US Army Corps
of Engineers
North Central Division

Great Lakes Update

No. 111 October 4, 1994

Water Current Meters

(First of a Two Part Series)

Introduction

In 1992, in a series of two consecutive update articles (Nos. 84 and 85), the Corps provided insight on how flows are measured in the connecting channels of the Great Lakes and ›w the information is used. This ‹irst article, of two articles, is dedicated to the history of flow metering was practiced by the world's early hydraulic engineers.

Ancient Concepts

Although legends and archaeological investigations have extended our knowledge of man's involvement with flowing water farther into the past than has written history, one written record about it has survived from ancient times. It is in Section 53 of the famous Code of Hammurabi, said to have been written between 1955 and 1913 B.C.E. It contains the following regulation:

: anyone be too lazy to keep nis dam in proper condition, and does not keep it so: If then, the dam breaks and all the fields are flooded, then shall he in whose dam the break occurred be sold for money and the money shall replace the corn which he has caused to be ruined".

Ditches were the earliest structures devised for the control of water on the great floodplains of rivers like the Nile, Hwang-Ho (Yellow), Tigris-Euphrates, and Indus. They served two purposes: first, to drain off the excess water after floods, and second, to irrigate the crops during long dry periods.

Hero of Alexandria was a Greek mathematician and mechanician of the first century A.D. His accomplishments, too numerous to list here, are so impressive that he has been credited with having conceived almost every extraordinary mechanical device then existing. In his book, "Dioptra", he described a way to measure the discharge of a

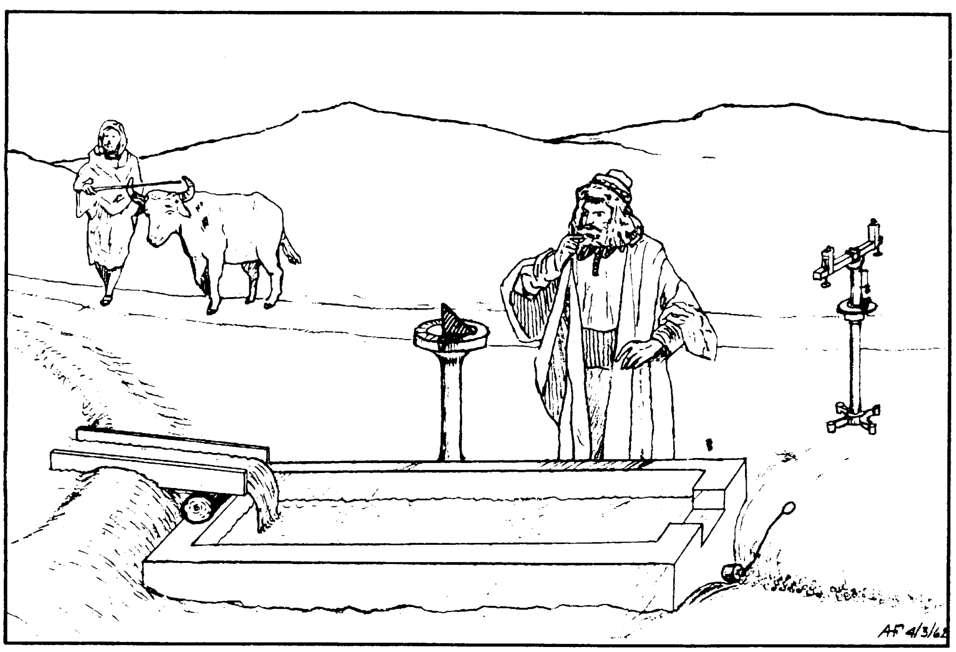

Figure 1. The world's first valid streamflow measurement as described by Hero of Alexandria, first century A.D. (***Drawn by A. H. Frazier***)

spring, which is now known as the volumetric method (Figure 1). This method which has never been surpassed in accuracy, is based on the concept that the area of a channel multiplied by the velocity of flow equals the amount of water passing a given point at a particular moment in time.

Free Floats

Philosophers of the Middle Ages contended that the water in rivers flowed much faster near the bottom than at the top. In support of that contention, they would point to the well known fact that if several holes were drilled in a large wooden tank filled with water, the velocity with which water emerged from the lower hole was always greater than that from any other holes. To them, the conditions prevailing in large water tanks and large rivers are identical, and they would condone no experimentation that would either confirm or deny any of their conclusions.

Leonardo da Vinci (1452 - 1519) was intensely curious about all aspects of nature. Among the more than 8,000 pages of notes still in existence on which da Vinci had written and drawn sketches, by far the greatest number of entries on any major subject therein, was concerned with hydraulics. His notebooks reveal the manner in which his experiments were made on the velocity distribution in rivers. The sketch and notes about the rod floats he prepared for that purpose appear in Figure 2 along with a recently-built replica of one of them. Figure 3 illustrates a conceptual drawing, showing da Vinci, conducting experiments on the velocity-distribution in streams.

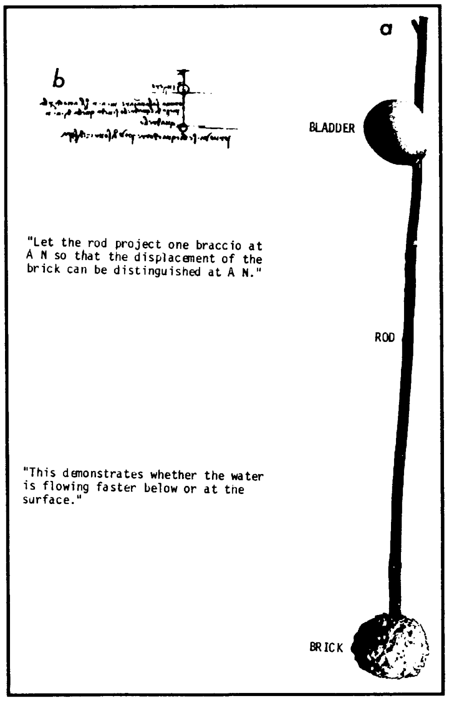

Figure 2. Leonardo da Vinci's rod float and notes. ***(From da Vinci's notes Manuscript "A", folio 42v.)***

Tethered Floats

The advent of "free" floats was followed by one that will called here, "tethered" flo because a major feature thereof consisted of a ball, generally heavier than water, to which a cord was attached to limit the distance that it would travel downstream. The use of such devices had been anticipated in the navigation field by an early "ship's log", a description of which appeared in a booklet entitled "Nuove Inventione di Camillo Agrippa" published in 1595. A portrait of Agrippa, his ship, and a close-up view of his invention appear in Figure 4.

Whether Domenico Guglielmini (1655 - 1710) had ever heard of Agrippa's "ship's log" is not known, but in his book, "Aquarium Fluentium Nc Methodo Inquisita", published 1690 and 1691, he described a velocity-measuring device called a "quadrant and ball", which

Figure 3. Leonardo da Vinci conducting experiments on the velocity-distribution in streams. ***(Drawn by A. H. Frazier.)***

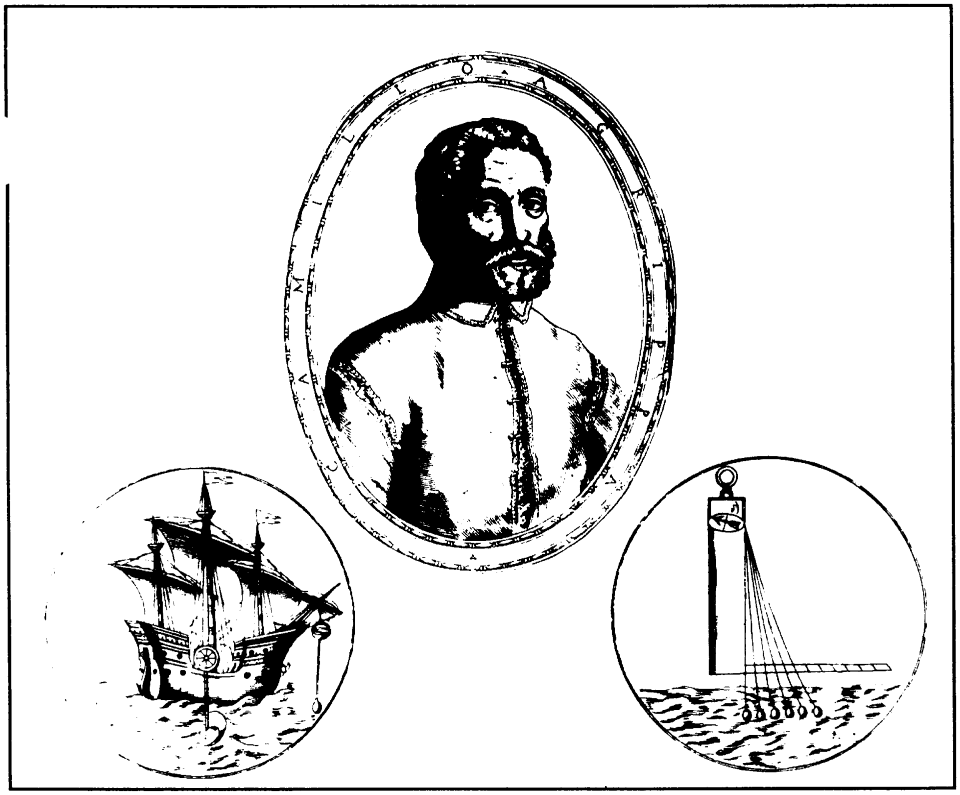

Figure 4. Camillo Agrippa, his ship, and ship's log, ca. 1595. ***(From Agrippa, Nuove Inventione.)***

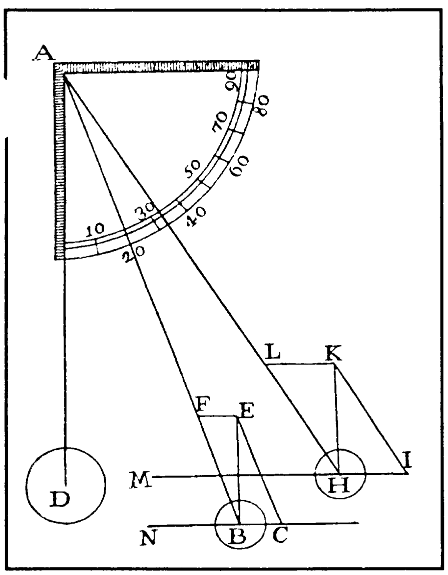

Figure 5. Guglielmini's "quadrant and ball", ca. 1690, with force diagrams. ***(From Guglielmini, Opera Omnia.)***

operated on exactly the same principle. Figure 5 shows two positions of the ball (as would be caused by two different veloc-ies), and force diagrams that he used for determining the proportions the two velocities bore to each other. While most of his work was quite sound, his quadrant and ball produced very misleading results particularly when used on deep swift rivers. Because of the great advances in hydraulics following the 17th century, most modern hydrographers are not likely to display as much enthusiasm for Guglielmini's work as did his contemporaries.

Paddles

Man's early use of crude paddles to help propel a log or craft across a stream obviously extends back to prehistoric times, and the principles learned on these occasions was ultimately applied to a considerable group of current meters. If a person sitting in a canoe heading upstream applies a backward force to the paddle, for example, the canoe will tend to move upstream, whereas if the person were sitting on the bank of the stream and held the paddle in the current, the paddle would tend to be pushed backward, or downstream. It is the latter effect that was ultimately adopted in the design of current meters for measuring the velocity of running water. The earliest record of a paddle-type current meter was that reported by Dr. Santorio Santorio (1561-1636). Figure 6 shows several of Dr. Santorio's inventions for measuring water and wind currents.

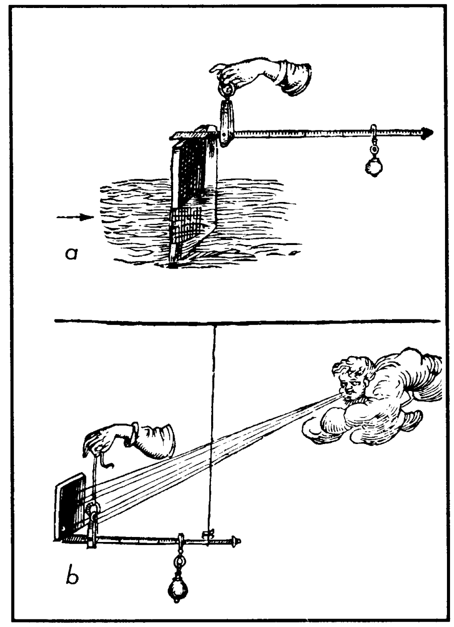

Figure 6. Santorio's inventions: a, water current meter; b, anemometer. ***(From Santorio, Commentaria)***

Paddle Wheels

The earliest paddle wheel to have been found which was built specifically for measuring the velocity of water flowing in open channels, was made by Luigi Ferdinando Marsili (1658 - 1730), sometimes spelled

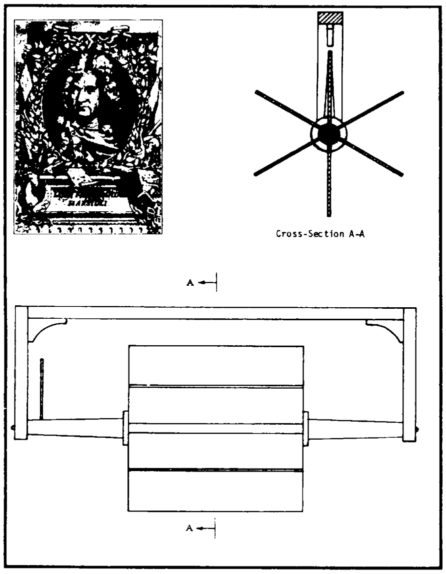

Figure 7. Marsili (Marsigli) and drawings of his current meter. ***(Portrait from Enciclopedia Italiana di Scienze; drawings from Milanese, "Santorio").***

Marsigli (Figure 7). He used it in 1681 for studying the velocities in the Bosphorus Straits between the Black Sea and the Sea of Marmara, and later on rivers in the Danube Valley. Many historic writers, obviously unaware of Marsili's earlier work, have credited Fransesco Domenico Michelotti (1710 - 1777), Professor of Mechanics at the University of Torino (Turin), with the invention of the paddle-wheel-type current meter. His two-volume work on hydraulics entitled "Sperimenti Idraulici" contains among its illustrations, the two shown in Figure 8.

During the 1700s, leadership in the field of hydraulics slowly shifted from Italy to France. Then, too, during that century mathematics had reached a stage where astute researchers could apply it to their hydraulic investigations. Prominent among those

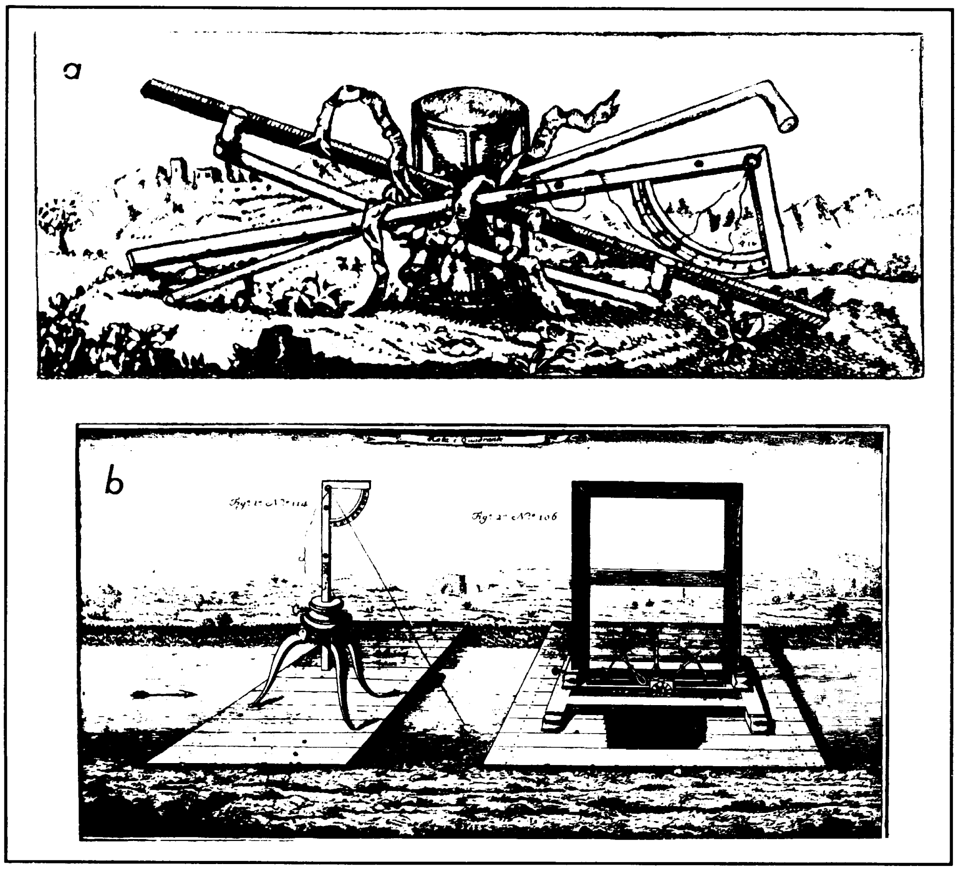

Figure 8. Stream-gaging equipment: a, ca. 1767; b, Michelotti's devices, ca. 1767. ***(From Michelotti, Sperimenti Idraulici).***

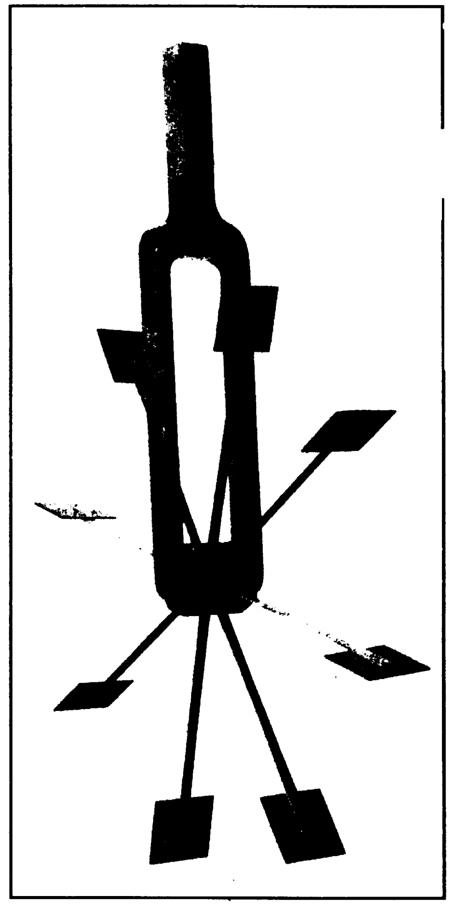

Figure 9. Replica of Dubuat's "moulinet" for measuring the surface velocities of water in rivers and canals, ca. 1780. ***(Photo by A. H. Frazier).***

who made use of both laboratory and mathematical facilities was Pierre Louis Georges Dubuat (1734 - 1809), a lieutenant in France's Royal Corps of Engineers. Dubuat's most important laboratory facility for measuring surface velocities consisted of a wooden paddle wheel (Figure 9). A replica of this paddle wheel is in the Smithsonian collection.

The obituary of Sir David Brewster (1781 - 1868) that appeared in the 11 April 1868 issue of Harper's Weekly, described him as "one of the greatest philosophers of our age". No doubt the major triump'

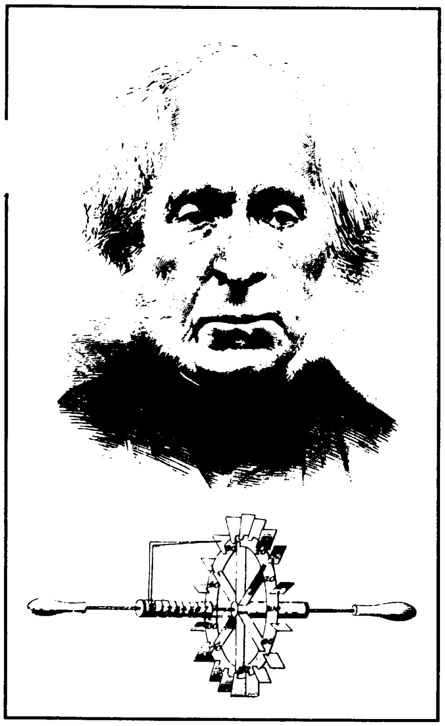

Figure 10. Sir David Brewster and his paddle wheel type meter. ***(Harper's Weekly, 11 April 1868; Ferguson, Lectures on Select Subjects.)***

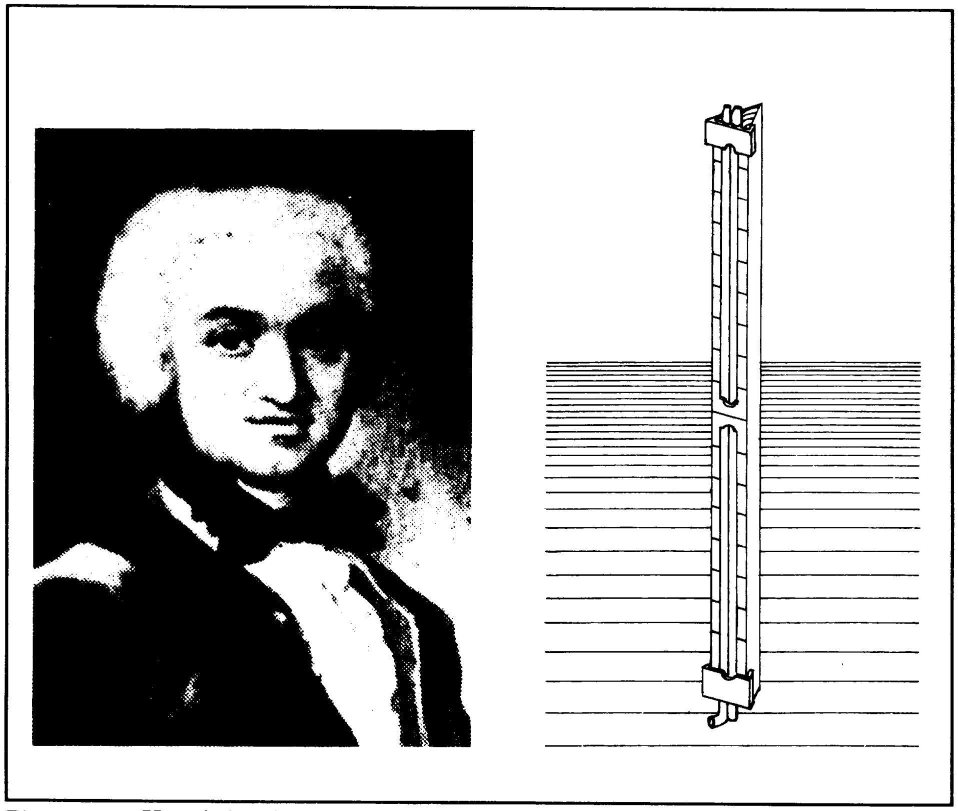

Figure 11. Henri de Pitot and his tube. ***(Portrait from Rouse and Ince,* History of Hydraulics; *sketch by A. H. Frazier.)***

nong his many literary accom- shments was his 22-year editorship of the monumental Edinburgh Encyclopaedia. That encyclopaedia has special significance in this article because its Volume 10 contains, under the heading "Hydrodynamics", the most comprehensive and learned historical review of that subject to have been written up to 1832, the time of its publication. The third edition of James Ferguson's multivolume work, entitled "Lectures on Select Subjects....", contains the earliest description and illustration of Brewster's paddle wheel current meter (Figure 10). To measure the velocity of water, this meter was held so that just the lowermost paddles were completely nersed in the water while they ed directly into the current. The number of revolutions could be checked by counting the number of threads which the wheel had advanced along the threaded axle.

Tubes

The Pitot Tube

During the two thousand years between 300 B.C.E. and A.D. 1700, many studies were made on how to evaluate the flow of water through pipes, orifices, nozzles, etc., but it was not until near the end of that period that significant progress was made. In 1732, Henri de Pitot (1695 - 1771) (Figure 11) introduced his "tube" which, although it was especially intended for use in open channels, became useful in closed conduits. His paper thereon was presented before the French Academie Royale de Sciences, Paris, on 12 November 1732.

The original meter consisted merely of two slender glass tubes mounted side by side onto one of the three flat surfaces of a triangularly shaped wooden rod. The lower inch or two of the first tube was bent at 90 degrees to allow it to point directly upstream while the main portion thereof was held vertically. The second tube was straight throughout its entire length, with its lower end at the same level as the bent section of the first tube.

Water entering the open end of the bent tube would cause the column of water in that tube to rise above the level of water in

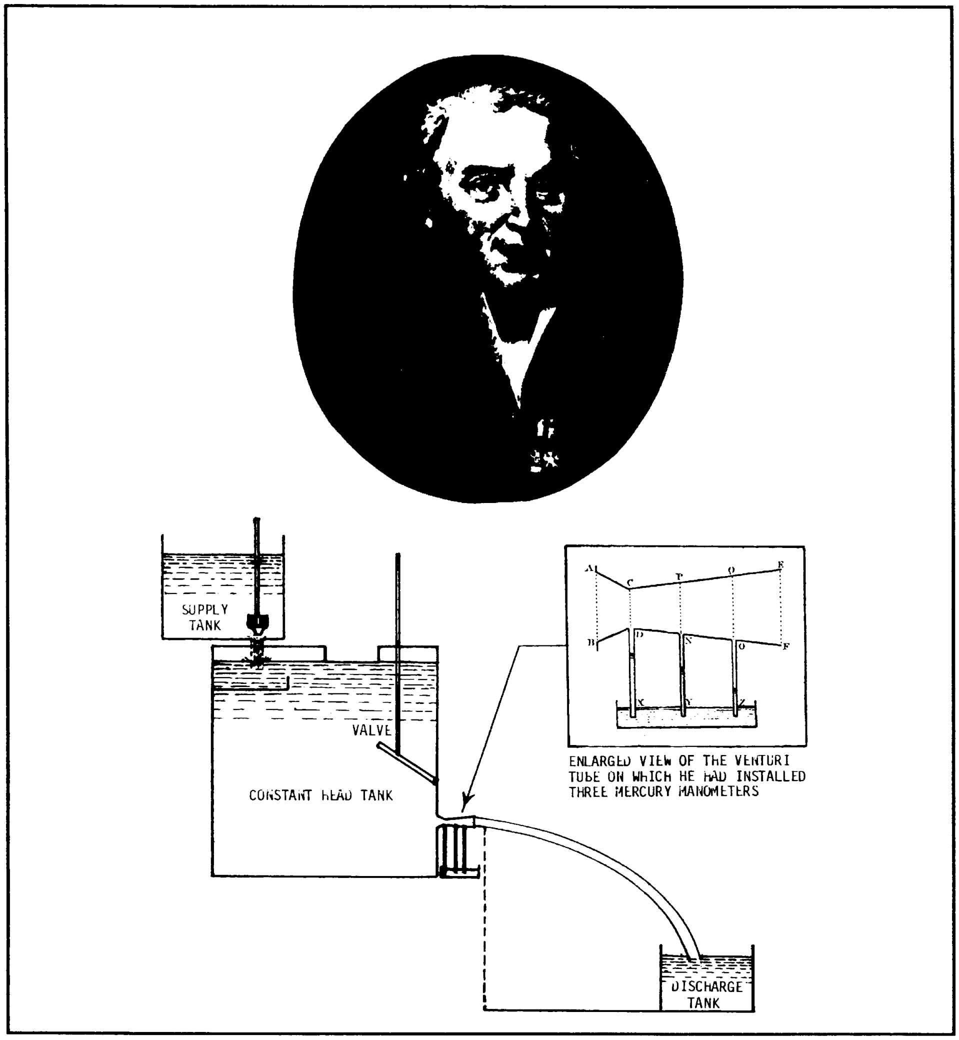

Figure 12. Schematic of equipment used to test Giovanni Battista Venturi's "Venturi tube" outlet. ***(Adapted from Venturi, "Experimental Inquiries.")***

the surrounding stream as a result of kinetic energy in that filament of water being converted into a pressure head. No corresponding rise would take place in the straight tube. The differences in the elevations of water in those two tubes accordingly became a function of the velocity of the oncoming water.

As is true of almost every invention, later experimenters attempted to improve on their predecessor's device. For example, Henri P.G. Darcy, circa 1858, replaced the straight tube with one where the lower end was bent 90 degrees in the downstream direction. This caused a draw-down to occur in the elevation of its column of water, thus doubling the reading made on the scale, and reducing the probable errors entering into such readings.

The Venturi Tube

In 1797, Giovanni Battista Venturi (1764 - 1822), Professor of Natural History at Modena, published two works, entitled "Essai sur les ouvrages physico-mathematiques de Leonardo da Vinci" and "Experimental Inquiries Concerning the Principle of Lateral Communication of Motion in Fluids" both originally in French. In 1837, the secc of Venturi's publications v translated into English by Thomas Tredgold, a civil engineer, in his "Tracts on Hydraulics". By means of laboratory equipment, such as previously designed by the Marquis Giovanni Poleni, Venturi studied the manner in which water emerged from a constantly filled tank through different types of outlets. One such outlet, to which he had attached three manometer tubes, is shown along with Venturi's portrait in Figure 12. This particular design of the tube bearing his name, allows any volume of water flowing through a conduit to be metered continuously without using instruments that would interfere with the flow.

Next month, in the concluding part of this series, innovations made by American scientists and engineers will be presented.

Acknowledgment

Many thanks to the Smithsonian Institution Press for their kind permission to use excerpts from their Smithsonian Studies in History and Technology Number 28 publication **"Water Current Meters"** by Arthur H. Frazier, Smithsonian Institution Press, Washington D.C., 1974.

RICHARD W. CRAIG
Colonel, EN
Commanding

Table 1

Possible Storm Induced Rises (in feet) at Key Locations on the Great Lakes
October 1994

Degrees of Possibility

	20%	10%	3%	2%	1%
LAKE SUPERIOR					
Duluth	0.7	0.9	1.0	1.1	1.2
Grand Marais	0.5	0.6	0.8	0.9	1.0
Marquette	0.9	1.0	1.2	1.3	1.4
Ontonagon	0.6	0.8	1.0	1.1	1.3
Point Iroquois	1.2	1.4	1.7	2.0	2.2
Two Harbors	0.6	0.7	0.8	0.9	1.0
LAKE MICHIGAN					
Calumet Harbor	1.3	1.6	2.1	2.4	2.8
Green Bay	1.9	2.2	2.5	2.8	3.0
Holland	0.7	0.8	0.9	0.9	1.0
Kewaunee	0.7	0.7	0.8	0.9	0.9
Ludington	0.7	0.8	0.9	1.0	1.1
Milwaukee	0.8	1.0	1.2	1.4	1.5
Port Inland	1.1	1.3	1.5	1.7	1.8
Sturgeon Bay	0.7	0.8	0.8	0.9	1.0
LAKE HURON					
Detour Village	0.5	0.6	0.7	0.7	0.8
Essexville	1.7	1.9	2.2	2.4	2.6
Harbor Beach	0.7	0.8	0.9	0.9	1.0
Harrisville	0.5	0.5	0.6	0.6	0.6
Lakeport	1.3	1.5	1.8	2.0	2.2
Mackinaw City	0.8	0.9	1.0	1.1	1.2
LAKE ST. CLAIR					
St. Clair Shores	0.4	0.5	0.5	0.6	0.7
LAKE ERIE *					
Barcelona	2.0	2.6	3.4	4.0	4.7
Buffalo	3.7	4.4	5.4	6.1	6.7
Cleveland	1.1	1.3	1.5	1.6	1.7
Erie	1.8	2.1	2.6	2.9	3.3
Fairport	0.9	1.0	1.2	1.4	1.6
Fermi Power Plant	1.6	1.9	2.1	2.3	2.5
Marblehead	1.3	1.6	2.0	2.3	2.7
Sturgeon Point	3.0	3.5	4.1	4.5	5.0
Toledo	2.4	2.8	3.4	3.8	4.2
LAKE ONTARIO					
Cape Vincent	0.8	0.9	1.0	1.1	1.2
Olcott	0.4	0.4	0.5	0.5	0.6
Oswego	0.7	0.8	0.9	0.9	1.0
Rochester	0.5	0.7	0.9	1.1	1.4

* The water surface of Lake Erie has the potential to tilt in strong winds, producing large differentials between the ends of the lake.

Note: The rises shown above, should they occur, would be in addition to the still water levels indicated on the Monthly Bulletin. Values of wave runup are not provided in this table.

Great Lakes Basin Hydrology

During the month of September precipitation on each of the Great Lakes basins was below average. For the year to date, precipitation on the entire Great Lakes basin has been about 3% above average. The net supply of water to Lakes Superior, Michigan-Huron and Ontario was above average, while that to Lake Erie was below average. Table 2 lists September precipit and water supply information for all of the Great Lakes.

In comparison to their long-term (1918-1993) averages, the September monthly mean water level of Lakes Superior, Michigan-Huron, St. Clair, Erie and Ontario were 1, 9, 12, 11 and 2 inches above average respectively. Shoreline residents are cautioned to be alert whenever adverse weather conditions exist, as these could cause rapid short-term rises in water levels. Should the lakes approach critically high levels, further information and advice will be provided by the Corps of Engineers.

TABLE 2
GREAT LAKES HYDROLOGY[1]

PRECIPITATION (INCHES)								
BASIN	SEPTEMBER				YEAR-TO-DATE			
	1994[2]	Average (1900-1991)	Diff.	% of Average	1994[2]	Average (1900-1991)	Diff.	% of Average
Superior	3.2	3.5	-0.3	91	22.7	23.0	-0.3	99
Michigan-Huron	2.6	3.5	-0.9	74	26.1	24.1	2.0	108
Erie	1.9	3.1	-1.2	61	25.4	26.7	-1.3	95
Ontario	2.4	3.2	-0.8	75	26.2	26.0	0.2	101
Great Lakes	2.7	3.4	-0.7	79	25.1	24.4	0.7	103

LAKE	SEPTEMBER WATER SUPPLIES[3] (CFS)		SEPTEMBER OUTFLOW[4] (CFS)	
	1994[2]	Average (1900-1989)	1994[2]	Average (1900-1989)
Superior	92,000	73,000	75,000	84,000
Michigan-Huron	51,000	31,000	202,000[5]	194,000
Erie	-36,000	-18,000	217,000[5]	203,000
Ontario	7,000	5,000	270,000	247,000

[1]Values (excluding averages) are based on preliminary computations.
[2]Estimated.
[3]Negative water supply denotes evaporation from lake exceeded runoff from local basin.
[4]Does not include diversions.
[5]Reflects effects of ice/weed retardation in the connecting channels.

CFS = cubic feet per second.

For Great Lakes basin technical assistance or information, please contact one of the following Corps of Engineers District Offices:

For NY, PA, and OH:
COL Walter C. Neitzke
Cdr, Buffalo District
U.S. Army Corps
of Engineers
1776 Niagara Street
Buffalo, NY 14207-3199
(716) 879-4200

For IL and IN:
LTC David M. Reed
Cdr, Chicago District
U.S. Army Corps
of Engineers
111 North Canal Street
Chicago, IL 60606-7206
(312) 353-6400

For MI, MN, and WI:
COL Randolph O. Buck
Cdr, Detroit District
U.S. Army Corps
of Engineers
P.O. Box 1027
Detroit, MI 48231-1027
(313) 226-6440 or 6441