgarten (1805–1856) for the Garonne from 1837 to 1856. Probably the discharges were computed by the various slope-velocity formulae which abounded during the period. The first international discharge measurement was organized in November, 1867, on the Rhine at Basle.[42]

Baron Cornelis Rudolf Theodorus Kraijenhoff (1758–1840) published[43] a comprehensive set of hydrographic and topographic tables for Holland in 1813. This early work is of considerable value as it gave detailed records of discharge using the slopes of the water surfaces, gauge heights, and velocities. Velocities were determined by finding the time required for a vertical float-pole, extending from above the water surface to nearly the bottom of the rivers, to travel from one base line to another. All gauge heights were referred to a common datum.

DEVELOPMENT OF THE RATIONAL FORMULA

Probably the first logical attempt to estimate flood flow was made by a group of Irish engineers[44] during the period 1842 to 1847. The method, in brief, was to design drainage channels capable of carrying off a certain percentage of recorded maximum daily rainfall. It was assumed that the total rainfall was disposed of in three ways: evaporation, infiltration and stream flow, with the first two losses being constant throughout the year. Thus, it was reasoned that if a certain percentage of total annual precipitation found its way to the streams, a similar proportion of daily rainfall would do likewise.

According to Dooge,[44] Samuel Roberts, in his report of December, 1843, on the river Dee, anticipated a maximum daily rainfall value of 1.6 in., and a run-off factor of 0.4 for his design. Later, the run-off factors were varied to take into account the various characteristics of the catchment area, particularly slope. Thus, William Fraser, in his report on the Longford district (river Camlin), published in February 1844, considered two run-off factors for the catchment – 0.4 for the southern part having a fall of about 5 ft per mile, and 0.6 for the northern part with a slope of 10 to 20 ft per mile. It was believed that the rate of run-off from steeper catchments was higher, since the time available for percolation and evaporation losses was less. Generally, factors used for design were 0.4 and 0.6 (or ⅓ and ⅔) for flat and steep lands, respectively. In the beginning, the Irish engineers assumed a maximum daily rainfall value of 1.5 or 1.6 in., but later, those amounts were gradually increased. Thus, by 1847, a flood formula could be written as follows:

$$Q = 2.52\ C.I.A$$

where Q = design discharge in cu. Ft/min, C = run-off factor, I = maximum daily rainfall (1.5 to 2 in.), and A = catchment area in acres.

The originator of the present so-called rational method was Thomas James Mulvaney (1822-1892), younger brother of the Commissioner of Drainage, William T. Mulvaney. In a paper entitled *On the use of self-registering rain and flood gauges in making observations of the relations of rainfall and of flood discharges in a given catchment*, presented to the Institution of Civil Engineers of Ireland,[45] in February, 1851, he laid the foundation of the method. Mulvaney pointed out therein the necessity of a general and uniform method of collecting precipitation data, so that it could be analysed successfully to establish practical rules. He briefly describes the existing concept, and stated that the empirical approach gave results 'tolerably near the truth' within certain limits only for an average catchment that was 'neither mountainy nor very flat'.[46]

Mulvaney's statement on the procedure of estimating maximum flood discharge is valid to a great extent even today:

'After having ascertained al¡ these facts and feeling satisfied that each of them must have an important effect on the result as to the maximum flood which he is called upon to provide for, he has no faithful guide, that I am aware of, to help him to a conclusion as to the *amount* of effect on the discharge due to each or all of these conditions; he is, in fact, left to guess at the result after all, and unless he happens to have had some previous experience of similar cases, his guess will probably be very wide of the truth.'[47]

For maximum discharge to occur,

'a combination of circumstances as to the fall of rain and the peculiar character of the catchment may be required, that may not occur more than once perhaps in two or three years, but which it is nevertheless necessary that he should provide for.'[48]

Mulvaney also pointed out that a long period of data on the depth and intensity of precipitation and stream flow would be necessary to determine their interrelationship.
Mulvaney can be credited with the first correct understanding of the concept of the time of concentration as applied to the rational method:

‘The first matter of importance to be ascertained in the case of a small or mountainy catchment, is *the time* which a flood requires to attain to its maximum height, during the continuance of a *uniform rate of fall* of rain. This may be assumed to be the time necessary for the rain which falls en the most remote portion of the catchment, to travel to the outlet, for it appears to me that the discharge must be greatest when the supply from every portion of the catchment arrives simultaneously at the point of discharge, supposing, as above promised, the *rate* of supply to continue constant, and this length of time being ascertained, we may assume that the discharge will be the *greatest possible*, under the circumstance of a fall of rain occurring, of the *maximum* uniform rate of fall for that time... This question of time, as regards any catchment, must depend chiefly on the extent, form, and rate of inclination of its surface; and, therefore, one great object for investigation is the relation between these causes and their effect; so that, having ascertained the extent, form and average inclination of any catchment, we may be able to determine, in the first place, the *duration of constant rain* required to produce a maximum discharge, and consequently to fix upon the maximum rate of rain-fall applicable to the case.’[49]

The coefficient *C* could be estimated by studying the retention capacity of the soil which would primarily be dependent on the geological formation and the degree of cultivation of the catchment. Mulvaney also suggested to study a series of specially selected small and suitable catchments to determine the effect of various factors on flood run-off. Thus, the rational formula was clearly implicit in Mulvaney’s paper.

In another part of the paper, the Irish engineer describes an automatic rain gauge (figure 6) which would cost the princely sum of £2: £1 for the rain gauge and another £1 or so for a clock!

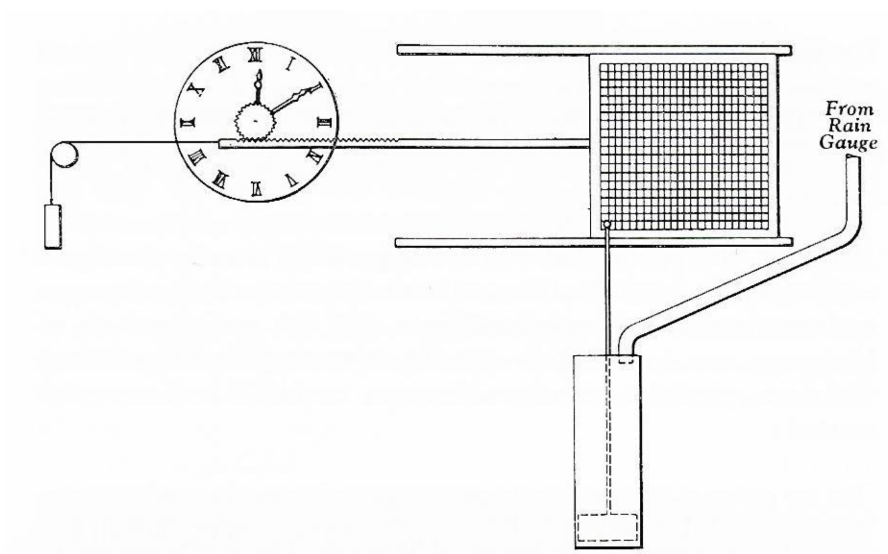

Figure 6. Automatic rain gauge of Mulvaney

Manning, in his paper of May, 1851, on arterial drainage, pointed out that drainage works could reduce the time for floods to reach their peak, and thus increase the value of the peak flow. The maximum flow would depend on the rainfall, and the extent and circumstances of the catchment basin. He neglected the effect of evaporation and infiltration losses because

‘It is evident that there may be such a state of the atmosphere that no appreciable amount of evaporation may occur during the continuance of a flood, and no matter what may be the water storing properties of the geological formation of the district, they may have been completely exhausted by previous rains; and, therefore, the maximum discharge will mainly depend upon the quantity of rain, and the extent and comparative elevation of the catchment to the discharging channel.’[50]

He listed maximum daily rainfall values at five locations based on 4 to 10 years of record. Those values, however, were all exceeded during the same year as well as during the subsequent year (1852). The rational formula was later recommended by Emil Kuichling[51] in 1889, George Chamier[52] in 1898, and D. E. Lloyd-Davies[53] in 1906. It is currently known as the Kuichling formula in the United States and the Lloyd-Davies formula in the United Kingdom – after the names of the engineers who first introduces it in their respective countries. This is a rather unfortunate circumstance, as in all fairness, it should have been named the Mulvaney formula internationally.

HERSCHEL AND THE VENTURI METER

Clemens Herschel (1842–1930) was probably born in Austria (both Boston[54] and Vienna have been mentioned as his birth place), but he was educated at Harvard, Paris, and Karlsruhe. Through his association with James Francis[55] at Lowell, Massachusetts, he acquired a keen interest in hydraulic engineering. His two main contributions to hydrology were his invention of the Venturi water meter and his work on the history of hydrology. It may be recalled that it was Herschel who took photographs of the manuscript of Frontinus at the Montecassino monastery and who located the original Chézy work – both of which he translated into English. He received the Elliott Cresson medal of the Franklin Institute for his 1898 paper on the Venturi meter, and was elected the president of both the American and Boston Societies of Civil Engineers. While at Holyoke, Massachusetts, Herschel found himself faced with the problem of finding an economical method of estimating discharge so that the local power companies could be charged an amount that was commensurate with the quantity of water they were furnished. The most obvious solution at that time was to construct a weir, but that was an uneconomical type of installation. He stated:

‘There was another draft of water out of the canals, unseen by human eyes, which sorely troubled me. This was the large quantity used by the manufacturing corporations, including some 25 large paper mills, as wash-water; roughly estimated at 10 percent of the quantity used for power. This water was drawn through cast-iron pipes, most of them 20 to 24 inches in diameter, painted black on the outside, and they ¡ay there, usually in the basement of the mill, silent as the grave, and most provokingly

secretive of what was passing within their interior. Many a time did I stand beside such a pipe and exert myself to invent how to force these pipes to reveal the secret of their hidden action.
These endeavours resulted in a determination at the first opportunity to try how an apparatus like this would work: place an orifice at some point in the pipe, circular and in the form of an adjutage, from choice, and then place an expanding cone downstream from the orifice, in order that the loss of head occasioned by the first orifice may be regained, and no material loss of head be occasioned by the whole apparatus.'[56]

Herschel noted that his water meter had been developed from a study of the combination of Bourdon's anemometer, Venturi's experiments and Boyden's turbine diffuser. His reason for naming the new water meter after the Italian, Venturi, was the

'supposition merely that as Venturi had discovered there was a sucking action at the throat, the intensity of this action would be found to have a valuable relation to the throat Velocity.'[56]

Soon after Venturi meters came into general use for measuring the flow in pipes (it had its fair share of criticisms), the concept was extended (through the construction of Venturi flumes) to determine the discharge of canals and small water courses.

GROUND WATER HYDROLOGY

William Smith

In the field of ground water, one of the early applications of the principles of geology to the solution of hydrologic problems was made by the Englishman, William Smith (figure 7). Born at Churchill in Oxfordshire, in 1769, Smith is often described (somewhat unfairly to his predecessors) as the father of English geology. He describes himself variously as either a geologist, a mineralogist or a civil engineer, and spent most of his fortune publishing his geological maps. In 1815, Smith bought property near Bath, England, containing freestone, but ironically, he was hopelessly wrong on both the quantity as well as the quality of the stones available. He lost heavily on the deal, and was forced to sell his excellent geological collection to the British Museum. He died at Northampton, in 1839.

Smith's main contribution to hydrology is in the field of ground water. In a paper entitled *On retaining water in the rocks for summer use*, presented in 1827 to the Yorkshire Philosophical Society,[57] he discussed the utilization of ground water for the town of Scarborough. The paper first discussed the necessity and the desirability of conserving water; then it describes a method for supplementing the town's summer water supply. A bore hole dug several years previously, to drain the land, had been found to discharge a small quantity of water. An open channel was subsequently cut there to a depth of 9 to 10 ft, and it increased the flow to about 24 hogshead per hour. It encouraged Smith to deepen the channel by another 4 ft whereupon the discharge became further increased to 50 or 60 hogshead per hour. He suspected that the water came from a confined aquifer, and suggested the 'propriety of damming up the produce of this spring' for summer and winter use, as the supply available during spring was more than adequate for that season's use. The water-bearing stratum was found to be a yellowish fine grained crumbly sand-stone occurring in thick beds with open joints. A basin, 6 ft in diameter and 4 ft deep, was excavated about 6 ft from the nearly upright edge of the rock to receive the flow of water, and pipes were laid at the bottom of the basin to carry the water to the city reservoir. In order that the water of the spring could be utilized partly or wholly as desired, Smith used four vertical pipes, each 12 in. long and removable as necessary, at the end of the pipe line. In winter, when the top of the vertical pipe was closed, the geologist was pleasantly surprised to find that the water table height at the spring rose at 14 ft, some 10 ft higher than anticipated.[58]

Figure 7. William Smith (by courtesy of the Geological Society of London).

Darcy and Dupuit

The foundation of the theoretical aspect of ground water hydrology was laid by Darcy in his Report[11] of 1856 on the water supply system for Dijon. In one of the appendices[59] of the

Report, discussing the technique of purification of water by filtration through sand, he suggested the following well-known expression which at present bears his name:

$$Q = \frac{K.A}{L}(\mathrm{H} + \mathrm{L})$$

where L and A are the length and the cross-sectional area of the sample; K is a constant, and H is the head of water above the sample. The velocity V was equal to Q/A, but he did not introduce any special velocity concept or the idea of porosity.

Darcy emphasized the empirical nature of the relationship proposed which was based on careful field and laboratory observations. His main interest was to investigate the possibility of increasing the yields of wells. With the exception of the filtration tests, he did not conduct any additional studies in the field, of ground water hydrology. He completely rejected the hypothesis that rain-water was unable to penetrate more than a few feet into the soil, and offered a rational explanation for the seasonal variation of the productivity of the wells. In case of artesian wells, Darcy considered the aquifer to be analogous to a large pipe connecting two reservoirs at different levels. Artesian wells were sort of pipes, withdrawing water from a main line that was under pressure.

Darcy's work on ground water was extended by another Frenchman, Arsène Jules Emile Juvenal Dupuit (1804–1866), whose name is at present synonymous with the equation for axially symmetric flow toward a well in a pervious medium. The problem was treated in his 1863-treatise in a chapter on seepage.[60] He was familiar with Darcy's work on filtration, and attempted to solve the problem by using De Coulomb's resistance law (as modified by De Prony) for expressing open channel flow. He assumed that a mass of sand is analogous to a collection of tiny channels to which De Prony's equation could be applied. He further assumed that all channels were subjected to identical conditions, and hence, the gradient and the velocity for all 'microchannels' in a vertical section would be the same. Since the velocity of flow through a pervious medium is slow, he neglected the term containing v^2. Thus, he reduced the De Prony equation for seepage to:

$$i = \eta v$$

where η is a constant depending on the nature of the soil.[61] He pointed out the similarity between his quasi-theoretical expression and Darcy's empirical formula.

Dupuit then deduced the following theoretical expression for the rate of flow into a gravity well by considering an arbitrary cylindrical surface surrounding it:

$$q = \frac{\pi k\,(H^2 - h_o^2)}{\log R/r_o}$$

where, q = discharge per unit time, k = coefficient of permeability, H = height of water table above the impervious stratum beyond the zone of influence, h_o = depth of water in well, R = radius of the zone of influence, and, r_o = radius of the well.

He also deduced two other similar equations for recharge and for artesian wells. The two basic assumptions for all three of his formulae were:

(1) the same gradient obtains at all points in a section, and,
(2) the gradient of the phreatic surface at any point is equal to the slope of the surface at that point.

The above two assumptions obviously impose serious limitations to the Dupuit formulae. But, it was rather strange that Dupuit, after having deduced the simplified formulae, persisted in disregarding his own fundamental assumptions. Unlike Darcy, Dupuit failed to conduct extensive field and laboratory investigations to check his theoretical expressions, nor did he explain any limiting value for R in his equations. If the value of R, in case of a pervious stratum were assumed to be infinity, the practicability of the formulae, would have been seriously hampered. Later, Adolph Thiem suggested a reasonable value of R based on field investigations which he performed.

Dupuit's work, in spite of the limitations mentioned, greatly advanced the knowledge of ground water hydrology, even though the equation for the gravity well contained incorrect assumptions for the phreatic line and for the distribution of the piezometric head along the impervious base. It is, however, still used to calculate the discharge and/or the coefficient of permeability because the actual discrepancies between the true values and the values obtained thereby, are negligible.

Adolph Thiem

The pioneering work of Darcy and Dupuit in France, in the field of ground water hydrology, was later taken up by the Germans and Austrians.[62] The most notable German trail-blazer in this field was Adolph Thiem (1836–1908) – a civil engineer for the city of Dresden. In a paper[63] published in 1870, he made theoretical analyses of problems concerning the flow of water toward gravity wells, artesian wells and filter galleries. By adopting the necessary assumptions, he derived the same expressions as Dupuit had derived for gravity and artesian wells. He too, was as casual as Dupuit about the limitations of such assumptions. Probably both of them preferred to consider the two conditions as logical inferences, rather than as simplifying assuniptions.[64]

In the same paper, Thiem considered the problem of partially penetrating gravity wells. He was, however, guilty of oversimplification, and concluded that the effect of partial penetration on yield would be inconsiderable. He also attempted to analyse the problem of non-steady seepage, but the results, he himself admitted, were of little practical use.

In later papers,[65-67] Thiem presented extensive field observations in support of his formulae. He suggested that the radius of the zone of influence in a pervious medium need not be taken as infinity. It could be restricted to the point where the drawdown is so small that it could be neglected with very little sacrifice in accuracy. Initially, Thiem attempted to measure velocity of ground water flow by injecting dye at one point and then noting the time of its subsequent appearance in an observation well. The method, however, proved to be rather inaccurate because of the tendency of the dye to disperse even in still water. Later, he resorted to the practice of injecting salt solution.[68,69] Using a salt solution of known concentration in still water, he determined the concentration at various points after some time. Armed with the calibration chart, he was able to apply the necessary corrections by determining the salt content in an observation well, at a fixed distance from the injection point and after the elapse of a specific period of time. Thiem wrote extensively in the field of ground water hydrology. Probably his greatest contributions were the stress he placed on experimental techniques, and the efforts he made to reconcile theoretical and field observations.

Forchheimer and Slichter

One of the greatest contributors to the field of ground water theories, during the late nineteenth century and the earlier half of the twentieth century, was undoubtedly Philip Forchheimer (1852–1933). A native of Vienna, and a professor of hydraulics at Aachen and later at Graz, Forchheimer, for the first time, applied advanced mathematics to this subject. One of his major contributions was a determination of the relationship between equipotential surfaces and stream lines. The analytical method on which flow net principle is based was discussed in the first edition of his book on hydraulics[70] published in 1914. This was certainly not the first work published on the subject, as Richardson[71] had already published a paper in 1908, in England, quite independently of Forchheimer, but Forchheimer's very earliest paper on ground water[72] published in 1886 makes it clear that the idea had begun to form in his mind at that time.

Holzmüller, in 1882, had applied the technique of conformal mapping to heat flow problems,[73] and this inspired Forchheimer to approach ground water flow analyses in a similar fashion. Starting with Darcy's law and Dupuit's assumptions, he arrived[72] at Laplace's equation for the phreatic surface for gravity flow in a pervious stratum underlain by a horizontal impervious base:

$$\frac{\delta^2 z}{\delta x^2} + \frac{\delta^2 z}{\delta y^2} = 0$$

where x and y are the co-ordinates of the point in question on a horizontal plane, and z is the elevation of the phreatic surface above a horizontal impervious base.

He pointed out that the above equation is valid for the movement of ground water at great depths, but for shallow depths, where changes from point to point were appreciable, it was modified to:

$$\frac{\delta 2(z^2)}{\delta x^2} — \frac{\delta^2(z^2)}{\delta y^2} = 0.$$

Forchheimer was not only the first man to indicate the applicability of Laplace's equation to the phenomena of ground water flow, but he was also the first to offer a clear explanation of the Dupuit assumptions.[74]

Forchheimer introduced the theory of functions of a complex variable to analyse the gravity flow toward a group of wells. He used the concept of an imaginary equivalent single well which had the same rate of discharge as the group of wells. The proposed equation for a steady state flow assumed that the yield would be the same from each well, and it did not impose any restriction on the equivalent single well, except perhaps of an implied requirement of a roughly central location.

Forchheirner was also the first to apply the method of mirror images to the ground water flow problems.[74] He analysed the case of a gravity well near a river, both being underlain by a continuous impervious base. The ground water table at the well was assumed to be at the same level as the water surface of the river. For his analysis, Forchheimer replaced the river by a continuous pervious stratum with an imaginary recharge well located as the mirror image of the given well with reference to the river bank. The imaginary well was capable of supplying as much water to the surrounding pervious medium as the real well was capable of removing. He then introduced the feature of natural ground water flow to the river, and using the method of mirror images again, determined the critical distance between a river and a well, beyond which no water would be contributed by the river to the well.

In the above cases, Forchheimer assumed that the wells penetrated to the underlying impervious base, but he also considered partially penetrating gravity wells. The approach was semiempirical, and the resulting equation was rather formidable.[74]

Forchheimer had an excellent mathematical background. He successfully used the methods of conformal mapping, mirror images, complex variables, and potential theory to solve problems in ground water hydrology, and, in nearly all cases, he was the first man to have used them. With regard to Forchheimer's contribution to hydrology, Terzaghi had this to say:

> 'In my opinion his contribution accomplished more in the line of clarifying our ideas concerning the movement of ground water than those of all the other contemporaneous hydrologists of Europe combined.'[75]

Much of Forchheimer's work was duplicated in the United States by Charles Sumner Slichter (1864–1946). Slichter's knowledge of European developments in the field of ground water hydrology was very limited, and apparently he was not even aware of Forchheimer's existence. Slichter derived an analytical solution for discharge from artesian wells which proved to be identical to the Dupuit-Thiem solution. Slichter, like Forchheimer, was impressed by Holzmüller's work, and successfully applied Laplace's equation to conformal transformation, and to the potential theory to ground water problems.[76]

Slichter suggested an elaborate expression for flow of water through a vertical column of soil:

$$Q = 1.0094 \frac{\Delta P \,.\, d^2 \,.\, A}{\mu h k}$$

where Q = rate of flow in cc/sec, p = difference, in 'pressure' at the two ends of the column in cm of water, d = mean diameter of soil grains in cm, A = cross-sectional area in cm^2, μ = coefficient of viscosity of water in g.sec/cm^2, and k = a constant depending on the porosity and geometrical characteristics of the medium.

He realized that the expression was a form of Darcy's law but, unlike Darcy, who used a single constant k, he divided it into its various constituents. The form of the equation makes it obvious that Slichter had used the Hagen-Poiseuille equation for its derivation. Slichter used a circuit containing electrodes in observation wells and an ammeter to obtain ground water flow velocities. By injecting an electrolyte into the ground water, he could detect the rate of seepage between two points from the ammeter readings (which were dependent on the electrolyte concentration in the water). Even though a major part of Slichter's work had already been done in Europe, his contribution to the development of the science of ground water hydrology should be recognized. He did his work independently, and was largely instrumental for the advancement of the subject in America. He undoubtedly made Americans more ground water conscious.

BEARDMORE AND MANUAL OF HYDROLOGY

The book *Manual of hydrology*[77] by Nathaniel Beardmore, published in 1862, was the first work in the English language that began to approach the subject of hydrology as it is known today. It was an enlarged and revised version of his earlier work, entitled *Hydraulic tables*, published in 1850. Beardmore, born in 1816 at Nottingham, England, was responsible for the planning and design of various railways, harbours, bridges, drainage, and waterworks. He was elected the president of the Royal Meteorological Society, in 1861, and was an advisor concerning water supply schemes for cities as far apart as Edinburgh and Glasgow to Moscow and Odessa.[78] He died in 1872.

Beardmore did not suggest any new hydrologic principles. His main contribution to the subject was to popularize it. This he accomplished through his book – an excellent compilation of the state of knowledge thereon in tabular form.[79] He commented that:

'refined but practical questions of surface slope and velocity of water and, above all, of the volume accompanying a given fall and velocity or certain known rainfall, were subjects almost untouched (until publication of the first edition of this volume); the source or supply of water in reference to the amount of rain was a subject which only a few canal and waterworks engineers had investigated; and they were not much disposed in olden times to communicate the practical experience acquired by the hard labour of years.

Hydrological science embraces the widest conditions; not only has climate to be considered, but the elevation, inclination, and geological formation of the substratum. Practical construction requires great previous experience, when the science has to be applied; for instance in drainage and waterworks . . .'[77]

The book, intended to be a practical manual for everyday use, was divided into four parts: hydraulic and other tables, rivers and flow, tides and rainfall. It contained hydrologic data from various parts of the world primarily for the use of the British consulting engineers who, towards the latter half of the nineteenth century, were involved in planning and design of water resource projects on an international scale.

OTHER DEVELOPMENTS

Toward the latter half of the nineteenth century, the United States Geological Survey and its antecedent organizations began a systematic collection and publication of the average daily discharge values for representative streams throughout the entire nation. Charles Ellet, Jr. (1810–1862), a hero of the Civil War, was a real pioneer of hydrometry.[80,81] He was probably the first to tabulate records of the daily discharges based on actual velocity measurements at various stages for the Ohio river near Wheeling, West Virginia. The Geological Survey was created in 1879, and, by 1906, according to Nathan C. Grover (1868–1956), Chief Hydraulic Engineer of the Survey during the period 1903 to 1939:

'stream gaging was nation wide; investigations of underground waters were being successfully made in both the East and West; Gilbert had begun his monumental work on the transporting capacity of flowing water; Slichter had pioneered in measuring the rate of motion of water through the ground ... Congressional authority had been obtained for the preparation of reports on the best method of utilizing the water resources ... the complete yearly records of the gaging station had been brought into one publication; studies had been made of the essential accuracy of streamflow records; Murphy had investigated the reliability of the current meter; progress was being made in obtaining winter records...

This was a record of accomplishment that would be hard to equal in such a relatively short period.'[82]

Also towards the later half of the nineteenth century, various simple flood formulae of the type

$$Q = C \cdot A^n$$

were proposed, where C was a coefficient, n was an index (both depending on locality), and A was the drainage area in acres. Probably the earliest such formula was proposed by Colonel C. H. Dickens[83] based on his observation in India:

$$Q = C \cdot A^{0.75}$$

where C varied from 1.56 to 17.2.

Chow[84] has excellently summarized various flood formulae proposed during the period of 1860 to 1950.

Rippl, in 1883, suggested a method[85] for determining the minimum effective storage required so that no water shortage occurs during the time period under consideration. The method was based on residual mass diagram, and assumed that both inflows and outflows were known functions of time. It was pointed out during the discussion of the paper that the suggested method had been used by many engineers several years prior to the publication of Rippl's paper.

At the forefront among the Italian hydrologists of this period were Giuseppe Venturoli (1768–1846), Giorgio Bidone (1781–1839), and Elia Lombardini (1794–1878). Bidone was probably the first man to analyse the phenomenon of hydraulic jump on a systematic basis, and it is still known as the 'jump of Bidone' in Italy. He conducted experiments on discharge over weirs, and his results were published in the *Mémoires de l'Academie des Sciences de Turin* in 1820, 1826 and 1827. Venturoli's contribution was to derive the elementary backwater equation for rectangular channels in 1823. He was able to plot various reaches of the surface profile by graphical integration of the differential equation. He also analysed the flow of the river Tiber over a number of years. The last, but not least, of this group was Lombardini, who in a series of articles and treatises describes the hydrology of the river Po, and discussed various flood control programmes. He pointed out the possibility of the occurrence of higher floods due to the deforestation of mountain sides – thus, causing more rapid run-off. He analysed statistically the monthly flows of several Italian rivers.

The Hagen-Poiseuille equation for flow through circular tubes was derived during the nineteenth century, and to a certain extent it contributed to the development of ground water hydrology. The men who developed it from experimental data, were the German hydraulic engineer Gotthilf Heinrich Ludwig Hagen (1797–1884), and the Paris physician, Jean Louis Poiseuille (1799–1869). Strangely enough, the analytical solution was also proposed independently at about the same time by two physicists, Franz Newmann (1798–1895) of Königsberg and Eduard Hagenbach (1830–1910) of Basle. However, it was Hagenbach who named his resistance law for laminar flow after Poiseuille, and that identification, somewhat unfairly, still persists.

Two European meteorologists deserve special mention for their effort to systematize precipitation measurements. They are George James Symons (1838–1900) and Johann Georg Gustav Hellmann (1854–1939), and both of them made serious studies of the history of various aspects of meteorology (see chapter 12). Symons spent nearly forty years of his life co-ordinating the various rainfall observations throughout Britain, and it was primarily because of his efforts that the first volume of English rainfall was published in 1860–1861. The annual precipitation values have been published regularly ever since. In the twentieth annual volume of the British rainfall, 1880, he pointed out that:

'There is no point in the study of rainfall of greater interest and practical utility, than the accurate determination of the average annual fall.'[62]

Symons realized that it is all too easy to obtain an approximate measurement of rainfall, but it is progressively more difficult to improve on it, and extremely difficult to obtain and verify an absolute rather than a conventionally standard measurement. He suggested that even if such a method were found, it would probably not be practicable to adapt it to a national net. The use of current meters became popular toward the latter half of the nineteenth century. The origin of current meters is rather obscure, but their antecedents can be traced to the designs of anemometers, windmills, water wheels, or ship's logs[86] – which were available long before the first current meter made its debut. Some of the current meters used during this period were devised by Daniel Farrand Henry[86] (1833–1907), General Theodore G. Ellis (1829–1883), William Gunn Price[87] (1853–1928) and Clemens Herschel. The number of revolutions of the meter wheel of the earlier instruments were indicated by a mechanical counting device, and hence it was necessary to raise the meter out of the water for each reading. In about 1860, Daniel Farrand Henry of the United States Lake Survey, Detroit, Michigan, invented an electrical facility for recording the number of revolutions of the wheel while the meter was still in water, thus making it less cumbersome than the earlier models.[86] Other contributors to the development of hydrology in the nineteenth century were Jean Baptiste Belanger (1789–1874), Marie Francois Eugène Belgrand (1810–1878), Emmanuel Joseph Boudin (1820–1893), Jacques Antoine Charles Bresse (1822–1883), Alfonse Fteley (1837–1903), John Fletcher Miller, Abbé Paramelle (1790–1875), Jean-Claude Barré de Saint Venant (1797–1886), Frederic Pike Stearns (1851–1919), and Julius Weisbach (1806–1871).

CONCLUSION

The major achievement of the nineteenth century was the firm establishment of the principle of conducting experimental investigations either to establish a theory or to determine an empirical relationship. It is true that often the various formulae proposed with regard to the same phenomenon differed substantially from one another, but that took place mainly because of a tendency to generalize from a limited amount of experimentation. This criticism is especially valid with regard to many of the equations proposed for determining the flow in open channels.

The two major developments in hydrology of this period were in the field of streamflow observations and ground water. The perfection of current meters revolutionized the methods of evaluating river discharges, and the availability of automobiles greatly reduced the transportation problems generally associated with such activities. From the time of Leonardo da Vinci to about 1870, surface floats were extensively used to determine the velocity of flowing water. The mechanical current meters, that were available, were extremely cumbersome to use, and, hence, it is not surprising to find that they were not preferred until the number of revolutions could be counted through the use of an electrical device.

The United States Geological Survey deserves primary credit for the innovation of systematic collection and publication of stream-flow data for representative streams across the nation. From an overall viewpoint, it has probably become the greatest boon the engineering profession has ever been handed.

For the first time in history, attempt was also made to estimate the design flood for a catchment on a logical basis. Credit for this must go to the group of enterprising Irish civil engineers – especially Mulvaney.

In the field of ground water hydrology, the marriage between geology and hydrology was performed by William Smith, who has often been called the father of English geology. The lead, however, was soon taken over by the French engineers who became very active in this field of geohydrology. The most notable among those engineers were Darcy and Dupuit. A serious difficulty of this period was the limited exchange of information between investigators; it was responsible, for example, for Thiem having duplicated the work of Dupuit – even after a reasonable time lag. This circumstance is rather difficult to explain because the various works in the field of making discharge measurements do not seem to have been confined to any national boundaries. For instance, Kolupaila lists 39 reviews and discussions of the Humphreys and Abbot Report, out of which no less than 18 are in foreign languages. From that it would seem that during this period surface water measurements were considered to be of greater importance and of more practical use than the investigations which were being made in geohydrology.

REFERENCES

1. EYTELWEIN, J. A., Handbuch der Mechanik fester Körper und der Hydraulik. Berlin (1801).
2. EYTELWEIN, J. A., A summary of the most useful parts of hydraulics, an English extract of ref. 1 by Young. In: Tracts on hydraulics, edited by T. Tredgold. London J. Taylor (1826).

3. EYTELWEIN, J. A., Handbuch der Hydrostatick. Berlin (1826).
4. DE COULOMB, C. A., Expériences destinées à déterminer la cohérence des fluides et les lois de leur résistance dans les mouvements tres lents. Mémoires de I'Institut National des Sciences et Arts, vol. 3 (1800).
5. GIRARD, P. S., Mémoires de I'Institut National des Sciences et Arts, vol. 9 (1803) p. 246.
6. RENNIE, G., Report on the progress and present state of our knowledge of hydraulics as a branch of engineering. Report of the British Association for the Advancement of Science, part 1, 3rd meeting, Cambridge, 1833 and part II, 4th meeting, Edinburgh, 1834. London, J. Murray (1834) pp. 153–184; (1835) pp. 415–512.
7. DE PRONY, G. C. F. M. Recherches physico-mathématiques sur la théorie des eaux courantes. Paris (1804).
8. COURTOIS, E., Principes d'hydraulique rationale applicables aux courants naturels tels que les rivières et les fleuves. Paris, Mallet-Bachelier (1850).
9. LAHMEYER, J. W., Erfahrungs-Resultate über gleichförmige Bewegung des Wassers in Flussbetten und Kanälen. Braunschweig (1845).
10. DE ST. VENANT, J. C. B., Formules et tables nouvelles pour la solution des problèmes relatifs aux eaux courantes. Annales des Mines (1851).
11. DARCY, H. P. G., Les fontaines publiques de la vine de Dijon. Paris, V. Dalmont (1856).
12. LELIAVSKY S., River and canal hydraulics. London, Chapman and Hall (1965) p. 6.
13. DARCY, H. P. G. and H. E. BAZIN, Recherches hydrauliques. Paris (1865).
14. BAZIN, H. E., Etude d'une nouvelle formule pour calculer le débit des canaux découverts. Paris, P. Vicq-Dunod (1898). (Extrait des Annales des Ponts et Chaussées, 1897.)
15. DAVIES, S. J. and C. M. WHITE, A review of flow in pipes and channels. Engineering *128* (1929) 69–72; 98–100; 131–132.
16. HUMPHREYS, A. A. and H. L. ABBOT, Report upon the physics and hydraulics of the Mississippi river. Philadelphia (1861).
17. KOLUPAILA, S., Bibliography of hydrometry. Notre Dame, Indiana, University of Notre Dame Press (1961) pp. 253–258.
18. Ref. 16 2nd ed. Washington, D.C., Government Printing Office (1876) p.187.
19. GANGUILLET, E. O. and W. R. KUTTER, Versuch zur Aufstellung einer neuen allgemeinen Formel für die gleichförmige Bewegung des Wassers in Kanälen und Flüssen. Bern, Druck von Lang (1877).
20. MERRIMAN, M., Treatise on hydraulics, 8th ed. New York, John Wiley & Sons (1905) pp. 281–283.
21. MANNING, R., Observations on subjects connected with arterial drainage. Proceedings of the Institution of Civil Engineers of Ireland, May (1851) 90–104.
22. MANNING, R., On the flow of water in open channels and pipes. Proceedings of the Institution of Civil Engineers of Ireland *20* (1890) 161–206.
23. *Ibid*., p. 161.
24. ROUSE, H. and S. INCE, History of hydraulics. New York, Dover Publications (1957) p. 179.

25. GAUCKLER, P. G., Etudes théoriques et pratiques sur I'écoulement et le mouvement des eaux. Comptes Rendus du L'Academie des Sciences *64* (1867) 821.
26. GAUCKLER, P. G., Du mouvement de I'eau dans les conduites. Annales des Ponts et Chaussées *15* (1868) 229–281.
27. HAGEN, G. W., Neuere Beobachtung über die gleichförmige Bewegung des Wassers. Zeitschrift für Bauwesen *31* (1881) 403–408.
28. POWELL, R. W., The origin of Manning formula. journal of the Hydraulics Division, ASCE *94* (1968) 1179–1181.
29. MANNING, R., Ref. 22, p. 177.
30. FLAMANT, A., Méchanique appliquée – hydraulique. París (1891).
31. WILLCOCKS, W. and R. HOLT, Elementary hydraulics. Cairo, National Printing Office (1899).
32. BUCKLEY, R. B., Design of channels for irrigation and drainage. London, Spon (1911).
33. BISWAS, ASIT K., The Nile: its origin and rise. Water and Sewage Works *113* (1966) 282–292.
34. JARVIS, C. S., Flood-stage records of the river Nile. Proceedings ASCE *61* (1935) 803–812.
35. MAASS, Die Wasserstände der Elbe in den Jahren 1727 bis 1870. Zeitschrift für Bauwesen, Berlin (1870) 496–502.
36. BERGHAUS, H. C. W., Allgemeine Länder- und Völkerkunde, 2nd vol., Umrisse der Hydrographie. Stuttgart (1837).
37. WEX, G. V., First treatise on the decrease of water in springs, creeks, and rivers, translated by G. Wietzel. Washington, D.C., Government Printing Office (1881) p. 27.
38. KOLUPAILA, S., Die Bestimmung des Abflüsses des Memelströmes (Nemunas, 1812–1932). IV Hydrologische Konferenz der Baltischen Staten, Leningrad, September (1933).
39. DAVENPORT, R. W., Long records of river flow. In: Hydrology, edited by O. E. Meinzer. New York, Dover Publications, Inc. (1942) pp. 499–506.
40. KOLUPAILA, S., *op. cit*., pp. 12–15.
41. MIAMI CONSERVANCY DISTRICT, Storm rainfall of eastern United States. (Revised Technical Report, part 1, Dayton Ohio pp. 314–328.
42. GREBENAU, H., Die Internationale Rheinstrom-Messung bei Basel vorgenommen am 6–12, November 1867. Munich, J. Lindauer (1873).
43. KRAIJENHOFF, C. R. T., Recueil des observations hydrographiques et topographiques faites en Hollande. Amsterdam, Chez Doorman et Comp. (1813).
44. DOOGE, J. C. I., The rational method for estimating flood peaks. Engineering *184* (1957) 311–313; 374–377.
45. MULVANEY, T. J., On the use of self-registering rain and flood gauges in making observations of the relations of rainfall and flood discharges in a given catchment. Proceedings of the Institution of Civil Engineers of Ireland *4* (1850–1851) 18–31.
46. *Ibid*., p. 20.
47. *Ibid*., pp. 19–20.

48. *Ibid*., pp. 20–21.
49. *Ibid*, pp. 23–24.
50. MANNING, R., Ref. 21, p. 94.
51. KUICHLING, F., The relation between the rainfall and the discharge of sewers in populous districts. Transactions, ASCE *20* (1889) 1–56.
52. CHAMIER, G., Capacities required for culverts and flood openings. Proceedings of the Institution of Civil Engineers *134* (1898) 313–323.
53. LLOYD-DAVIES, D. E., The elimination of storm water from sewerage systems. Proceedings of the Institution of Civil Engineers *164* (1906) 41–67.
54. RICHARDSON, C. G., The 50th year of a great invention. Water Works Engineering *90* (1937) 1326–1329; 1382.
55. HERSCHEL, E., A farewell word on the Venturi meter. Engineering News Record *102* (1929) 636–637.
56. HERSCHEL, E., The Venturi water meter: an instrument making use of a new method of gauging water. Transactions, ASCE *17* (1887) 228.
57. SMITH, W., On retaining water in the rocks for summer use. Philosophical Magazine, New Series 1 (1827) 415.
58. SHEPPARD, T., William Smith: his maps and memoirs. Proceedings of the Yorkshire Geological Society 19 (1917) 189–191 (published as a book in 1920 by A. Brown & Sons Ltd., Hull).
59. DARCY, H. P. G., Ref. II, Appendice – note D, translated by J. J. Fried. Water Resources Journal, AWRA I (1965) 5–11.
60. DUPUIT, A. J. F. J., Etudes théoriques et pratiques sur le mouvement des eaux courantes, 2nd ed. Paris, Carilian-Goeury (1863).
61. DUPUIT, A. J. F. J., Traité théorique et pratique de la conduite et de la distribution des eaux. Paris, Carilian-Gocury (1854).
62. BISWAS, ASIT K., Development of hydrology in the nineteenth century. Water Power *21* (1969) 16–21.
63. THIEM, A., Die Ergiebigkeit artesischer Bohrlöcher, Schachtbrunnen, und Filtergallerien. Journal für Gasbeleuchtung und Wasserversorgung *14* (1870) 450–467.
64. HALL, H. P., A historical review of investigations of seepage toward wells. Journal of the Boston Society of Civil Engineers *41* (1954) 251–311.
65. THIEM, A., Beitrag zur Kenntnis der Grundwasserverhältnisse im norddeutschen Tieflande. Journal für Gasbeleuchtung und Wasserversorgung *24* (1881) 686–695.
66. THIEM, A., Der Versuchsbrunnen für die Wasserversorgung der Stadt München. Journal für Gasbeleuchtung und Wasserversorgung *23* (1880) 156–164.
67. THIEM, A., Resultate des Versuchsbrunnens für die Wasserversorgung der Stadt Strassburg. Journal für Gasbeleuchtung und Wasserversorgung *19* (1876) 707–718.
68. THIEM, A., Neue Messungsart natürlicher Grundwassergeschwindigkeiten. Journal für Gasbeleuchtung und Wasserversorgung *31* (1888) 18–28.

69. THIEM, A., Verfahren für Messung natürlicher Grundwassergeschwindigkeiten. Polytechnische Notizblatt *42* (1887).
70. FORCHHEIMER, P., Hydraulik. Leipzig, Teubner (1930).
71. RICHARDSON, L. F., A freehand graphic way of determining streamlines and equipotentials. London, Edinburgh and Dublin, Philosophical Magazine and Journal of Science 15 (1908) 237–269.
72. FORCHHEIMER, P., Über die Ergiebigkeit von Brunnen-Anlagen und Sickerschlitzen. Zeitschrift der Architekten- und Ingenieur-Verein *32* (1886) 539–564.
73. HOLZMÜLLER, G., Einführung in die Theorie der Isogonalen Verwandtschaften und der Konformen Abbildungen. Leipzig (1882).
74. FORCHHEIMER, P., Grundwasserspiegel bei Brunnenanlagen. Zeitschrift der österreichische Ingenieur- and Architekten-Vercin *50* (1898) 629–635; 645–648.
75. Quoted by O. E. MEINZER in: Hydrology. New York, Dover Publications, Inc. (1942) p. 23.
76. SLICHTER, C. S., The motion of underground waters. Water-Supply Paper *67*, US Geological Survey Washington, D.C., Government Printing Office (1902).
77. BEARDMORE, N., Manual of hydrology. London, Watelow & Sons (1862).
78. ANONYMOUS, Nathaniel Beardmore, Memoir. Proceedings of the Institution of Civil Engineers *32* (1872–1873) 256–264.
79. BISWAS, ASIT K., A short history of hydrology. Proceedings of the International Seminar for Hydrology Professors, University of Illinois, Urbana (1969).
80. KOLUPAILA, S., Early history of hydrometry in the United States. Journal of the Hydraulics Division, ASCE *86* (1960) 1–51.
81. FOLLANSBEE, R., A history of the water resources branch of the United States Geological Survey to June 30, 1919. Geological Survey, Washington, D.C. (1938) p. 41.
82. GROVER, N. C., Progress in branch activities to June 30, 1906. Geological Survey, Washington, D.C. (1938) p. 183.
83. DICKENS, C. H., Flood discharge of rivers. Professional Papers on Indian Engineering. Roorkee, India, Thomson College Press (present University of Roorkee) *2* (1865) 133–136.
84. CHOW, V. T., Hydrologic determination of waterway areas. Bulletin No. 462. Engineering Experiment Station, University of Illinois, Urbana (1962) pp. 70–79.
85. RIPPL, W., The capacity of storage reservoirs for water supply. Proceedings of the Institution of Civil Engineers *71* (1883) 270–278.
86. FRAZIER, A. H., Daniel Farrand Henry's cup type 'telegraphic' river current meter. Technology and Culture *5* (1964) 541–565.
87. FRAZIER, A. H., William Gunn Price and the Price current meters. Contributions from the Museum of History and Technology, Paper 70, Smithsonian Institution, Washington D.C. (1967).

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