Reprint. "The Historical Development of Hydraulic Researches..." 1929

THE HISTORICAL DEVELOPMENT OF HYDRAULIC RESEARCHES

AND

SOME NOTEWORTHY HYDRAULIC LABORATORIES IN AMERICA

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I. Foreword: Historical Development of Hydraulic Researches and Some Noteworthy Hydraulic Laboratories in America*

By John R. Freeman, Providence, R. I.

IN THIS introductory chapter, which Dr. Conrad Matschoss, Secretary of the German Society of Engineers, has kindly asked me to write, it may be well first of all to explain how I happened to be admitted to this distinguished company of authors.

It was more than fifty years ago that I served an apprenticeship in a hydraulic laboratory, and I have since that time kept tolerably familiar with what has been going on in that line and in hydraulic constructions.

My personal connection with the present publication followed closely upon recent visits to England, France, Germany, and Czechoslovakia, in the course of which I inspected several river-structure and water-turbine laboratories, notably those of the great engineering colleges at Charlottenburg, Dresden, Karlsruhe, Brünn, and Grenoble, and the naval research tank at Berlin. I was amazed at the great development made since I inspected certain of these laboratories ten years before, particularly in the extent and success with which they are using long tanks, from one to two meters wide (40 to 80 in.), with plate-glass sides and models on a scale of anywhere from 1/10 to 1/100 of the full-size structure, river or harbor. I became so greatly impressed with the great practical value of the results that were being obtained, that I urged upon Dr. Matschoss that the skilled hydraulicians in charge of these laboratories, Professors Engels, de Thierry, Krey, Rehbock, and Smrček, be invited to join in a series of monographs in which each should describe the laboratory under his charge, and describe also some of his principal researches, showing his successes in the use of these models; and in which also should be set forth some of the abundant proofs (accumulated by comparisons between model tests and the full-size structure or channel or waterfall in nature) which show that the flowing stream behaves very much in nature as in its small laboratory counterpart when this is wisely proportioned and skilfully managed. I urged that through joining in the discussion of these matters of high scientific interest and of great practical utility, friendly international relations between engineers and teachers of engineering would be quickened and strengthened the world around.

It has given me great pleasure to note the broad and friendly spirit of response, and that my German friends immediately invited to join with them eminent professors of hydraulic engineering in the great technical universities of other countries of Europe, including those at Vienna, Brünn, Stockholm, and Leningrad.

It is my strong belief that the heartiness of this response and the value of the information thus brought together will greatly stimulate hydraulic research in America, England, Italy, and France, and even extend to the engineering schools of far-off China and Japan; and that the science and arts of "Controlling these great forces in nature for the benefit and convenience of man" in many countries will be advanced through the contributions found in the following chapters.

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On Hydraulic Laboratory Researches in General

A hydraulic laboratory is a place fitted for investigations concerning the physical laws that control the motion of water.

The following collection of monographs in which a number of laboratories, among the foremost of their kind in the world, are described by their designers, with a brief summary of some of the chief researches recently made in each, will make plain what such a place is like, its purpose, and its usefulness.

We find three general types of hydraulic laboratories:

1 Those designed primarily for purposes of instruction at engineering colleges.

2 Those designed primarily for research; some established by national government, others by builders of hydraulic machinery.

3 Those in which both purposes are combined.

Hydraulic laboratories may also be classified as follows:

a The ordinary hydraulic laboratory, commonly a temporary installation of apparatus, designed for giving, once for all, for use in the routine work of the engineers, accurate constants to be applied in formulas for computing the discharge of water from orifices, nozzles, and weirs of various shapes under various heads, or for estimating the discharge of pipes, conduits, and open canals under a given hydraulic gradient, or for giving the height and range of jets under given heads.

The general laws or formulas governing the motion of water for each of the above problems are tolerably well known, but with the progress of the arts, more precise coefficients or constants are required.

b The "Flussbau," or river-structure laboratory, designed as a permanent structure with facilities for various set-ups of apparatus, for establishing hydraulic laws applicable to special problems within the field of the civil engineer, particularly those which deal with the improvement of rivers and harbors (involving erosion, transportation, and deposit of sediments), the building of dams and the out-of-doors accessories of water-power development, and the storage and distribution of water for municipal supply. This type is proving useful in the preparation of designs such that obstruction of sluiceways by ice or logs will be minimized, that floods will be most readily discharged, and that stability of river structures will be increased.

c The water-turbine laboratory, especially designed for helping the mechanical engineer in the development and perfecting of various types of turbine water wheels and centrifugal pumps, and adjusting a design to give the best practicable efficiency for a particular head and speed of revolution, and for various percentages of full discharge.

d The naval tank or laboratory, designed for providing the naval architect with means for studying the resistance to the propulsion of ships or canal boats of various forms at various speeds by experimenting upon a small model of the ship, and for improving the design of screw propellers by means of tests on small models.

The hydraulic laboratories to be described in the following pages are chiefly river-structure laboratories of the research type, designed both for purposes of instruction and to help in solving the problems of the civil engineer who deals with rivers, canals, harbors, and dams, and are mostly the product of the last ten years. A description of one of the foremost water-turbine laboratories of the world — that at Munich—has been included. It should be understood that there are several other water-turbine research laboratories in Europe, also under exceptionally able scientific control.

Regarding important types of hyraulic laboratories not included among those to be described in the following pages, it is hoped that means may be found for publishing descriptive reports upon plants and researches at other noteworthy water-turbine laboratories in Germany, Switzerland, Sweden, Norway, and America; also of plants and of researches in some of the chief naval tanks of the world, such as that of the magnificent ship-model research laboratory at Hamburg, that of the British National Physical Laboratories, that of the U. S. Navy Department at Washington, and that of the University of Michigan; also a description of plants and researches at several of the hydraulic laboratories at American colleges, designed particularly for the purpose of instruction in the fundamentals of hydraulics. Such a book might be very helpful to progress.

I have seen on the lecture table in German class-rooms, several pieces of apparatus for illustrating fundamental hydraulic phenomena, which I believe have as yet no equivalent in American engineering colleges. Motion pictures also have been prepared of the more elaborate laboratory set-ups on special problems; for example, that prepared in the laboratory of Professor Smrček at Brünn, for illustrating the method of failure of a rock-fill dam, duplicates of which could be exchanged with other engineering colleges with great advantage.

Although much has been learned about the general laws of water flowing through orifices, pipes, canals, weirs, and jets, as used in the constructive arts, there is still vast opportunity for valuable research, both in increasing the precision of present data over a wider range of dimensions, and in new fields of research which will lead to economy in engineering design and be helpful to water transportation and flood relief and of benefit to mankind in many ways. The papers which follow deal largely with an epoch-making development in the river-structure and water-turbine laboratories by the use of small models for representing large structures and natural water courses, under the principles of dimensional analysis and hydraulic similitude; which development began with the researches of Osborne Reynolds about forty years ago. These methods have been developed in recent years in German laboratories, also in certain laboratories in Sweden, Austria, and Czechoslovakia, to an extent that is not yet appreciated in America or in England. Such laboratory methods with models offer great promise in regard to many important problems which urgently await solution in America.

Evolution of the Laboratory Idea

As one delves into the history of the development of hydraulics as a science, it becomes plain that those who observed natural rivers, far apart and not subject to experimental control, mostly failed to discover the laws that controlled their movements of water and sediments, and that those who treated hydraulics as a branch of mathematical research instead of as a branch of experimental physics, mostly got lost in their *a priori* theorizing. It becomes plain that those who used the laboratory method made most of the useful discoveries.

Although the name "hydraulic laboratory" is modern, the underlying idea is old. Apparatus and methods answering to this name doubtless were used by da Vinci, by Galileo, perhaps by Archimedes. In its earliest forms the laboratory was extremely simple, a tank with an orifice and a measuring basin; or a small water course, like that used by Fargue in France, within which the motion of small streams of water could be studied, and the laws of motion for rivers inferred. Within recent years, the name has come to suggest a special building, filled with many kinds of apparatus, pumps, measuring tanks, weirs, channels with plate-glass sides, special photographic cameras, small-scale models of channels and structures, spouts, meters, manometers, and glass tubes.

The most powerful instrument for research in the latest and best laboratories for studying river structures and water turbines has come to be the small-scale model, used with an understanding of the mathematical principles of hydraulic similitude. By these methods of hydraulic similitude many great problems of highest importance and involving quantities and forces on a grand scale can be taken from the great out-of-doors into the laboratory and solved by means of experiments upon a model having linear dimensions only one-tenth or one one-hundredth part of those in the original channel or structure.

However, when one takes large problems from the flowing river, or tide-swept harbor, into the laboratory, it is of the highest importance that comparison between the original and the model be maintained step by step, and that traps be set in which to catch and measure every conceivable source of error; because some of the relations of cause and effect in rivers — in shift of current and in behavior with sediment — are extremely delicate and elusive. Although the forces which control the movement of particles of sediment may be as delicate and variable as those which control the dance of the individual motes of a sunbeam, all are subject to definite laws; and while the paths of individual particles may be beyond our grasp, the general mass-effect is commonly found subject to analysis and control. The laboratory can tell us how to predict and how to control these mass effects.

I have been told by one of the foremost of present-day mathematical physicists that hydrodynamics is among the most abstruse and difficult branches of applied mathematics that can be imagined. Nevertheless, many researches, the results of which have been of great benefit to the hydraulic engineer in his designing, have been made in hydraulic laboratories of simple character, by men of but modest mathematical attainment, who had inborn mechanical sense, patience, and love for the Baconian method of seeking the truth through experiment; and there is still a vast field in which that type of student can work with the certainty of making discoveries that will benefit mankind.

Although the mathematics mostly used in hydraulic laboratories is of a simple order, such, for example, as is used in the reduction of observations to a common denominator for more precise comparisons; or such as used in so laying out graphs that by means of experiment and by variation of conditions they will give empirical formulas, with coefficients accurate enough for practical use in engineering; nevertheless there are many other opportunities for the use of mathematical skill in modern hydraulic research, as, for example, in laying out the lines for dimensional analysis.

Studies of River Hydraulics with and without Laboratory Models

Some years ago, after calling to my aid a particularly well-qualified assistant who spent many months in making careful compilations of all that could be found in print upon river hydraulics in substantially all of the great libraries of the Eastern United States, and after myself plodding through more than a thousand pages of abstracts, I was forced regretfully to conclude that the science and art of river hydraulics are still in much the same status as those of chemistry prior to the use of the balance, when fire was explained by phlogiston; or in the status of electric science prior to establishing the centimeter-gram-second standards for precise measurement; or in the old days when all descriptions of natural phenomena were loosely qualitative and not precisely quantitative. From those compilations it appeared that the rules and reasons presented in books and papers about many important lines of engineering work in rivers and harbors still present chiefly *records of opinion,* not records of carefully measured facts. In the course of this search through the records, diametrically opposite opinions on many important questions were found, those on each side strongly set forth by an equally eminent authority.

Observation on natural rivers has proved a slow and almost hopeless road for one who desires to discover the laws through which rivers can be controlled and regulated, or by which they can be made to dig their own channels where man wants them; or to one who desires to learn how to cause rivers to sustain their burden of silt and sediment and carry it to the sea. There has been a painful lack of precision of measurement throughout nearly all the vast mass of recorded observations, and a general failure in the attempts to apply rigorous mathematics and devise precise formulas, largely because of lack of precise data from precise observation.

Often, it has been said by engineers and others that " Nature prefers a gently curving course for rivers," and therefore man should curve his channels for navigation, or for flood relief, or for leading a volume of water to a power drop. This is more the expression of a poetic dream than a careful statement of facts.

It is a wise provision of nature that has caused rivers to seek meandering courses because, thereby, fertile plains are slowly built up from the sedimentary material brought down from the erosion of the mountains. Man commonly desires channels of a different order, straighter and deeper, and better adapted for navigation.

Sometimes in engineering practice there are good reasons for curving the course of a channel, as for causing the swifter current near the concave shore to maintain a well-defined channel for navigation, or for concentration of deposits at "cross-overs" between reversed curves; but commonly the strongly curving channel may be far from the best for purposes of navigation or flood control.

Sometimes there is need of quicker discharge of floods, and sometimes need for detention. Often it is important to control the movement or deposition of sediments ranging from boulders and coarse gravels brought down by Alpine torrents to the finest sands or to colloidal silt. We can best find out how to change and regulate natural water courses, and can most quickly learn how to call the great forces of nature to our aid, by means of the laboratory model, checking up, step by step, and comparing the action in the model with observations on the river or harbor.

One must be extremely cautious about generalizing from the scant data and the uncertain parallels of observations upon natural rivers, in which many distinct causes combine to control flow, erosion, and sedimentation. A confusion of causes prevents accurate deduction. On the contrary, in the laboratory these diverse causes, such as burden, or kind, or coarseness of sediment, roughness of bed, curvature, velocity, turbulence, salinity, temperature, etc., can be singled out, controlled, and varied one at a time.

I have long been strongly of the opinion that by means of a patient study of this kind, with field observation and laboratory experiment continually supplementing one another, we can learn to deal more boldly and more successfully than heretofore with many of these problems of changing the course of large rivers, and sometimes can straighten them with great advantage, and that the forces of nature can be invoked to perform a large part of this work.

I believe that even the problem of straightening the Mississippi may be solved by long-continued experimentation in laboratory and river, showing how its great bends, like those near Greenville, may be changed to far shorter, gentler curves, thereby giving a greater declivity and greater scouring force to the current, which then will dig deeper its river bed, so as to carry great floods within banks with lower levees — perhaps ultimately with no levees at all in certain long reaches — and with far greater safety to life and property than now, and without need of any such vast spillways as are now being proposed. Also it is my belief that the flood surface can be lowered by lessening the height of the cross-over bars through narrowing the river at the cross-overs, by means to be worked out partly in the laboratory and partly in the field; also that as the culmination of certain lines of research, one may learn how to build cheaper, quicker, and more permanent river-bank revetments, and how to keep the South Pass open without constant dredging.

It has been proved abundantly, at laboratories described in the following pages, that a well-equipped modern laboratory can aid in the analysis and separation of causes in these complex phenomena of river-bed erosion and sand-bar formation, also that it can aid greatly in regulating harbor currents, in the lessening of turbulence in filling navigation locks, and in problems of estimating boat resistance in canals of scant cross section. The methods of the modern hydraulic laboratory are also needed for the perfecting of siphon spillways, for the further improvement of high-speed turbine runners, and for the development of higher efficiency in high-lift centrifugal pumps; for establishing more precise formulas for estimating the discharge over dams and through sluices of various forms; for a better form of weir for metering large quantities of flowing water; for studying the errors of the ordinary current meter actuated by a revolving cup-wheel, or screw, in disturbed currents; for learning how best to conserve energy while changing the direction of water courses; and for a score of other problems of large commercial importance.

Last summer, at Karlsruhe, I was told that with each practical major problem that had been taken from out-of-doors into their river-structure laboratory, the saving in structural cost due to the information thus gained had been more than equal to the entire cost of laboratory building, apparatus, and research. At Charlottenburg, and elsewhere, I gathered that laboratory research with the aid of small models had been similarly profitable.

Personally, I have little doubt that a suitable river structure or laboratory, in skilful hands in the United States, could be made to pay dividends of a thousand per cent per year on its cost! One has only to study the vast appropriations for river and harbor improvement made by the United States during a term of years — two millions of dollars wasted in futile experiments on the Mississippi for narrowing the channel by permeable dikes, about $600,000 wasted along the lower Colorado, and nearly twenty millions spent before success in trying to open the South Pass of the mouths of the Mississippi for big ships — or to consider the problems of the California Debris Commission or the present conditions along the Missouri River, to see that such a statement is not extravagant.

Some Waiting Problems

In certain quarters there has been a mistaken idea that the fundamental science and data of hydraulics have been sufficiently worked out so that there now is no pressing need for an expensive hydraulic research laboratory, inasmuch as we already possess tolerably good rules and coefficients set forth in the engineering handbooks by which we can estimate quantities with an error not exceeding from 2 to 20 per cent, according to circumstances, in the following problems:

1 The discharge of various kinds and shapes of orifice under various heads.

2 The discharge over sharp-crest weirs with depths up to two feet with a margin of error of 1 per cent, under favorable conditions, but perhaps 10 per cent under eddying approach or over broad or irregular crests.

3 The discharge of a pipe of specified form and roughness under a given fall per 1000 ft. within from 2 to 20 per cent, the uncertainty being due to lack of precise knowledge of quality of surface or effect of bends and minor obstructions.

4 The discharge or slope of an open canal or river of specified quality of bed and form, under a given slope or fall per 1000 ft. within from 5 to 25 per cent, according to its straightness and accurate knowledge of its smoothness of wetted perimeter.

5 The height to which a jet of given diameter will rise or can be thrown, under a given pressure, in still air.

These five classes of problems of measurement comprise nearly all those treated in the ordinary textbook, and, outside of river and harbor problems, cover probably 90 per cent of the requirements of the civil or mechanical designing engineer with sufficient accuracy, but cases often arise where greater precision is desirable, and where this greater precision would permit important economies.

Solutions of these five classes of problems fail utterly to meet the needs of river and harbor engineering and also largely fail to meet all of the needs of the modern engineer in many other lines of work.

Five years ago, in a paper before the American Society of Civil Engineers, I enumerated the following list of studies in which a proposed National Hydraulic Laboratory could be used. This laboratory was to be modeled somewhat on the lines of those in Germany but on a larger scale and was to have a tilting river flume 250 ft. long, 20 ft. wide, and 3 ft. deep, with its slope variable from 0 to 3 per cent.

Parallel to the river flume was to be a weir flume 245 ft. long, 15 ft. wide, and 20 ft. deep, suitable for many experiments on model dams, etc. Electrically driven pumps were to be provided to circulate up to 600 cu. ft. of water per second, although commonly less than one-tenth of this amount would be needed. Precise measurement of discharge was to be made in a large rectangular tank by means of a swinging gate and chronograph, also by venturi meters. Forty studies were suggested to be carried on in the river flume, and twenty-four for which the weir flume could be used. This list was by no means exhaustive. Other engineers could quickly add enough problems of perhaps even greater importance to double its length.

Reviewing that list today, I should say that one of the earliest and most important problems of such a laboratory should be *thoroughly to test out the errors and limitations in the doctrine of hydraulic similitude,* in the use of scale models for experimentation in various lines of research, particularly in the problem of river control, and also the effects of distortion of scale.

The list of researches then suggested covered the following problems:

1 A further investigation of Thompson's theory of scour at river bends due to spiral flow.

2 An investigation of the path of material scoured out from the concave shore at a bend, whether moved across the river, or to a downstream sand-bar.

3 Best inclination of the river banks. The best shape for the ends of spur dikes in a straight river channel for producing minimum scour and undercutting at the end of the spur. The best shape for preventing undermining of a submerged spur dike by scour from a swift current flowing over the dike.

4 Relative merits of permeable and impermeable spur-dikes of different forms for meeting various conditions.

5 Best horizontal outline—whether inclined upstream or downstream or at right angles to the river bank — for a sub-surface dike reaching from the bed to slightly above low water but submerged at high water, and thence extended up the bank by a thicket of willows or other trees.

6 Development of shape and construction of cross section of spur dikes faced with riprap, for minimum cost.

7 Necessary distance between spur dikes in relation to width and velocity of river, for maintaining straight alignment and protecting the shore between spurs.

8 Formation and travel of sand waves in straight and curving rivers, and their relation to a navigable low-water channel, with various coarseness of grains and various velocities of current.

9 Study of the effect of the coarseness of grain, as between fine sand and coarse gravel, in its relation to the upbuilding of cross-over bars on curved rivers under various velocities and depths of current.

10 Study of the mechanical theory and the action of the Haupt reaction jetty with relation to its limiting curvature.

11 Study of the economy of shortening a bridge across a meandering river by the use of "Bell-Bunds," similar to those developed in India, with study of minimum distance between abutments and proper curvature and alignment of upstream and downstream wings.

12 Investigation of obstruction and backwater caused by bridge piers and of tendency to undermine them on an earth bottom by a swift current, and of economies of protection by riprap.

13 Form of bridge pier base and abutment for producing minimum scour on the bed, combined with maximum stability.

14 Miscellaneous studies in training a river like the Missouri or Platte, within erodible banks and bed, in the most economical way for flood relief, by causing it to dig itself deeper, so as to minimize the need of levees, and cause it to carry its sediment forward toward the sea with minimum deposition en route, and with the minimum tendency toward caving banks.

15 Best form of sea-harbor or river-harbor jetties to minimize the obstruction of harbor entrance by littoral currents carrying sand.

16 A study of maximum bottom velocities consistent with stability for various sizes of sand grain and various degrees of cohesion.

17 Transportation of larger gravels and small boulders by rivers. Extensions of the Gilbert California experiments to broader conditions, larger pieces of gravel, and high velocities in larger channels.

18 Investigation of the truth of Kennedy's law relating to the movement of sand and silt in suspension, and the limits to its application.

19 Development of the law of backwater effect from dams and obstructions in straight and curving channels.

20 Investigation of fluid-filament theory of parallel flow and limitations of vortex motion near sides, at various velocities.

21 Distribution of velocity for various degrees of roughness of sides and bed of stream or flume.

22 Study of vortex motions and boils and how produced — whether caused by obstructions at bottom or by collision of currents.

The preceding experiments (and many more that can be thought of) relate to the improvement of natural rivers and harbors and would be made in the proposed river flume, or in a harbor model tank.

The following experiments, which also could be made in the river flume, relate to flow in artificial channels, such as canals, flumes, sewers, culverts, and large pipes partly filled.

23 An extension of the Darcy and Bazin experiments, of 60 years ago, to other shapes of channel and to greater velocities of flow, and with various definite forms of roughness and surface.

24 Effect of twisting or spiral currents on loss of head.

25 Loss of head with water carrying nearly a maximum load of sediment, in comparison with clear water.

26 A test of the Eads theory as to the maximum percentage by weight of sediment of various sizes of sand grain which can be transported at a given velocity. (The probabilities are that nowhere on the Mississippi or even on the Missouri is the water "saturated" with sediment, and that very much higher percentages of sediment could be carried in a regular channel if it could be dug up from the bottom by a quickened velocity in a channel narrowed at the cross-overs and kept moving in a straightened river.)

27 Determine the relative proportions of sediment that can be carried in suspension at various high velocities, when walls of conduit are relatively smooth and when roughened, or when the water is thrown into eddies by spur dikes.

28 Determine more precisely the relations of roughness to laws of flow. (This can be done readily with the tilting flume for a wide range of velocities by changing the depth, or the speed of the pump, or by control of its inlet valve.)

29 Develop formulas of discharge for sewers or conduits of circular or egg-shaped cross section filled to various depths.

30 Study effect on velocity or loss of head caused by a roughening of various proportions of the wetted perimeter much less than the whole, or from 1 to 50 per cent.

31 Study laws of loss at sudden enlargements. Also the conditions of minimizing this loss by divergent channel walls set at various angles.

32 Study action of sand-bar formation in tidal rivers in which the action of the rising or falling tide on the river flow is simulated by water introduced or withdrawn at downstream end of flume.

33 Test the law of wave transmission for various depths and forms of channel, and effect of pulsations of flow on sand waves and sand-bar formation.

34 Study the law of flow for the "bore" or "cloud-burst" type of flood wave, at various inclinations of bed.

35 Repeat the Francis "whitewash experiment" under various conditions for determining the course of threads of current, and the reason why the maximum velocity is below the surface at center of stream.

36 Study of merits of straight versus curved river channel for Missouri River conditions.

37 Study of straight versus curved channel for a deeper river, as for certain bends on the Lower Mississippi.

38 A model of the mouth of the Mississippi on a horizontal scale of about 1 to 100 might prove very instructive in finding the most efficient means of making the South Pass available for deep-draft steamers, with a minimum of dredging.

39 Possibly, also, extremely useful information could be had by experiments on a model of the proposed spillway from the Mississippi to Lake Borgne, as to the results that would be achieved in flood relief and subsequent silting or absence of silt in the river mouth.

The city engineer of New Orleans has presented a tentative design for an extremely broad spillway. The writer believes that an extremely narrow but deep spillway, only one-fifth of the width of the other design, would cost less and give better service. Models could serve to point the way to the best possible design before spending the suggested $4,000,000 or $5,000,000, and perhaps save a million dollars by one inexpensive research of three months' duration.

40 Along the Colorado River below Yuma, Ariz., in view of the present and potential values at risk in the Imperial Valley of California, some new form of groin, or spur dike and proper spacing for it, with willow plantings between the groins, probably could be worked out advantageously by experiments in the proposed laboratory, combined with observations and experiments on the river.

For the weir flume the following studies were suggested in the paper referred to previously:

41 Extend the standard weir formula by new experiments to depths up to 5½ ft. with crest 15 ft. long, and to greater depths with shortened crest.

42 Test in great variety the effect upon accuracy of measurement of swirls and irregularities of flow in the current approaching a standard weir.

43 Determine the coefficient of discharge for various forms of round-crest weir, and, incidentally, experiment to develop a new standard form of weir, less subject than the present standard sharp-crest weir to error from disturbance by irregular eddying, approaching currents, and by contraction.

44 Determine form of crest for giving the least rise in flood height over a dam for a stated discharge in cubic feet per second per foot of length.

45 Test effect of submergence and backwater on weirs at various depths and proportions of backwater, to a depth of 5 ft. above the crest. (More extended experiments on this subject are greatly needed.)

46 Test thoroughly the new Herschel type of

gaging weir and the dependability and precision of its method of depth measurement.

47 Determine the coefficient for discharge over models of many dam crests now in use in America, which are of necessity utilized for gaging the discharge of rivers.

48 Check and extend the deep-waterway dam-crest experiments made some years ago at Cornell University, some of which are open to question regarding the precise accuracy of the depth measurement on the standard weir used for gaging the discharge.

49 Determine coefficients of discharge for various common types of sluiceway used by the U. S. Geological Survey in gaging stream flow.

50 Experiment on coefficients of discharge for ordinary canal headgate sluices of different forms, with gates fully and partly open, seeking to lessen the loss of head for a given discharge.

51 Test the effect of twisting and disturbed flow in channels upon the accuracy of measurement by current meters of various types. Some types of current meter are more accurate in disturbed currents than others. It is stated that the " Price " meter can be made to revolve in still water by moving it up and down and it is inferred, therefore, that vertically inclined currents may adversely affect its accuracy.

52 Develop the most accurate practicable type of current meter for avoiding the errors in measurement due to the disturbed currents found over a rough river bottom.

53 Develop and test a portable pitot-tube velocity meter and study its errors as caused by waves and twists of current.

54 Study the hydraulic-jump, or " standing-wave " phenomena, in an extension of the Miami researches.

55 Study efficiency of various types of " fall increaser " for use in economizing water power on rivers subject to high backwater.

56 Study various types of energy absorber for use at the foot of overfall dams, for lessening the depth of dangerous scour on soft river beds.

57 Develop best type of baffle piers, for absorbing dangerous energy at the foot of an ogee overfall.

58 Develop an open-top venturi type of sluice-gate for the headgates of irrigation canals and other waterways.

59 Develop the best form of bell-mouth entrance for tunnels to be used as the by-pass of dams under construction.

60 Determine the most efficient angle of divergence for a venturi tube with smooth current of approach, also with disturbed and twisting currents of approach, as in the draft tube of a water wheel. (It is possible that these studies would aid in the economies of power development.)

61 Study the limiting conditions for precision of measurement with venturi meters of various types, with disturbed approach currents and various angles of convergence and divergence.

62 Experiment on centrifugal pump discharge for a wide range of velocities and with throttled inlet or outlet.

63 Determine the overturning and scouring effects of currents at various high velocities on bridge piers and similar structures of various shapes.

64 Test the limitations of the siphon spillway with greater depth of throat, up to 12 ft. in height; try to get a larger percentage of discharge, measured at the crest area, by treating the whole course of the siphon as a long, curved venturi tube. Develop better forms for quick exhaust of air, and generally improve and standardize the siphon spillway design, once for all time.

A hundred or more siphon spillways have been built in various parts of the world with little knowledge as to the true theory of their operation. It is possible that by regarding this siphon as a gently curved and elongated venturi tube the capacity could be greatly increased for low falls, perhaps doubled. Also it is desirable to know if dangerous shocks can be caused by opposing surges meeting within the tube, when acting at the extreme limits of atmospheric pressure with its outlet submerged, and if so, how can these best be cushioned.

Also, it is desirable to learn the best form of automatic flashboard for placing on the crest of the overfall within a siphon spillway which will drop and provide slope for flood discharge in the river upstream.

A thorough study of these siphon-spillway problems is of great importance in the economical development of many reservoirs and mill ponds by bringing the ordinary working level nearly or quite up to the flood level.

I would not venture to prophesy that each of these researches would be fruitful in dividends any more than that everyone of the 200 or more Ph. D. chemists whom one may see experimenting in the great works at Leverkusen or Friederichshafen will reap a rich harvest, but the general result will greatly advance the state of the art, and here and there will be a development of great value.

The weir flume would be useful as a naval test tank for certain conditions of currents, by holding the model still while the currents flow swiftly past. It would be particularly instructive for cases in which high-velocity runs in the ordinary naval tank would be too brief.

In addition to the weir flume and the river flume for use in connection with the problems listed, the new laboratory should contain ample floor space for other flumes, served by the same pumping plant, regulator, and measuring apparatus, which could be used in a great variety of other problems and experiments.

A Museum of Hydraulic Laboratories

An exhibition of the apparatus and methods by which the present advanced status in science and in the industrial arts has been attained slowly and step by step, sometimes with long pauses between, has been shown by Dr. Oskar Von Miller, in the great industrial museum at Munich, to which he has given the best years of his life, to be one of the best ways in which to encourage future invention and progress. The laboratory idea has been so great a factor in the advance of hydraulic science that it is worth while to trace some of these developments and briefly describe some of the apparatus. In years long past I found it interesting to follow in old libraries the slow progress in the development of hydraulic science through experimentation, and now that the heralds are about to announce in the following pages some of the rapid advances of the past decade, and possibly foreshadow others which are coming, it may be well to devote a few pages to the consideration of the earlier history of hydraulic science and to its slow rate of advance.

Although the hydraulic arts are old, hydraulic science is young. The arts of hydraulics were practised long before the dawn of history. Sir William Wilcox, the eminent English engineer, who has spent much of his professional life in Egypt and the Holy Land, says, "Irrigation is the oldest branch of applied science in the world." For example, he quotes from the second chapter of Genesis: "Out of Eden came a river that watered a garden." In his years of exploration he believes he has discovered the very location thus referred to in Holy Writ. He tells how the rivers at the site of this Eden have lost their ancient beneficence because of the lowering of their beds through centuries of unchecked erosion. Too late, our hydraulic laboratory may teach how this could have been prevented!

Hydraulic science slumbered more than a thousand years after its birth and childhood in Mesopotamia, or Egypt, or China. It had an awakening in Greece and Rome, as is shown by the ruins of great aqueducts and as is set forth briefly in the writings of Frontinus and Vitruvius; but it again fell asleep for a thousand years until awakened by a loud call for aid in stopping the ravages of torrents in Northern Italy, and since this renaissance of four or five hundred years ago, its development has had several pauses of centuries and half-centuries.

It appears from the records that up to about 150 years ago the one and only correct mathematical equation that had been derived for expressing the laws of flowing water was $V=\sqrt{2gh}$. It took nearly one hundred years of creeping and groping onward, after the discovery by Galileo and Torricelli in 1643, of this law that the velocity of efflux varied as the square root of the head, to get the value of the gravity factor, "$2g$," into the above equation, which now is our fundamental hydraulic formula for efflux. The development of the fundamental formula, $V=C\sqrt{RI}$, for giving the rate of velocity of flow in pipe or open channel in terms of the declivity or slope causing it, was similarly slow of development. With regard to the river hydraulics it may be said with much truth that after being awakened successively by Guglielmini, Frisi, Chézy, Dubuat, Weisbach, Humphreys and Abbott, Darcy and Bazin, and Francis, at one time and another, from two hundred to seventy-five years ago, the advance in the science of river flow slumbered again from 1865 until, after a partial awakening by the brief experimental work of Fargue in France, and that of Froude, Osborne Reynolds, and Vernon-Harcourt in England, it was aroused some thirty-five years ago by Prof. Hubert Engels in his first modest *Flussbau* laboratory at the engineering college in Dresden.

Very little has come down to us of the knowledge of the motion of water possessed by the ancients. Their rules and records of experiences were hardly well enough organized to be worthy of the name of science; and although some of their aqueducts and reservoirs were of stupendous magnitude and endured through centuries of successful operation, these works, instead of being shaped by the aid of mathematical formulas, may largely have been the slow result of " average judgment," after lifetimes of experience handed down from father to son, and success attained through the slow and expensive process of " cut and try."

Like the great canals of China, or like the gigantic cut of the drainage canal of the city of Mexico, these great works of antiquity were trimmed into shape with crude and simple tools by what we would now consider an extravagant use of human labor; and with small ability to predict the precise quantity of water that would be discharged by a canal of prescribed cross section and a given rate of fall per mile. The doctrine that " 'Tis through our failures we achieve success " may have had many illustrations in these ancient works, where now we see only the final success. Lake Moeris, constructed about 4000 years ago to store flood waters of the Nile, into which they were led by the Canal of Joseph and made available for irrigation, was larger by far than any artificial reservoir of modern times. There was in existence, 2500 years ago, a canal from the Red Sea to the Mediterranean, sufficient for the ships of those days, the site of which is followed closely by the line of the present Suez Canal. The " Fresh Water Canal," used by the French engineers in 1863 to bring water from Cairo to Suez, had been in use 2500 years. In China, 4000 years ago, the half-legendary Wu, the great hydraulic engineer and emperor, whose memory was honored by many temples, is said to have so perfected the art of protection against the river floods by means of dikes that for several thousands of years safety followed the application of his rules. In the far-interior Chinese province of Sczechuan, irrigation still follows canals admirably designed some thousands of years ago by a skilful engineer, who set monuments to mark the proper water stages and made rules for operation that are said still to be carefully followed.

We wonder how these old-timers ran their levels, how they measured the quantity of water discharged by their rivers in flood or in drought, how they adjusted their gradients, how they estimated or regulated the hydraulic capacity of their canals, and what was an ordinary margin of error between expectation and delivery. It has been said that lack of an instrument for measuring seconds of time, and thereby the lack of a unit of measurement corresponding to " second-foot," or " cusec " as English engineers call it, for a measure of discharge, was the greatest ancient obstacle to precise hydraulic knowledge.

The twilight zone of lack of precision in hydraulic measurement continued here and there until very recent times. The California " forty-niners," as do some of their present-day successors, used the " miners' inch," which is based on the same crude conception of water measure as the Roman *quinaria;* and the writer is even now helping a lawyer untangle the meaning of " three square feet of water " in a mill deed written little more than fifty years ago. Lack of precision of measurement, and therefore of precision of thought, is still painfully in evidence throughout the literature of river and harbor hydraulics.

The eighth book of Vitruvius, the great Roman writer on architecture and engineering topics, written 2000 years ago, records a few precepts about necessary gradients for aqueducts; and Frontinus tells much of interest pertaining to the rules of practice in the office of water commissioner in ancient Rome. They record the fact that water would flow at about the proper velocity down an aqueduct having a slope of one or two feet per mile; that water could be measured by the *area* of the nozzle or short pipe through which it was let out from the aqueduct, and that the discharge of a short pipe could be increased by adding to its outlet a divergent pipe of increasing diameter. Pliny, in his " Natural History," recommends for the *very least* slope in clay pipe conduits, the equivalent of one-fourth inch in 100 feet, or about one foot per mile.

Ancient Rome had important river problems. The question of cutting off a river bend in the Tiber which threatened Rome, was gravely discussed by the Roman Senate and dropped, for the profound reason that " Nature understood what was best when it formed the river in its present shape." Two thousand years later, Professor Rehbock, of Karlsruhe, by means of experiments upon five successive laboratory models, showed how a similar problem could best be solved by a short cut across the neck of a horse-shoe bend, from which the backwater threatened Nuremburg in times of flood. Meanwhile fifty years or more ago, by methods of " cut and try," German engineers had cut out the great bends and concentrated the flow of the Rhine into a single channel, between Basel and Mannheim, shortening the river 23 per cent,* with great advantage to all concerned.

Outside the books of Vitruvius and Frontinus, I have learned of nothing written about hydraulic science or art until the treatise " On the Motion and Measurement of Water," written 530 years ago by Leonardo da Vinci, engineer, artist, architect, poet, sculptor, anatomist, student of aeronautics, and greatest genius of all time. I have enjoyed turning the pages of a reprint of his book made nearly one hundred years ago at Bologna, Italy, noting his quaint conceptions and studying his excellent drawings, which plainly show such a remarkable understanding of eddy motion, waves, etc., that one is forced to believe that he had some sort of a hydraulic laboratory in which to study the motion of water while he was engaged in building the earliest chambered navigation locks in the world, near Milan, and that he had been a close observer of many natural streams. Surely his remarkably accurate drawings of the contraction of the jets from weirs and orifices and their trajectories could not have been made without models. Many of his illustrations are of what, in effect, were pieces of laboratory apparatus. Some of his diagrams foreshadow researches which I saw going on in the laboratories of Drs. de Thierry, Engels, Smrček, and Rehbock, 530 years later!

It is not strange that hydraulic science had its birth in Northern Italy, because here lived a people of special genius and mechanical skill; and because here were found problems of great importance to the welfare of the people, presented by need of protection from destructive torrents that came down from the Alps and Apennines. Frisi's treatise of 1770 tells how the foremost mathematicians and scientists of Italy were called into council over the problems of protecting the fertile bottom-lands of the Po and other rivers from inundation and loss of crops.

After the time of Leonardo da Vinci, hydraulic science slumbered for a hundred years until the days of the great Galileo (contemporary of Bacon), professor of mathematics at Pisa and Padua, and his eminent pupils, Castelli and Torricelli. Galileo experimented particularly upon the laws of efflux, apparently with a view toward the construction of a more perfect water clock. Each of these Italians was a scientist in the modern sense, and these three seem to have been the real founders of hydraulic science, as distinctive from hydraulic arts, by beginning to discover the laws which control the flow of water and finding how to express the broad generality of these laws in exact mathematical terms.

In 1628, Castelli appears to have been the first to publish a treatise upon rivers, also the first to introduce velocity as a definite factor in the measurement of discharge of rivers, but since he wrongly concluded that the velocity of efflux varied in direct proportion to the head, we may conclude that his laboratory facilities were crude.

In 1643, or only 285 years ago, the fact that the efflux of water varies as the square root of the head appears to have been first discovered by Torricelli, pupil of Castelli and of Galileo, who identified this law with that of the velocity of falling bodies deduced some years previously by Galileo, and which Galileo had demonstrated by experiments at the leaning tower of Pisa. Lest it be thought I have spoken harshly of the part mathe-

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* Der Einfluss der Korrektion des Rheins zwischen Basel und Mannheim auf die Geschiebebewegung des Rheims (The Influence of the Corrections of the Movement of Sedimentary Material in the Rhine, between Basel and Mannheim). By Heinrich Whittmann. *Zeitschrift*, " Deutsche Wasserwirtschaft," 1927, Nos. 10, 11, and 12.

maticians have had in developing hydraulics, I note that Torricelli also was a professor of mathematics. These three mathematicians tested their theories by experiment more than did their predecessors.

The writings of Vitruvius, Frontinus, and Pliny had made plain nearly 2000 years ago that to get proper flow in aqueducts one must have a fall of from one foot to two feet per mile, although the cave man must have recognized that water ran down hill. But Torricelli seems also to have been the first plainly to set forth the fact that the acceleration of flow in rivers was in some way proportional to the slope down which they ran.

In 1684, or 244 years ago, the French physicist, Mariotte, gave a fresh impetus to hydraulic science by new experiments on the discharge from tubes and orifices, and by his treatise on the motion of water. He appears to have been among the very earliest to record the use of laboratory experiments constantly for testing theory. He dealt chiefly with the discharge from orifices, the height to which jets would rise, and with the motion of water in tubes. His experiments were on a very small scale and crude, but he taught the proper method.

Mariotte's great contribution to progress was the promotion of an understanding that *experiment rather than mathematical reasoning must be the source of hydraulic science.* Da Vinci also taught this in his writings, but his seed fell on barren ground.

It was not until 1697, or 231 years ago, that more rapid progress in the science of river hydraulics was begun by the publication of the first part of Guglielmini's treatise " Della Natura de Fiumi," the second part of which was published 15 years later, after the author's death. Guglielmini appears to have gained a clearer understanding of the nature of the motion of water in rivers than any who had preceded him, although he went sadly astray on some details. For example, in his notions about the distribution of velocity at various depths, he thought that, like efflux from an orifice in a tall vessel, it must move fastest at the bottom. We may join with Italian engineers in honoring Guglielmini as the " Father of the Science of River Hydraulics."

Between 100 and 200 years ago, many distinguished Italian engineers and hydraulicians published treatises in hydraulics. About 100 years ago, no less than 63 of these treatises were collected and republished in 11 volumes comprising 5500 pages, under the titles " Raccolta d'autori italiani che trattano del moto dellacque " and " Nurova Raccolta." The first two volumes are devoted to the works of Guglielmini. The third volume tells of the hydraulic studies of Archimedes, Galileo, Castelli, Boreth, Torricelli, and Vivicini. The fourth is by D. Guido Grandi, on the movement of water, etc. The fifth volume deals with studies by Manfredi, and the sixth with those of Poleni, Frizi, and others.

In 1730, Pitot, Member of the French Academy of Science, invented the tube with curved end turned upstream for measuring the velocity of currents, which in greatly improved form we use today, and disproved Guglielmini's idea about the variation in velocity from top to bottom of a flowing river.

In 1732, experiments made by Couplet on the discharge of the water pipes leading to the fountains of Versailles, showed an astonishing discrepancy between the actual discharge and that expected from theory as it then stood, and brought attention to the need of improving these theories. It is said that some of these cast-iron pipes are still in use after 200 years of service. It would be of interest to again test their coefficient of flow.

In 1738, Daniel and John Bernoulli (father and son) extended the foundation of sound mathematical theory as a basis for hydraulic science by establishing the generalization that has come to be known as " Bernoulli's principle " and which is one of the most fundamental and far reaching that has been made.

From 1743 to 1752, d'Alembert, another early great mathematical physicist, added to these mathematical foundations of hydraulic science.

The era of intensive experimental research, however, was hardly begun until 164 years ago, in about the year 1764, by Micholetti in Turin, and Bossut in Paris.

In 1764, Paul Frisi, professor of physics at the University of Milan, wrote his celebrated treatise on the " Nature of Torrents " and gave great credit to the work of Guglielmini, published half a century before.

Frisi paid his compliments to the mathematicians for the absurd results they had reached by reasoning from *a priori* grounds, and declared that hydraulics is not a branch of mathematical science, but is a branch of physics. Although today its conceptions and its science appear crude, this work of Frisi was so highly regarded that more than a century ago it was translated into the English language at the cost of the English government for the use of its engineers in India, who even then had begun their gigantic water-storage and irrigation works.

Up to that time, 164 years ago, the sum total of contributions to hydraulic theory, other than the one formula, $V = \sqrt{2gh}$, was of small practical importance, *mainly because of the lack of hydraulic labora-*

tories with suitable apparatus in which to conveniently vary conditions, one at a time, while studying the effects of so doing.

In 1771, Abbé Bossut published his "Theoretical and Experimental Treatise on Hydrodynamics." This work, the most valuable of those which had yet appeared, contains details of a very large number of experiments made with the greatest care, and intended to furnish reliable data for estimating discharge, etc., in the problems that commonly occur in practice. Among other matters Bossut sought to determine with greater accuracy than heretofore the value of the coefficient of contraction of the fluid vein, which occurs when water flows from an orifice in a thin plate, and the laws of efflux when the orifice has added to it tubes of various lengths and figures. He also experimented on the motion of water in conduit pipes of considerable length, of various diameters and inclinations, and upon the motion in open canals and rivers.

The eminent American engineer, Charles S. Storrow, said in 1835 that "The experiments of Bossut were on a small scale, it is true; yet their great accuracy, and the judgment which he manifested in his selection of the questions to be submitted to the test of experiment, place him among the highest on the list of those to whom the science of hydraulics owes its present advancement."

It was not until 1775, or 153 years ago, that Chézy, Chief Engineer of the French Department of Bridges and Roads, who gave much attention to the expression of hydraulic laws in algebraic form, derived the fundamental formula by which, in a simplified form, we today compute the rate of flow in all sorts of conduits.

$$V=C\sqrt{RI}$$

In the preceding half-century, mathematical theory had been well developed and the differential calculus invented, and mathematical discussion had been applied to many problems in physics, including sundry theorems about flowing water. In brief, the mathematicians seem to have been looking in all directions for fields in which to apply their inventions, but without attaining results in hydraulics of much practical importance until at about the time of which we now write. About 150 years ago, the era of hydraulic experimentation became fairly well inaugurated in both Italy and France, and since that time progress in some branches has been far more definite and more rapid than before.

In 1782, Belidor published, in Paris, a thick volume on hydraulic architecture, profusely illustrated, which set forth the state of the art of building water mills at that time, but gave little of hydraulic science or empirical laws of flow.

In 1784, The Academy of Toulouse, France, reported experiments on the discharge of orifices, and published some notes upon river flow.

In 1786, Dubuat reported the results of his ten years of experimentation. Although Dubuat's apparatus was on a small scale, judged by recent examples, it was larger than used by earlier experimenters and his researches covered a wider range. From the practical character and scope of his researches, and from his care in the arrangement of apparatus, I am inclined to believe that *we must select either Bossut or Dubuat as entitled, more than any of those who had preceded them, to be called the "Father of the Hydraulic Laboratory."*

Of Dubuat, Storrow says: "Following the example of Bossut and supporting by experiment everything which he advances, Dubuat has furnished a most important guide to practical engineers. He proposes first an hypothesis, suggested by analogy, or by the various causes which may influence the motion of a stream of water, and then calls experiment to his aid until he has brought them to represent, with sufficient accuracy, the actual results."

Chézy apparently was concerned with water pipes and artificial canals when he derived his famous formula, for he was charged with bringing an additional water supply into Paris. Dubuat gave greater attention to the flow in rivers and derived a much more complicated two-term formula, which contained a logarithmic factor. Dubuat introduced the mean hydraulic radius "R" as a factor and expressed the propelling force by the single term of slope instead of the two terms of fall and length. He proceeded to show the great utility of his river-flow formula in studying channels, sinuosities, and obstructions.

The very fact that laws of water discharge and flow can be expressed by an algebraic formula, presupposes laws of hydraulic similitude. That Dubuat, Chézy, and others had some glimmerings of the great truths of hydraulic similitudes and dimensional analysis is proved by their efforts to give algebraic expression to hydraulic laws covering a wide range of dimensions, but it was not until about 70 years after Dubuat's experimenting that the value of small-scale models for large river structures began to come clearly into view.

Coulomb, in 1800, next brought out a further development in river hydraulics in the two-term expression for resistance, of which the first term varied as the square and the second, as the first power of the velocity; finding that this served with greater accuracy for moderate velocities. The need of giving in the formula differing values of the coefficient for different degrees of roughness seems not to have been fully realized until the epochmaking researches of Darcy and Bazin a half-century or more after Coulomb.

About a hundred years ago several important works were written by French engineers relating to river hydraulics; for example, De Prony's report on the Pontine Marshes, and the report of Fabre, Chief Engineer of Ponts et Chaussees, " Essai sur la Théorie des Torrens et Rivières "; also a treatise entitled " Les Moyens les plus Simples d'en Empêcher les Ravages et d'en Rétrécir le Lit et d'en Facilité la Navigation," which, although comprising 280 pages, tells little of hydraulic science.

Should this list of authors in hydraulic science that I have recited seem tediously long, one must remember that it covers most of the important writers throughout two centuries. From this point of view, the number is not large.

About the year 1800, hydraulic experimentation became very active. The three works of the great French engineer, De Prony, were published in 1790, 1802, and 1804. With great mathematical skill he took the observations and experiments of Dubuat and others, and deduced laws which for more than half a century afterward guided engineers safely in many lines.

In 1814 and 1815, the German hydraulic experimenter Eytelwein contributed the results of his own experiments to the memoirs of the Academy of Berlin, and thus added to the precision with which such computations could be made.

In 1827 to 1832, the French engineers Poncelet and Lesbros published the results of their laboratory experiments, made at the expense of the French Government, on the discharge of orifices with sharp edges or in thin plates; these were such beautiful examples of precise experimentation that their coefficients stand unchallenged after nearly a century. About 15 or 20 years later the French engineers Darcy and Bazin made the most magnificent series of hydraulic laboratory experiments ever undertaken. These, also, were at the expense of the French Government. Their outstanding work was the definite measurement of the influence of roughness of conduit surface upon loss of head by friction. The only feature in which we may not feel satisfied with these researches is that their largest size of orifice was so much less than those with which engineers of today must work, and that they tell little of the effect of disturbance in the approaching current, with which the engineer in practice must often deal.

These researches of Poncelet and Lesbros, Darcy and Bazin, comprised the highest development of the hydraulic laboratory up to 75 years ago and within their range of dimensions and discharges their quality of research has not been excelled. Bazin later made a series of most valuable experiments on the discharge over weirs.

The fact should be emphasized that in many such lines, if a research in hydraulics is well done originally, it need never be done again until a demand comes for experimental values of coefficients having a proved wider range, or until the advance of the art requires a more miscoscopic precision.

Ninety years ago, Charles S. Storrow, of Boston, published a small but remarkable treatise on hydraulics which sets forth admirably the state of hydraulic science 100 years ago. Storrow was the best-educated engineer in America in his day. He had led his class at Harvard College, had continued his studies by reading for some months in the library of Loammi Baldwin, who has been called the "Father of Civil Engineering in America," and whose library contained most of the best engineering books of the day in English, French, and Italian, and then had gone to France for three years' further study in the celebrated engineering school at Paris, the École des Ponts et Chaussées. Estimates made from the equations given in Storrow's book from the formulas of

Prony and Eytelwein upon the delivery of pipes or open canals, would be in error to no greater extent than that caused by different degrees of roughness in conduits of the same area, shape, and slope; and estimates of quantity discharged over a sharp-crest weir with end contractions, by the formula he gave 90 years ago, are near enough for many practical purposes to the discharge computed by the Francis or Bazin weir formulas in common use today.

For example: A comparison of the results of computing velocity in feet per second in a straight cast-iron water pipe having a given slope, or loss of head per 100 feet, by the best formulas of a hundred years ago with some of those most used today comes out as follows:

Slope, or loss of head per 100 ft.	0.1	0.1	0.1	1.0	1.0	1.0
Diameter of pipe, in.	6	12	24	6	12	24
Velocity by de Prony's formula	1.01	1.45	2.10	3.35	4.76	6.80
Velocity by Eytelwein's formula	0.95	1.22	1.48	3.00	3.86	4.70
Velocity by Hazen & Williams formula: (for C=100, pipes 15 to 19 years old)	0.86	1.32	2.05	2.94	4.59	7.08

In a straight uniform channel in earth, 50 ft. wide at top, 10 ft. deep in center, depth at side walls 4 ft., thence sloping inward 1 on 3, for given slopes:

Slope, or loss of head per 1000 ft.	0.1 ft.	1.0 ft.
Velocity by de Prony's formula	2.41	8.10
Velocity by Eytelwein's formula	2.32	7.55
Velocity by Chézy formula: (Kutter n=0.25, Chézy C=	(C=84) 2.14	(C=81) 6.55

For the discharge of water in cubic feet per second over a sharp-crest weir with two end contractions:

Head on weir, in.	6	12	24
Quantity by Dubuat's formula	12.03	34.3	97.0
Quantity by Francis' formula	11.65	32.6	90.5

For weirs without end contraction Dubuat appears to have left the data for computating the discharge in a very indefinite form.

With regard to computations of pipe and channel flow by formulas of a hundred years ago, the above comparisons happen to show close agreement because these old authors made a wise selection of coefficients for an average case. Nevertheless, the difference in discharge due to variations in roughness of the interior surface of the conduit has since been found so great that for the roughest surfaces the discharge for a very rough channel might be 63 per cent smaller than given in the above formulas, and if the channel was very smooth, the discharge might be 133 per cent greater than by the formulas of a century ago. For a very smooth pipe the discharge might be 114 per cent greater, or 50 per cent less for a very rough pipe.

Lack of space prevents recital of the successive hydraulic laboratory investigations made during the past 75 years, beginning with the notable treatise of Prof. Julius Weisbach, of Freiburg, Germany, although the list is not so long as one might expect, considering the importance of the subject. It would take but a few pages of tables to show, as has been done to a limited extent in the manuals of Hazen and Williams, of Trautwine and Hering, of Safford and Johnston, and that of Mr. Alfred A. Barnes, Associate Member of the Institution of Civil Engineers, London, 1916, the chief elements in all of the reliable hydraulic experiments that have been recorded since the days of Frontinus, nearly 2000 years ago. Such tables would show the small scale and limited range of many lines of hydraulic data.

When one about to use a formula, or to take hydraulic coefficients from a published table, is in a cautious mood and seeks the original record in order to learn the degree of precision with which these data were determined, often he is startled to find the extremely small scale of the original experiments, surprised at the extent to which liberties of extrapolation must be taken, and is thankful for the laws of hydraulic similitude. The frequent citation of Dubuat's century-old determinations of the velocity of current required to move sand grains or gravel of various sizes is a conspicuous example. His experiments in determining the velocity at the bottom of a stream required to move sand grains or pebbles of given size made by dropping them into a smooth plank trough about 18 inches wide, with water less than a foot deep, have been quoted without qualifications in textbook after textbook, as if these velocities were the proper guide to the scouring velocity in beds of great rivers, or the velocity needed both for detachment and for moving the grains of clay, sand, or pebbles over the rough, irregular river bottom.

There is still great need for at least one hydraulic laboratory built upon an exceptionally generous scale in which many of these experiments can be tried over again, so as to cover dimensions with which the engineer of today has to deal in his design. In order that the apparatus should be on a properly large scale and that the researches should have proper support and status, it seems that this laboratory would best be under some national government. Obviously such a laboratory would serve the purposes of engineers all around the world almost equally well regardless of whether it was located at England's National Physical Laboratory near London, or at the Reichs-Anstalt at Berlin, or in the congenial surroundings of any one of the several other possible localities. Therefore, not many of these large laboratories are needed for the sole purpose of extending data of the class mentioned on page 6. Several could divide this field, and after the work had all been done there would still be plenty of research problems left.

Obviously, when work on the fundamentals of discharge from orifices and flow in conduits has been thoroughly done on a sufficient scale, it will not need to be done over again.

For three years past I have been pleading that the United States Government provide such a new laboratory of generous dimensions and ample facilities. This, if located at the Bureau of Standards, in Washington, could within two or three years of diligent work determine sufficient coefficients and formulas for orifices, weirs, pipes, and canals, with all necessary precision and completeness to satisfy the needs of the next century; and after this particular line of research was finished there would remain other fields but yet little explored in which these same laboratory facilities could be of great use, particularly in such problems of river improvement and flood control as those mentioned on page 7 *et seq.* There is room for generous rivalry between five or ten such laboratories in the training of student engineers for work for which the world is waiting.

The New Awakening

One might reckon the new awakening of hydraulic laboratory research as having been begun in France with the excellent researches of Poncelet and Lesbros, followed by those of Darcy and Bazin. These were all models of precision, and those of Darcy and Bazin were epoch-making in their recognition of the influence upon flow of roughness of the conduit wall.

In river hydraulics, following Humphreys and Abbott, after a rather long interval, came Cunningham's Roorkee experiments on canals, and Revy's measurements and studies of laws of flow in certain South American rivers; but neither of these can be classed as laboratory research; in fact, *the lack of a laboratory in which to supplement the observations made on the river seems to have been the main reason why each of these authors did not make more progress toward establishing a science in river hydraulics.*

The experiments of Fargue in France and of Osborne Reynolds and Vernon-Harcourt in England were of narrow range and few, but they made use of models and of the principles of similitude, and so started the new era.

From all I have read and seen, I think it may fairly be said that the new awakening in river hydraulics began actively in the modest laboratory of Dr. Hubert Engels at Dresden, Germany, about 35 years ago. Here Engels succeeded Zeuner, and Zeuner had been a pupil of Weisbach. This Dresden "Flussbau Laboratorium" was soon followed by laboratories and researches of similar character at several other European engineering colleges.

Strange to say, in view of the size of our rivers and the importance of the problems they represent in navigation and flood control, there is not yet in America even one laboratory well equipped for the study of river problems; and still more strange, the military engineers to whom American river and harbor problems have been given to keep them employed in times of peace, have not yet awakened to the utility or understanding of research of this kind. They are still in the " phlogiston age " of applied science.

At nearly all of the large engineering schools in America hydraulic laboratories of the simple character needed for demonstrating to undergraduate students the elementary principles of flow through orifices and pipes and over weirs, have been in course of development for from ten to thirty years. In a few American engineering colleges, notably at Cornell University, at Worcester Polytechnic Institute, and at the University of Iowa, these student laboratories have been built outside of the main college buildings, on a remarkably generous scale, and in addition to their aid in teaching have served for important researches in establishing coefficients for discharge over various forms of dams, for improvement in turbine draft-tubes, for testing velocity meters, and for many other valuable investigations. Also, at the University of Pennsylvania a small laboratory is being developed on original lines. At Cornell, Saph and Schoder made an extremely valuable set of experiments of limited range on the loss of head and capacity of small pipes, and on temperature effects. At Magill, some interesting experiments were made on orifice discharge, etc. At the Massachusetts Institute of Technology and at the California Institute of Technology, experiments have been made on models of siphon spillways, etc. I have been greatly interested in what I have seen at the laboratories named, and there doubtless is much that is worthy of notice to be found in others that I have not visited; but so far as I have been able to learn, not one of these American college laboratories is equipped for the larger problems of river and harbor regulation.

It is my strong belief that within a few years, largely as a result of the demonstrations to be found in the following papers on European hydraulic laboratories, there will be five or ten new hydraulic laboratories in American engineering colleges, each well provided with canals having glass walls, in which practice will be given in the application of dimensional analysis and the use of scale models; and with river-flow tanks in which researches can be worked out on sedimentation and erosion, and on groins, retards, and the laws of transportation of debris.

The awakening in laboratories for improvement of water turbines, following the epoch-making tests of Francis and Mills at Lowell, was chiefly promoted by the Holyoke testing flume. Several American manufacturers of hydraulic turbines, notably the S. Morgan Smith Co., the I. P. Morris Corp., the Allis-Chalmers Mfg. Co., and possibly some others, have since built private laboratories in which to perfect the design of their turbines by means of experiments upon models having about one-fifth part of the linear dimensions of their largest turbines. Since discharge capacities for the same head vary somewhat as the square of the linear dimensions and roughly as the 3/2 power of the head, this means that the model, by means of which designs are perfected, may have only a hundredth part of the discharge capacity, or perhaps (as in the case of recent Niagara installations) *only one-thousandth part of the power* of the turbine which is to be shaped from the model. This shows a proved faith in models and the principles of hydraulic similitude which our river engineers would do well to note! Certain manufacturers of centrifugal pumps have followed a similar course.

In certain problems of great practical importance, for example, the determination of the ratio of useful effect to power expended in some of the giant hydro-turbines of recent years, the laboratory has been taken into the field and methods of wonderful delicacy and precision devised for measuring the quantity of water discharged. Such are the methods of chemihydrometry of B. F. Groat applied to testing the great turbines drawing water from the St. Lawrence river at Messina, N. Y., and the salt-solution-injection method of Professor Allen; also the marvelously simple and effective method devised by Mr. Gibson, Assistant Chief Hydraulic Engineer of the American Niagara Falls Power Plant, for gaging the discharge by weighing — by means of a photographic record of a manometer combined with a seconds pendulum — the momentum of a water column, hundreds of tons in weight, quickly brought to rest by closing the turbine gate. The water supply to a 60,000 horsepower turbine can thus be weighed with an apparatus that can be carried in a man's hand!

These methods are described in the Transactions of the American Society of Civil Engineers and of The American Society of Mechanical Engineers, so that, here, we hardly need do more than express appreciation of the ingenuity and beauty of these methods of making the great turbine structures a part of a hydraulic laboratory.

That in America we have not yet even one river-flow laboratory comparable with those of Germany is strange, because the rivers of the United States present some of the most important hydraulic problems that can be found anywhere in the world. Also, this absence is strange because it was in America that, seventy years ago, the most ambitious research on river hydraulics ever attempted anywhere in the world was carried out in the "Researches on the Physics and Hydraulics of the Mississippi by Captain Humphreys and Lieutenant Abbott," of the U. S. Army Engineers. These young but able observers began on broadly conceived plans which they were prevented from completing mainly by the American Civil War. I believe the close student of their work will conclude that they fell short in their great opportunity because of not having a laboratory in which they could work out the problems of the large river by means of models, and in which they could control and vary the conditions affecting flow, one by one, and in which they could develop a better current meter.

Meanwhile, outside the schools and laboratories, certain American hydraulicians of remarkable genius have left their impression on the art, if not on the science, and helped largely in this hydraulic awakening. Foremost perhaps among these stood Captain James B. Eads, of St. Louis bridge and Mississippi jetty fame, who seems to have acquired through many years of steamboat life and of raising wrecks, a marvelous understanding of the moods and habits of the Mississippi River, with no laboratory other than that found in the river itself.

Swain and McCormick, among the American turbine designers, made their first revolutionary designs prior to any extended experimentation, largely "out of their own heads," as the saying is, but later made much use of models in perfecting them. Boyden, also a self-taught genius, was more of a laboratory man and is to be reckoned among the founders of the Lowell group of precise, large-scale experimenters.

Some Noteworthy American Hydraulic Laboratories and Experiments

Although the title for this volume indicates that it deals only with European laboratories and their work, nevertheless it seems worth while to review briefly some of the experimental work that has been done on a grand scale in certain American hydraulic laboratories, in order properly to complete the picture of the present state of the art.

About 87 years ago a group of American engineers began some remarkable experiments on a far larger scale and with far greater precision than found in the earlier European work, and some 70 years ago (as already mentioned), American engineers made an auspicious start in river hydraulics by field studies upon one of the chief rivers of the world.

What we may call the New England School of precise, large-scale hydraulic-laboratory experimentation was begun at Lowell, Massachusetts, about 87 years ago, and was carried on there and in its vicinity by five remarkable engineers in succession: Charles S. Storrow, Uriah Boyden, James B. Francis, Joseph P. Davis, and Hiram F. Mills. I had the good fortune and inspiration as a young engineer of knowing intimately all but Boyden of this group. Each was a rare spirit and an apostle of accuracy. Their work was of wide influence in setting up and carrying abroad new standards of careful, precise experimentation, as many young men trained under their influence went forth to other fields.

The researches of James B. Francis were made in the immediate interest of the water-power development on the Merrimack River at Lowell, and were reported in part in a volume entitled " The Lowell Hydraulic Experiments," which is a classic for methods of precision, clear thinking, and positiveness of its proofs. The particular experiments reported in this volume related to the precise measurement of large volumes of water, and to testing the efficiency of turbine water wheels with a high degree of precision.

This Lowell series began in 1841, prior to Francis' becoming chief engineer of the Locks and Canals Company, with experiments made by Baldwin, Whistler, and Storrow to determine precisely the relations of the measured mean velocity to the center-surface velocity as shown by surface floats carefully timed. These experiments were made in three parallel rectangular flumes, each about 150 ft. long and 27.25 ft. wide by 8 ft. deep. The doctrines of hydraulic similitude, so much used nowadays, were not then clearly understood, and so they felt compelled to construct a measuring apparatus within this flume which constituted the most gigantic rotary water meter that has ever been built.

The current to be measured was spread out in a canal 80 ft. wide by 4.5 ft. deep, in which seven large paddle wheels, each 17 ft. in diameter by 10 ft. long, all coupled to one shaft, were closely fitted to the channel walls with only one-quarter inch of clearance. A curved bedplate, longer than the distance between the outer edges of the paddles, prevented passage except within the space between the paddles. The depth of water was only about half the radius of the paddle wheel and was carefully measured continuously, so that the product of the space between the paddles and the number of revolutions per minute measured the discharge with high precision.

Many tests were made in two canals having slightly different depths and velocities of flow. In the western canal, 27 ft. wide by 8 ft. deep, with mean velocity about 3.20 ft. per sec. and 580 cu. ft. per sec. discharged, the coefficient, or relation of mean velocity to center-surface velocity, was found to be 0.847.

In the Merrimack canal, 30 ft. wide by 8 ft. deep, having a mean velocity of about 2.14 ft. per sec. with 420 cu. ft. per sec. passing, the coefficient, or relation of mean to center-surface velocity, was found to be 0.814.

Repeated tests showed few variations of more than 1 per cent from these means.

I believe these discharges, from 420 to 580 cu. ft. per sec., were the largest volumes of flowing water which had ever been measured with so high a degree of precision up to that time anywhere in the world. All through these hydraulic researches of the Lowell School upon coefficients for measurement of large discharges by surface floats, deep-tube floats, or weirs, it was the fixed purpose to take such extreme care in design and use of apparatus that the margin of error should not exceed 1 or 2 per cent. This was a standard of precision in measurement of large volumes that previously had been unknown, and is seldom equalled today, 87 years later than the tests by Storrow, Baldwin, and Whistler.

These engineers compared their results with those obtained many years earlier by Dubuat, reported by De Prony, in experimental flumes only 1.5 ft. wide, with depths of from 0.2 to 0.8 ft. and velocities of from 0.5 to 4.25 ft. per sec. and a discharge only one five-hundredth part as great; and noted that the coefficients found for determining mean velocity from the measured center-surface velocity were practically the same for the small as for the large flume. Although they do not say so, by their noting of this constancy of relation over a wide range of dimensions they helped to establish the doctrine of hydraulic similitude.

It is of interest as proving the zeal of these early American engineers for extreme accuracy of measurement, that they were not content to apply these coefficients to measuring the discharge in certain other Lowell mill canals where it seemed to them possible that irregularities in the approaching channel might cause irregular distribution of velocities such that the relation of mean velocity to center-surface velocity would no longer be sufficiently close to 0.847 or 0.814. Therefore, Mr. Francis was later given opportunity to make his careful studies for establishing convenient and accurate methods of using floating rods or tubes, deeply immersed and traversing successively almost the entire width of the cross section, by means of which the velocity of flowing water in open rectangular channels could be measured.

These latter deep-float tests were calibrated by means of the Francis standard methods of weir measurement, which had been perfected in the intervening ten or twelve years. In general, with velocities all the way from 0.5 to 5.0 ft. per sec., Mr. Francis found that the velocity in flumes 100 ft. long by 10 ft. deep, as determined by averaging the transit times of all of the floats by means of a graph, *for the case in which the clearance beneath the float was 1 per cent of the length of the float, was precisely the same as the mean velocity of the entire cross section of the flume.*

When the clearance beneath the floating tube was 10 per cent of the float length, the velocity of the floats was 2.5 per cent greater than the mean velocity of the cross section. Determinations were made for intermediate percentages of clearance and an empirical formula and a table of coefficients were presented covering the ordinary range.

Certainly, it was well worth while to prove that enormous quantities of water could thus be expeditiously gaged with a margin of error of less than 2 per cent, if only they could be brought through a long, straight rectangular flume of uniform cross section.

The methods and coefficients thus developed by Mr. Francis over seventy years ago for measurement of velocity in open rectangular canals by means of deep floats have regularly been used up to the present day in measuring the water drawn by most of the large Lowell mills and by several of those at Lawrence. The six flumes in which most of these measurements are made at Lowell are about 150 ft. long by 50 ft. wide and 8 or 10 ft. in depth, and ordinary quantities are from 1500 to 2000 cu. ft. per sec. Also, many measurements are made in flumes about 5 ft. deep by 15 ft. wide with velocities of from 2 to 6 ft. per sec.

Next in the Lowell series were Mr. Francis' experiments upon large weirs. The formula that has been standard in American practice now for seventy years was the result of these experiments.

Up to the time of the Francis experiments, the best data for the weir discharge were those from the experiments of Poncelet and Lesbros in 1828, made with depths only about one-eighth as great and with the quantity discharged not more than 0.20 cu. ft. per sec., or 1/320 part of that handled by Francis. Also, there were experiments by Castel in 1835, with a maximum depth of 4 in. and a maximum quantity of about 1.27 cu. ft. per sec.; and others by Boileau in 1846 with depths up to 8.6 in.; all of which were carried on with great care, although with diminutive apparatus. Earlier experiments than these were crude approximations.

Positive measurement of discharges up to 65 cu. ft. per sec. was made by Mr. Francis with high precision in the chamber of a navigation lock, by means of a swinging gate which switched the current of water in or out within a fraction of a second, while the time record was made by means of an electric contact and a chronometer. The depths above the crest of the weir ranged from 0.6 to 1.57 ft. In general the limit of error in the quantity measured was held down positively to about 1 per cent.

This series, with direct measurement of the discharge in a tank, was preceded by other weir experiments of a different character, in which no direct measurement of the quantity was made, but in which the discharge was kept at a constant rate while the form of weir orifice was varied. In some experiments there was no end contraction; in others there were two or four end contractions. In some experiments the length of weir was shortened and the depth thereby increased and the law was deduced that discharge varied as the 1.47 power of the depth. This is so near to the 3/2 power that the greater convenience in computing the square root of the cube justified its use, although it is slightly less precise.

Francis' formula, based on these large-scale experiments, when compared with the earlier experiments on a small scale is found to give results about 2 per cent smaller than those of Poncelet and Lesbros, about 3 per cent smaller than those of Castel, and from 0.5 to 1.5 per cent smaller than those of Boileau. This remarkably accurate application of the formula over the wide range covered by these smaller quantities of the early experiments up to quantities from 50 to 300 times as great, again justified the law of hydraulic similitude.

Francis found, as did Boileau, that heads were the same when measured by a simple orifice in the side of the flume 8 ft. upstream from the crest, as when measured by means of a perforated pipe across the flume immediately below the weir. Fteley and Stearns made similar observations years afterward, but did not find precise agreement.

All through Mr. Francis' experimentation, he took great pains to measure the effect of disturbances upon the precision of measurement. In the course of other experiments upon weirs, the level of the water on the downstream side of the weir crest was gradually raised until the crest was slightly submerged. By precise measurements he found that discharge was not affected sensibly so long as it was 3 in. or more below the crest. When just level with the crest, the effect was barely sensible. When ¾ in. above, the contraction of the under side of the sheet of water going over the weir was partially suppressed and the discharge increased about 0.7 per cent. When raised to 1.25 in. above the crest, a diminution of discharge occurred. This diminution increased rapidly as the backwater was increased.

Experiments for the improvement of turbines were next in order at the Lowell Laboratory, and out of these grew the inward-flow type known as the Francis turbine, now in general use throughout the world. This inward-flow type is a sort of antithesis to the outward-flow, Fourneyron or Boyden type, which at that time and for many years later was the favorite in the larger American water-power plants.

Although this inward-flow type bears Francis' name, its shape was largely changed, first by a skilled Lowell mechanic, A. M. Swain (already mentioned), who was possessed of an inborn sense of avoiding friction loss in eddies by leading water gently around corners, and who added the feature of downward flow. Improvement was aided by suggestions from Hiram F. Mills. Later the inward-flow design was modified by McCormick and others, who added a partial outward turn to the discharge.

In line with other examples of use of small models and confidence in the doctrine of similitude, it is worthy of note that Francis' first center-vent model turbine was only 1.9 ft. in diameter, its water passages only 0.24 ft. high, its head only 2.5 ft., and its discharge only 2.2 cu. ft. per sec., or 1/50 part of the discharge, and its power only 0.46 or only 1/300 part of the horsepower of the full-sized practical turbine which he next built for the Boot Cotton Mills at Lowell. This again showed understanding of the principles of hydraulic similitude, which has become so fruitful in the development of the optimum shape for turbine buckets in both

European and American laboratories during the past 10 or 15 years.

EXPERIMENTS BY HIRAM F. MILLS

Mr. Mills was another graduate of the New England school of precise large-scale hydraulic experimentation. In his younger days he had worked under a commission of which Charles S. Storrow was the leading member, gaging the flow of the Concord and Sudbury Rivers with a view to the drainage of large marshes. In the course of time it became important accurately to gage the water supplied to the Lawrence factories on the Merrimack River 10 miles downstream from Lowell, and from which was developed a total of about 15,000 horsepower. Mr. Mills, who had in the meantime also assisted Mr. Francis in his Lowell hydraulic experiments, was called to become chief engineer of the Lawrence Water Power. He forthwith set about to devise improved methods for water measurement on a large scale.

He built two important testing flumes, or laboratories, as we now call them. In these he tried out and perfected several modifications of the pitot tube, improving on Darcy's model, and finally greatly simplified the application of Pitot's idea, by using piezometers on the conduit wall for determining the zero line and by using a small, plain, smooth hole in the side of a 1-in. brass tube, without mouthpiece or any projection for receiving and transmitting the pressure due to velocity head.

In some of his instruments used for measuring velocity in conduits 9 ft. in diameter simultaneously at many points across the diameter, a single tube 1 in. in diameter contained as many as twenty of these pressure-measurement orifices, all carefully in line, and each connecting with a separate small tube inside the long, straight brass tube 1 in. in diameter that was inserted in the turbine penstock. From each of these small tubes a rubber tube led to a glass-tube manometer on the scaleboard. All these glass tubes were connected by a manifold across their tops, within which air pressure could be raised or lowered as desired above or below the atmospheric pressure.

These instruments could be revolved and the inclination of their orifices to the axis of the conduit measured on a dial. The twisting or spiral motion of water existing in many conduits having an irregular entrance for water was revealed by revolving the instrument until a given orifice showed pressure equal to that of the piezometers, reading the dial, and then similarly revolving the instrument in the opposite direction. Midway between the two readings was the direction of flow.

As a first step toward researches on the laws of flow in open and closed conduits, Mr. Mills undertook an extensive research to determine if pressure measured by an open water column communicating with a conduit through an orifice in the conduit wall, rose to precisely the same level as the water surface in the conduit at a point immediately above this orifice. He made experiments upon such orifices of various shapes and inclinations and over a large range of velocities.

He concluded, after many hundred observations, that if the edges of the orifice were truly in the plane of the surface, the indications of the piezometer would be correct. In other words, he found the level of the still water in the small chamber connected with the orifice was precisely level with the water surface in the open conduit in the same cross section, whatever the velocity past the orifice, or whether near top or bottom. These experiments, made fifty years ago, are described in the Transactions of the American Academy of Sciences, Boston, Mass., for 1878. I had the great good fortune of being Mr. Mills' principal assistant for nearly 10 years.

About this time Mr. Mills established a laboratory for calibrating his various forms of pitot tube by means of a weir of the standard Francis model, in connection with a flume 4 ft. wide, 6 ft. high, and about 400 ft. long, known as "The Experimental Penstock," in which a great variety of tests were made.

Later, he built a second laboratory at the lower locks in Lawrence, primarily, also, for testing special forms of pitot tube to be used in measuring velocity of discharge in closed conduits leading to the water wheels of the mills; but fitted for a large variety of other experiments. A 12-in. pipe about 350 ft. long led to a tall forebay, from which the discharge and velocity through the entire system could be regulated at a very precisely made gate, 12 in. wide, having sharp edges, which could be set to any desired height from zero to 12 in. The jet from this orifice gave beautiful illustrations of the changing shape of the contracted vein and, as depth of orifice was increased, gave opportunity also for experiments on coefficients of discharge.

This jet, in turn, fed a series of carefully built, smooth plank flumes from two to four feet in width, each about a hundred feet long, one leading into the next, and each series set at a different slope. The depth in these flumes could be varied from an inch up to more than a foot by varying the discharge. Finally the discharge was measured directly in terms of cubic feet per second, in one of the old, unused navigation locks which had been tightened and carefully calibrated, first, by direct linear measurement, and, second, by precise determinations of dilation and leakage.

Particular attention was given to determining the distribution of velocity throughout the various cross sections of the experimental flume, in various of the water-wheel penstocks of Lawrence, and also in the cross section of the long twelve-inch pipe; also, to noting the departures from the parabolic law near the walls, and to tracing the change in the law of flow near the conduit walls.

Unfortunately, the results of these elaborate experiments made 40 to 50 years ago have never been published or completely reduced to usable form. At about the time that they apparently were nearing completion Mr. Mills was appointed a member of the Massachusetts State Board of Health and became profoundly interested in the improvement of the sanitary quality of public supplies of water for drinking and domestic purposes, and the writer, who had been Mr. Mills' principal assistant, left his employ for other fields of activity.

For 28 years Mr. Mills gave his services without fee or salary to the State, and the loss to hydraulic science was compensated for by his virtually founding the new science of purification of water by filtration and that of purifying sewage by intermittent filtration. His hydraulic laboratory was refitted for a laboratory of sanitary science. Under his inspiring leadership Nature's methods of purifying water through bacterial action and nitrification, or " wet burning," were worked out by Professor Sedgwick, Professor Drowne, and others. Several of his assistants of those days have since become leaders in the profession of public health engineering, notably Allen Hazen, George W. Fuller, and Harry W. Clarke. Seldom has there been a finer example of a great man giving the best of his life to problems of public welfare without thought of pecuniary gain, or of a man more modest in telling of his own part in the researches published under the official title of a Government Bureau.

After his retirement from active practice, and at an age of from 80 to 84 years, Mr. Mills resumed his hydraulic studies and began writing out his notes upon the laws of flow of water in straight cylindrical pipes, which have been recently published by the American Academy of Arts and Sciences. Some time I hope to join with one or two of Mr. Mills' other former assistants in digging out extracts from his old notebooks and publishing some of the results of his many other hydraulic experiments.

Mr. Mills also made valuable contributions to turbine design, particularly in his test upon a 42-in. Swain inward- and downward-flow turbine, and particularly in his suggestions to the inventor about improving this design. This wheel was an improvement on the original Francis inward-flow turbine, and after 53 years is still a leading modern type.

BOSTON WATER WORKS EXPERIMENTS

Joseph P. Davis, city engineer of Boston in the golden age of its engineering department, had been a college-mate and a warm friend of Mr. Mills, and was himself an inspiration to all of his engineering corps. In due course this enthusiasm resulted both in sound engineering and in various contributions to hydraulic engineering data, such as "Researches on Evaporation," by Desmond Fitzgerald; the weir experiments of Fteley and Stearns; the experiments on friction loss at various velocities of discharge in the tunnel of the Boston main drainage works; the pipe-flow experiments on the Rosemary Siphon and in the Sudbury Conduit; and in a series of printed technical reports recording facts and giving drawings of important structures built under the city engineer's department.

Noteworthy among these contributions from the Boston Water Works are the experiments on discharge of weirs with sharp crest and with rounded crest, made at the Sudbury Aqueduct, just prior to its being put into service. A section of the aqueduct was used as a measuring basin and the circumstances permitted a high order of accuracy. The apparatus used in these experiments had been erected for the purpose of accurately measuring the discharge of the new conduit, and this was made to serve the double purpose of providing new data on the laws of conduit flow and discharge of weirs.

Fteley and Stearns sought to more precisely determine:

1 The effect of velocity of approach upon discharge.

2 Greater precision in measuring discharge with smaller depths than those with which Mr. Francis experimented.

3 The effect upon discharge of broadening the crest of a weir, or of change from a sharp crest to one rounded at various small radii.

4 The effect of submergence of weir crest by backwater. (Their apparatus did not permit a wide range for this series.)

The Boston city engineer's office also contributed some precise and valuable experiments on the discharge of new cast-iron water pipe 4.0 ft. in diameter; experiments upon a section of the Sudbury Aqueduct having natural rough rock sides and also on a long section smoothly lined with brick, showing the great economy of a smooth lining; and experiments upon the hydraulic qualities in discharge and friction loss of the new tunnel of the Boston main drainage works.

I have gone into details with these examples quoted above to an extent unnecessary except for the purpose of emphasizing the fact that *these hydraulic experiments of the New England engineers were with large-scale apparatus, and that their observations were made with a refinement of method and a degree of precision that has never been excelled in hydraulic experimentation.* This work of Storrow, Francis, and their successors may fairly be said to mark the beginning of a new era, in awakening all of the young engineers around them to the value of extreme care and precision of measurement and to the importance of experimenting with large-scale apparatus and to setting traps for possible errors. None of these men, however, became engaged on problems of river structures or particularly in the fields cultivated by Engels and his successors.

HOLYOKE TESTING FLUME

Next in order we may describe the laboratory built by the Water Power Company at Holyoke, Massachusetts, about 1880, chiefly in order to provide a convenient place in which tests and experiments could be made on turbine water wheels of modern commercial sizes and in which the power company could rate as water meters the turbines that were to draw from their canals by determining their discharge at various heights of gate, speed, and effective head. This Holyoke laboratory also has served for sundry other lines of hydraulic experiment and has been of inestimable value in the development of American water wheels of high efficiency, manufactured in quantity at extremely moderate cost, or built at short notice from a few sets of standard foundry patterns.

This Holyoke laboratory also has given an opportunity for inventors (as in case of McCormick) to have their new inventions put to impartial accurate test at low cost, and has given an opportunity to American turbine builders to perfect the shape of their models by the method of "cut and try," until a line of standard patterns could be worked out for quantity production, each well adapted to meet various conditions of speed, head, and capacity.

In all of these various tests and experiments on turbines, orifices, etc., at the Holyoke flume, the discharge has been measured by a weir set up in strict accordance with Mr. J. B. Francis' rules and computed by his formula.

The maximum head available is 17 ft. and the maximum discharge for accurate measurement about 225 cu. ft. per sec. Because of occasionally overcrowding its capacity in order to test a larger turbine than that for which the flume was designed, there has been some question as to whether at these higher discharges their weir measurement is accurate within 1 or 2 per cent; nevertheless these experiments with large quantities were particularly useful in spite of this possible lack of extreme precision. Moreover, there was no other place at the time where tests of this kind could be made with such large quantities.

EXPERIMENTS OF HAMILTON SMITH, JR.

A place among American experimenters in hydraulics also should be given to Hamilton Smith, Jr. His laboratory was a mobile institution located chiefly in California, at whatever locality he was called to by his profession of civil and mining engineering. His large treatise on hydraulics published in 1886, a quarto volume of nearly 400 pages, was a labor of love, written in his mature years, and is a painstaking, critical review of all dependable experiments that he could find recorded upon flow in pipes and upon discharge through orifices and nozzles and over weirs. Among his experiments, of chief interest are those upon the relations of pipe velocities to loss of head, as found in the early practice in the hydraulic mines of California, where thin riveted sheet-iron pipes were used under high heads with extremely high velocities and remarkably small factors of safety against bursting. His own experiments occupy nearly 90 pages of this volume.

We have space here only to note that he obtained accurate experimental values for the "miners' inch" (which was the common unit of water measurement in the mines and still is prominent in old deeds and litigation) from various "Modules" in practical use, and that he measured the discharge from conical nozzles under high head in the course of his tests of the efficiency of the Pelton type of water wheel, which latter seem to have been the earliest tests on record for proving the remarkably high efficiency that could be obtained with what, then, was a crude type, but has since been refined into the most useful water wheel yet devised for extremely high heads.

Also, Mr. Smith records a few experiments upon the flow of quicksilver through an orifice about one-quarter inch in diameter, with full contraction, under two heads of 3.16 ft. and 1.76 ft., respectively, which gave a coefficient of 0.602, which is of special interest in the agreement found for coefficient of efflux of water.

His researches into the laws of flowing water were the scientific recreations of a man of broad experience in the hydraulic arts as applied to mining. Where he found a gap in a line of data he sometimes undertook to fill this by experiments of his own. I met him in London in 1889, while he was largely occupied with great mining problems in South Africa, but found him still interested in hydraulic science.

HERSCHEL'S EXPERIMENTS

In a book of 127 pages published in 1897, Clemens Herschel, inventor of the Venturi water meter and founder of the Holyoke testing flume, set forth important new data upon the friction loss in riveted steel conduit pipes.

The history of events leading to these experiments presents a remarkable illustration of the great and wasteful cost of inaccurate or incomplete data which, as Mr. Herschel remarks, could have been saved by experiment in a hydraulic laboratory, or "observatory," as he names it. A steel conduit guaranteed to carry 50,000,000 gallons per day for the domestic water supply of Newark and adjacent municipalities had been designed upon the supposition that a large riveted steel pipe, made slightly rough on the inside by the projecting edges of pipe (alternating large and small courses of steel plate about 5/16 in. thick) and by hemispherical rivet heads projecting about 3/8 in., and the whole coated with asphalt, *would present substantially the same coefficient of friction as new cast-iron pipe,* and the further supposition that this coating of prepared Trinidad asphalt would prevent any large increase of friction loss as the pipe aged.

Both of these suppositions were sadly in error, although apparently justified by the previous experiments of Hamilton Smith, Jr., on thinner pipe with smaller rivets and more smoothly coated, and justified, also, by measurements reported to have been made carefully of the discharge and loss of head in a new steel-plate water main 36 in. in diameter supplying the city of Rochester, N. Y. A second pipe had to be built beside the first, in order to fulfill the guaranty of 50,000,000 gallons daily.

Mr. Herschel gives, with great care and detail, the losses of head actually found in the two East Jersey conduits, 48 in. and 42 in. in diameter, after several years of tuberculation, and his series presents the best data extant upon the loss of head in pipes of that kind. The appendices of Mr. Herschel's book contain some admirable notes on the early development of hydraulic science.

GILBERT'S EXPERIMENTS ON TRANSPORTATION OF GRAVEL, ETC.

In 1907-1908, the United States Geological Survey provided the funds and the assistants for building a temporary hydraulic laboratory on the grounds of the University of California for experiments designed to discover the laws of transportation of materials, such as stones, sand, and silt, down river channels. These laboratory studies are described in Professional Paper No. 86, U. S. Geological Survey, by Grove Karl Gilbert.

For more than a century the textbooks had been repeating the results of Dubuat's observations upon the velocity with which grains of sand and small stones were transported down small, smooth, plank troughs, only about 18 in. wide by less than one foot deep, without giving proper notice to the extremely limited range of those experiments, and without emphasis upon the vastly different conditions presented by Dubuat's smooth plank walls and the rough irregular bed of a natural stream.

The field studies of river channels, etc., to which these researches by Gilbert pertained, are described in a later Professional Paper of the U. S. Geological Survey, No. 105, under the title "Hydraulic Mining Debris in the Sierra Nevada."

Dr. Gilbert long had been one of the most distinguished among American geologists, and after many years of observation of nature's processes of earth erosion and delta building, was now particularly desirous of aiding the California River Debris Commission in its attempts to improve conditions in certain California rivers that had become badly obstructed by material brought down by floods from the debris of hydraulic mining.

These researches, although incomplete, present as far as they go the best laboratory study of traction of sand and gravel by running water yet published, but the data derived from them seem to have been buried beyond the reach of most practical men by the 260 pages of careful language in which the researches are described. Moreover, these experiments stopped far short of covering this field.

Dr. Gilbert became ill before the research had been carried so far as he desired. I am told by one of his former associates that he wrote much of the text and directed the computations of this report a few hours at a time as strength permitted during a partial recovery of health, but he did not live to give the research the completeness that he desired.

Dr. Gilbert noted in the beginning the distinctions between flume traction and stream traction, and stated that little was previously known of the quantitative laws of stream traction. He sought to determine the laws of capacity of streams for transportation of gravels, with variations of slope, depth, and width of current, using sands and gravels of representative quality and varying degrees of fineness, taken from typical California river beds.

His apparatus consisted of wooden troughs, one about 2 ft. wide by 30 ft. long, with depths of from 1.0 to 1.8 ft.; a second 15 ft. long, and a third 14 ft. long; each for a particular purpose. One had a sheet of plate glass inserted in its side, the first example, so far as the writer knows, of the glass-wall flume, which has since become such an extremely fruitful apparatus in European laboratories. He used stream beds of various degrees of roughness, formed by pebbles of various sizes embedded in cement.

He began with a review of researches in these fields that has been made in England, France, and Germany, and proceeded with an analysis of his own experiments in much greater detail.

Dr. Gilbert noted five principal modes of transportation:

1 Simple sliding
2 Simple rolling
3 Jumping, or "Saltation," as he calls it
4 Suspension
5 Collective movement in sand waves, or submerged dunes, under a great variety of controlled conditions.

He classified these methods of transportation primarily into four groups:

1 Stream suspension
2 Flume suspension
3 Stream traction
4 Flume traction,

noting that transportation in flumes with smooth and rigid walls and beds was radically different from that in natural rivers with an earth bed typically plastic.

He experimented, first, with particles separated by sieves to uniform sizes; and, second, with mixed material containing various sizes. He studied the motion of particles and of masses traveling in the form of sand waves and also noted the effect of the rhythmic motion of the water. We cannot attempt, here, to summarize this book of 260 closely printed pages in which he describes these experiments.

By the completeness of his analysis, he seems to have laid an excellent foundation for future research in many of the problems of river hydraulics, such as are concerned with erosion, transportation of sediments, and the formation of sandbars.

RESEARCHES OF THE MIAMI CONSERVANCY BOARD

On March 23-25, 1913, what probably was the largest concentrated rainfall in the middle United States within more than a century occurred over the valley of the Miami River in the state of Ohio, upstream from the populous industrial cities of Dayton and Hamilton. Along the path of the storm center, for a width of from ten to fifteen miles, the total rainfall in these three days was about eleven inches in depth, and over the entire drainage area of about 2600 square miles above Dayton the average depth was about nine inches. This resulted in a run-off, which at its peak reached about 100 cubic feet per second per square mile and a flood volume near Dayton of 250,000 cu. ft. per sec. This flooded city streets to a depth of from 5 to 10 ft., caused the loss of 360 lives and a direct property loss estimated at $67,000,000, or, with indirect losses added, a total flood loss of about $100,000,000.

These cities were fortunate in possessing certain captains of industry of uncommon breadth of vision and executive force, foremost among whom was E. A. Deeds, Mem. A.S.M.E., who led the citizens to establish a Conservancy Board, which selected an engineering corps of exceptional ability for a thorough study of the various problems of preventing damage from future floods. In due course many technical investigations were made and protective works were laid out on a grand scale. The execution of these works cost about $30,000,000. They comprised both the construction of great flood-detention reservoirs and the improvement of river channels.

As the works neared completion, the engineering corps under its chief, Mr. Arthur P. Morgan, and with the support of members of the Conservancy Board, who desired to make its costly researches of the broadest possible use to other communities, prepared for publication reports describing many of these researches. This series of technical reports comprises ten volumes and one atlas of drawings, containing in all more than 2300 printed pages, and makes one of the most comprehensive treatises upon protection against floods and the control of flood flows that has ever been published.

In brief, these studies comprised:

1 A record of study of this particular flood.

2 An extended historical and analytical study of storm rainfall in the Eastern United States, comprising intimate records and maps of all great storms and floods of which record could be found.

3 Studies of the discharge capacity of natural flood channels, with a careful analytical review of all data that could be found the world over for the calculation of discharge of water in open channels.

4 The possibilities of detention reservoirs of great capacity, that ordinarily would be empty so their beds could remain useful for agriculture save in the case of one of those rare and unusual floods, at which time their outlets of predetermined capacity constantly kept wide open would discharge the flood waters only at such restricted rate as could safely be carried by the improved river channels.

5 Means of dissipating the energy of the flood escaping from these reservoirs through the sluiceways at great velocity and of promptly lessening this velocity of efflux to such extent that it could be carried by channels in earth without eroding their beds.

6 Reports on contract forms, methods of accounting and cost keeping, and construction plant methods and costs.

I have long had an intimate personal acquaintance with most of the engineers who took part in these various Miami researches and visited the site of the works while under construction and again after completion, and take pleasure in here calling attention to the preparation and publication of these volumes for the use of other engineers as one of the most creditable efforts of the kind of which there is record.

Particular attention was paid to the phenomena and theory of the "hydraulic jump" previously described by Bidone, Unwin, Kennison, Ferriday, and Gibson.

A temporary hydraulic laboratory was built for the studies last named, in which, by means of models of reduced size, it was sought to determine the best and most economical form of structure for promptly dissipating the energy in a flood discharge of 10,000 cu. ft. per sec. issuing with a velocity of about 55 ft. per sec., which was to be the designed capacity of the sluiceways at the Germantown detention dam. These researches were entrusted to Professor Woodward, of the University of Iowa, one of the most skilful of American hydraulicians.

The models were built on a scale of 1/16 of the linear dimensions of the sluiceways; thus the area and passageways in the model were as 1 to 256 and the relative discharge was 1/1024 part of that provided for in the final structure. According to the laws of hydraulic similitude the velocity in the model was to be ¼ of that in the final structure, and the apparatus was thus designed for a maximum discharge of about 9.8 cu. ft. per sec. with a velocity of 13.75 ft. per sec.

At first, dissipation of energy in fluid friction within eddies was induced in a divergent channel, the floor of which was obstructed by baffle blocks of various shapes, also by weirs and by various other devices; but soon attention was directed to the hydraulic jump as the most efficient means of dissipating energy that could be found. Experiments next had for their chief object the shaping of the floor and the side walls of a discharge chamber so as *to make certain that this jump would occur at the desired position* and that at a very short distance from the jump the discharge should be well distributed with a velocity so low that it would preclude danger of eroding the river bed composed of earth. Had the engineers in charge of building the Wilson Dam at Muscle Shoals, Alabama, heeded the results of these researches, the deep erosion below the limits of the concrete apron and costly repairs necessitated thereby, could have been avoided.

In the several detention reservoirs built by the Miami Conservancy Board, the saving in the cost of the final structure evidently paid many times over for the cost of this temporary laboratory and the several months of expert research.

One who reads the technical portions of these reports prepared by Professor Woodward will find ample illustration of the statement made on a preceding page that one gifted in powers of mathematical analysis can find ample scope for employing these gifts in working out the problems of the hydraulic laboratory.

EXPERIMENTS BY JOHN R. FREEMAN

The writer has set up in years long past two or three hydraulic laboratories in which elaborate hydraulic researches have been made. In 1888, on the premises of the Washington Mills at Lawrence, Mass., a long series of experiments was made upon the flow of water in ordinary fire hose of ordinary size and various qualities of smoothness of interior surface. Practical conditions were reproduced in great variety, and with such great care and precision of measurement that the work will not need to be done over again while present methods of fire-fighting with hydrants, pumpers, hose, and nozzles continue in use.

Experiments were made upon the discharge of nozzles and the heights of jets under pressures up to 130 lb. per sq. in., also with nozzles of many forms from $\frac{3}{4}$ in. up to 2 in. diameter, and with careful measurement of their vertical and horizontal effective range.

The pressures were accurately measured by mercury gages to within 0.01 lb. per sq. in., and discharges were measured in a tank to within about 0.1 per cent. These experiments are described in the Transactions of the American Society of Civil Engineers for 1889, in a paper which received the Society's annual Gold Medal.

In the following year a second series of precise experiments was reported to the American Society of Civil Engineers in a paper on "The Nozzle as an Accurate Water Meter," which received another Gold Medal.

The writer's next laboratory was also a temporary collection of apparatus built in 1893 on the premises of the Indian Head Mills in Nashua, N. H., and furnished with water from the municipal supply.

Here, an elaborate series of experiments was made upon loss of head in each commercial size of ordinary wrought-iron pipes, from $\frac{1}{4}$ in. to 8 in. in diameter; also in new seamless brass pipes from $\frac{1}{2}$ in. to 4 in. in diameter; and in many sorts of commercial pipe fittings, elbows, bends, and tees, of various radii of curvature. Both new pipe and old corroded pipe were experimented upon and the precise quality of surface of each piece noted with great care.

The widest range possible in roughness of surface was provided in order to determine the laws by which this factor influenced the friction loss at various velocities. New seamless drawn brass pipe served for experiments with smooth surface, while for extremely rough surface there was used 8-in. pipe lined with expanded-metal lath. Heads and discharges were measured with extreme precision.

Other demands on the writer's time have delayed completion of the reduction of data to usable form, but it is now expected it will be completed and results published in the near future.

HYDRAULIC RESEARCHES BY THE UNITED STATES DEPARTMENT OF AGRICULTURE AND OTHERS

Several noteworthy publications have been made by the U. S. Department of Agriculture for the benefit of irrigation engineers and others, which comprise a brief résumé of the previous formulas and many excellent new data.

The first is Bulletin No. 194, U. S. Department of Agriculture, May, 1915, "The Flow of Water in Irrigation Channels," by Fred C. Scobey. The Chézy and the Kutter formulas were used as the framework on which to arrange new data, and measurements were made of slope and discharge in a wide range of existing irrigation flumes and ditches, as found in use in the states of Nebraska, Colorado, Utah, Idaho, Oregon, Montana, California, Texas, and Louisiana, ranging in discharge capacity from less than 1.0 cu. ft. per sec. to more than 2600 cu. ft. per sec., with channel walls and beds of wood, concrete, earth, rubble masonry, cobblestones, and combinations. Velocities were found up to 10 ft. per sec.

The values of C and n in the Chézy and the Kutter formulas were determined for 260 different channels, nearly all artificial, and most of them as found in practical use. Since the methods and instruments and skill of the observer and the variety of specimens were those of the laboratory practice, it does little violence to the term to call these laboratory experiments.

I judge from the records that *as a whole this was the most valuable piece of work of this kind that has ever been carried out up to the present time.*

It is interesting to compare this modest and condensed pamphlet of 68 pages and its wealth of original observations with some of the more ponderous tomes on hydraulics and their small amount of original data.

Another similar publication by the U. S. Department of Agriculture of exceptional interest and value to hydraulic engineers and prepared by the same engineer, Fred C. Scobey, is its Bulletin No. 376, Nov. 25, 1916, on the "Flow of Water in Wood Stave Pipe."

This type of pipe, composed of plank from 1.5 to 2.5 in. thick in the form of staves with edges carefully planed true and straight, bound around with iron rods proportioned to the head, and set up tightly with clamps, nuts, and screw threads, has been used on a bold scale up to large sizes, high pressures, and high velocities, in the Western United States during the past 30 years, and in some localities where lumber is cheap it presents great advantage in low first cost and facility of erection.

Mr. Scobey calls particular attention to one good quality as compared with iron, namely, that it suffers no serious loss of carrying capacity through tubercles of rust, and that it will continue indefinitely to carry, for the same diameter, about 15 per cent more water than a new riveted steel pipe or a cast-iron pipe 10 years old.

This bulletin contains careful tests of discharge and friction loss or slope on about 50 different pipes in service in a great variety of sizes and conditions, from 0.105 to 13.5 ft. in diameter, and computes for each the value of the coefficient C in the Chézy formula, also the value of the Kutter coefficient of roughness n, and makes comparison of the results actually found by experiments with those by several formulas in common use.

Mr. Scobey also discusses the formulas in common use for computing discharge or loss of head in pipes, and finally proposes a new formula of exponential form for the factors of both head and diameter for wood-stave pipe, namely,

$$V=1.62D^{0.65}H^{0.555}.$$

Still another of these useful contributions to hydraulics of the U. S. Department of Agriculture is Bulletin No. 832, on "The Flow of Water in Dredged Drainage Ditches," by C. E. Ramser, Senior Drainage Engineer. This gives the results of many measurements of discharge and loss of head in irrigation ditches as found in use in the states of Mississippi, Tennessee, Iowa, Florida, and North Carolina.

These experiments are of special interest in showing the retardation or additional loss caused by the presence of water-weeds; and conditions of bed are described with much care.

Bulletin No. 854, on "The Flow of Water in Drain Tile," by D. L. Yarnall, Senior Drainage Engineer, and Professor S. H. Woodward, of the University of Iowa, is another collection of original data with a great variety of diameters, velocities, and slopes, covering each ordinary commercial size from 4 to 12 in. pipe, all made with much care and skill.

The difference in loss of head between well laid and poorly laid tile was carefully experimented upon, and data were obtained on coefficients of flow for tile partially filled. Computations of the new data with the older formula are given.

Studies of a similar character are reported in Bulletin No. 194, January, 1914, Colorado Agricultural College Experiment

Station, in cooperation with the U. S. Department of Agriculture, under the title "Frictional Resistance in Artificial Waterways," by Cone, Trimble, and Jones. This bulletin reports an extensive series of observations and experiments on the flow of water in semi-cylindrical metal flumes of from 5 to 9 ft. horizontal diameter, straight and curved, with observations also upon the loss of head in timber flumes, concrete flumes, and channels of earth, made for the purpose of obtaining accurate data on the values of n and C in the Kutter and Chézy empirical formulas. The observations appear to have been made with skill and care. Discharge was measured by current meter, and slope by precise levels. Observations on distribution of velocity throughout the cross section were made for the purpose of learning the margin of error and coefficient to be used in measurements of velocity at proportional points.

Taken as a whole, these many careful determinations on a great number of flumes in use, including a great range of depth, velocity, and quality of surface, constitute an extremely valuable contribution to hydraulic data, and would seem to meet all requirements of the irrigation engineer or others using conduits of these several kinds for many years to come.

Extensive experiments on the loss of head in valves and pipes of from 0.5 to 12 in. in diameter were made, in 1922, by Prof. Charles Ives Corp, assisted by Roland O. Ruble. These are described, with results obtained, in the Bulletin of the University of Wisconsin, Engineering Series, Vol. IX, No. 1.

Conclusion

Much more could be written upon all of these topics. Space is not here available for giving due credit to some who have been mentioned by name and to others not mentioned at all.

After trying to make it clear that while the hydraulic arts are old, hydraulic science is still very young and still in the making, the writer has tried to show that whenever real progress has been awakened in the centuries past, *it has come chiefly from laboratory experiment,* supplemented and confirmed by observations under laboratory methods upon full-sized specimens in the field.

Also, the writer has tried to make plain his strong belief that one of the most useful pieces of apparatus for hydraulic research, particularly in river and harbor problems, is the small-scale model *used in connection with observations made directly upon the river or harbor under discussion,* and that among the theories in which engineering students should be most carefully grounded are those of hydraulic similitude.