these planks are smeared with pitch and bound with iron bands, so that they may not be dislodged by the effect of the water. The ends of the shaft are capped with iron. On the ends of the screw beams are placed with cross pieces at each end fixed to both. In this way the screws can be turned by men treading them. The mounting of the screw will be at such an angle that it corresponds to the construction of a Pythagorean right-angled triangle: that is, so that the length is divided into five units and the head raised three of the same units.

DOCUMENT 16
Natural Irrigation in Egypt and Mesopotamia

Egypt and Mesopotamia were favored for agricultural productivity because of the silt-laden waters of their river systems. Here, Pliny (Natural History *5.57–58) describes the annual Nile flood from early summer to early fall, and Herodotus* (Histories *1.193.1–3) the use of canals and water-lifting devices to bring water to the fields from the Tigris and Euphrates Rivers.*

The Nile River begins to rise at the first new moon after the summer solstice, by gradual degrees as the sun passes through Cancer. It reaches its crest when the sun is in Leo, and in Virgo subsides at the same rate as it rose. . . . The amounts of its rise are determined with calibrated marks in water shafts: a rise of 24 feet is just right; if any less, the waters do not irrigate all the fields and there is no time for sowing because the earth is still thirsty; if any more, the floods delay work by receding too slowly and waste the time for sowing since the ground is sodden.

The land of the Assyrians receives little rainfall, enough to fatten the roots of the grain. But the standing crop is watered from the river, which brings it to ripeness and causes the grain to mature. This is done not as in Egypt, where the river by itself overflows its banks into the fields; here there is manual irrigation with the use of *shadufs* or swipes. For the whole countryside of Babylonia, like that of Egypt, is partitioned by canals, the largest of which is navigable: it extends southeast from the Euphrates to another river, the Tigris. . . . It is so productive of grain that it usually yields 200-fold, and as much as 300-fold in the best harvests.

DOCUMENT 17
Building a Roman Aqueduct

While Frontinus gives detailed descriptions of the individual aqueducts that supplied Rome with water, Vitruvius (On Architecture *8.6.1–11) here supplies a generic description of the components of an aqueduct system, including the (rare) construction of "inverted siphons" and the distribution of the water once it has reached the city.*

Water can be conducted in three ways: by flow in masonry channels, lead pipes, and terracotta pipes. Here are their specifications. If in channels, the construction must be as solid as possible, and the streambed must have a uniform slope of no less than six inches in every hundred feet. The channel is to be vaulted over so that the sun does not touch the water at all.

When it reaches the city walls, a reservoir is to be built, and adjoining the reservoir a triple tank for receiving water. Three pipes of equal bore are to be installed in the reservoir, leading to the receiving tanks, which are connected in such a manner that when the two outside tanks overflow, they pour into the middle tank. Pipes run from the middle tank to all the basins and fountains, from the second to the baths, that they might provide an annual public income, and from the third to private homes. In this way water for public use will not be lacking, for private parties will not be able to draw it off, since each has its own separate supply from the source. I have set up these divisions so that those who draw water off to their homes for private use might by their rents help the maintenance of the aqueducts by contractors.

But if there are hills along the course between the city and the water source, the following procedure is used. An underground channel is to be dug with the uniform slope described above. If the bedrock is tufa or hard stone, the channel is to be cut directly in it, but if it is earth or sand, a vaulted channel with floor and walls is to be built in the tunnel and the water carried through it in this manner. Vertical shafts are to be cut from the surface every 120 feet. . . .

If from the source there is an even slope to the city without any higher intervening hills capable of interrupting it, but with low spots, it is necessary to build it up to an even slope as with the flow in channels. And if the way around these depressions is not long, a detour is made, but if they are unbroken, the water course will be directed along the sunken area [that is, in an "inverted siphon"]. When it comes to the bottom, it is carried on a low substructure to give it as long a level course as possible: this, then will be the *venter* ["belly"], which the Greeks call *koilia*. Then when it comes up against the hill, the long stretch of the *venter* prevents a sudden burst of pressure: the water is forced up to the height of the hilltop. . . .

But if we wish to incur less expense, we must proceed in the following manner. Terracotta pipes with walls no less than two digits thick are to be made in such a way that they are flanged at one end, so that one pipe can slide into and join tightly with another. . . . Aqueducts employing terracotta pipes have these advantages: first, that if some defect occurs, anyone can fix it; secondly, that the water from terracotta pipes is much more healthful than that from lead pipes. Lead seems to make water harmful for this reason, that it generates lead carbonate, and this substance is said to be harmful to the human body. So if what is generated by it is harmful, it cannot be doubted that it is itself not healthful. Lead workers can provide us with an example, since their complexions are affected by a deep pallor.

DOCUMENT 18
Rome's Urban Water Supply

The Romans were justifiably proud of their achievements in hydraulic engineering. Here, Pliny (Natural History *36.121–123) gives a brief but impressive list of the practical and decorative elements of the system that supplied Rome, while Frontinus* (On the Aqueducts of Rome *1.16), always the practical bureaucrat, compares the utility of a good water supply to the achievements of Rome's cultural predecessors.*

But we must speak of marvels a true evaluation will find unsurpassed. Quintus Marcus Rex, when ordered by the senate to rebuild the channels of the Appia, Anio, and Tepula aqueducts, brought to Rome within the term of his praetorship a new aqueduct named after himself, driving underground channels through the mountains. Agrippa, too, while aedile, after adding the Virgo and repairing and putting in order the other aqueducts, constructed 700 basins, along with 500 fountains and 130 reservoirs, many of them magnificently decorated, and added 300 bronze and marble statues to these works, and 400 marble columns: all this in the space of a year. In the report of his aedileship, he himself adds that he celebrated games for 59 days and that admission to all 170 baths was made free: these are now infinitely more numerous at Rome. . . .

Now if someone shall carefully appraise the abundance of water in public buildings, baths, pools, channels, houses, gardens, and suburban villas, the distance the water travels, the arches which have been built up, the mountains tunneled, and the level courses across valleys, he will acknowledge that nothing more marvelous has ever existed in the whole world.

With such numerous and indispensable structures carrying so many waters, compare, if you please, the idle pyramids, or even the indolent but famous works of the Greeks.

DOCUMENT 19
Roman Public Baths

An essential element of Roman hydraulics, and indeed of Roman culture, was the construction of huge public bathing facilities, called thermae *because of their use of heated water* (aquae thermae)*, in cities throughout the empire. Vitruvius* (On Architecture *5.10) describes their layout and the complexity of the heating systems, including multiple hot-water tanks, the double-flooring system (hypocausts) that artificially warmed the bathing rooms with radiant heat, and even the harnessing of passive solar heating through the orientation of the building.*

First of all, a site as warm as possible must be chosen, that is, turned away from the north and east. Further, hot and warm bath areas are to receive their light from the direction of the winter sunset—or if the configuration of the site does not allow it, in any case from the south—because the favorite time for bathing is fixed between noon and evening. And one likewise must see to it that women's and men's hot baths are adjoining and have the same orientation: for in this way it will be brought about that there is a common heating system for both of them and their fittings. Three bronze tanks are to be installed over the furnace, one for the hot bath, another for the warm bath, a third for the cold bath, and so arranged that the amount of hot water which flows from the warm tank into the hot will be replaced by the same amount flowing from the cold tank into the warm. The vaulted ducts are to be heated from a common furnace.

The hanging floors [hypocausts] of the hot rooms are to be made as follows: first, the ground is to be paved with tiles 18 inches on a side, sloping towards the furnace in such a way that when a ball is thrown in it cannot stop inside but rolls back to the furnace door by itself. In this way the heat will more easily spread out beneath the floor. On this surface piers of bricks eight inches square are to be built in such a pattern that tiles two feet square can be placed above them. These piers are to be two feet high, put together with clay kneaded with hair, and the two-foot tiles are to be placed on them to carry the pavement. . . .

Let the dimensions of the baths suit the size of the crowd. They should be planned in the following manner. Let the breadth be two-thirds of the length, not counting the room with the basin and tank. The basins should be placed below the light source so that those standing around it might not darken it with their shadows. The rooms containing the basins ought to have enough space that when first comers have taken their places around the basins those waiting their turn might be able to stand in order. The width of the tank between the back wall and the front edge should be no less than six feet, of which the lower step and the seat occupy two.

The *laconicum*, or sweat room, should be adjacent to the warm room. The dome should spring at a height equal to the width of the room. A window is to be left in the centre of the dome and a bronze disk hung from it by chains: raising and lowering this disk allows adjustment to the sweating.

SHELTER AND SECURITY

DOCUMENT 20
The Ingredients for Roman Concrete

Vitruvius (On Architecture *2.4.1–5.1) describes the components of Roman concrete in considerable detail; in the second passage, Pliny* (Natural History *35.166) draws attention to pozzolana, a special ingredient from the neighborhood of Mount Vesuvius that allowed concrete to set underwater.*

In cement structures it is necessary first to enquire concerning the sand, that it is suitable to mix into mortar and that it does not have earth mixed in with it. The following are the types of quarried sands: black, grey, red, and carbuncular. Of these, the one that makes a crackling noise when rubbed in the hand or struck is best; while the one that is earthy will not be rough enough. Likewise if it is covered up in a white cloth, then shaken up or pounded, and it does not soil the cloth and the earth does not settle into it, then it is suitable. But if there are no sandpits from which it can be dug, then it must be sifted out from riverbeds or from gravel or even from the seashore. But these have the following defects when used in buildings: the wall dries with difficulty and this type of wall does not allow continuous loading—it requires interruptions in the work—and it cannot carry vaults. But even more, when seashore sand is used in walls and stucco is applied onto them, a salty residue leaches out and destroys the surface. But quarried sand dries quickly in the buildings, the plaster coating is permanent, and it can carry vaults. Here, however, I am speaking of sand that is recently taken from the sandpits. For if it is taken out and lies too long, weathered by the sun and moon and hoar frost, it breaks down and becomes earthy. As a result, when it is thrown into the masonry it is not able to bind the rubble, but the rubble sinks and falls down because the walls cannot support the loads. But freshly quarried sand, although it exhibits such great excellence in buildings, is not so useful in plaster, because with its richness the lime mixed with the straw cannot dry without cracking on account of the strength of the sand. River sand, on the other hand, although useless in *signinum* [waterproofing work] because of its fineness, attains a solidity in plaster when worked by polishing tools.

After considering the account of the sources of sand, one must be careful that, in regard to lime, it is burned from white rock, whether [hard] stone or [softer] silex. The lime from close-grained, harder stone will be most useful in structural forms, while that made from porous stone will be best in plaster. Once it has been slaked, then let the mortar be mixed three parts quarried sand to one of lime; or if river or marine sand is thrown in, two parts sand to one of lime. These will be the proper proportions for the composition of the mixture. Furthermore, if anyone adds a third part of crushed and sifted burnt brick into the river or marine sand, he will make the composition of the material better to use.

But other creations belong to the Earth itself. For who could marvel enough that on the hills of Puteoli [Pozzuoli] there exists a dust—so named because it is the most insignificant part of the Earth—that, as soon as it comes into contact with the waves of the sea and is submerged, becomes a single stone mass, impregnable to the waves and every day stronger, especially if mixed with stones quarried at Cumae.

DOCUMENT 21
The Need for Fortification Walls

We saw earlier the almost simultaneous development of settled life and defensive fortifications at Neolithic sites like Jericho. Here, Aristotle