During the eighteenth century notable advances were made. Daniel and John Bernoulli extended the theory of the equilibrium and motion of fluids, and this theory was much improved and generalized by D'Alembert. Bossut and Dubuat made experiments on the flow of water in pipes and deduced practical coefficients, while Chezy and Prony, near the close of the century, established general formulas for computing velocity and discharge.

During the nineteenth century progress in every branch of hydraulics was great and rapid. Eytelwein, Weisbach, and Hagen stood high among German experimenters; Venturi and Bidone among those of Italy; Poncelet, Darcy, and Bazin among those of France; while Kutter in Switzerland, Rankine in England, and James B. Francis and Hamilton Smith in America also took high rank for either practical or theoretical investigations. By the experiments and discussions of these and many other engineers the necessary coefficients for the discussion of orifices, weirs, jets, pipes, conduits, and rivers have been determined and the theory of the flow of water has been much extended and perfected. The invention of the turbine by Fourneyron in 1827 exerted much influence upon the development of water power, while the studies necessary for the construction of canals and for the improvement of rivers and harbors have greatly promoted hydraulic science. In this advance the engineers of the United States did much good work during the latter part of the nineteenth and are continuing it during the present part of the twentieth century, as is shown by the numerous valuable papers published in the Transactions of the American engineering societies and in the scientific press, many of which will be cited in this book.

Galileo said in 1630 that the laws controlling the motion of the planets in their celestial orbits were better understood than those governing the motion of water on the surface of the earth. This is true today, for the theory of the flow of water in pipes and channels has not yet been perfected. Experiment is now in advance of theory, but it is intended to present both in this volume as far as practicable, for each is necessary to a satisfactory understanding of the other.

Prob. 7. Who was the author of a book called Lowell Hydraulic Experiments? When and where was it published? What influence has it exerted upon hydraulic science?

Art. 8. Numerical Computations

The numerical work of computation should not be carried to a greater degree of refinement than the data of the problem warrant. For instance, in questions relating to pressures, the data are uncertain in the third significant figure, and hence more figures than three in the final result must be delusive. Thus let it be required to compute the number of pounds of water in a box containing 307.37 cubic feet. Taking the mean value 62.5 pounds as the weight of one cubic foot, the multiplication gives the result 19 210.625 pounds, but evidently the decimals here have no precision, since the last figure in 62.5 is not accurate, and is likely to be less than 5, depending upon the impurity of the water and its temperature. The proper answer to this problem is 19 200 pounds, or perhaps 19 210 pounds, and this is to be regarded as a probable average result rather than an exact quantity.

Three significant figures are usually sufficient in the answer to any hydraulic problem, but in order that the last one may be correct four significant figures should be used in the computations. Thus, 307.37 has five significant figures and this should be written 307.4 before multiplying it by 62.5. The zeros following a decimal point of a decimal are not counted significant figures; thus, 0.0019 has two and 0.0003742 has four significant figures.

The use of logarithms is to be recommended in hydraulic computations, as thereby both mental labor and time are saved. Four-figure tables are sufficient for common problems, and their use is particularly advantageous in all cases where the data are not precise, as thus the number of significant figures in final results is kept at about three, and hence statements implying great precision, when none really exists, are prevented. The four-place logarithmic table at the end of this volume will be found very convenient in solving numerical problems. As an example, let it be required to find the weight of a column of water 2.66

inches square and 28.7 feet long. The computation, both by common arithmetic and by logarithms, is as follows, and it will be found, by trying similar problems, that in general the use of

By Arithmetic		By Logarithms	
2.66	0.04914	2.66	0.4249
2.66	28.7		2
5.32	9828		0.8498
1 596	39312	144	2.1584
160│144	3439		$\bar{2}$.6914
7.076(0.04914	1.410	28.7	1.4579
576	62.5	62.5	1.7959
1316	846	Ans. 88.1	1.9452
1296	282		
20	70		
14	Ans. 88.1 pounds.		
6			

logarithms effects a saving of time and labor. The common slide rule, which is constructed on the logarithmic principle, will also be found very useful in the numerical work of many hydraulic problems.

The tables of constants, squares, and areas of circles at the end of this volume will also be advantageous in abridging computations. For instance, it is seen at once from Table E that the square of 2.66 to four significant figures is 7.076, while Table F shows that the area of a circle having a diameter of 0.543 inch is 0.2316 square inch. Logarithms of hydraulic and mathematical constants are given in Tables A, C, and K. Tables 1*a*, 1*b*, and 6 of this chapter and others in the next chapter give multiples of constants which may be advantageously used when it is necessary to multiply several numbers by the same constant. For example, when it is required to reduce 333.4, 318.7, and 98.6 cubic feet to U. S. gallons, the book is opened at Table 1*b*, where the multiples of 7.481 are given, and the work is as follows:

333.4	318.7	98.6
2244.2	2244.2	673.2
224.4	74.8	59.8
22.4	59.8	4.5
3.0	5.2	737.5
2494.0	2384.0	

These results are more accurate than can be obtained with four-place logarithmic tables. The logarithmic work for this case would be the following:

333.4	318.7	98.6
2.5229	2.5034	1.9939
0.8740	0.8740	0.8740
3.3969	3.3774	2.8679
2494	2384	737.7

As this book is mainly intended for the use of students in technical schools, a word of advice directed especially to them may not be inappropriate. It will be necessary for students, in order to gain a clear understanding of hydraulic science, or of any other engineering subject, to solve many numerical problems, and in this a neat and systematic method should be cultivated. The practice of performing computations on any loose scraps of paper that may happen to be at hand should be at once discontinued by every student who has followed it, and he should hereafter solve his problems in a special book provided for that purpose, and accompany them by such explanatory remarks as may seem necessary in order to render the solutions clear. Such a note-book, written in ink, and containing the fully worked out solutions of the examples and problems given in these pages, will prove of great value to every student who makes it. Before beginning the solution of a problem a diagram should be drawn whenever it is possible, for a diagram helps the student to clearly understand the problem, and a problem thoroughly understood is half solved. Before commencing the numerical work, it is also well to make a mental estimate of the final result.

In this volume Greek letters are used only for signs of operation and for angles. The letter δ is employed as the symbol of differentiation and it should be called "differential." Following are names of some Greek letters:

α Alpha	η Eta	ν Nu	ϕ Phi
β Beta	θ Theta	π Pi	ψ Psi
γ Gamma	κ Kappa	ρ Rho	ξ Zeta
δ Delta	λ Lambda	σ Sigma	ω Omega
ϵ Epsilon	μ Mu	τ Tau	

In every rational algebraic equation it is necessary that all the terms should be of the same dimension, for it is impossible to add together quantities of different kinds. This principle will be of great assistance to the student in checking the correctness of algebraic work. For example, let a and b represent areas and l a length; then such an equation as $al-l^2=b$ is impossible, because al is a volume, while l^2 and b are areas. Again, let V represent velocity, Q cubic feet per second, and a area; then the equation $Q=aV$ is correct dimensionally, for the dimension of V is length per second and hence aV is of the same dimension as Q. The equation $Q/a=V^2$ is, however, impossible, for Q/a is of the same dimension as the first power of V, and this cannot also be equal to its second power.

Prob. 8. When the height of the water barometer is 33.5 feet, what is the height of the mercury barometer, and what is the atmospheric pressure in pounds per square inch?

Art. 9. Data in the Metric System

When the metric system is used for hydraulic computations, the meter is taken as the unit of length, the cubic meter as the unit of volume, and the kilogram as the unit of force and weight. Lengths are sometimes expressed in centimeters and volumes in liters, but these should be reduced to meters and cubic meters for use in the formulas. The unit of time is the second, the unit of velocity is one meter per second, and accelerations are measured in meters per second per second. Pressures are usually expressed in kilograms per square centimeter and densities in kilograms per cubic meter. The metric horse-power is 75 kilogram-meters of work per second, and this is about $1\frac{1}{2}$ per cent less than the English horse-power. Tables at the end of this book give the equivalents in each system of the units of the other system, but the student will rarely need to use such tables. He should, on the other hand, exclusively employ the metric system when using it, and learn to think readily in it. The following matter is supplementary to the corresponding articles of the preceding pages.

(Art. 2) At about 0° centigrade ice is generally formed. When water is kept perfectly quiet, however, it is found that its temperature can be reduced to — 7° or — 9° before freezing begins, but at this instant the temperature of the water rises to 0° centigrade.

(Art. 3) In the metric system the following approximate values are used for the weight of water:

1 liter of water weighs 1 kilogram
1 cubic meter weighs 1000 kilograms

It may be noted that the constants for the weight of water differ slightly in the two systems. Thus, the equivalent of 62.5 pounds per cubic foot is about 1001 kilograms per cubic meter. The weight per unit of volume of pure distilled water is greatest at the temperature of maximum density, 4°.1 centigrade, and least at the boiling-point. Table 9*a* gives weights of distilled water at different temperatures in kilograms per cubic meter, as determined by Rossetti.* River

Table 9*a*. Weight of Distilled Water

Metric Measures

Temperature Centigrade	Kilograms per Cubic Meter	Temperature Centigrade	Kilograms per Cubic Meter	Temperature Centigrade	Kilograms per Cubic Meter
− 3°	999.59	16°	999.00	55°	985.85
0	999.87	18	998.65	60	983.38
+ 3	999.99	20	998.26	65	980.74
4	1000.00	22	397.83	70	977.94
5	999.99	25	397.12	75	974.98
6	999.97	30	995.76	80	971.94
8	999.89	35	994.13	85	968.79
10	999.75	40	992.35	90	965.56
12	999.55	45	990.37	95	962.19
14	999.30	50	998.20	100	958.65

waters are usually between 997 and 1001 kilograms per cubic foot, depending upon the amount of impurities and the temperature, while the water of some mineral springs has been found as high as 1004. It appears then that 1000 kilograms per cubic meter is a fair average value to use in hydraulic work for the weight of fresh water. Brackish and salt waters are heavier. For the Gulf of Mexico the weight per cubic meter is about 1023, for the oceans, about 1027, while for the Dead Sea there is stated the value of 1169 kilograms per cubic meter. For Great Salt Lake the weight of water varies from 1105 to 1227 kilograms per cubic meter. The weight of ice per cubic meter varies from 916 to 921 kilograms.

* Annales de chemie et de physique, 1869, vol. 17, p. 370.

(Art. 4) Near the sea level the average reading of the mercury barometer is 76 centimeters, and since mercury weighs 13.6 grams per cubic centimeter, the average atmospheric pressure is taken to be $76 + 0.0136 = 1.0333$ kilograms per square centimeter. One atmosphere of pressure is therefore slightly greater than a pressure of one kilogram per square centimeter. Conversely, a pressure of one kilogram per square centimeter may be expressed as a pressure of 0.968 atmosphere. In a perfect vacuum water will rise to a height of about $10\frac{1}{3}$ meters under a mean pressure of one atmosphere, for the average specific gravity of mercury is 13.6, and $13.6 \times 0.76 = 10.33$ meters. Table 9*b* shows atmospheric pressures, altitudes, and boiling-points of water corresponding to heights of the mercury and water barometers.

TABLE 9*b*. ATMOSPHERIC PRESSURE

Metric Measures

Mercury Barometer Millimeters	Pressure Kilograms per Square Centimeter	Pressure Atmospheres	Water Barometer Meters	Elevations Meters	Boiling-point of Water Centigrade
790	1.074	1.04	10.74	− 325	101°.1
760	1.033	1.00	10.33	0	100 .0
730	0.992	0.96	9.92	+ 340	98 .9
700	.952	.92	9.52	690	97 .8
670	.911	.88	9.11	1045	96 .6
640	.870	.84	8.70	1420	95 .4
610	.829	.80	8.29	1820	94 .1
580	.788	.76	7.88	2240	92 .8
550	.748	.72	7.48	2680	91 .5
520	.707	.68	7.07	3140	90 .1

(Art. 5) If the weight of a cubic meter of water is 1000 kilograms at the surface of a pond, the weight of a cubic meter at a depth of $10\frac{1}{3}$ meters will be

$$1000\,(1 + 0.00005) = 1000.05 \text{ kilograms},$$

and at a depth of $103\frac{1}{3}$ meters a cubic meter will weigh

$$1000\,(1 + 0.0005) = 1000.5 \text{ kilograms}.$$

Hence the variation due to compression is too small to be generally taken into account. The modulus of elasticity of volume for water is

$$E = \frac{1.033}{0.00005} = 20\,700 \text{ kilograms per square centimeter},$$

while that of steel is about 2 100 000. Using $g = 9.8$ meters per second per second, the mean velocity of sound in water is

$$v = \sqrt{Eg/w} = 1420 \text{ meters per second}.$$

(Art. 6) The formula of Peirce for the acceleration of gravity on the earth's surface is

$$g = 9.78085\,(1 + 0.0052375 \sin^2 l)(1 - 0.000000314\,e) \qquad (9)_1$$

in which g is the acceleration in meters per second per second at a place whose latitude is l degrees and whose elevation is e meters above the sea level. The greatest value of g is at the sea level at the pole; here $l = 90°$ and $e = 0$, whence $g = 9.8322$. The least value of g in hydraulic practice is found on high lands at the equator; here $l = 0°$ and $e = 4000$ meters, whence $g = 9.7683$. The mean of these is 9.800, which closely agrees with that found in Art. 6, since 32.16 feet equals 9.802 meters; accordingly

$$g = 9.800 \text{ meters per second per second}$$

is the value of the acceleration that will be used in the metric work of this book. From this are found

$$\sqrt{2g} = 4.427 \qquad 1/2g = 0.05102 \qquad (9)_2$$

Table 9*c* gives multiples of these values which will often be of use in numerical computations.

TABLE 9*c*. ACCELERATION DUE TO GRAVITY

Metric Measures

No.	Multiples of g	Multiples of $2g$	Multiples of $1/2g$	Multiples of $\sqrt{2g}$	No.
1	9.800	19.60	0.05102	4.427	1
2	19.60	39.20	0.1020	8.854	2
3	29.40	58.80	0.1531	13.282	3
4	39.20	78.40	0.2041	17.71	4
5	49.00	98.00	0.2551	22.14	5
6	58.80	117.60	0.3061	26.56	6
7	68.60	137.2	0.3571	30.99	7
8	78.40	156.8	0.4082	35.42	8
9	88.20	176.4	0.4592	39.84	9
10	98.00	196.0	0.5102	44.27	10

(Art. 8) The remarks as to precision of numerical computation also apply here. Thus, if it be required to find the weight of water in a pipe 38 centimeters in diameter and 6 meters long, Table F gives 0.1134 square meter for the sectional area, the volume is then 0.6804 cubic meter, and the weight is 680 kilograms, the fourth figure being omitted because nothing is known about the temperature or purity of the water. In general, hydraulic computations are much easier in the metric than in the English system.

Prob. 9*a*. Compute the acceleration of gravity at Quito, Ecuador, which is in latitude $-0^\circ 13'$ and at an elevation of 2850 meters above sea level.

Prob. 9*b*. What is the pressure in kilograms per square centimeter at the base of a column of water 95.4 meters high?

Prob. 9*c*. Compute the velocity of sound in fresh distilled water at the temperature of 12° centigrade, and also its mean velocity in salt water.

Prob. 9*d*. How many cubic meters of water are contained in a pipe 315 meters long and 15 centimeters in diameter? How many kilograms? How many metric tons?

Prob. 9*e*. What is the boiling-point of water when the mercury barometer reads 735 millimeters? How high will water rise in a vacuum tube at a place where the boiling-point of water is 92° centigrade?

CHAPTER 2

HYDROSTATICS

Art. 10. Transmission of Pressure

One of the most remarkable properties of a fluid is its capacity of transmitting a pressure, applied at one point of the surface of a closed vessel, unchanged in intensity, in all directions, so that the effect of the applied pressure is to cause an equal force per square inch upon all parts of the enclosing surface. Pascal, in 1646, was the first to note that great forces could be produced in this manner; he saw that the total pressure increased proportionally with the area of the surface. Taking a closed barrel filled with water, he inserted a small vertical tube of considerable length tightly into it, and on filling the tube the barrel burst under the great pressure thus produced on its sides, although the weight of the water in the tube was quite small. The first diagram in Fig. 10*a* represents Pascal's barrel, and it is seen that the unit-pressure in the water at B is due to the head AB and independent of the size of the tube AC.

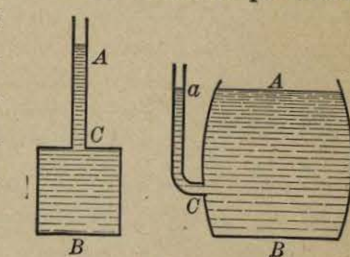

Fig. 10*a*.

Pascal clearly saw that this property of water could be employed in a useful manner in mechanics, but it was not until 1796 that Bramah built the first successful hydraulic press. This machine has two pistons of different sizes, and a force applied to the small piston is transmitted through the fluid and produces an equal unit-pressure at every point on the large piston. The applied force is here multiplied to any required extent, but the work performed by the large piston cannot exceed that imparted to the fluid by the small one. Let a and A be the areas of the