

Water Wheels

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From classical times, there have existed 3 general varieties of water wheels: the horizontal wheel and 2 variations of the vertical wheel (see illustration 1). A typical water wheel was used to drive a millstone.

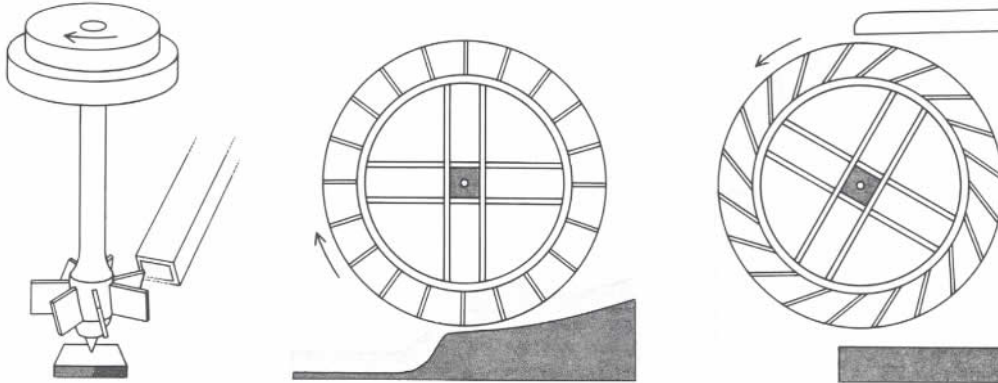


Illustration 1. Water wheels designs in order of increasing complexity and efficiency. Norse wheels (left) turn millstones directly, undershot wheels (center) require gears, and overshot wheels (right) also require an elevated stream (drawing from Scientific American).

Technology

The horizontal wheel has vanes protruding from a wooden rotor. A jet of water turns the rotor. In modern Europe the design was altered to use water moving axially, like air flowing through a pinwheel, creating a water turbine. Wheels with curved blades onto which the flow was directed axially are described in an Arabic treatise of the 9th century. A horizontal wheel turns a millstone directly.

The more powerful vertical wheels come in 2 designs: undershot and overshot. The former is a paddle wheel that turns under the impulse of water current. This technology requires gears to drive a typical millstone. When the levels of rivers fall in the dry season, and their flow diminishes, undershot wheels lose some of their power. In fact, if they are fixed to the banks of rivers, their paddles can end up above the water flow. One way this problem was mitigated was by mounting the water wheels on the abutments of bridges and taking advantage of the flow there. Another common solution was provided by the ship mill, powered by undershot wheels mounted on the side of ships moored in midstream (see illustration 2).

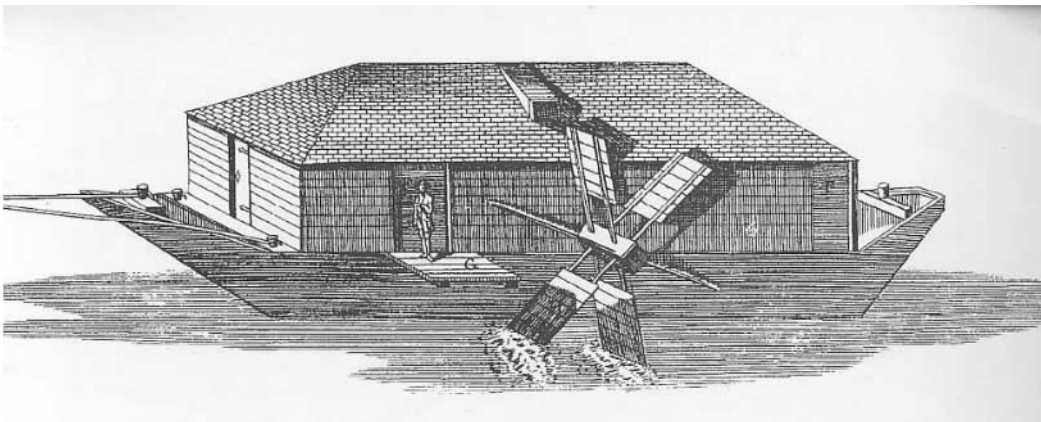


Illustration 2. Undershot wheel on a ship mill.

The overshot wheel receives water from above, often from specially constructed channels; it adds the impetus of gravity to that of the current. An overshot wheel requires gears and an elevated stream of water.

An interesting theoretical take on water wheels is provided by Edward Bowser, a long-time professor of mathematics at Rutgers University. In his textbook titled *An Elementary Treatise on Hydromechanics* (first published in 1885, with the last edition printed in 1921), Medieval machines keep popping up. Bowser shows how to calibrate a medieval water clock and calculates the performance of a flap valve pump (the kind used by sailors to pump bilge water, post-Columbus). But the real surprise is a long discussion on every kind of water wheel. Today, Bowser's book, with the front cover in medieval Europe and the back cover in industrial America, seems much older than its one hundred years.

Romans

The first description of a water wheel that can be definitely identified as vertical is from Vitruvius, an engineer of the Augustan Age (31 BC - 14 AD), who composed a 10 volume treatise on all aspects of Roman engineering. Vitruvius described an undershot wheel, but remarked that it was among the "machines which is rarely employed." One of the reason hypothesized for its sparse application was the availability of cheap slave labor which prevented the Romans from developing alternative sources of power.

One of the most remarkable Roman application of a waterwheel was at Barbegal, near Arles in southern France. Dating from the 4th Century AD, the factory was an immense flour mill which employed 16 overshot water wheels.

There were at least 2 other multiple-wheeled Roman mills, but neither was as ambitious as the one at Barbegal. One was at Chemtou in western Tunisia, where a combination bridge/dam spanned the Medjerda River. Three horizontal water wheels, side-by-side, were set into the bridge abutments. The other mill was in Israel on a dam on the Crocodile River near ancient Caesarea, halfway between Haifa and Tel Aviv. Here there were 2 horizontal wheels, each at the bottom of a penstock. According to Hodges (p. 111): "Neither installation has been fully studied, but together they remain the only known parallels to Barbegal." But he feels strongly that there are probably other Roman mills that remain to be discovered. "Other Barbegals must surely await discovery in the more remote and less studied parts of the Roman Empire. If this one could escape notice until 1940, what masterpieces may yet lie hidden in Iraq and North Africa, where desert sands now enshroud the remains of Roman cities?"

One innovation development occurred when Rome was under siege in 537 AD. When the Goths shut off the aqueducts whose water drove the city's gristmills, Belisarius, the Byzantine general defending the city, ordered floating mills installed close to the Tiber bridges, whose piers constricted and accelerated the current. Two rows of boats were anchored with waterwheels suspended between them. The arrangement worked so well that cities all over Europe were soon copying it.

Ancient China

Waterpower was important source of energy in ancient China civilization. One of the most intriguing applications was for iron casting (see illustration 3). According to an ancient text, in 31 AD the engineer Tu Shih "invented a water-powered reciprocator for the casting of [iron] agricultural implements." Smelters and casters were "instructed to use the rushing of water to operate their billows."

Waterpower was also applied at an early date to grinding grain. Large rotary mill appeared in China about the same time as in Europe (2nd century BC). But while for centuries Europe relied heavily on slave- and donkey-powered mills, in China the waterwheel was a critical power supply.

Chinese waterwheels were typically horizontal. The vertical wheel, however, was known. It was used to operate trip hammers for hulling rice and crushing ore (see illustration 4). The edge-runner mill was another commonly used crushing device. With the latter a circular stone on edge running around a lower millstone was used to pulverize. The edge runner appeared in China in the 5th century AD. Both the trip hammer and edge runner were not used in Europe until eight centuries later.

Throughout the first 13 centuries AD, technological innovations filtered slowly but steadily from the advanced East to the somewhat more backward West. Carried at first through central Asia over the 4,000-mile Silk Route and later by sea, some innovations were exported swiftly, while others (like waterwheel paraphernalia) took centuries.

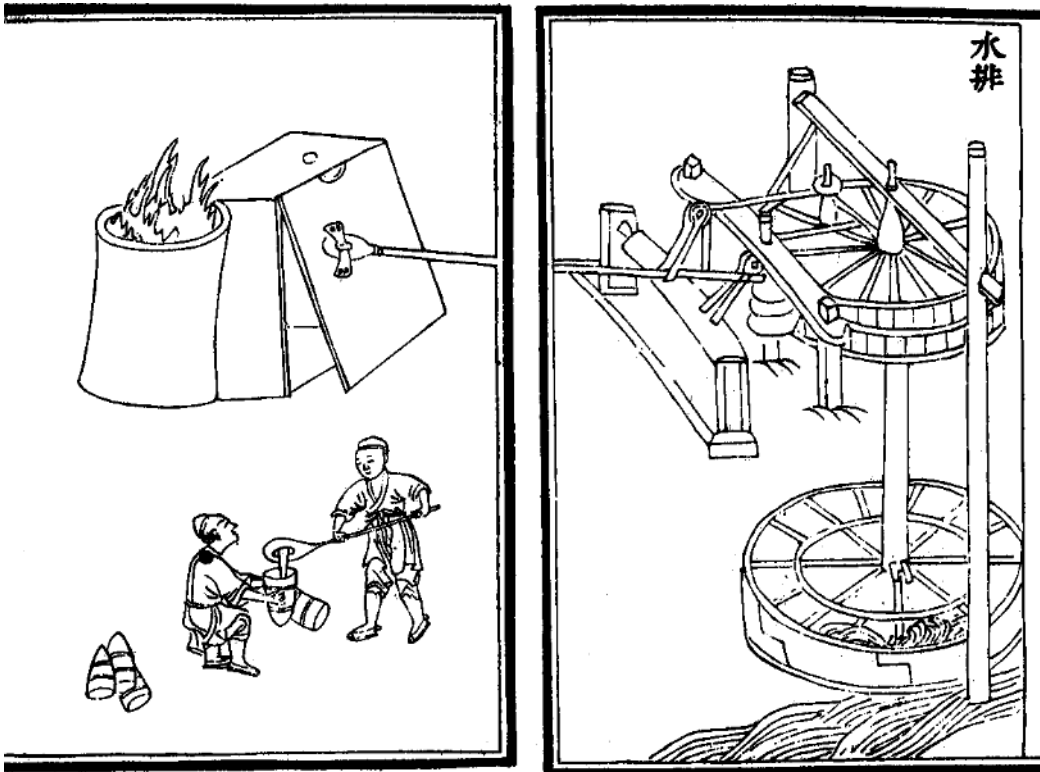


Illustration 3. Metallurgical bellows, powered by a horizontal waterwheel, from the Chinese work of 1313 AD.

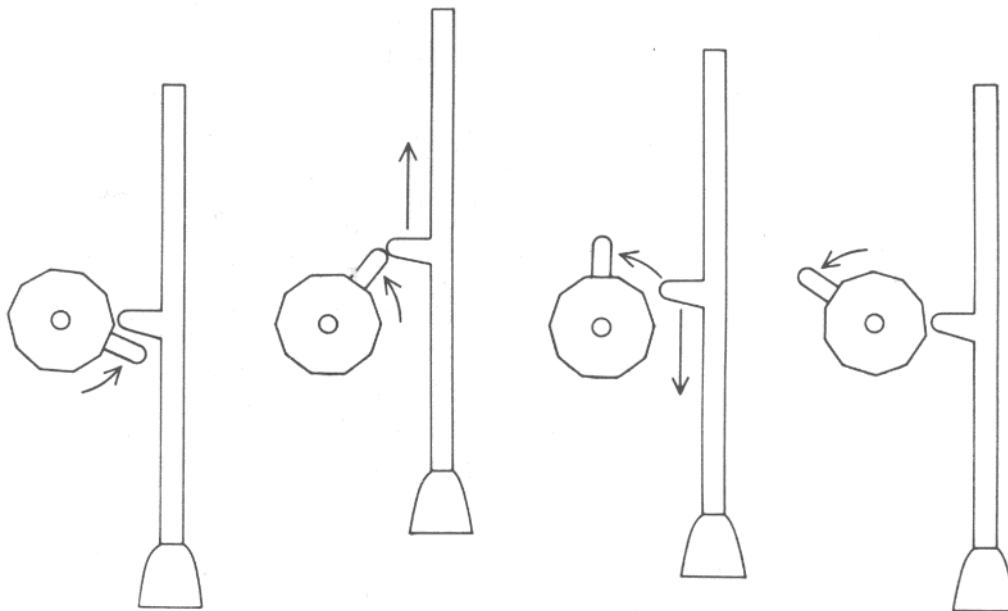


Illustration 4. Transformation of rotary motion into linear motion can be achieved by having a cam on the axle of the wheel (drawing from Scientific American).

Medieval Europe

In medieval Europe, social and economic conditions increased the need for replacing manual labor with powered machines. Several reasons have been suggested for the increased use of water power: (1) the rise of monasticism (see below); (2) a shortage of labor brought about by the Black Death and other disasters; and (3) the abundance of good sites for waterwheels.

From the 10th century on there was steady progress in land reclamation. Areas in northern and western Europe, once sparsely populated, came under cultivation. Grain was an important crop, and most of it was ground by water mills. Historic records provide useful insights. The Domesday Book, a survey prepared in England in 1086 AD, lists 5,624 water mills (this number is low since the book is incomplete). A century earlier, fewer than 100 mills were counted.

French records tell a similar story. In the Aube district, 14 mills operated in the 11th century, 60 in the 12th, and nearly 200 in the 13th. In Picardy, 40 mills in 1080 grew to 245 by 1175. Boat mills, moored under the bridges of early medieval Paris and other cities, began in the 12th century to be replaced by structures permanently joined to bridges.

Tidal mills were apparently a medieval invention. They were first mentioned in the 12th century in both England and France. Their numbers increased every century until modern times. These mills were constructed in low-lying areas near the ocean. Dams containing swinging gates were built along shallow creeks. As the tide came in, the gates swung open inwardly. Water filled the area behind the dam. When the tide turned, the gates swung shut, forcing the water to flow seawardly through the mill race of the tidal mill.

The obvious disadvantage to tidal mills is that the time of the tides shifts every day. Thus the millers had no choice but to work hours dictated by the tides. These mills seem only to have been used to grind grain (although the water wheels on London Bridge were definitely affected by tidal action on the Thames River). There were never many of them when compared to "ordinary" water wheels.

Cistercians

In the year 1098, the Cistercian monastic order was formed. Fourteen years later, St. Bernard took charge of the order and moved it in a direction that would encourage technological innovation. The Cistercians were a strict branch of the Benedictine Order who fled worldly temptations to live "remote from the habitation of man."

By the middle of the 12th century the order rode the cutting edge of hydro-power and agriculture. A typical Cistercian monastery straddled a millrace (artificial stream). This stream ran near the monastery shops, living quarters, and refectories, providing power for milling, wood cutting, forging, and olive crushing. It also provided running water for cooking, washing and bathing, and finally sewage disposal.

Cistercian monasteries were, in reality, the best-organized factories the world had ever seen – versatile and diversified. The Cistercian monk/engineers developed their new technologies and spread them throughout Europe. They tinkered and innovated.

Mining and Other Uses

During the late Middle Ages, the increasing demand for metals drove miners deeper into the earth. Old mining methods were no longer adequate. Miners started using water wheels to pump water from the mines, grind ore, run bellows at the blast furnace, and operate hammers at the metalsmith's forge.

A good picture of metallurgy and water wheels can be obtained from *De Re Metallica*, by Georgius Agricola, published in 1556. An excellent translation of this work was prepared by Herbert Hoover (a mining engineer and future President) and his wife (the first woman geologist to graduate from Stanford University). *De Re Metallica* is illustrated with woodcuts (see illustration 5). Agricola was one of the first to record mining and metallurgical practices, and in so doing has left us impressive images of water wheel technology.

Among the other uses of water wheel technology included the fulling of cloth, rice husking, papermaking, and pulping of sugar cane. The usual method of adapting water wheels for such purposes was to extend the axle and fit cams to it. The cams caused trip-hammers to be raised and then released to fall on the material (see illustration 4). Water wheels were also used to pump water (the water wheels on London Bridge).

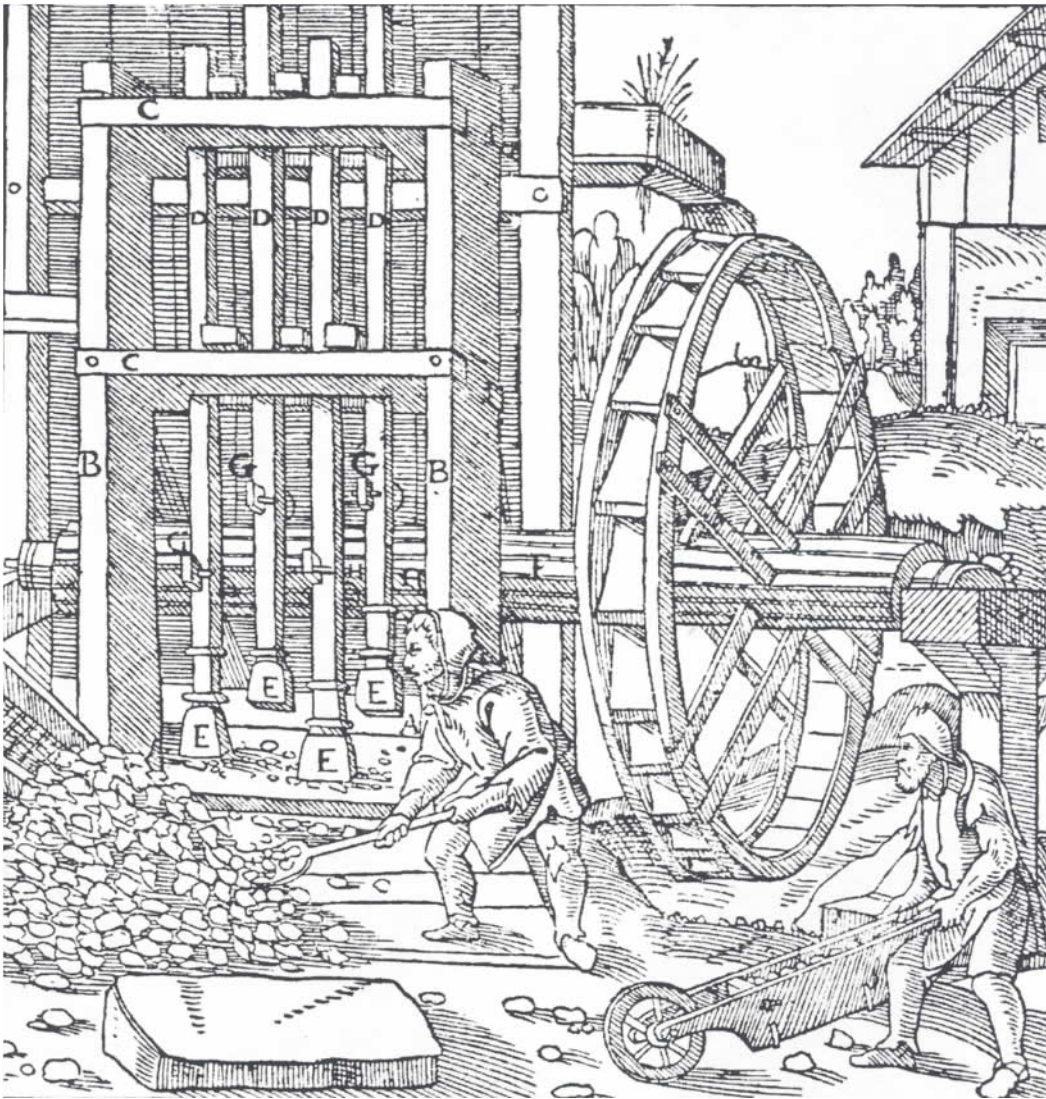


Illustration 5. The cam principle was applied in a rock-crushing mill illustrated by Georgius Agricola's *De Re Metallica* (1556).

Eighteenth-Century Mills

In Murcia, Spain, the Molinos Nuevos (New-Mill) was constructed on a site with a long history of mills. The last incarnation had 21 horizontal wheels (later expanded to 24) located in a line parallel to the Segura River. Water was diverted from a weir pond into a channel; the differential head between the channel and the river was used to turn the wheels (see illustration 6). Today Molinos Nuevos is a museum.

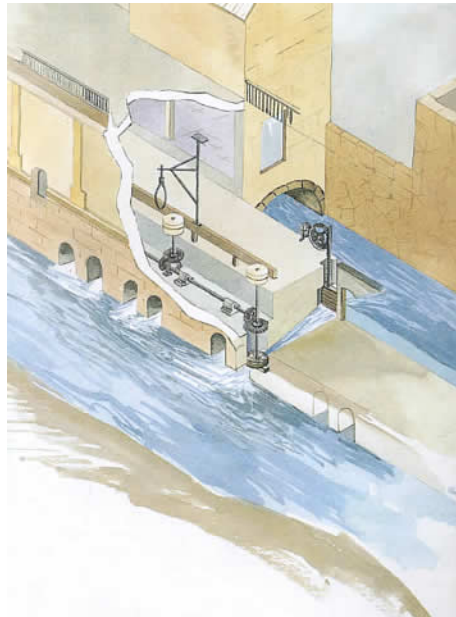


Illustration 6. Cross section of the mill setup at Molinos Nuevos, Murcia, Spain.

Contemporary Water Wheels

In 1989, gristmills were operating outside the historic walls of Diyarbakir, Turkey (see photographs 1 and 2). The water supply to turn the millstones was provided from urban runoff which was diverted into a tank above the mill. The water channel leading to the tank was elevated for a short distance. The interior design is similar to Nuristani (Afghanistan) watermills (see illustration 7) operational in 1970. Edelberg and Jones (1979) reported, that on a tributary of the Bashgal River, a series of four gristmills was operational, one built just below the other. There was a total of 13 in the area.



Photograph 1. Gristmill outside the city wall in Diyarbakir, Turkey (1989).



Photograph 2. Inside the gristmill in Diyarbakir, Turkey (1989).

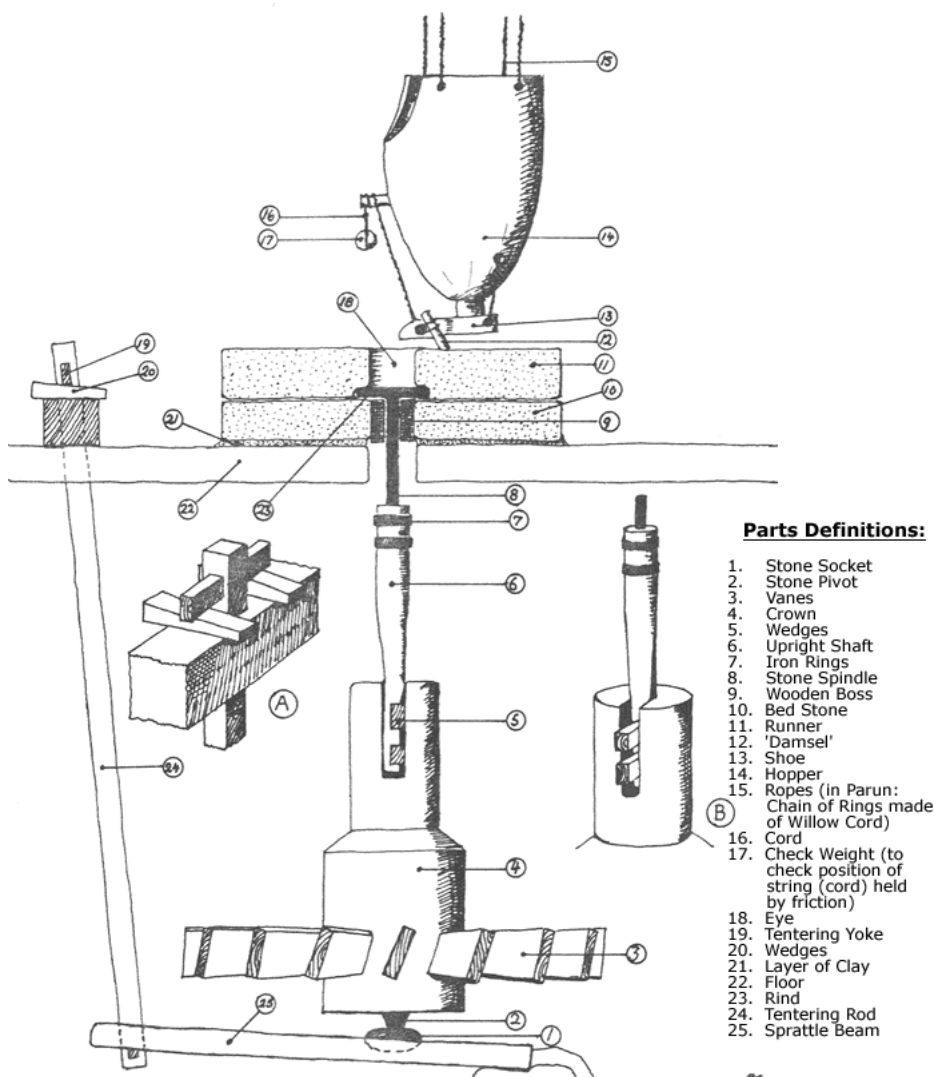


Illustration 7. Schematic of a Nuristani gristmill (from Edelberg and Jones, 1979).

Montell Seeley, of Castle Dale, Utah, is working on an overshot wheel (see photograph 3). Water to turn the wheel will be provided from a spring located near his home. In the future, he hopes to use the wheel to power a sawmill. Montell, a pioneer enthusiast, is interested in preserving historic technologies.



Photograph 3. Montell Seely's Waterwheel in Castledale, Utah (2002).

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