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HYDROLOGIC ENGINEERING PRIOR TO 600 B. C.

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INTRODUCTION

When and where did the science of hydrology begin? It is difficult to answer, as the roots of modern hydrology lie deeply buried in antiquity. From the beginning, man realized that water is essential for survival, and hence it is not surprising to find that the earliest civilization grew up along the banks of rivers: the Tigris and the Euphrates in Mesopotamia, the Nile in Egypt, the Indus in India, and the Hwang-Ho in China. Gradually, they developed their water supply systems, constructed dams and levees, made channel improvements, and dug canals for irrigation. The presence of these structures proves that man had some knowledge of water, its powers and limitations—although it was admittedly not very scientific. The first hydrologic principles were extremely crude, but in the beginning man was only interested in controlling nature; and only later, during the Hellenic civilization[2] (around 600 B.C.), did he try to understand nature. It may be said that one can not treat a branch of science as such until a certain degree of development has taken place, but who will define and measure that degree? To paraphrase the great historian of science, George Sarton, a 2-in. high Sequoia gigantes may not be very conspicuous, but it is still a Sequoia. After all, when the first primitive mathematician realized that there was

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[2]Biswas, Asit K., "Hydrology During the Hellenic Civilization," Bulletin, International Association of Scientific Hydrology, Vol. 12, No. 1, Mar., 1967, pp. 5-14.

something similar in three palm trees and three donkeys, how abstract was his thought?

ANCIENT "HYDROLOGIC" WORKS

Three major civilizations that were flourishing some 4,000 years ago were those of the Egyptians in the Nile Valley, the Sumerians in Mesopotamia, and the Harappans in the Indus Valley. Much is known about the Egyptian

TABLE 1.—A CHRONOLOGY OF RECORDED HYDROLOGIC ENGINEERING PRIOR TO 600 B.C.[a]

Date	Event
3200 B.C.	Reign of King Scorpion; first recorded evidence of water resources work.
3000 B.C.	King Menes dammed the Nile and diverted its course.
3000 B.C.	Nilometers were used to record the rise of the Nile.
2850 B.C.	Failure of the Sadd el-Kafara dam.
2750 B.C.	Origin of the Indus Valley water supply and drainage systems.
2200 B.C.	Various waterworks of "The Great Yü" in China.
2000 B.C.	Water from spring was conveyed to Palace of Cnossos (Crete).
1900 B.C.	Sinnōr constructed at Gezer (Palestine).
1850 B.C.	Lake Moeris and other works of Pharaoh Amenmhet III.
1800 B.C.	Nilometers at Second Cataract in Semna.
1750 B.C.	Water codes of King Hammurabi.
1500 B.C.	Two springs joined by a sinnōr in the city of Tell Ta'annek in Palestine.
1300 B.C.	Irrigation and drainage systems of Nippur.
1050 B.C.	Water meters used at Oasis Gadames in North Africa.
750 B.C.	Marib and other dams on River Wadi Sadd in Yemen.
714 B.C.	Destruction of qanāt systems at Ulḫu (Armenia) by King Saragon II.
	Qanāt system gradually spread to Persia, Egypt, and India.
690 B.C.	Construction of Sennacherib's Channel.

[a] Note that in the absence of accurate information, most of the dates used are approximate.

and the Sumerian civilizations, but little about the Harappans; yet theirs embraced an area more extensive than either of the others. In contrast to the abundance of written records available of the Egyptians and the Sumerians, the history of the Harappans must be gleaned from the archaeological findings at Harappa and Mohenjo-daro, mainly because written records are scanty and are yet to be deciphered (the civilization was unearthed only in the 1920's). It has been argued recently that the Harappan civilization

came to an end in a catastrophic flood of the River Indus due to tectonic disturbances.[3]

There was a fourth civilization, that of the Chinese, which grew up on the river banks of China. All four civilizations had, in general, similar geographical conditions: they were based on major rivers, rainfalls were scanty, summer temperatures were high, and the phenomena of river rises were comparable. The presence of legendary characters and feats, however, makes the interpretation of the Chinese civilization difficult.

A brief review of the development of early hydrologic and hydraulic engineering around the world is presented herein, and a chronology of hydrologic engineering is shown in Table 1.

"KING SCORPION" AND KING MENES

Probably the earliest available record of hydrologic work is in the imperial macehead of the protodynastic "King Scorpion,"[4] who gets his name

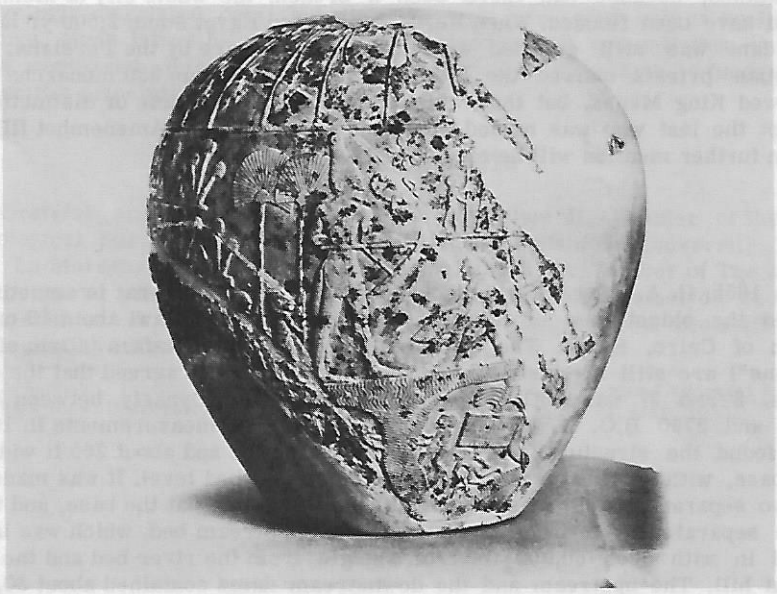


FIG. 1.—"KING SCORPION" CUTTING THE FIRST SOD OF AN IRRIGATION CANAL (Courtesy—Ashmolean Museum, Oxford)

from the scorpion in front of him (Fig. 1). He wears the white crown of Upper Egypt and is probably "cutting the first sod" of an irrigation canal. The ceremony of the inauguration of the inundation was still practiced during

[3] Dales, G. F., "The Decline of the Harappans," Scientific American, Vol. 214, No. 5, May, 1966, pp. 92-100.

[4] Drower, M. S., "Water-Supply, Irrigation, and Agriculture," A History of Technology, Charles Singer, E. J. Holmyard, and A. R. Hall, editors, Oxford University Press, London, 1954, Vol. 1, pp. 520-557.

the 19th century[5] at the festival of the "day of breaking the river." In front of the king is a man holding a basket (probably filled with seeds), and beyond him is another holding some ears of corn. Below the king are the workmen, giving final touches to the canal. He has a hoe in his hand, and is about three times larger than the men around him, which probably indicates his authority and power. The Pharaoh ruled sometime in the fourth millennium, probably around 3200 B.C. Little is known about this mysterious king with his characteristic scorpion and seven-petaled lotus sign.

King Menes, legendary first of the Pharaohs, ruled around 3000 B.C., and built his capital at Memphis. According to the historian Herodotus[6] he dammed the Nile about 12-1/2 miles south of Memphis, diverting the course of the river to a newly dug channel between two hills. The new capital of Memphis was then built on the old fertile river channel. Later, he excavated a lake outside the new town, to the north and west, and a canal was then dug to join the lake with the River Nile. The system of water-courses, viz., the lake, the canal, and the river, served as a moat to protect King Menes from his enemies. Consequently, the new dam had to be carefully guarded and maintained, because had there been a breach, the whole city of Memphis would have been flooded. When Herodotus visited Egypt some 2,500 yr later, the dam was still guarded with the greatest care by the Persians. The Egyptian priests showed the historian a list of some 330 monarchs who followed King Menes, but they were "personages of no note or distinction," except the last who was named Moeris (better known as Amenemhet III), of whom further mention will be made herein.

SADD EL-KAFARA DAM

In 1855, G. A. Schweinfurth discovered[7] the remains of what is sometimes called the oldest dam of the world, in the Wadi el-Garawi about 18 miles south of Cairo, Egypt. The abutments of the Sadd el-Kafara ("Dam of the Pagans") are still in existence, and it is now generally agreed that the dam (Figs. 2 and 3) was built during the 3rd or the 4th Dynasty, between 2950 B.C. and 2750 B.C. G. W. Murray[8] made detailed measurements in 1935, and found the structure was 348 ft long at the top and about 265 ft wide at the base, with its crest some 37 ft from the lowest bed level. It was made up of two separate rubble masonry dams, each 78 ft thick at the base, and they were separated by a space of 120 ft along the stream bed, which was later filled in with over 60,000 tons of shingle from the river bed and the adjacent hill. The upstream and the downstream dams contained about 30,000 cu yd of dry rubble masonry. The upstream face of the dam had a carefully placed covering of roughly dressed limestone blocks weighing about 50 lb each, in steps 11 in. high. Probably the engineer was pressed for time,

[5] Lane, E. W., Manners and Customs of the Modern Egyptians, ed. E. Rhys, Everyman's Library, J. M. Dent and Sons Ltd., London, 1908, Chap. 14.

[6] Herodotus, The History of Herodotus, translated by George Rawlinson, Great Books of the Western World, Encyclopaedia Brittanica, Inc., Vol. 6., Book 2, Chicago, 1952, pp. 68-69.

[7] Schweinfurth, G. A., Auf unbetretenen Wegen in Aegyten, Hoffmann und Campe, Hamburg, Germany, 1922, pp. 213-231.

[8] Murray, G. W., "Water from the Desert: Some Ancient Egyption Achievements," The Geographical Journal, Vol. 121, June, 1955, pp. 171-181.

FIG. 2.—SADD EL-KAFARA DAM (2800 B.C.) LOOKING DOWNSTREAM (Courtesy—Mrs. G. Murray)

FIG. 3.—FACING THE SADD EL-KAFARA DAM (Courtesy—Mrs. G. Murray)

as the downstream portion must have been hurriedly built; this would account for the shoddy workmanship of the downstream side compared to the upstream construction.

Two curious features of the dam were that there was no provision for a spillway (was the dam supposed to be a temporary structure?), and that no mortar was used in its construction. Schweinfurth believed that the dam had been constructed to provide drinking water for the workmen and beasts of an alabaster quarry located about two miles to the east, and hence its failure probably did not have catastrophic consequences. The capacity of the reservoir was only 460 acre ft, and the drainage area was 72 sq miles. Assuming that the climate of 5,000 yr ago was similar to what it is today (in fact Murray[9] has shown it to be so), the first heavy rains would have been enough to fill the reservoir and overtop the dam.[10]

Complete absence of sediments upstream of the dam probably indicates the dam had failed in its first flood season. Murray stated that "it is hard not to feel sympathy with the unknown engineer who so boldly attempted the impossible—for that age. His was as notable a failure as that of Brunel with his "Great Eastern" or that of Winstanley with the first Eddystone Lighthouse; but with a difference. The modern attempts were not absolute failures. They pointed the way for the successful designers of the next generation. But the Sadd el-Kafara is no landmark in the history of engineering. It was an outstanding solitary adventure which merely taught the ancient Egyptians never to attempt anything of the sort again. Its designer thought far ahead of his time. Had he made use of mortar, had he provided a spillway, had he chosen a wadi with a gentler slope, how different might have been the history of Egyptian irrigation!"[8]

YÜ, THE GREAT

According to Matschoss,[11] the legendary hero-emperor of China Yü, the Great, was asked by Emperor Yau to build great waterworks, dams and dikes around 2280 B.C. He studied the rivers, and showed genius in controlling them. He was instrumental in reclaiming much land and was said to have "mastered the waters." So impressive was his work that after the death of Emperor Shun, he became the new Emperor of China. In later times he became the patron of all hydraulic, irrigation, and water resources engineers. Even early in the 20th century prayers were offered to this great engineer-emperor everywhere in the river temples of China. Emperor Yü, as the eminent sinologist Joseph Needham has pointed out,[12] is a legendary character, and no one has any idea when exactly he lived—or indeed even whether he was a single historical person at all. Nor can one point to any specific hydraulic or hydrologic undertaking that can be attributed to the times of Yü. Anything to do with hydrologic engineering, in medieval China, was always

[9] Murray, G. W., "Desiccation in Egypt," Bulletin de la Société Royale de Géographie d'Egypte, Vol. XXIII, Nov., 1949.

[10] Hellström, B., "The Oldest Dam in the World," Bulletin No. 28, Institution of Hydraulics, Royal Institute of Technology, Stockholm, Sweden, 1951.

[11] Matschoss, C., Great Engineers, translated by H. S. Hatfield, G. Bell & Sons Ltd., London, 1939, p. 5.

[12] Needham, J., Science and Civilisation in China, Vol. 3, University Press, Cambridge, England, 1959, p. 515.

considered to be under the aegis of the great legendary imperial engineer. For example, Fig. 4 shows a diagrammatic chart of the river systems of West China,[12] from a printed work of 1160 A.D. which carries the name of Yü for the same reason.

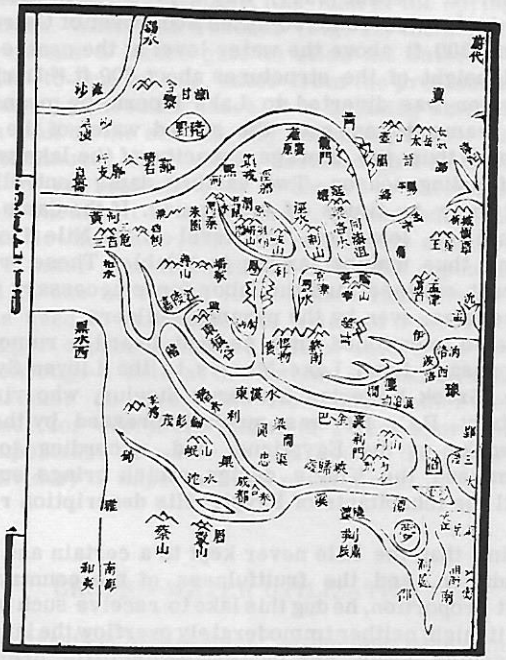


FIG. 4.—DIAGRAMMATIC CHART OF THE RIVER SYSTEMS OF WEST CHINA FROM FU YIN'S YÜ KUNG SHUO TUAN (Courtesy—Joseph Needham)

It must be pointed out that the Chinese classified their emperors into "good dynasty" or "bad dynasty" depending on whether they maintained their waterworks carefully or allowed them to fall into disrepair.[13]

PHARAOH AMENEMHET III

The Egyptians made great advances in water resources engineering during their Middle Kingdom (2160 B.C.—1788 B.C.). Artificial lakes were built to store the high flood flows of the Nile through canals,[14] and marshlands were drained. The most famous Pharaoh of this period was Amenemhet III (whom Herodotus described as King Moeris). He ruled for nearly 50 yr, and during his time hydraulic and hydrologic engineering rose to new heights.

[13] Brittain, R. E., Rivers, Man and Myths, From Fish Spears to Water Mills, Doubleday & Co., Inc., New York, N. Y., 1958, p. 59.

[14] Payne, R., The Canal Builders, The Macmillan Co., New York, N. Y., 1959, pp. 13-16.

Herodotus was much impressed by the artificial Lake Moeris—named after Amenemhet III—during his visit to Egypt in the fifth century B.C. This astonishing lake had a circumference of 450 miles, which is equal to the entire Egyptian coast line. Of elongated shape, the lake had an area of 656 sq miles, a capacity of 40,000,000 acre ft,[15] and its maximum depth was 50 fathoms. At present (1967), this depression is known as the province of Fayoum. It is located some 50 miles southwest of Cairo. There were two pyramids rising 300 ft above the water level at the centre of the lake, which made the total height of the structures about 600 ft.[16] During the high floods of the Nile, water was diverted to Lake Moeris by means of a canal. When the inundation came to an end, the stored water of the lake was returned to the Nile, and thus the storage capacity of the lake was made available for the next flooding season. Two earthen dams controlled the flow,[17] and they were cut only in times of emergency. If the dams were cut during a year of normal or low flow, the level of the Nile dropped substantially in Lower Egypt, thus making famine inevitable. These breaches were later repaired at great expense, and the labor force necessary for such work was considered excessive, even by the pyramid builders.

Herodotus also mentioned that he had heard a rumor that there was a subterranean passage from Lake Moeris to the Libyan Syrtis. This is confirmed by the Greek historian Diodorus Siculus, who visited Egypt during the first century B.C. He was much impressed by the water resources development works of the Egyptians, and, according to him, "no one can adequately commend the King's design, which brings such usefulness and advantage to all the inhabitants of Egypt." His description reads:

> "For being that the Nile never kept to a certain and constant height in its inundation, and the fruitfulness of the country ever depended upon its just proportion, he dug this lake to receive such water as superfluous, that it might neither immoderately overflow the land, and so cause fens and standing ponds, nor by flowing too little, prejudice the fruits of the earth for want of water. To this end he cut a trench along from the river into the lake, fourscore furlongs in length, and three hundred feet broad; into this he let water of the river sometimes run, and at other times diverted it, and turned it over the fields of the husbandmen, at seasonable times, by means of sluices which he sometimes opened, and at other times shut up, not without great labour and cost; for these sluices could not be opened or shut at a less charge than 50 talents. This lake continues to the benefit of the Egyptians for these purposes to our very day, and is called lake of Myris or Meris to this day." [18]

Talent was the largest unit of weight used to weigh gold, silver, iron, and bronze. Two types of talents were in use, light and heavy, weighing about 28.53 kg and 59 kg, respectively. Thus the charge for operating the sluice

[15] Hathaway, G. A., "Dams—Their Effect on some Ancient Civilizations," Civil Engineering, ASCE, Vol. 28, Jan., 1958, pp. 58-63.

[16] Herodotus, op. cit., p. 81.

[17] Willcocks, W., From the Garden of Eden to the Crossing of the Jordan, 2nd ed., E. & F. N. Spon Ltd., London, England, 1926.

[18] Diodorus Siculus, The Historical Library of Diodorus, the Sicilian, translated by G. Booth, J. Davis, London, Vol. 1, 1814, p. 57.

gate was exceedingly high although it must be admitted that Diodorus is not a very reliable historian. The geographer Strabo, however, confirmed the description of the complex around 20 B.C. He saw the canal, and made careful observations of the sluice gate which controlled both inflow and outflow—but unfortunately he forgot to describe them!

It is likely that the canal, Lake Moeris, and the nearby labyrinth were the work of several Pharaohs, and that they were only completed during the reign of Amenemhet III. The world according to Herodotus is shown in Fig. 5; he was wrong about the direction of the Nile.

C. Herschel, in his translation of Frontinus' book[19] on the water supply of the city Rome, contended that the Romans knew little more than the fact that water flows downhill. The Egyptians were aware of the principle many centuries before. During the latter half of the 14th century B.C., King Akhenaten built a dream city on the existing wasteland on the eastern

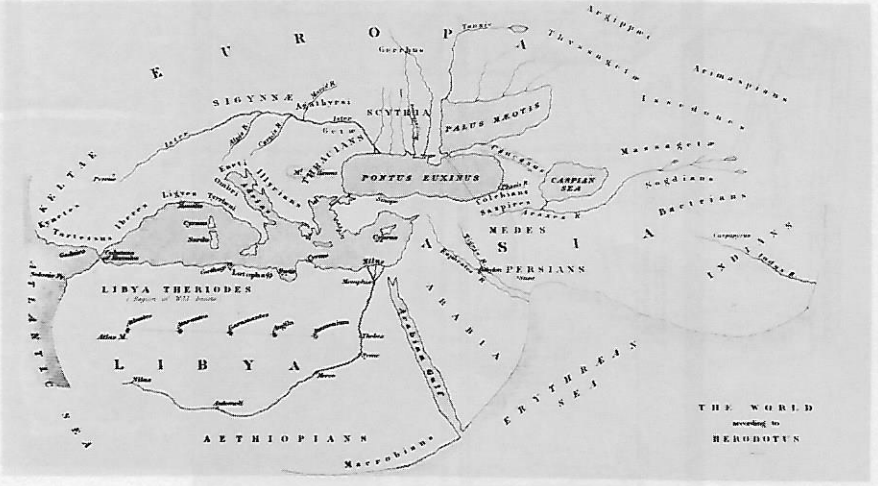


FIG. 5.—THE WORLD ACCORDING TO HERODOTUS

bank of the Nile near Deir Mawas (present Tell el Amarna), and called it Akhetaten, "the horizon of the Aten." The king hoped that the city would exist "until the swan grows black and the raven becomes white, until the mountains rise up to walk and the waters flow uphill."[20]

NILOMETERS

As the name indicates, the nilometer is used to measure the levels of the Nile. Since survival of the Egyptians practically depended on the annual inundation of the river, this was considered to be the most important event

[19] Herschel, C., Frontinus and the Water Supply of the City of Rome, Dana Estes & Co., Boston, Mass., 1899.

[20] Noblecourt, C. D., "Tutankhamen's Golden Trove," National Geographic Magazine, Vol. 124, No. 4, Oct., 1963, pp. 625-646.

of the year, and the maximum levels were noted at several nilometers. This is a form of quantitative measurement of the river flow—probably the earliest in history. The levels were marked at several places, on the walls of a quay or outer wall of a temple on the river bank, all the way up to the First Cataract. Nilometers may be as old as the invention of writing,[4] and one of the earlier ones was probably on Roda Island (Fig. 6). No less than 179 distinct engravings have been found in a section of the Second Cataract at Semna which dates back to the 12th Dynasty (1750-1800 B.C.), or earlier.[21] Records of Nile levels can be traced back to about 3000-3500 B.C. from the fragments of an ancient monument now in Palermo Museum, Sicily. But most of the nilometers now extant were of the Persian, Ptolemaic, and Roman Periods.[22]

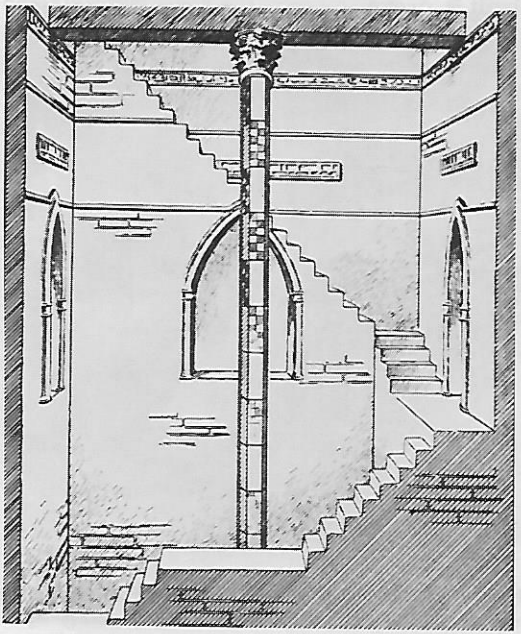


FIG. 6.—THE RODA NILOMETER IN 1798 A.D., A RECONSTRUCTION FROM DESCRIPTIONS (Courtesy—University of California Press)

The Egyptians depended on the regular inundation of the Nile for their livelihood, but the river in a high flood was entirely another question. It then turned from creation to destruction, and one such flood recorded in 638 B.C. turned the whole valley into "a primordial ocean, and inert expanse." Since the Egyptians repeatedly had to face the problem of serious

[21] Biswas Asit K., "The Nile: Its Origin and Rise," Water and Sewage Works, Vol. 113, No. 8, Aug., 1966, pp. 282-292.

[22] Borchardt, L., "Nilmesser v Nilstandsmarken," Preussichen Akademie der Wissenschaften, Phil.-Hist., Abh. nict zur Akad. gehor. Gelehrter, No. 1, Berlin, Germany, 1906.

flooding, they gradually developed a system of flood warning encompassing the various temples and their nilometers. At present, little evidence is available of actual technical co-operation between the temples,[23] but according to Diodorus[24] flood warnings were sounded to the population from the nilometer at Memphis in case of emergency. With the approach of the flood season, the levels of the Nile were carefully watched and compared with the markings of the previous year. Swift rowers were sent from the furthest upstream of the gaging stations, one after another, to report the latest level at the capital. These extremely good rowers, rowing with the current, were able to outpace the approaching peak flood and give sufficient advance warning to the townspeople of the forthcoming catastrophe.

Diodorus reports that "out of the fear of inundation, a watch-tower is built in Memphis, by the Kings of Egypt, where those who are employed to take care of this concern, observing to what height the river rises, send letters from one city to another, acquainting them how many cubits and fingers the river rises, and when it begins to decreases; and so the people, coming to understand the fall of the waters, are freed from their fears, . . . and this observation has been registered from time to time by the Egyptians for many generations."[24]

The flood observations continued without a break even during major religious or political upheavals. F. E. Engreen believes[25] that an interrelation developed between the observations of the Nile flood and the cult of the god Serapis. He quotes Rufinus' statement on the nilometer in the Serapeum at Alexandria in support of his theory: "But as it was common use in Egypt, that the measuring of the river Nile during its rise was reported to the temple of Serapis, reported, as it were, to the originator of the increased waters and inundations."[25]

The various concepts of the origin and rise of the River Nile, as well as nilometers, have been considered by the wirter in greater detail elsewhere.[21]

UR BABYLONIAN TABLET

The Old Babylonian cuneiform test shown in Fig. 7, at present in the British Museum, has many problems with solutions on both sides of the tablet. The side shown has 16 problems on dams, walls, wells, waterclocks, and excavations. There is no information on the precise provenance of this Ur Babylonian tablet, BM 85194, but its date can roughly be said to be 18th century B.C.

Part of the fourth problem, illustrated by a drawing, requires the construction of a dike profile in the form of an isosceles trapezoid.[26,27] The

[23] Otto, W., Priester und Tempel im Hellenistichen Aegypten, Leipzig-Berlin, Germany, 1905-1908, Vol. 1, pp. 22, 43-44; Vol. 2, pp. 311-313.

[24] Diodorus Siculus, op. cit., p. 42.

[25] Engreen, F. E., "The Nilometer in the Serapeum at Alexandria," Medievalia et Humanistica, 1943, pp. 3-13.

[26] Waerden, B. L. V. D., Science Awakening, translated by A. Dresden, P. Noordhoff Ltd., Groningen, Netherlands, 1954, p. 68.

[27] Neugebauer, O., and Sachs, A., Jr., Mathematical Cuneiform Texts, American Oriental Society and American Schools of Oriental Research, New Haven, Conn., 1945, pp. 96-97.

base b, inclination α, and area A, are given (Fig. 8), and the top width a is to be calculated. It actually calculates a^2 from

$$a^2 = b^2 - 4\,\alpha\,A \quad (1)$$

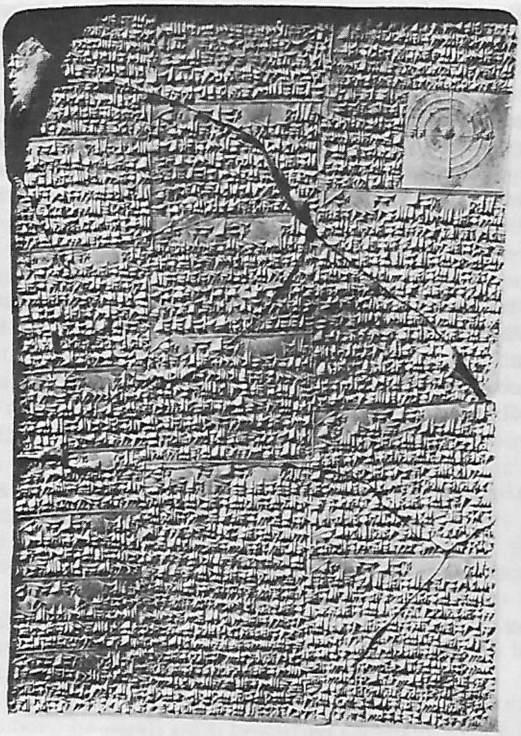


FIG. 7.—PART OF UR BABYLONIAN TABLET, 1800 B. C. (Courtesy—Trustees of the British Museum)

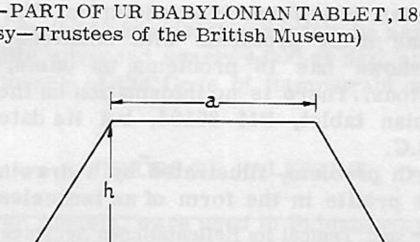


FIG. 8.—CONSTRUCTION OF A DIKE PROFILE, 1800 B. C.

This is correct, as

$$\alpha = \frac{b - a}{2h} \quad (2)$$

and $A = \left(\frac{b + a}{2}\right) h$ ..... (3)

Hence, $4 \alpha A = b^2 - a^2$ ..... (4)

In another problem in the same text, a is known, and b is calculated from Eq. 1.

CODE OF HAMMURABI

King Hammurabi, the self-styled "obedient and god-fearing prince," conquered Mesopotamia around 1760 B.C. He was the sixth and the greatest

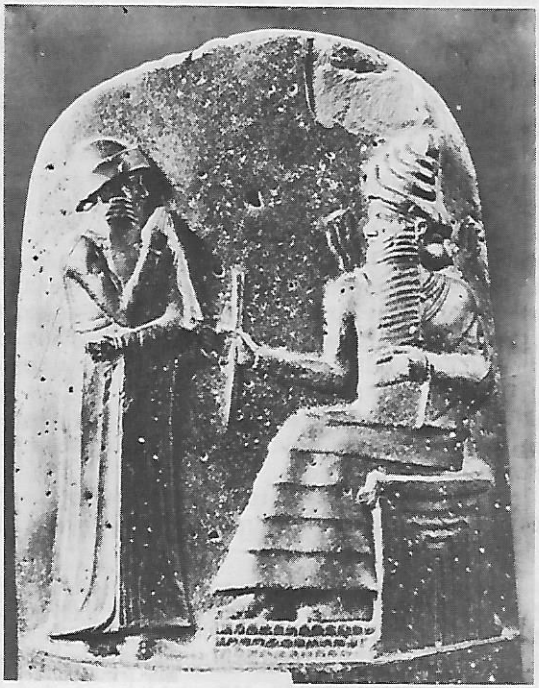


FIG. 9.—PART OF THE CODE OF HAMMURABI IN THE LOUVRE MUSEUM

King of the 1st (Amorite) Dynasty of Babylon, and was aware of the necessity of having a good network of canals for irrigation as well as for communication and transportation. Unlike the Egyptians with the Nile, the Sumerians had two extremely unpredictable rivers in the Tigris and Euphrates. Flooding was a constant danger, and if it occurred simultaneously in both rivers, it brought untold misery. The story of Noah comes from the legendary greatest flood of the Sumerians,[28] and hence it is no surprise to

[28] Kazmann, R. G., Modern Hydrology, Harper and Row, Inc., New York, N. Y., 1965, pp. 1-20.

find the art of building flood protection works, like earthen walls or levees, was quite well developed during this period.

The rulers of this period were as much interested in their hydraulic works as in their conquests, and justifiably so. According to Sarton,[29] traces of their early canals can still be seen from the air. The documentary evidence available at present (1967) indicates that King Hammurabi often directed his provincial governers to dig canals as well as to dredge them regularly. In a memorandum to one Sid-idinnam, the King complained that a canal was so imperfectly dug that the boat could not enter Erech, and also the canal needed repairing near the banks of the Druru. He ordered the official to rectify the defect within three days of receipt of his writing, using the men at his disposal. Thus, with the gradual political integration of the country, there was a strong centralized control of water.

The famous Code of Hammurabi is the most complete codification of Sumerian and Babylonian law. It was discovered in Susa in 1901 by the French Assyriologist Jean Vincent Scheil, and is at present in the Louvre Museum in Paris. Fig. 9 shows the top part of the Code of Hammurabi, depicting the King as either being charged by Shamash (Sun God) to write his code, or else as offering it to the Sun God. The laws concerning irrigation were carefully contrived, and it seems that they were primarily aimed at preventing flood damages due to negligence, as will be clear from the following excerpts.

> "Sec. 53. If any one be too lazy to keep his 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.
>
> Sec. 55. If any one open his ditches to water his crop, but is careless, and the water flood the field of his neighbor, then he shall repay his neighbor with corn for his loss.
>
> Sec. 56. If a man let out the water, and the water overflow the land of his neighbor, he shall pay 10 gur of corn for every 10 gan of land flooded."[30]

In the absence of further records, it can safely be assumed that hydrologic engineering was quite advanced nearly 4,000 yr ago, and that even today one can detect the influence of the Code of Hammurabi on modern water laws.

SINNŌRS OF PALESTINE

Sinnōrs, or water tunnels, were used in Palestine prior to 1200 B.C. The cities in Palestine and Syria were usually built on the tops of hills, having their stream for water supply at the bottom. Thus, during times of war, cities were rather vulnerable as invaders could easily cut the water off from the city. To protect the city, first a tunnel was dug, of which one end had

[29] Sarton, G. A History of Science: Ancient Science Through the Golden Age of Greece, Harvard University Press, Cambridge, Mass., 1959, p. 79.

[30] Butler, M. A., "Irrigation in Persia by Kanats," Civil Engineering, ASCE, Vol. 3, No. 2, Feb., 1933, pp. 69-73.

a secret approach to the stream and the other was within the city boundary. The entrance to the sinnōr was by a shaft, with a flight of stairs. Later, a conduit on the floor of the tunnel was used to bring water from the spring to the foot of the shaft.[31]

EVIDENCE AT NIPPUR

Around 1300 B.C., Nippur in Mesopotamia was one of the most famous centers of Sumerian religion, and recently American archaeologists have excavated thousands of tablets at the site. Most of these tablets were unbaked, and hence they are not well preserved, as well as being more difficult

FIG. 10.—MAP OF IRRIGATION SYSTEM NEAR NIPPUR, MESOPOTAMIA, AROUND 1300 B.C. (Courtesy—University of Pennsylvania Museum)

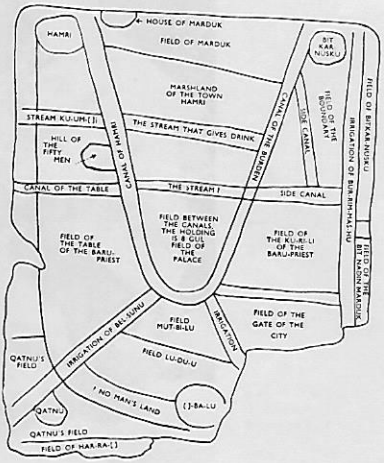


FIG. 11.—TRANSLATION OF THE CUNEIFORM TEXT

to decipher. Some of the maps excavated at Nippur were so faithfully made that the archaeologists even continued the excavations with their help.

Fig. 10 is a map of fields and canals found at Nippur, and the cuneiform captions have been translated in Fig. 11. Probably "Canal of Hamri" was the main canal, and water entered it during the river's periods of high flow. It is likely that channels marked 'irrigation' or 'canal' were meant for irrigation, whereas those marked 'stream' could have been drainage ditches. It is interesting to note the designation "Marshland of the town of Hamri," where in all probability cane-read was cultivated. Since the country was almost treeless, reeds were used for everything—building, basketry, furniture, and firewood. Reed-matting was used to strengthen the dikes by

[31] Forbes, R. J., Studies in Ancient Technology, Vol. 1, E. J. Brill, Leiden, Netherlands, 1955, p. 151.

protecting the alluvial soil. The drainage ditches were perhaps used to get the water out of the cultivated areas during periods of low flow.

The fields not marked were either common lands for grazing or in the process of changing hands.

WATER METERS

A primitive water meter was first used in the Gadames oasis of North Africa more than 3,000 yr ago,[32,33,34] and it is still being used without any modification. The oasis contains a small spring called Ain el Fras "(Spring

FIG. 12.—PRIMITIVE WATER METER AS USED IN OASIS GADAMES, STILL BEING USED WITHOUT MODIFICATION

of the Mare") which, according to legend, was discovered by a horse of an Arabian conqueror. The stream has a discharge of around 180 cu m per hr, which is collected in a basin and distributed through a main canal and two side canals. The process was developed for proper distribution of irrigation

[32]Richardson, C. G., "The Measurement of Flowing Water," Water and Sewage Works, Sept., 1955, pp. 379-385.

[33]Schaak, M., "Hundert Jahre Wassermessung," Neue Deliwa Zeitschrift zur Forderung des Gas-,Wasser- und Elektrizitatsfaches, Hanover, Germany, Vol. 1. No. 5, May, 1953, pp. 132-135.

[34]Committee 861DD, "Water Meters—Selection, Installation, Testing, and Maintenance: Chapter 1, Early History of Water Measurement and the Development of Meters," Journal, American Water Works Association, Vol. 51, No. 6, June, 1959, pp. 791-799.

water from the stream to the various agricultural fields.

A container with a hole at the bottom is lowered into the water and is pulled up when filled by means of a rope. The water runs out through the hole and the pot is emptied in 3 min. The water commissioner decides the number of pots of water each field should receive. Once the share of a particular land proprietor is complete, the man at the spring drops a piece of straw in the drain. When this reaches (Fig. 12) the next field to be irrigated, the owner opens a sluice gate to allow the water to enter his field, and closes another to cut off the water from the previous land, which will by then already have received its share. It is amazing that for over 3,000 yr there is always a man by the stream, day and night, to see that the distribution of water is continuous. The water allocated to a field depends directly on its size, and every resident gets a chance to water his field every 12 days, regardless of whether it is day or night. Undoubtedly it is a crude form of measurement of flowing water, but it is reasonably effective all the same.

Another type of water meter, which is exactly the opposite of the one described, has been in use in Yemen for a considerable time.[35] In this case a "floating clock" is used to distribute the water of a stream. A copper bowl is placed in a bigger copper container full of water. The bowl is gradually filled with water through a hole at the bottom; it sinks in 5 min., which is a signal for the farmer to divert the flow into another field. The bowl is allowed to sink once for every 100 lubnah (2/3 acre approximately) of land. Because of the importance of water in the desert, the job of Muqassim ad-dayri (the water-divider) is important and prestigious.

GROUND-WATER UTILIZATION

Undoubtedly the greatest achievement of ancient times, in the utilization of ground water, was the building of qanāts (or kanāts). The qanāt is an artificial underground channel which carries water over long distances either from a spring or from water-bearing strata, and it solved several problems in water resources engineering. First, evaporation was undoubtedly a major problem in hot and arid climates, and hence, with the limited water supply, surface transport was a distinct hazard. Secondly, it was difficult to maintain a regular slope in hilly country; and finally, qanāts kept water cool and pollution free. Fig. 13 is an aerial photograph of qanāt systems originating in the talus deposits at the foot of the mountain near Kashan in Iran.

Contrary to present belief, qanāt building probably started in Armenia[31,36] and not in Persia. In his invasion of Urartu (present Armenia), King Saragon II (721-705 B.C.) of Assyria destroyed the irrigation network of the town of Ulhu. He described the irrigation system of the vanquished King of Ulḫu in these terms: "Following his ingenious inspiration Urŝa, their King and Lord. . . revealed the water outlets. He dug a main duct which carried flowing waters. . . waters of abundance he caused to flow like the Euphrates. Countless ditches he led out from its interior . . . and he irri-

[35] Abercrombie, T. J., "Behind the Veil of Troubled Yemen," National Geographic Magazine, Vol. 125, No. 3, Mar., 1964, p. 423.

[36] Lehmann-Haupt, C. F., Armenien einst und jetzt, Vol. II, B. Behr, Berlin, Germany, 1910, p. 111.

gated the fields."[37] This indicates that the concept of qanāt came from the Armenians.

The construction of this remarkable system, which according to C. F. Tolman[38] was "the greatest waterworks of the ancients," was directed by an engineer called Mukanni. He first found out the water-bearing strata by digging a number of test wells, and when a good stratum was hit, a mother well was dug. Another well was dug some distance away, usually about equal to the depth of the well, and the two wells were joined by a tunnel. By this procedure the construction continued. The direction and depth of the tunnel was found by a crude but adequate system of plumb bobs.

Fig. 14 shows a typical water supply system by qanāts; the cross section was somewhat egg-shaped. Since the Persians rarely dug through rock, the routes of the qanāts had numerous twists and turns, and large deviations

FIG. 13.—AERIAL PHOTOGRAPH OF QANĀT SYSTEMS IN PERSIA

were also made for hills. Only one man could dig at one time, and the excavated material was taken out in a goat-skin bag through vertical air-shafts, and, if necessary (depending on the soil conditions), lining materials were carried in it on the return journey. As reflected light was used for digging, and working conditions were rather grim, one would expect that accidents were rather common and loss of lives frequent.

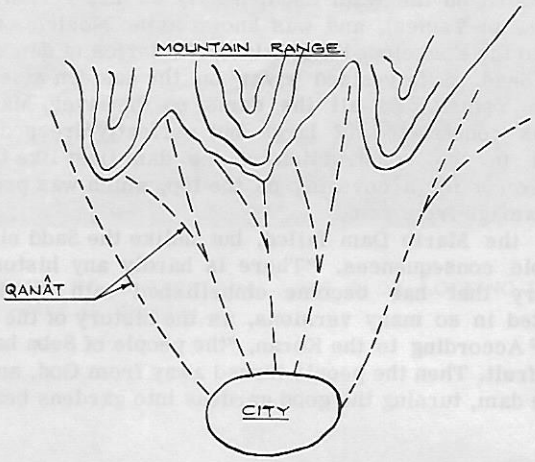
South of Dizful in Persia is one of the old qanāt systems, which consists of three pairs of tunnels taking water from the gravel bars near the River Ab-i-diz, about seven miles north of Dizful. Two pairs of qanāts supply water to the neighboring land for agriculture, and the remaining pair supplies

[37] Lassøe, J., "The Irrigation System at Ulḫu," Journal of Cuneiform Studies, Vol. 5, No. 1, 1951, pp. 21-32.

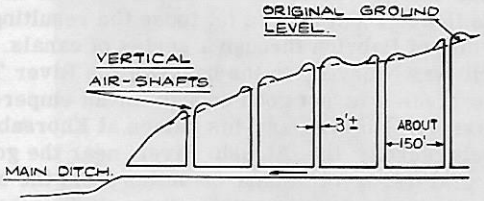
[38] Tolman, C. F., Ground Water, McGraw-Hill Book Co., Inc., New York, N. Y., 1937, pp. 1-25.

the city. These qanāts are at such a depth that some houses in the city go down six stories under the ground to tap the water.

During the time of Darius I (521-485 B.C.), his Caryandan Admiral Scylox went to the oasis of El Khargeh[39] in Egypt and introduced the qanāt system of irrigation. Investigations have been made in recent times, but the length of these qanāts is still unknown. Butler believes[20] that they must extend far enough eastward—in fact over a hundred miles of rolling desert—



a. A TYPICAL QANÂT LAYOUT FOR WATER SUPPLY.



b. LONGITUDINAL SECTION OF A QANÂT

c. CROSS-SECTION

FIG. 14.—DETAILS OF QANĀT SYSTEMS (NOT TO SCALE)

to intercept the seepage from the Nile, as the locality itself is practically rainless.

Use of these long infiltration galleries to tap ground water from soft sedimentary rocks or alluvial fan deposits soon spread from Armenia to as far as Northern India.

The qanāt used the principle of gravity flow. Its average length in desert regions was 25 to 28 miles. It had a gentle slope of 1 to 3 on 100, and in some

[39] Caton-Thompson, G., and Gardner, E. W., "The Prehistoric Geography of Kharga Oasis," Geographical Journal, Vol. 80, 1932, pp. 369-409.

places was at a depth of nearly 400 ft[40]—considering the state of knowledge during the period in question, it was no mean achievement.

MARIB DAM

The Marib dam, which was probably constructed somewhere between 1000 and 700 B.C., was considered to be one of the wonders of the ancient world.[41] It was located on the Wadi Sadd, nearly 40 miles from the ancient city of Marib (now in Yemen), and was known to the Moslems as Sudd-el-Arim. According to the Encyclopedia of Islam,[42] a series of dams controlled the River Wadi Saad, a fair-sized river on the eastern side of the high mountain range in Yemen.[15] Of all the dams on the river, Marib was the largest and it was constructed of large but perfectly dressed stones. No mortar was used in the construction of the dam (just like the ill-fated Sadd el-Kafara), except for a covering on the top, which was probably used for prevention of damage from rain.

In due course, the Marib Dam failed, but unlike the Sadd el-Kafara its failure had terrible consequences. "There is hardly any historic event of pre-Islamic history that has become embellished with so much that is fanciful, and related in so many versions, as the history of the bursting of the Marib Dam."[42] According to the Koran, "the people of Seba had beautiful gardens with good fruit. Then the people turned away from God, and to punish them, He burst the dam, turning the good gardens into gardens bearing bitter fruit."

WORKS OF SENNACHERIB

No work on ancient hydrologic engineering can be complete without reference to Sennacherib (705-681 B.C.). Out of shear barbarism, the Assyrian King dammed the Euphrates in 689 B.C., only to let loose the resulting flood on the vanquished and burnt city of Babylon through a series of canals.

The capital of Sennacherib was Nineveh, on the banks of the River Tigris; but the muddy water of the river was not good enough for an emperor, and hence he sought clear water for Nineveh and his palace at Khorsabad. He constructed a weir obliquely across the Atrush River near the gorge of Bavian, which formed a natural reservoir some 50 miles from the capital. He constructed a magnificient canal, Sennacherib's Channel, to convey the water from the reservoir. The canal followed the natural course through the foothills with a slope of 1 on 80. It took 13 yr to complete[43] the 50-mile long canal, which was extensively paved with limestone blocks and crossed several brooks and valleys over arched aqueducts. The aqueduct of Jerwan was nearly 1,000 ft long, 39 ft wide, and had two side walls 5 ft high and 8 ft

[40] Feilberg, C. G., "Qanaterne, Irans Underjordiske Vandingskanlen," Øst og Vest, Copenhagen, Denmark, 1945, pp. 105-113.

[41] Phillips, W., Qataban and Sheba: Exploring the Ancient Kingdoms on the Biblical Spice Routes of Arabia, Victor Gollancz Ltd., London, England, 1955, pp. 200-201.

[42] Encyclopedia of Islam, E. J. Brill, Leiden, Netherlands, Vol. 3, 1911-1938, pp. 263-293.

[43] Maner, A. W., "Public Works in Ancient Mesopotamia," Civil Engineering, ASCE, Vol. 36, No. 7, July, 1966, pp. 50-51.

thick. Fourteen buttresses were used to carry the aqueduct, and the bed consisted of three layers of limestone blocks. The inscription on the structure stated, "Over deep-cut ravines I spanned (lit., caused to step) a bridge of white stone blocks. These waters I caused to pass over upon it."[44] A rock carving near the headwork of the structure records, "To the great gods the King prayed and they heard his prayer; they directed the work of his hands. By gates and a tunnel the sluices opened of themselves and permitted the rich water to flow down; . . . according to the wishes of the gods' heart, he had dug the water, carried it from the stream, and directed its force."[4] Needless to say that the gods that aided the King were amply rewarded with great sacrifices.

CONCLUSION

All these facts indicate that prior to 600 B.C. man had a working knowledge of hydrology and hydraulics, even though he was unaware of any physical principle except possibly that water flows downhill. He had masses of seemingly unrelated data, but then he was interested only in controlling nature. Much later, he did try to understand nature, and only then were the data compared, interrelated, and generalized to give birth to fundamental scientific principles.

ACKNOWLEDGMENTS

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[44] Jacobsen, T., and Lloyd, S., "Sennacherib's Aqueduct at Jerwan," Oriental Institute Publications, University of Chicago Press, Chicago, Ill., Vol. 24, May, 1935.

5431 HYDROLOGIC ENGINEERING PRIOR TO 600 B.C.

KEY WORDS: dams; history; hydraulics; hydrology; irrigation; water supply

ABSTRACT: The development of the science of hydrology is traced from about 3500 B.C. to 600 B.C., from the recorded historical events. It starts with the Egyptian Pharaoh "King Scorpion" of the fourth millennium, and the legendary King Menes who dammed the Nile to divert it so that his capital Memphis could be built on the old fertile river bed. The ill-fated Sadd el-Kafara dam, which probably failed in its first flood season, and the work of the great Chinese engineer King Yü, are described. Flood control measures of King Amenemhet III of Egypt were admirable, and so were the nilometers, which can be traced back to about 3500 B.C. The latter obviously were a form of quantitative measurement of the river-flow—the earliest in history. Also considered are the famous code of King Hammurabi, sinnors of Palestine, irrigation and drainage systems of Nippur, the primitive water meters of Oasis Gadames and Yemen, Marib Dam of Yemen, aqueducts of King Sennacherib, and the qenāt system of utilization of ground water. A chronology of recorded hydrologic engineering events is given.

REFERENCE: Biswas, Asit K., "Hydrologic Engineering Prior To 600 B.C.," Journal of the Hydraulics Division, ASCE, Vol. 93, No. HY5, Proc. Paper 5431, September, 1967, pp. 115-135.