THE RELATION OF STREAM GAGING TO THE SCIENCE OF HYDRAULICS.

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Hydraulics has been defined as "that branch of natural philosophy which treats of fluids in motion."[1] It is a part of the broader science of hydrology, which is concerned with the properties and phenomena of water and its distribution over the earth's surface. The phenomena exhibited by water issuing from orifices; flowing in pipes, canals, and rivers; oscillating in waves; or opposing a resistance to the progress of solid bodies form the subject matter of hydraulics. The classification of knowledge relating to the laws governing the motion of water and the application of these laws to practical purposes may be called the first principles of hydraulic engineering.

A working knowledge of the science of hydraulics has been possessed by mankind since the beginning of history. The Egyptians in their ancient irrigation must have accumulated much practical information regarding the characteristics of flowing water, and the Romans in preparing for the construction of the extensive water-supply systems of Rome showed a good knowledge of hydraulic engineering. The hydraulic works of those times were simple in principle, although stupendous in size, and required only elementary scientific knowledge. It is nevertheless something of an anomaly that, despite these early beginnings, the verified knowledge relating to the laws of flowing water is to-day relatively small, and that hydraulics is as yet an imperfect science and essentially of modern formulation.

Considering water as a frictionless, incompressible, inelastic fluid, Torricelli in 1644 formulated the theorem which bears his name, thereby coming to be known as the founder of hydraulics. His law, $V \propto \sqrt{h}$, is accepted and in common use to-day, although modified by constants and coefficients. A hundred years later Bernouilli enunciated the law that "for steady flow without resistance the sum of the potential and kinetic energies is constant." Both these investigators left to later generations the task of reducing these laws to forms suited to practical application—a task indicative of the principle underlying

[1] Olmsted, Denison, An introduction to natural philosophy; designed as a textbook for the use of the students in Yale College, 1838.

all development in hydraulic science. Inductive reasoning based on the fundamental laws of this science, as discovered and enunciated by the ablest scholars, must be supplemented with deductions based on experience and experiment. Olmsted, in the introduction to his textbook on natural philosophy, already cited, was careful to state that "in this part of the doctrine of fluids the deductions of theory alone are of little value and are in fact so discordant with experience that little reliance can be placed on them except as modified by experiment. When thus modified, the truths learned respecting the laws that govern the motions of fluids have a high degree of practical utility."

The deductions from experience and experiment are usually introduced into hydraulic formulas as coefficients or constants. It is practically true that the application of any hydraulic formula involves the determination and use of coefficients or corrections. A coefficient that has been determined under a certain set of conditions may afterward become so associated with the formula that it comes to be regarded as part of a fundamental law. This is true of some of the so-called "standard" weir formulas, which are frequently applied to conditions entirely at variance with those under which the coefficients were determined.

Rational formulas must indeed be based on natural laws, and it is only by the application of inductive reasoning to practical problems that the fundamental natural relations may be determined. It is not always possible, however, to convert the basic natural law into a practicable working formula; the determination of the discharge in an open channel by a process of inductive reasoning would be so complicated as to make the use of such a method absurd. Chezy's suggestion, made in 1775, that the velocity might be expressed as a function of the hydraulic radius and the slope, $V=C\sqrt{RS}$, is the farthest advance science has yet made in that direction. It is an admirable attempt to express in a rational manner the factors that determine the flow in an open channel, and the form of the expression is not questioned to-day so much as the value of the coefficient to be used. Various methods for the determination of C have been proposed, but the results are so uncertain that no well-informed hydraulic engineer would attempt to apply Chezy's formula to the determination of river discharge except where roughly approximate results would be acceptable.

The earlier experimental work in the measurement of flowing water was necessarily based largely on volumetric measurements. This method, while giving the greatest accuracy, is unfortunately limited in its application to problems dealing with comparatively small quantities of water. The experiments on discharge over thin-edge weirs by J. B. Francis in 1851–52 and his expression of the law of flow by a rational formula constituted an important step toward standard methods for the measurement of water in motion. Later investigators, notably Fteley and Stearns in 1877 and Bazin 10 years later, suggested various modifications of Francis's formula and also somewhat different coefficients. The investigations of Bazin, especially, were exhaustive and his deductions marvels of mathematical exactness. Even more important, as a means of measuring the flow of natural streams, was the development of the velocity-area method. The possibilities of the wide application of this method were recognized as early as 1889, as was also to some extent the great amount of detail to be systematized and perfected. The ways devised for determining the velocity were many and ingenious. The simplest and probably the first way of estimating the velocity was by means of floats. This method was unsatisfactory, as it was soon discovered not only that a large number of observations were needed throughout the cross section, but also that the velocity of the water as related to the velocity of the float was somewhat indefinite. Various questions arose relating to the observation of velocity, such as the frequency with which these observations should be made across a stream and the best method for determining the mean velocity at a section. These questions could not be decided by abstract reasoning, but had to go through the evolutionary process of experience and experiment. Thus working rules were developed from existing knowledge, and as new facts became established by empiricism they were incorporated into the procedure.

From the demand for a method of determining the flow in an open channel—a method which should be as simple as possible consistent with the desired accuracy and at the same time of the widest application—stream gaging in its present status has been evolved. It is a very recently developed branch of a modern science. The status of hydrometry at the time of the beginning of water-resources investigations by the United States Geological Survey, no longer ago than 1889, is well shown by an extract from the Tenth Annual Report of the Director,[1] as follows.

> The measurement of water flowing in a stream is not an easy matter. It requires skill and rather costly instruments. While the general method has been the subject of much inquiry by a few men and has been practiced to a small extent, there is a wide variation in details and considerable uncertainty or discordance in results. At the beginning of the organization there were no men available who possessed the requisite experience and skill, except two or three men who were occupying responsible positions, and it was doubtful if they could be induced to relinquish them. Neither were any instruments to be found in the market as articles in regular supply, and such as were needed must be made to special order. The investigation of the amount of water available for catchment required the opening up of an entirely new field of research.

[1] Powell, J. W., U. S. Geol. Survey Tenth Ann. Rept., pt. 2, p. 78, 1890.

As stream gaging is so new an outgrowth of a modern science it must inevitably undergo many changes in the course of its evolution. The lines that will be followed in its future growth can be surmised only from its past history. The improvement of the current meter and its use in the velocity-area method marked a great advance in the science of stream gaging. To judge from the course of development of the meter, further improvements and simplifications of it will doubtless continue to appear from time to time.

Methods for the measurement of discharge—such as the method of using salt or other chemicals, or the relatively recent one of using a diaphragm in open channels of uniform cross section—are likely to become increasingly valuable. But, as with the use of the weir, they probably will not be universally applicable, though they may appreciably cut into the present field of the meter. As a generally applicable means of measurement the current meter is undoubtedly founded on the right principle, and it is hardly conceivable that the meter will be superseded.

A study of the evolution of stream gaging shows the important part played by empirical development together with scientific research, and it is even conceivable that in time the same results might have been obtained through the empirical process alone as through the joint application of theory and experiment. This fact is illustrated by some features of the present method of stream gaging. The observations of velocities at six-tenths of the depth or at two-tenths and eight-tenths of the depth have resulted from a large amount of experiment, but it is now well known that these methods are substantiated by the form of the vertical velocity curve, which is that of the parabola. Had this scientific fact been earlier recognized and applied, it would undoubtedly have materially reduced the amount of research necessary to establish these methods for obtaining the mean velocity. In fact, one criticism which may be made in regard to the development of the present status of stream gaging is that possibly too much reliance has been placed on empirical methods and the advantages to be gained from scientific analysis have been given too little recognition. Although the fundamental principles of stream gaging now seem to be fairly well developed, it should be remembered that before a step can be considered final, it must be confirmed by both theory and experience and that there is no method so well established that it may not be materially modified as a result of future research.

Theoretical considerations embraced under the science of hydraulics constantly appear as supplementary to the practical applications. For example, a thorough knowledge of Chezy's formula, in which the laws of uniform flow are succinctly expressed, may often be of great practical use in analytical studies of stream-flow data, regardless of the fact that the field of direct application of the formula is limited. A further example of the application of theory to practical problems is given by the discussion of velocity and area curves in Water-Supply Paper 146. In this discussion the formulas derived for the mean-velocity, area, and discharge curves give results that are both complicated and impracticable. The formulas show, however, in a more comprehensive manner than would be possible in other ways the relation of the elements that enter into the curves, and a study of them would assist an engineer to construct a discharge rating curve more intelligently and therefore more correctly. Thus, though the conditions at every gaging station define a law peculiar to that station, yet as a supplement to its study knowledge of hydraulic theory and familiarity with hydraulic research may be of great benefit. The importance of utilizing the established facts of the science of hydraulics receives emphasis from many examples in the present practice of stream gaging. The principle of the weir may often be used, as is illustrated by the recent development of artificial controls.

During the last decade stream gaging has come to be recognized as one of the most important branches of hydrometric investigations. The collection of data showing the run-off in second-feet per square mile from numerous drainage areas is but one of the many phases of stream gaging. As relating to the science of hydraulics, the determination of constants and coefficients for use with hydraulic formulas is a field for research even more important than the collection of general statistical information. The need for work of this sort is emphasized by the fact that several Government departments as well as private organizations engaged in large construction and maintenance projects have found it necessary to carry on extensive hydraulic investigations by means of stream gaging in order to obtain the most economical designs for construction and the most satisfactory methods of maintenance and operation.

The drainage investigations that have recently been undertaken in some of the Southern States for the purpose of reclaiming many thousands of acres of rich agricultural lands afford an excellent illustration of the need for stream gaging of a high degree of precision. Data regarding the rate and amount of seepage, the possible effect of sedimentation, and the carrying powers of different velocities are required in order to determine the magnitude and effect of the several complicated factors on which the final success or failure of the drainage projects will depend.

Many valuable experiments tending to increase the knowledge of hydraulic phenomena have been carried on in connection with irrigation work in the arid regions. The methods employed have in general been similar to those ordinarily followed in stream gaging and based on current-meter determinations of velocity. In some special investigations, however, where comparatively small quantities of water were concerned, volumetric methods were used.

The work of the United States Reclamation Service probably represents fairly well the present status of stream gaging in its practical application to the problems other than those encountered in the collection of statistical data. Determinations of the friction losses in large-sized wood-stave pipe, the varying effect of vegetation on the flow of water in canals, the values of the coefficient of roughness for different materials, the proper coefficient to be used in computing discharge through gates, the rate and amount of seepage losses and the economic possibility of lining canals to prevent such losses, the fluctuations in flow due to increased diurnal seepage and evaporation during the day, the efficiency of pumps and turbines, and the economic size and cost of power plants for pumping water for irrigation are some of the hydraulic problems to which the Reclamation Service engineers have applied the science of stream gaging.

The determination of the actual efficiency curves of power-plant operation is a field for the application of stream gaging at the present time. Various methods have been proposed for the testing of water wheels when installed and under everyday conditions of operation, the use of chemical solutions being advocated by some engineers, but for general application under ordinary conditions the current-meter method gives results more consistent than may be obtained in any other way. As in any application of stream gaging to intensive studies, the method must be used intelligently and by experienced engineers to be successful. The limitations of the meter must be known and precautions taken to insure favorable conditions for field work. Then with ordinary care it will be found that the measurements of water through the wheels are more accurate than the coordinate determinations of the electrical units on the switchboard. A study of power-plant efficiency is illustrated by figure 16, which gives the net efficiency curves for four units of a hydroelectric plant under ordinary working conditions. Units Nos. 1, 2, and 3 are identical in construction and consist of two 36-inch wheels set tandem on horizontal shafts direct-connected to 1,000-kilowatt generators of the General Electric Co. class 20, 1,000 kw., 240 r. p. m. type; the turbines are operated by swing gates. Unit No. 4 is of similar construction except that the generator is of larger capacity, being of the General Electric Co. class 16, 1,200 kw., 300 r. p. m. type, and the wheel gates of piston type. The normal operating head is 50 feet, half of which is derived from draft tubes. These curves were obtained as supplemental data incident to the rating of the power plant for a gaging station and are shown to illustrate the application of stream gaging to the study of power-plant efficiency.

During the last few years much time and energy have been expended in the development and standardization of methods in stream gaging. The special equipment needed has now been perfected to such a degree that the results obtained depend largely on the methods and the skill used in handling the instruments. With correct methods

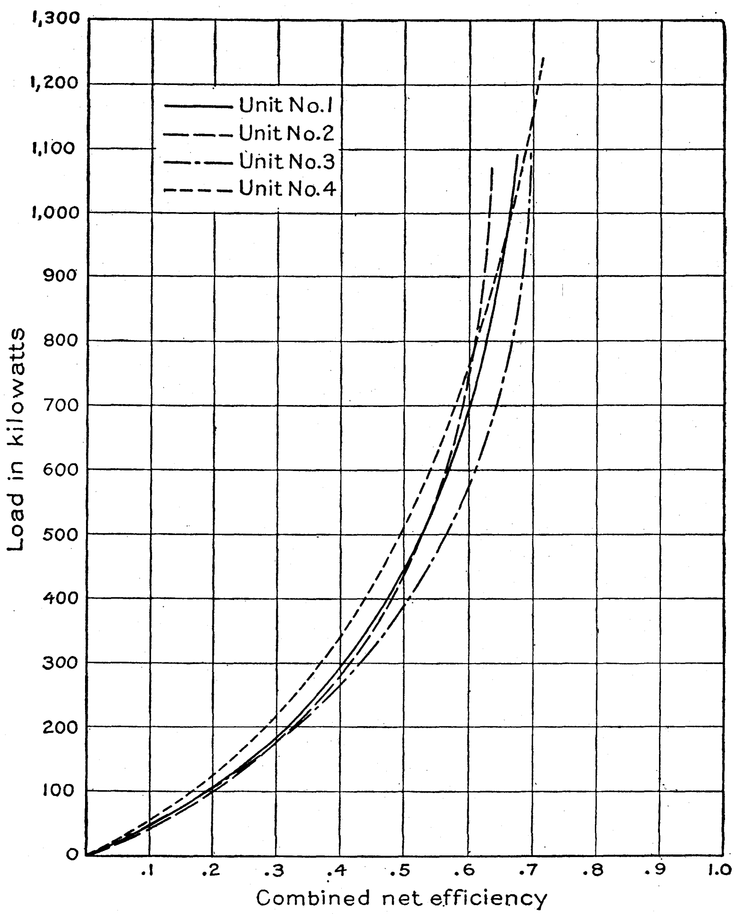

FIGURE 16.—Power-plant efficiency curves.

and experienced observers the accuracy of the results is well within the limits of all practical requirements, and the precise degree of accuracy can be mathematically determined. It seems probable also that in the future the results of accurate stream gaging will be utilized in connection with problems in meteorology and physiography. Although the determination of better coefficients for use in the accepted hydraulic formulas and the deduction of new laws not heretofore expressed may be confidently expected, it should also be remembered that the results of stream gaging have already been applied to the measurement of rainfall on a large scale and to problems involving no less complicated features than the determination of effects of deforestation on the navigability of interstate streams. A large amount of research is yet needed before hydraulics can be considered an exact science, but the recent developments in stream gaging point to the possibility that this branch of hydraulics may in time reach a state of perfection so commensurate with the requirements imposed upon it that all problems connected therewith may be solved with mathematical exactness and the term "probable error" be reduced to a rational quantity. With "accuracy" as the watchword and an "exact" science as the ideal the developments in the science of hydraulics that may be wrought by the means of the current meter and the stop watch should be such as to justify the highest expectation of the most enthusiastic stream gager of to-day.