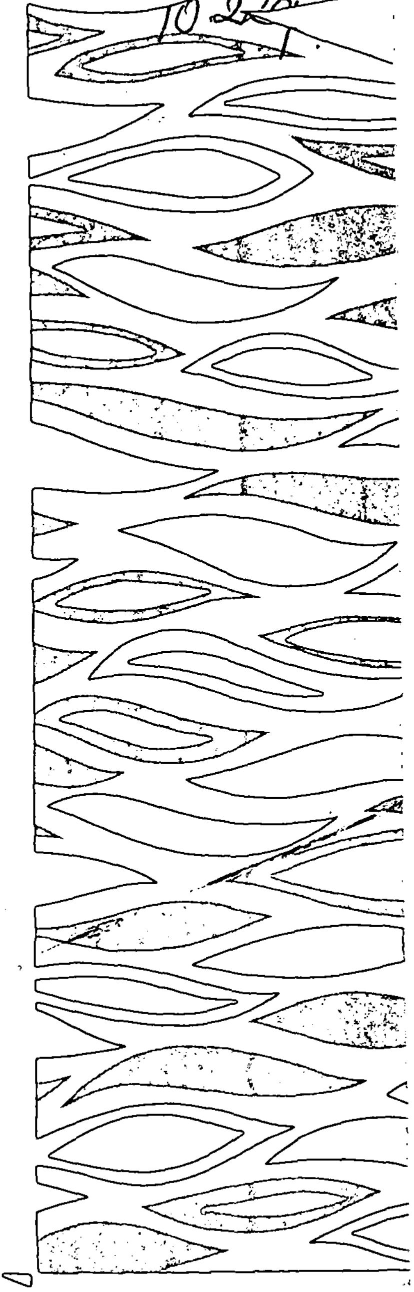
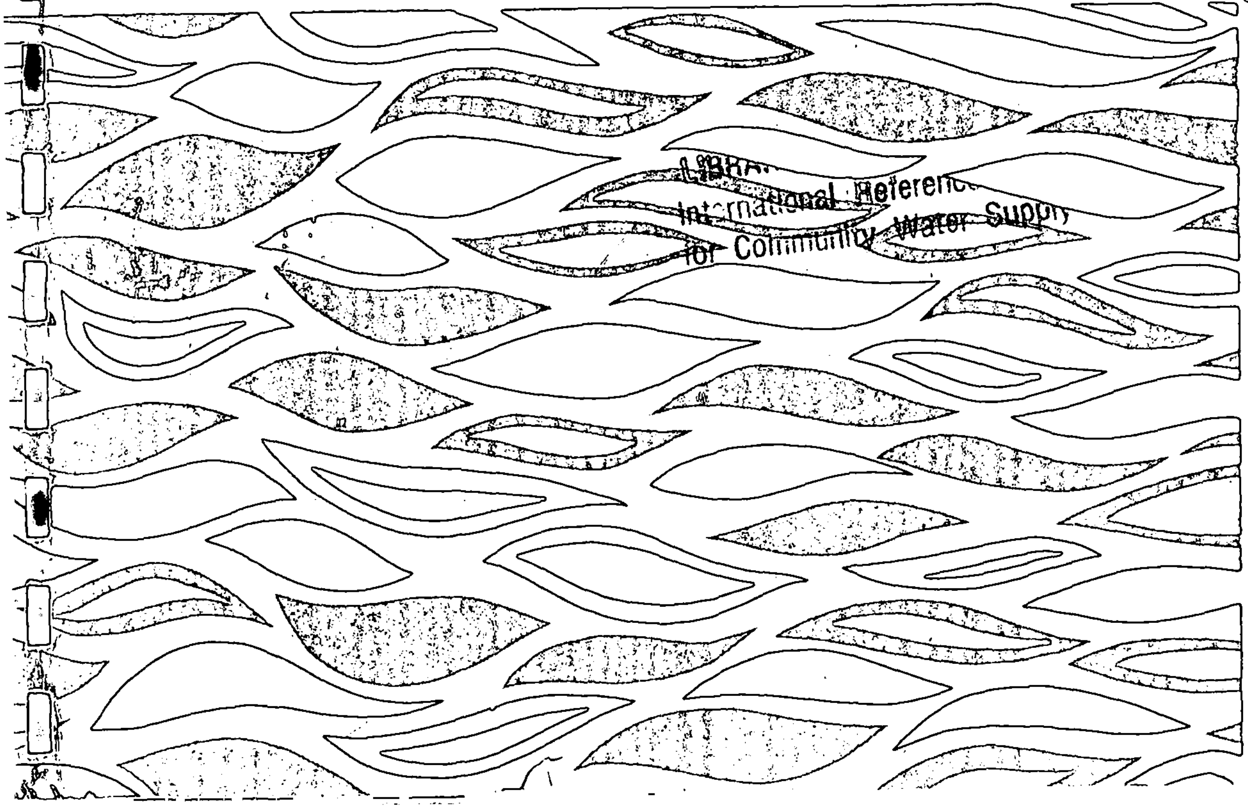
WATER LIFTERS AND PUMPS FOR THE DEVELOPING WORLD

by A. D. Wood





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THESIS

WATER LIFTERS AND PUMPS FOR THE DEVELOPING WORLD

Submitted by

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ABSTRACT OF THESIS

WATER LIFTERS AND PUMPS FOR THE DEVELOPING WORLD

This thesis presents a state-of-the-art on water lifters and pumps which are, or can be, utilized throughout the world and particularly in developing areas. A brief review is given of the historical development of these devices. Through an extensive literature review and survey of manufacturers and research organizations, this thesis inventories the wide range of water lifting methods which are randomly discussed by these sources and sets forth; (a) a unifying classification format, (b) the basic operation and typical applications of each class, and (c) a review of applicable prime movers. In addition, criteria used in the selection of water lifters and prime movers is presented with emphasis on water requirements, availability, and cost analyses. In this manner, the present status of water lifting in both developing and developed countries is reviewed and several recent projects by international organizations, e.g., AID, are identified which seek to improve existing methods, develop new ones, and disseminate educational material. Through this state-of-the-art, similar and additional areas of water lifting which need technological or sociological attention are then explicitly or implicitly identified.

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Introduction

1.1 Objectives

Raising water for irrigation and drainage were among man's first motives for developing water lifting devices. Without such water lifters, many areas of the world would not be fit for agricultural use; too arid to grow food or forage crops, or too wet to allow cultivation. Over some five millenniums, water lifting has grown into a major industry, producing thousands of types and sizes of devices both to lift water and to serve as prime movers.

This state-of-the-art will present a review of how water lifting has developed throughout the world, where it stands today, and provide some insight into its future needs. Recent literature goes into great depth discussing the highly specialized and complex pumps of today. A few other publications briefly mention the operation of several early water lifting devices which are still used in many developing countries today. Through an extensive literature review, this paper will inventory the wide range of water lifters which are randomly discussed in these publications and set forth; (a) a unifying classification format, (b) the basic principles of operation and typical applications and installations of each class, and (c) a brief review of applicable prime movers. Though this paper will identify some of the technological gaps which exist in the water lifting science, it is to serve primarily as a reference point for future research which is needed to; (a) improve efficiencies of existing water lifting devices, (b) develop designs suitable for manufacture, operation, and maintenance in developing countries, and (c) find both new water lifting devices and adaptions of existing devices which can be used with natural prime movers, in light of recent energy shortages. Although some of the fundamental theory and terminology of water lifting is presented to provide a foundation for discussion of each device, this state-of-the-art is not intended to cover the extensive sciences of hydraulics and mechanics which are the basis for the design and application of pumping devices. A wealth of references are available on these subjects and are included in the bibliography.

1.2 Historical Review of Water Lifting

In order to present a state-of-the-art of water lifting methods as they exist today, it seems appropriate to first briefly review water lifting as it developed through the ages. This is done for two reasons. First, such a review provides for completeness, i.e., covering even methods which have fallen into disuse. Secondly, with current changes in the world energy conditions, the use of natural prime movers, e.g., the windmill, are getting a revitalization and similar advantage may be gained by "reinventing" some of the water lifters presently of little or no use.

Archaeology gives us some clues as to the early forms of water lifting; however, early dates often vary among references. Ewbank, 1876, provides interesting accounts of man's earliest vessels, e.g., hollow gourds which were surely the beginning of the bucket. By attaching a vine or rope, the bucket could be lowered to deeper water supplies, or the simple basket could be used to scoop and throw water. This *swing basket* or *mental* (figure 3.9) used in Egypt was probably the first effort made to lift water at a rate sufficient for irrigation. The date of this device's earliest use cannot be ascertained, however, carvings on Egyptian tombs date the *counterpoise lift* (figure 3.7) back to about 2000 B.C. (Ewbank, 1876), and it would appear as the next logical step in water lifting methods, i.e., adding a lever to the basket and rope. About this same time, the lever was being used as a *gutter* in Eastern Asia. The *zigzag balance* (figure 1.1) is a good example of such a device.

Several sources (Flettner, 1926 and Golding, 1962) mention that the Babylonian Emperor Hammurabi reports the use of *windmills* for an extensive irrigation system in 1700 B.C. This report is frequently questioned and so credit for the first "working" windmill is often given to the Persians, who used a vertical shaft with radially mounted sails. Although these Persian mills were used primarily for grinding, they also introduce the use of crude gears. (For a history of windmills, see Vadot, September 1957 and Reynolds, J., 1970.)

Many references describe Joseph's well, which is the first account of the *Persian wheel* or chain-of-pots (figure 3.38); however, dates vary anywhere from 1500 to 3000 B.C. (Ewbank, 1876; Eubanks, 1971; Rouse and Ince, 1963). One author, Schoiler, says such a device could not have developed until the scientific advances of Archimedes' time, 200 B.C. About this same time, the pulley or roller appears to have evolved. In areas such as Mesopotamia where deep wells were dug, the pulley was soon brought into use for *mots* such as in figure 3.2 (De Camp, 1963). Writings on clay tablets also relate the use of water raising *treadmills* in Mesopotamia about 1200 B.C. (De Camp, 1963). Similarly, engravings on ancient medals depict the use of *bellows* for venting fires some three to four thousand years ago. Although their

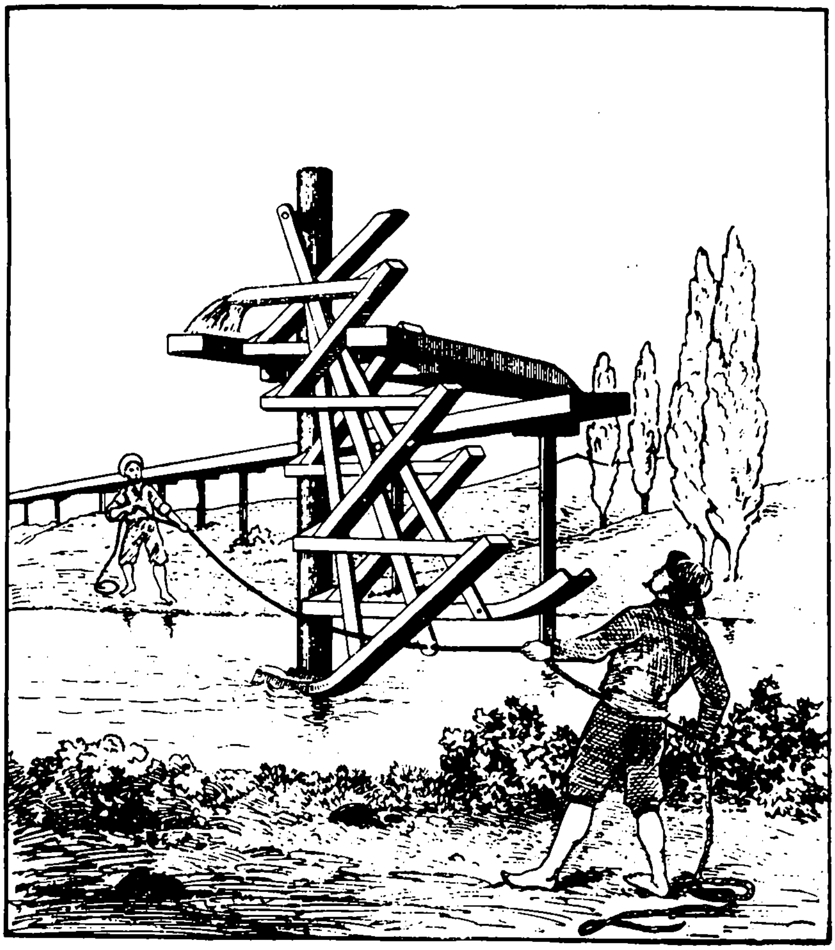


Figure 1.1 Double zigzag gutters

use for lifting water was not to come for several centuries, this did mark the early use of suction and the simple flap valve (Ewbank, 1876).

By 1000 B.C., the further refinement of gears allowed widespread construction of watermills in Egypt, Mesopotamia, and China. However, it is the Chinese who are credited with combining the watermill and the waterwheel into the *noria* (figure 3.40)--a self-powered waterwheel (Roger, 1905). Although wind and waterpower developed during the second millenium B.C., their acceptance in many areas, such as the Roman Empire, was delayed because of the large slave labor force available.

Sometime in the 5th century B.C., Athenagoras, a philosopher, observed the stylish sprinkling pots of the day which had holes in the bottom. In order to retain water in them, a person covered the top opening with a finger. Athenagoras proposed that when the top opening was covered, *atmospheric pressure* could not push down on the water, but only up, i.e., countering gravity and thus retaining the water. However, it was not until about 300 B.C. that Ctesibius combined the discovery of atmospheric pressure and the principle of the bellows into the first *suction* or *lift pump*, primarily for use in fighting fires with manual power.

During the 3rd century B.C., Archimedes did much to develop the science of hydraulics. King Hieron II of Syracuse (Sicily) asked him to invent a method for draining the holds of his ships. Archimedes' answer was to push the water up a tube using a simple *screw*, as in figure 2.3 (Tokaty, 1971). The Egyptians and Romans developed similar devices shown in figure 3.47. Another water lifting debate questions which of these screws came first.

In the 2nd century B.C., Hero (or Heron) of Alexandria used several methods to raise water, primarily for entertainment purposes. In one of his novel devices, the "Sun Fountain," he used the sun's heat to vaporize and lift water; the beginnings of solar powered pumping (Ewbank, 1876). Hero also developed the first air lift pump for his "Fountain of Hero" shown in figure 1.2 (Ivens, 1920). In addition, he utilized the reciprocating piston principle of Ctesibus to create the similar *plunger pump*, figure 3.16.

Although references do not mention the invention of the *paddle* or *scoopwheel* (figure 3.34), sometime during the last centuries B.C., the Chinese modified this scoop-rotary water lifter into the *water ladder* (figure 3.36). As this idea was being carried to Europe aboard trading ships, it was modified again into the *chain pump* for draining ship holds (Ewbank, 1876). About 31 A.D., the Chinese also have recorded use of a horizontal (vertical shaft) waterwheel to drive bellows (Reynolds, J., 1970).

During the first four centuries A.D., piston pumps, constructed from hollowed logs, gained widespread use throughout Roman-ruled England. They remained in use until cast-iron pumps were commercially manufactured in the 1880's. Then, throughout the Middle Ages (500-1500 A.C.), various combinations of water lifters, transmissions, and prime movers were experimented with and used by the increasing number of small farmers who did not have slave labor. Some of the more novel, yet practical, combinations are described by Ewbank (1876), Tokaty (1971), Rouse and Ince (1963), and Reynolds, J. (1970). Among the major improvements to come out of this time was the use of metal parts, particularly gears. In the 15th century A.D., Leonardo da Vinci used a

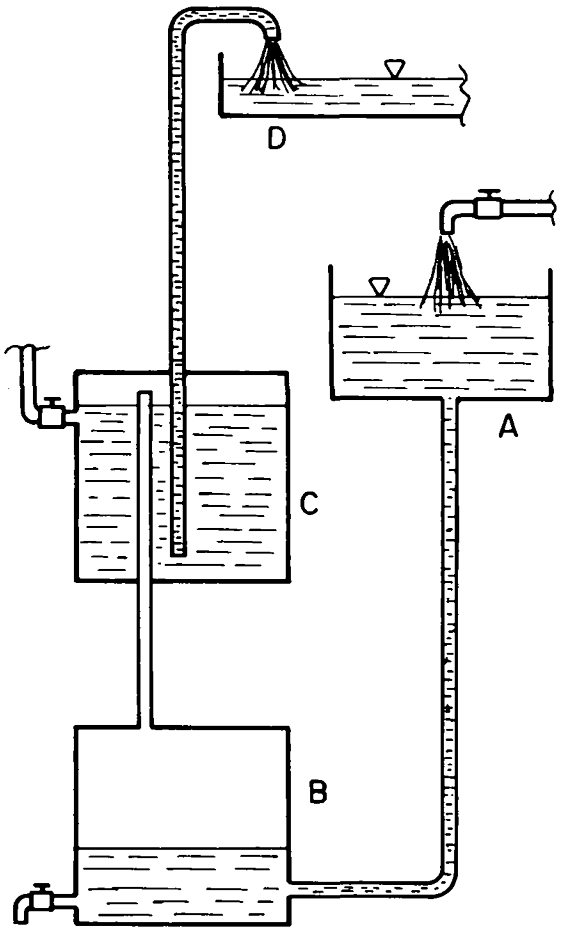


Figure 1.2 Principle of Heron's Fountain

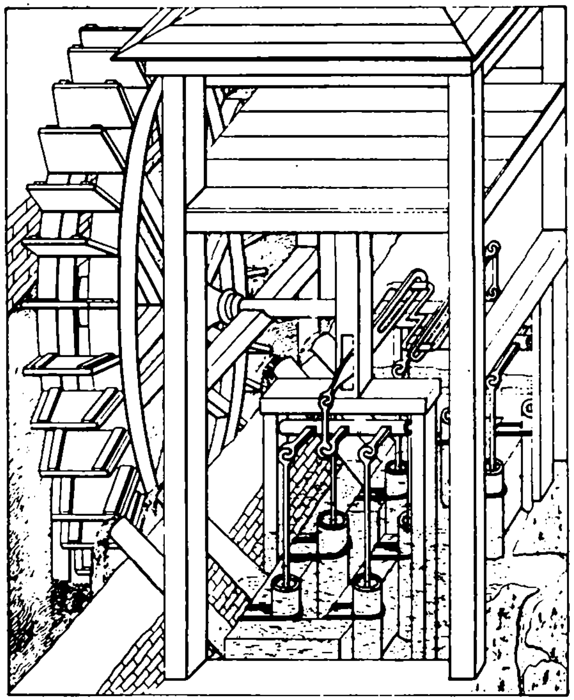


Figure 1.3 Ramelli's pump

watermill to drive a suction pump via an eccentric cam. This allowed the conversion of rotary motion into reciprocal motion. In addition, he investigated and suggested the use of centrifugal force to lift water, although it was not to be seriously considered for another 200 years (Tokaty, 1971).

In 1511, record is made in Germany of the use of bellows (the same design as fire bellows) to lift water. Another new method of lifting water, the *ejector*, was invented by Vitrio and Philebert de Lorme in 1570 (Kneass, 1903).

In 1557, Captain Ramelli, an Italian engineer, developed a *rotary pump* of four spring-loaded vanes in an eccentric cylinder, a crude wood version of figure 3.48. Some consider this to be the first centrifugal pump, however the action is purely positive displacement. In 1588, he also developed a set of suction pumps, similar to da Vinci's design, powered by a watermill via a cam shaft (figure 1.3).

Galileo worked during the 17th century to explain, among other things, the inability of a vacuum to lift more than "18 cubits" of water and extended the concept of atmospheric pressure (Rouse and Ince, 1963). Similar work by Giovanni Bapista della Porta in 1601 suggested using a vacuum to condense steam in Hero's steam pump. Several other people about this time also used steam to displace water for draining mines. In 1616, Gironimo Finugio of Italy used a surplus water supply and available head to develop the *gaining and losing buckets* pictured in figure 1.4 (Ewbank, 1876). In the 16th century, Francini used this same principle with a chain-of-pots, i.e., a chain of large buckets driving a smaller chain. In the early 17th century, the first *gear rotary pump* was invented by Grollierde Serviere.

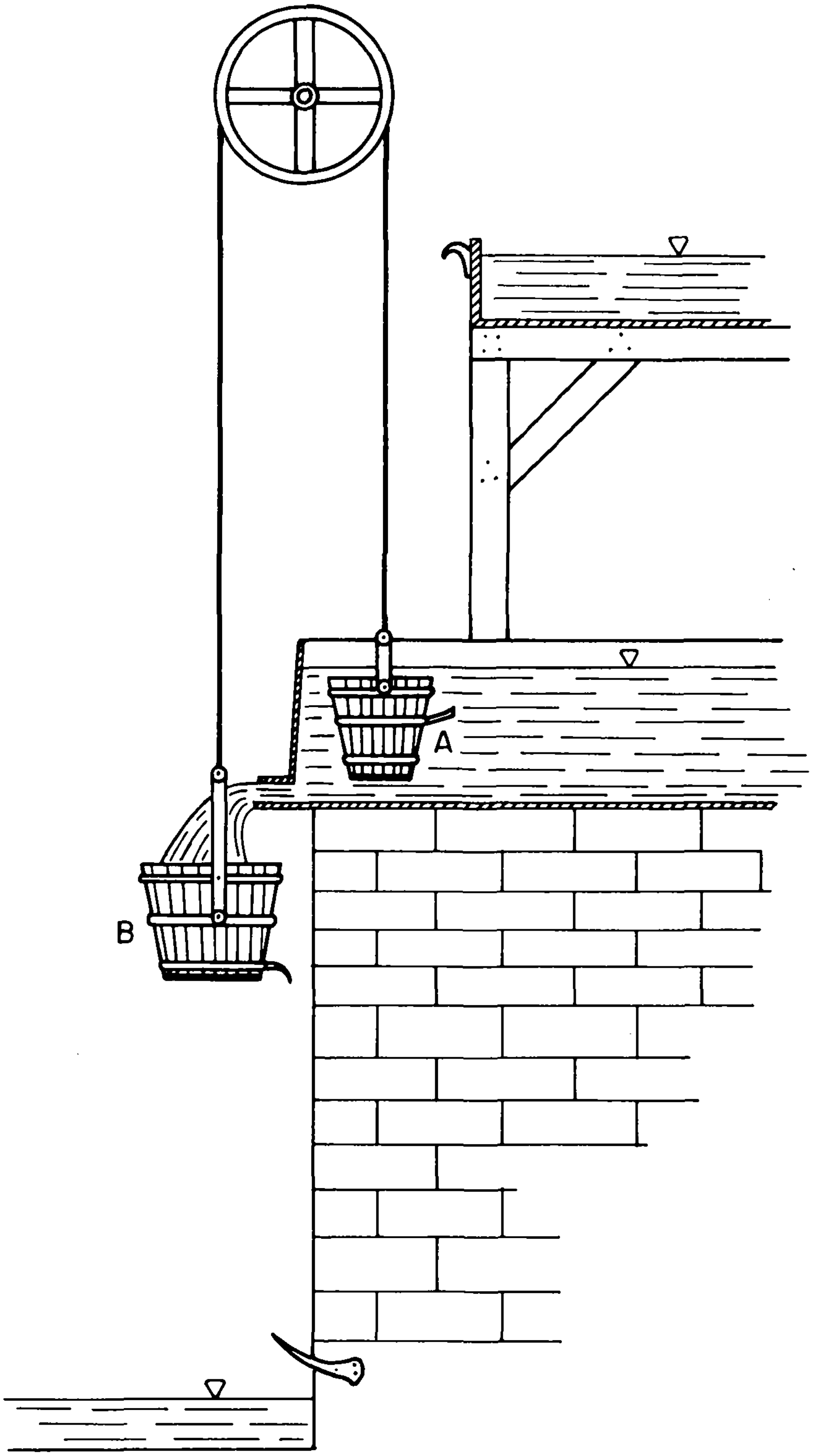


Figure 1.4 Gain and lose buckets

The 17th century also marked the beginning of *rotodynamic pumps.* In 1680 Johann Jordan designed a centrifugal pump, primarily out of curiosity, although it was not built until 1703. Denys Papin, in 1689, also built a centrifugal to drain some property of a friend. However, these wooden pumps were crude and due to the lack of a uniform, high speed driver, low in efficiency. The development of centrifugals was also suppressed by the popularity of piston pumps. Even in his 1841 *Hydraulics*, Ewbank states that "in a hundred years, the present day pump (reciprocating piston) would predominate over all other."

In 1698, Thomas Savery obtained a patent for a pump which displaced water by steam within two chambers. Because of the sometimes violent and rhythmic vibrations which this device produced, it became known as a *pulsometer* (figure 1.5). Two similar devices had been built by Santorio in 1626 (Rogers, 1905) and by Edward Somerset in 1628 (Greene, 1913), however Savery's pump was the first to use automatic valves, which made it of practical use for such applications as mine drainage. Although the pulsometer's dangerous and inefficient operation eventually lead to its abatement, it was widely used in many industrial situations until the early 20th century. With the development of steam power from fossil fuels about this time, many other interesting, if not always practical, pumping devices were invented (see Ewbank, 1876).

In 1705, Newcomen and Cawley utilized the work of Papin and Savery to develop their "Atmospheric Engine" (i.e., steam piston) which they later connected to a piston pump via a rocker arm giving it much the same appearance as a modern oil well pump. Leopold, in 1720, connected the steam piston directly to the water piston and strengthened

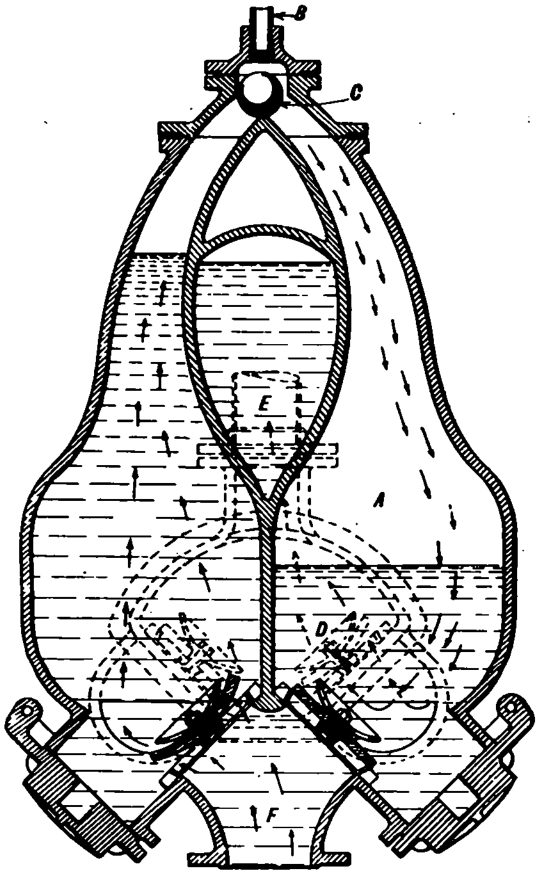


Figure 1.5 Pulsometer

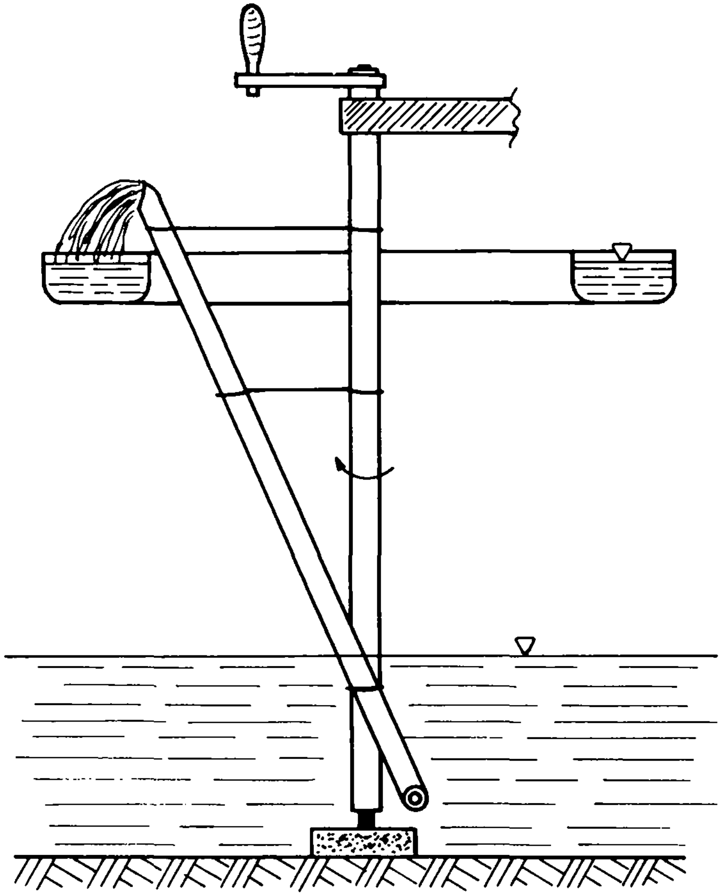


Figure 1.6 Demour's centrifugal pump

the design to increase steam pressure and thus, performance. Both these devices required a "cock boy" to open and close necessary water and steam valves. However, one such cock boy, Humphrey Potter, devised automatic valves which greatly improved the efficiency and performance of these single-action steam pumps (Greene, 1913).

In 1730, Demour designed and built the vertical pump in figure 1.6 which was the early basis for axial/mixed flow rotodynamic devices. The inclined tube rotated at 60 rpm, lifting 80 gpm six feet (Greene, 1913). A few years later, Fahrenheit worked with this idea in Holland and developed the "T" centrifugal in figure 1.7, complete with foot valve (Rogers, 1905).

About this same time in Paris, Gosset and Deuille took the bellows principle, combined it with a leather flap-valve and manually-operated, reciprocating piston, and developed the first diaphragm pump. The 18th century also saw the air lift method of Hero, first used practically in Hungarian mines.

About 1754, Leonhard Euler studied the early centrifugal devices of that century and set forth several theories which would later be used to systematically design rotodynamic pumps. During this same time, John Smeaton began to analyze the principles of over- and undershot waterwheels. From this work, he established the realtionships between wheel (and pump) performance and speed, i.e., that discharge, head, and power vary with speed directly, squared, and cubed, respectively. He is also credited with developing the idea of the hydraulic ram (Tokaty, 1971). However, the first ram known to be built was constructed by Whitehurst in 1772, although it required manual opening of a valve to operate. The first self-acting ram was built in 1796 by Montgolfier

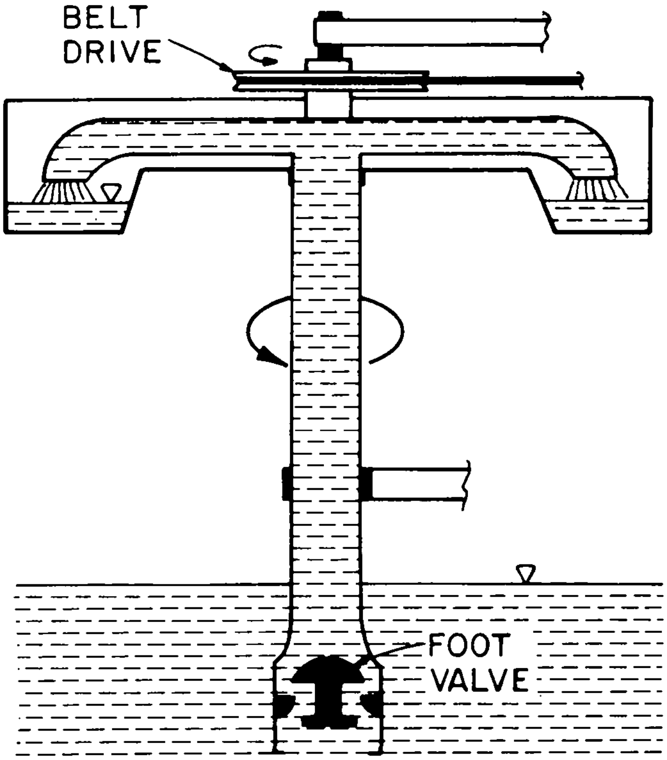


Figure 1.7 Early "T" centrifugal

and in 1797, Matthew Boulten got the first patent on such a hydraulic ram. Soon after the turn of the century, a *ram siphon, suction ram,* or *siphon elevator* (figure 1.8) was built by a French company. It utilized the principle of the automatic ram valve, but at the apex of a siphon instead of the bottom of a fall. In H. M. Wilson's 1896 USGS paper, he reports it obtained 90 percent efficiency in test trials. However, other than brief descriptions by Wilson, Ewbank, and Weisbach and Herrman (1897), all prior to 1900, this "efficient" device has not appeared in available modern literature.

About the time the ram was developing, James Watts also improved the steam pump via his idea of injecting steam at both ends of the piston stroke so as to provide double-action. Several years later, in 1782, Watts also got the first patent on a *semi-rotary* pump--an idea first proposed in the 16th century. Three years later, John Skeys also obtained a patent--on a *propeller* pump (Lazarkiewiez and Troskolanski, 1965).

With the beginning of the 19th century, rotodynamic pumps finally received notice and began to develop. In 1816, M. Jorge took the novel "T" centrifugal (figure 1.7) and showed that it was only necessary to rotate the arms (or vanes). Then in 1818, the first commercial production of a centrifugal began with the "Massachusetts" or "Boston" pump, using four straight, open vanes in a closed casing (Harris, 1953). In 1825, J. Eve received a patent on what was then considered a centrifugal, but was actually the beginning of modern rotary pumps. (The rotary history is well described by R. Hadeckel in the 1939 *The Engineer* (London). Blake, working in the United States, developed the semi-open

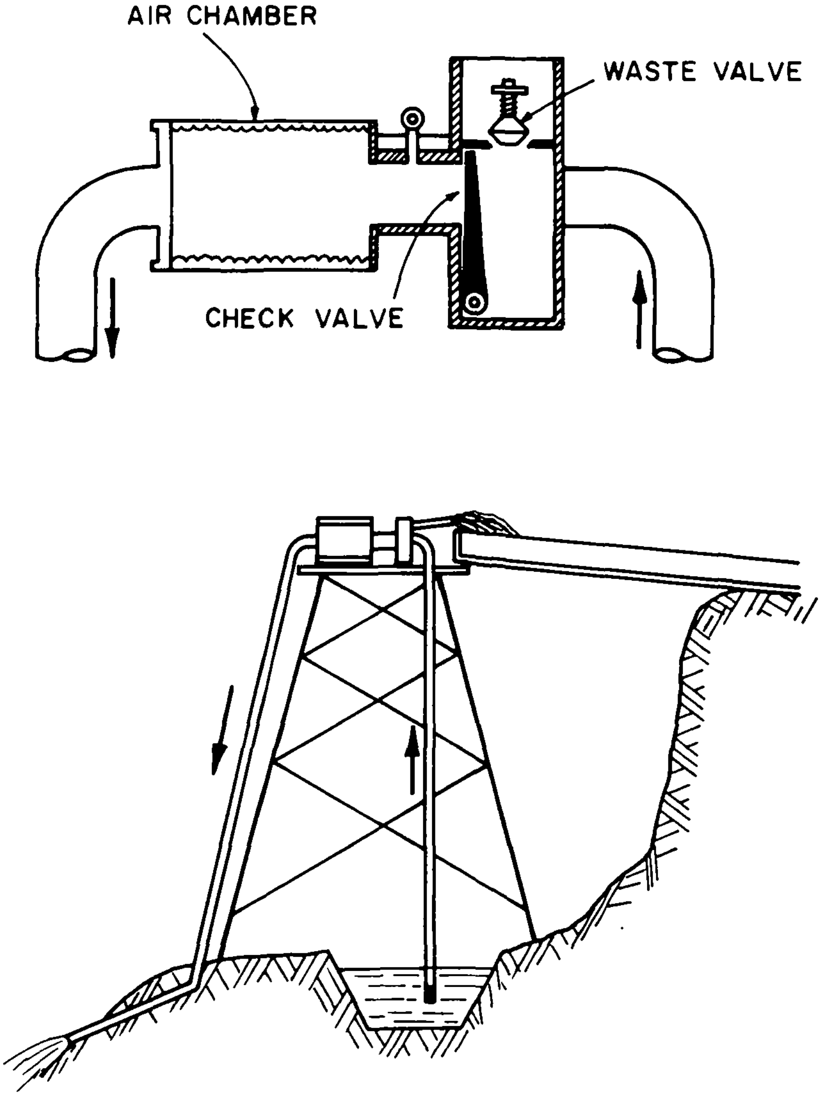


Figure 1.8 Siphon elevator

impeller in 1831, while another American, Andrews, found that curved vanes could increase efficiency threefold over straight vanes. Meanwhile in England, Appold and Thompson developed the currently used "backward" curved vanes and guide vanes, respectively. Then, in 1844, another Englishman, Gwynne, built a pump combining the semiopen impeller and guide vanes. About the same time, W. H. Johnston built the first multistage (three stages) vertical pump and Bessemer introduced the first close-coupled pump and motor combination.

Although rotodynamic pumps were beginning to gain acceptance, two events continued to overshadow and delay their development. In 1840, Henry Worthington culminated all previous work on steam pumps with his invention of the direct-acting steam pump--a timely device for the industrial revolution. Also about this time, the westward movement in the United States was starting settlement of the Great Plains. This settlement demanded the development of all available water resources and two important keys to this development were the piston pump and windmill. Although large Dutch type windmills had long been used in Eastern America, a small, easy-to-build mill was needed for the pioneer. Thus, such an "American style" windmill came into being with Daniel Halladay's patent in 1854. The design of this almost entirely wooden mill eventually lead to T. O. Perry's steel Aermotor in 1883. The windmill and "rod pump" remained the primary life-giving water lifter of the West until the Great Depression and rural electrification. (Vadot (1957), H. M. Wilson (1896), and E. C. Murphy (1901) give interesting accounts of Western windmill history.)

Also during the 19th century, much attention was given to the *scoop-* and *flash-wheels* in Holland. Using large steam engines, these wheels were the keys to draining the valuable polder land (*The Engineer*, 1869 and 1870, and C. S. Slichter, 1910).

In his 1841 edition of *Hydraulics*, Ewbank describes several "novel" devices for lifting water called *injectors* and *ejectors*. However, in 1850, Lord James Thomson of England received a patent on his "Thomson pump" which was the beginning of the modern ejector nozzle design. Then, in 1860, Henri Gifford designed a similar nozzle for steam boilers (i.e., injector) which grew rapidly in popularity with their use in locomotive boilers (Kneass, 1903).

In 1880, J. P. Frizell obtained the first patent on the *air lift* method, i.e., injecting compressed air into a column of water. The 1890 *Engineering News* discusses the "development of (this) absolutely new type of pump."

Meanwhile, the use of centrifugal pumps was growing as high-speed drivers such as steam engines, electric motors, turbines, and Pelton wheels became available. In 1875, Osborne Reynolds developed *diffuser vanes* which he later used to build the first *vertical turbine* pump in 1887. After these many years of intermittent centrifugal development, the Sulzer brothers began the first systematic and scientific testing program of pumps in 1890. This encouraged many other machinery works to undertake pump manufacturing. By 1905, Roger could write, "...centrifugals have attained a degree of perfection which makes them a serious rival of the plunger pumps." This progress was also spurred by the higher discharges (50-60,000 gpm) which irrigation was demanding (particularly southern rice fields) and which positive displacement devices were incapable of delivering.

Several other pumps were developed during this time, but the widespread use of direct-acting pumps and growing popularity of roto-dynamic pumps usually suppressed their development. However, one such unique pump was *Humphrey's gas pump* shown in figure 1.9. *The Engineer* of 1909 describes in detail the operation and testing of this pump developed from the principle of John Barbers' 1791 explosion engine.

In 1939, *Water Supply Engineering* discusses advances in pumping over the past decade which include the development of submersible pumps, invention of vertical, helical pumps, development of water lubricated vertical pumps, improvement of centrifugal efficiencies to as high as 93 percent, and increasing use of close-coupled units, as well as noting that "...electric (power) is holding its own...," but diesel engines are becoming more popular.

Except for many refinements and an ever increasing number of designs, this brief history has reviewed the development of water lifting devices to the state at which they exist in the world today.

1.3 Current Trends

The state of water lifters in the world today is highly diversified, both in levels of development and variety of designs. In some areas of the world, designated community members, using only hollow bamboo poles for containers, spend most of every day walking miles to distant water sources and returning with barely enough water for minimal domestic purposes--let alone irrigation. Meanwhile--typical of many unevenly distributed technical and natural resources--other areas have thousands of types and sizes of pumps with which to lift and transport ample water for all forms of domestic, industrial, recreational, and agricultural uses.

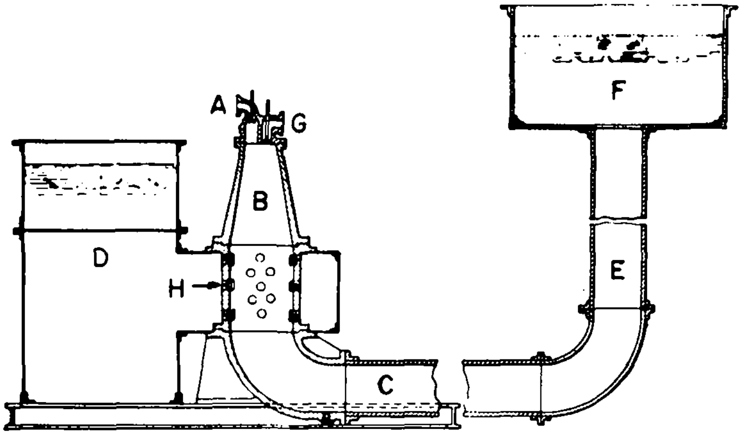


Figure 1.9 Humphrey's explosion pump

In industrialized nations, water lifting is a highly technical and competitive industry. The United States has well over 500 pump manufacturers (Thomas Publishing, 1974) with almost countless numbers of accessory suppliers, well contractors, and complementary industries (e.g., pipes, engines, motors, transmissions, etc.). Likewise, England has some 200 pump manufacturers (Pumping Manual, 1964). Deep well submersible pumps are used to lift water hundreds of feet to supply high-pressure-sprinkler systems which irrigate miles of once "desert" land. Giant axial-flow pumps move hundreds of thousands of gpm through vast pipelines of water supply systems. Equally sophisticated motors, engines, and control devices are used to drive and regulate these pumps.

In these developed countries, the irrigator has usually been concerned with getting the highest discharge possible out of his pump with little worry over maximizing efficiency (Colorado Power Council, 1975). However, with the rising cost of conventional energy forms (e.g., gas, diesel, electricity), the pump user is looking to improve efficiencies as a means of reducing increased operating costs.

Several users are also looking toward natural energy as a cheaper source of power. Until recently, conversion of natural energy, e.g. solar, to usable power was too expensive to compete with conventional power (i.e., gas, diesel, electric). However, shortages and the rising cost of these conventional sources of energy are making the harnessing of natural energy more competitive economically, while technology is increasing their feasibility. As will be seen in Chapters 3 and 5, solar pumps and engines are currently in use and being improved. Geothermal heat is being located and harnessed--

although not normally feasible for direct agricultural pumping, it can provide cheaper electric power. Many modern irrigators are returning to prime movers of the "past"--the windmill and watermill--to provide cheaper power.

Meanwhile, in developing countries, water lifting is caught among the inadequacies of ancient methods, the introduction of modern pumps, and the uncertainty of the world's energy situation. In these countries, it is not uncommon to see a farmer pedaling a wooden water paddle, while alongside his field runs a high speed railway. The cheap and abundant supply of human and/or animal power in most developing areas makes them the prime source of energy for driving water lifters and pumps. When modern pumps and drivers are available in these areas, they are often in poor condition due to lack of maintenance facilities and parts, and/or proper operational instruction to the user.

Several international assistance organizations, e.g., Agency for International Development (AID), Peace Corps, Food and Agriculture Organization (FAO), Volunteers in Technical Assistance (VITA), and International Rice Research Institute (IRRI), are working to improve existing water lifters in these areas and to develop new, more efficient methods, e.g., see Allison (1975), Fannon and Frink (1970), Kuether (1976). One of the major objectives of this work is to allow manufacture of these devices at the local level of industrialization. Prime movers, such as windmills, are also being studied to suggest improvements and provide simple construction plans for local craftsmen--e.g., see Bossel (1970), Bodek (1973).

This state-of-the-art reviews the present status of water lifting as it exists in both developed and developing countries. Examples of recent and current studies on water lifters and prime movers are mentioned throughout. Undoubtedly, some existing research in this vast industry has been missed, however, it is hoped that some technological gaps and needed improvements are suggested--either explicitly or implicitly.

Chapter 2

Water Lifting Principles

2.1 Classification of Methods

In order to provide a complete and methodical discussion of the wide variety of water lifting devices and pumps, a classification system is necessary. Throughout the available literature, several criteria are suggested as methods of classification. Table 2.1 lists these criteria and examples of each.

Table 2.1 Criteria for classifying water lifters

	Criteria	Examples
1)	Basic design	screw, piston, vane, wheel
2)	Method of energy transmission	steam, compressed air, mechanical
3)	Number of displacements	single, multiple, continuous
4)	Arrangement of components	internal gear, outside packing
5)	Orientation of axis	vertical, horizontal, incline
6)	Number of stages	single, double, multiple
7)	Casing type	volute, diffuser, split
8)	Material of construction	bronze, steel, wood
9)	Application of device	sewage, boiler-feed
10)	Working principle	rotary, reciprocating, centrifugal
11)	Method of increasing head	positive displacement, kinetic

The Hydraulic Institute, as well as many other references, combine several of these criteria into one classification arrangement--see Hydraulic Institute Standards (any edition) and Hicks and Edwards (1971).

Unfortunately, none of these classification systems include the numerous early devices, many of which are still utilized in developing countries and are included in this paper. Therefore, it was necessary to develop such an all-encompassing system which would be the basis for further discussion. Since all devices can be grouped under one of the two methods of increasing head (#11 in table 2.1)--*positive displacement* or *kinetic*--these are the two primary classes for the system shown in table 2.2 and the basis for the breakdown of all devices and discussion of their operation in Chapters 3 and 4. Within each of these two primary classes, table 2.2 further suggests an arrangement of subclasses, utilizing several of the criteria listed in table 2.1. For completeness, all major water lifters that could be found by the literature review for this paper are included in Chapters 3 and 4. However, several of these devices are not practically suitable for irrigation or drainage applications and are therefore mentioned only to the extent of explaining their basic operation. For example, the close tolerances and low capacities of most rotary pumps exclude their efficient use for pumping abrasive irrigation or drainage water. However, inclusion of their basic designs and operation may suggest improvements to, or combinations of, other water lifting devices which can be considered in future studies. After examining the operation of all the water lifters in Chapters 3 and 4, and discussing their applications in Chapter 5, a few such possible improvements and studies are proposed in Chapter 6.

In a few cases, water lifting methods are combinations of subclasses from both primary classes. For example, the hydraulic ram utilizes the *kinetic* energy of falling water to drive it, but has

Table 2.2a Classification of water lifters and pumps--positive displacement methods

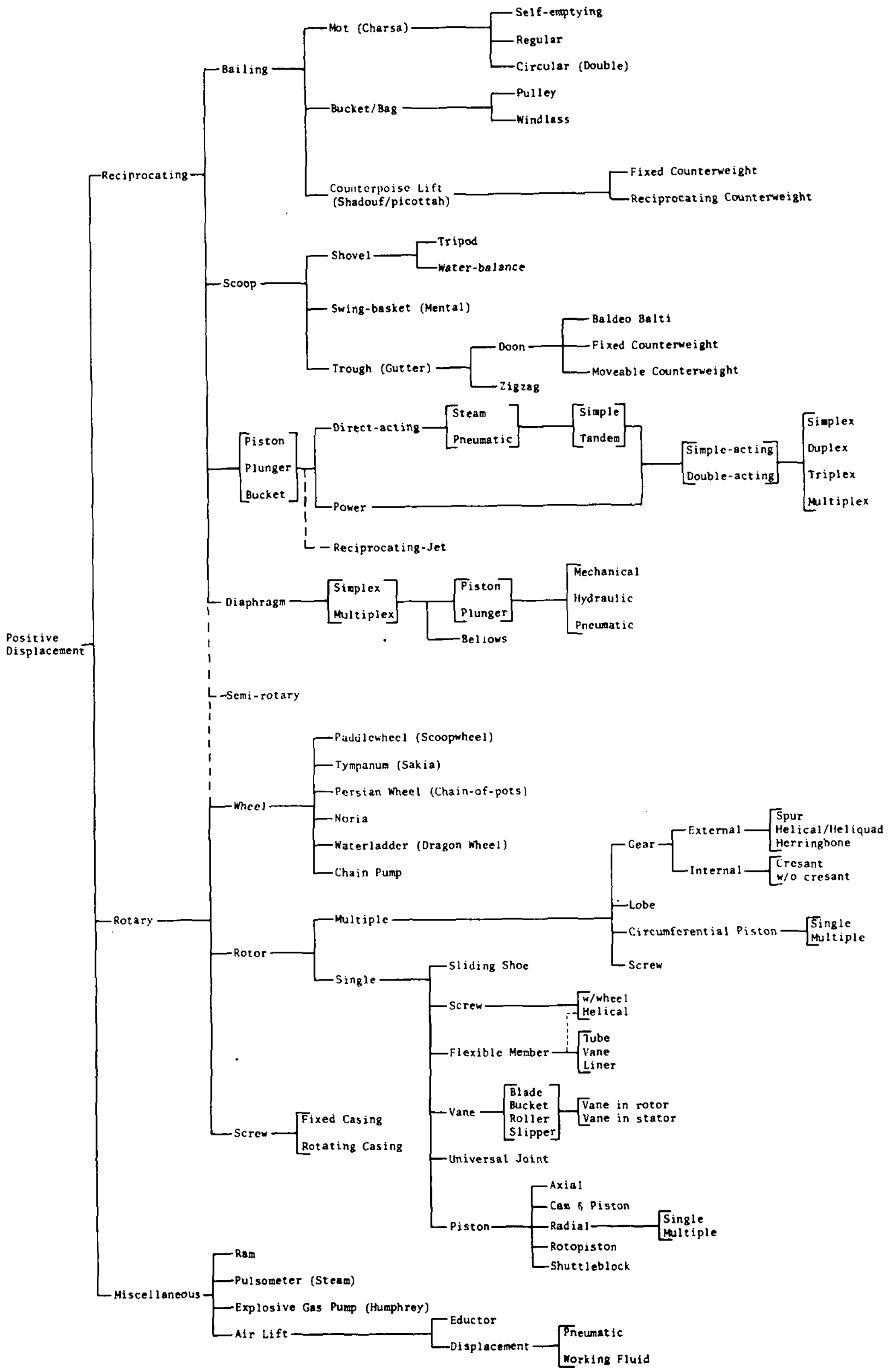
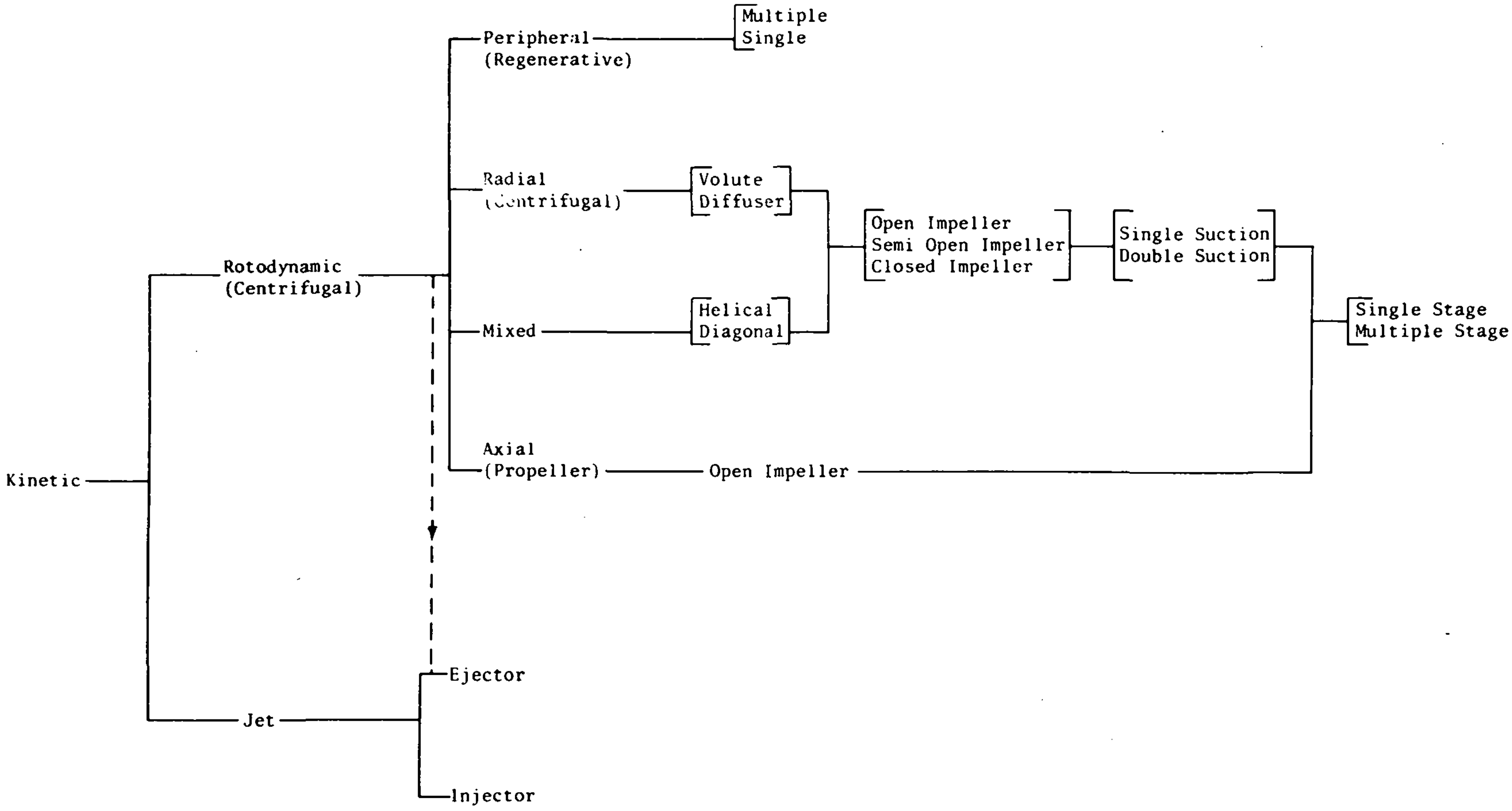


Table 2.2b Classification of water lifters and pumps--kinetic methods



a *positive displacement-reciprocating* action. However, because the ram, as well as each of the other combination cases, exhibit primarily positive displacement characteristics (see Chapter 3), they have been grouped under a "miscellaneous" positive displacement class.

Where possible, the operation of water lifting devices has been discussed without consideration for any specific driver, since in most cases, several prime movers can be adapted for each device, e.g., the centrifugal pump can be driven by manual, diesel, or electric power. However, for several water lifters, particularly the "early" manual methods, their operation is dependent on only one prime mover and will therefore be discussed as a single unit. Using the hydraulic ram again as an example, it cannot be operated with any other prime mover than a falling fluid, usually water. Similarly, the mot is characterized by using animal power to pull a rope and bucket and is discussed as such a single, lifter/prime mover combination. Although a specific driver may be given as an example of possible applications, the selection and operation of prime movers is reviewed in Chapter 5.

It should also be mentioned that the terminology used throughout this paper reflects either the most commonly used nomenclature where several terms exist for the same device or characteristic, or the most physically correct nomenclature where currently popular terms are confusing or misused. This is further explained in the following section and Chapters 3 and 4.

2.2 General Terminology and Theory

Several basic principles are common to all types of water lifting methods. Before selecting a specific method or installation for a given situation, several characteristics, e.g., head, discharge, and power, must be considered--see section 5.2. These considerations apply equally as well for the manually-operated devices such as the shadouf as for the high-speed centrifugal pump. For example, if the elevation difference through which a man must lift a bucket of water is too great for him to manage without tiring quickly, it may be necessary for him to utilize a different method of lifting. Likewise, if a centrifugal pump is not chosen correctly, it will operate inefficiently and waste energy. Therefore, this section will discuss the basic water lifting parameters; head, discharge, power, and efficiency as they apply to all methods. Additional discussion will follow on these parameters in the chapters on positive displacement and kinetic methods as they specifically apply to those methods. It is not the intent of this paper to review the theory of hydraulics, but only to define the terms basically relevant to water lifting as they will be used in later sections.

Throughout this text, an effort has been made to use the most common units of measurement as they appear in the literature. However, tables are available in the Appendix for conversion to other frequently used units.

2.2.1 Discharge or Capacity (Q)

Discharge is the quantity of water per unit time (e.g., cubic feet per second, cfs; gallons per minute, gpm) which a lifting device or pump handles. Since losses may occur with a device or pumping system, discharge is usually taken to be the quantity/time measured at the point where the water leaves the device or pump. Discharge depends on the size of the water lifter and the speed at which it is operated.

For example, a bucket filled with 2 cubic feet of water and lifted once every 10 seconds, discharges (if no leakage or spillage)

$$Q = \frac{2\ \text{ft}^3}{10\ \text{sec}} = 0.2\ \text{cfs},$$

as does a bucket filled with 4 ft^3 and lifted once every 20 seconds.

2.2.2 Head (H)

The term *head*, as applied to water lifting, has several components, each one a specific form of energy present in the lifting system. In most irrigation and drainage applications, head terms are usually expressed as the height of a column of water which contains an equal amount of potential energy, e.g., feet of water. Only in sprinkler and trickle irrigation does a pump discharge into a "closed" system, which more commonly expresses head as a pressure, e.g., pounds per square inch (psi). Table A.4 includes several head measurement units and their conversion. The components of head, as they normally apply to irrigation and drainage, are as follows:

(a) *Static suction head* (H_{SSH}) or *submergence* is the height of supply-water, if any, which exists above a pump centerline, as in figure 2.1, when the system is at rest. In devices, such as the screw in figure 2.2, which has no suction capability, H_{SSH} is the height of water above the device's inlet elevation, i.e., the elevation at which the minimum submergence (ms) necessary to have a discharge greater than zero from the device exists. As with other static head terms, the word *geometrical* is often substituted for static since static heads are the actual vertical distance measured between the supply water surface and the respective pump or device

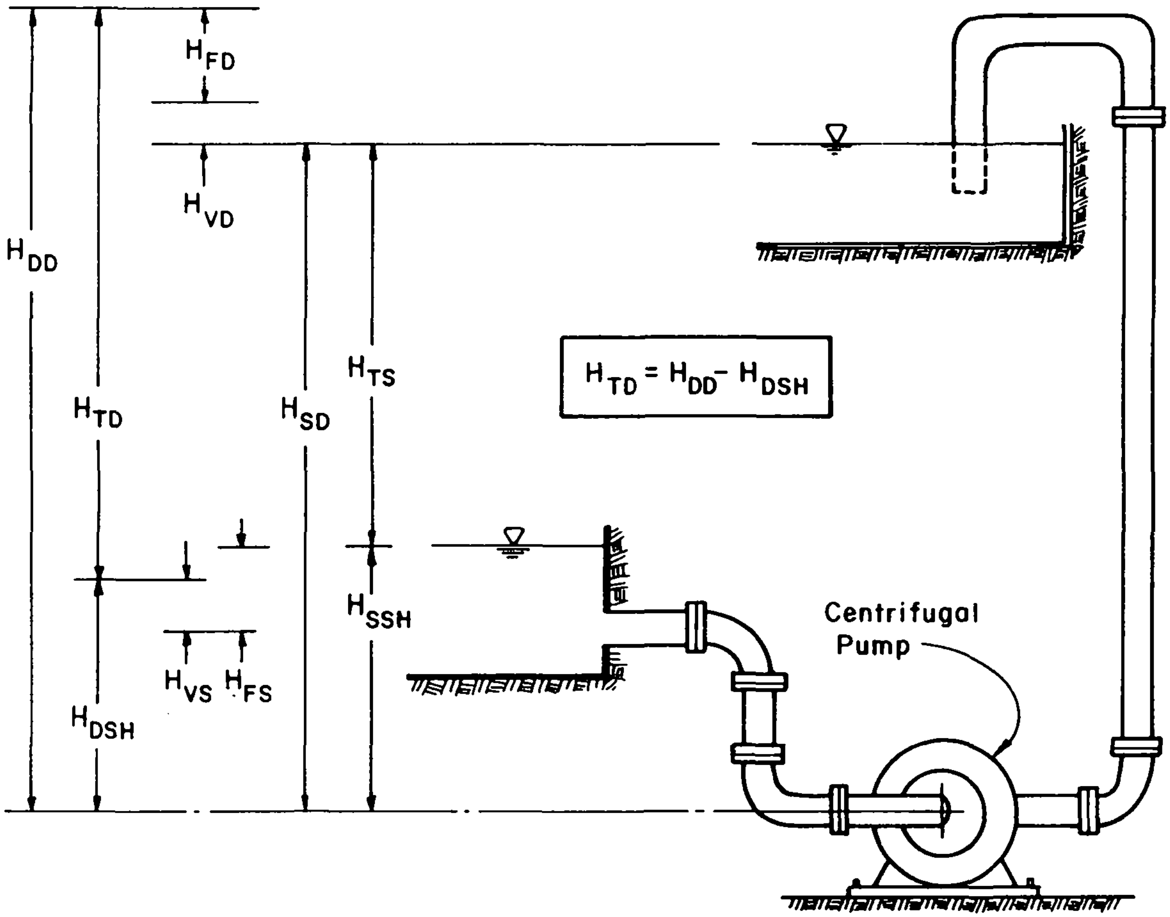


Figure 2.1 Pump with suction head

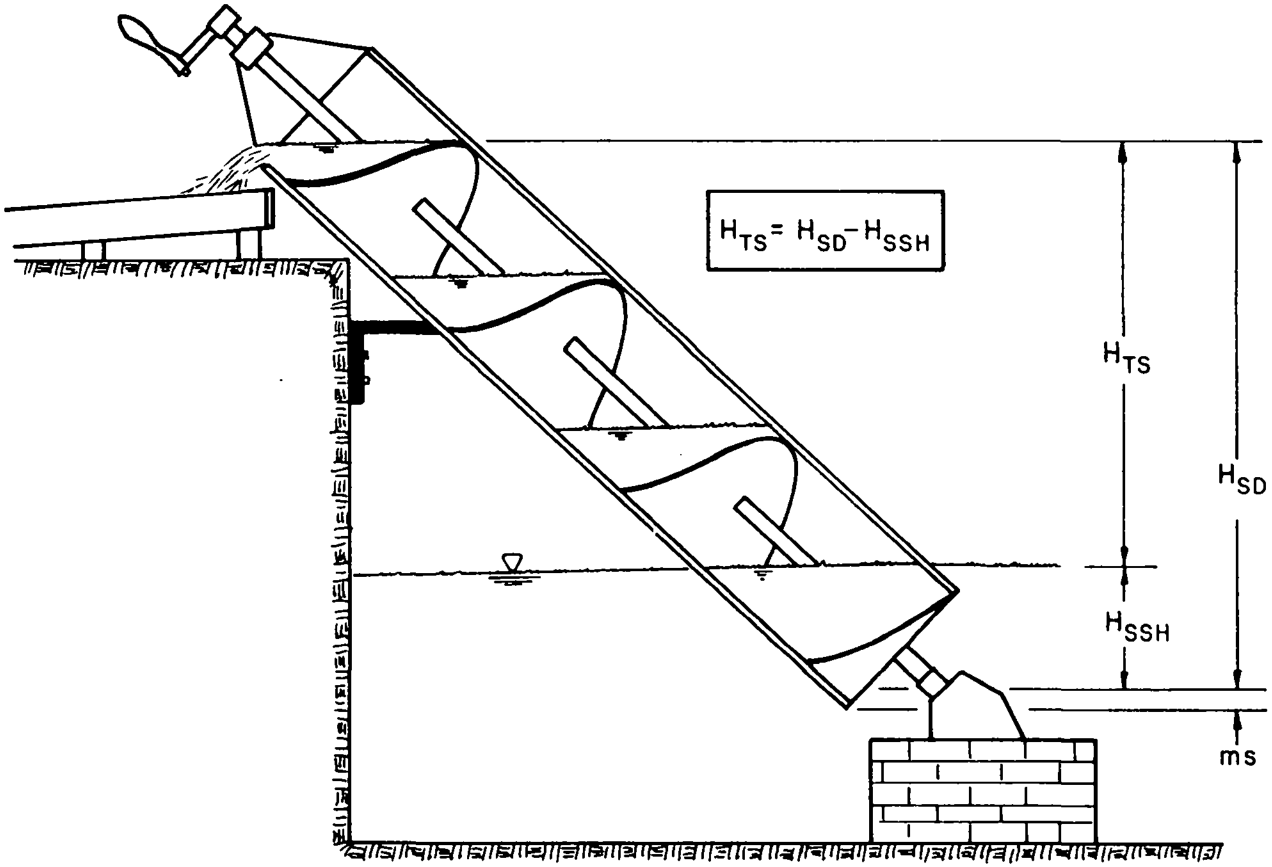


Figure 2.2 Head on Archimedean screw

elevation. As originally noted, if drawdown (D) occurs while the water lifter is operating, e.g., figure 2.4, H_{SSH} is measured from the starting, or static, water level.

(b) *Static suction lift* (H_{SSL}) is the vertical distance from the static water level to the pump centerline where the water supply exists below the pump as in figure 2.3.

(c) The *static discharge head* (H_{SD}) is similarly the vertical distance from the pump centerline or device inlet elevation to the elevation of "free" delivery. This free discharge point will vary with the lifting system. In figure 2.2, this point is at the orifice of the discharge pipe, while in figure 2.1, it is the water surface in the upper reservoir. In a pressure system, such as figure 2.4, this distance would be to the point at which a specified pressure is to be delivered, e.g., a sprinkler main.

(d) *Total static head* (H_{TS}) is the vertical distance from the static supply surface to the free delivery elevation, i.e., from figure 2.3.

$$H_{TS} = H_{SSL} + H_{SD} , \qquad (2.1)$$

or from figures 2.1, 2.3, and 2.4,

$$H_{TS} = H_{SD} - H_{SSH} . \qquad (2.2)$$

(e) *Velocity head* (H_V) can be expressed as the distance water must free fall to obtain a given velocity, i.e., $H_V = v^2/2g$. This is the amount of kinetic energy which exists as moving water. Except at very high velocities, in low head systems, and for accurate testing, this head term is usually not

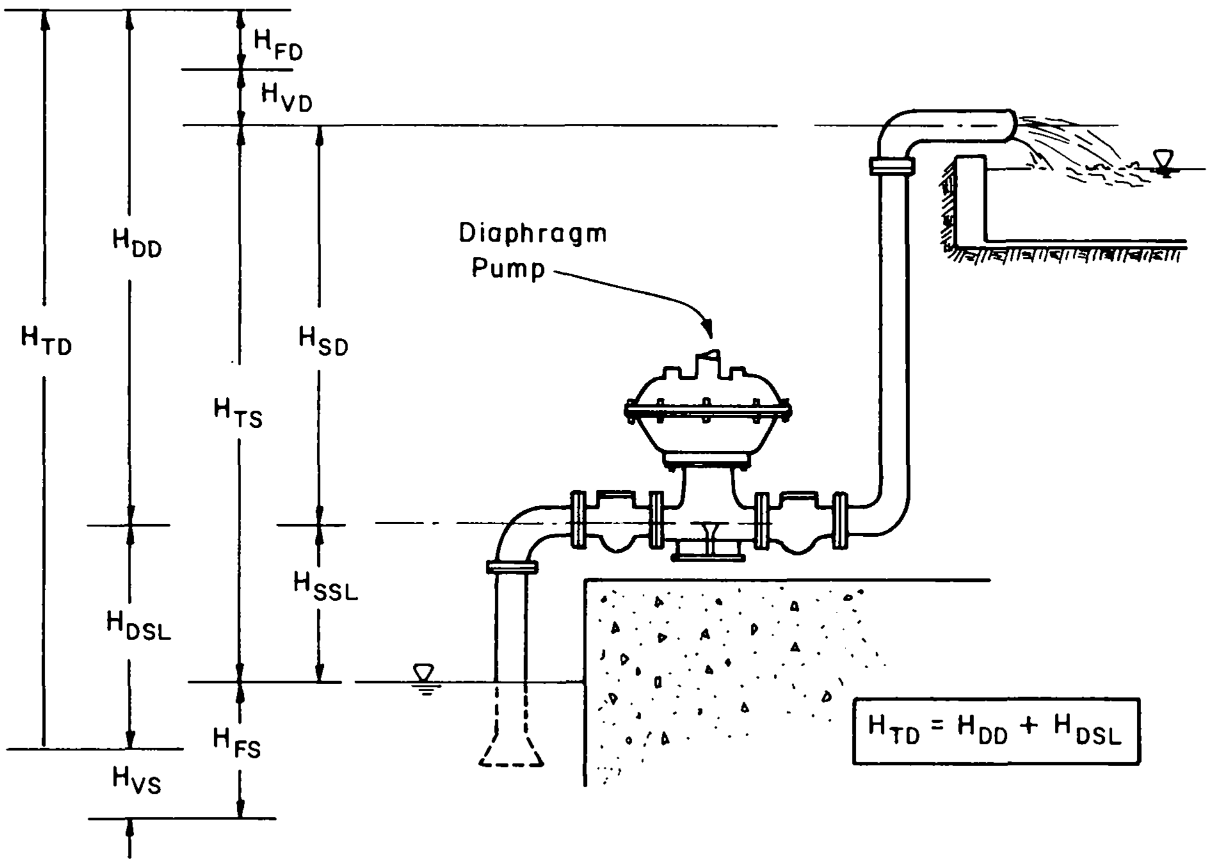


Figure 2.3 Pump with suction lift

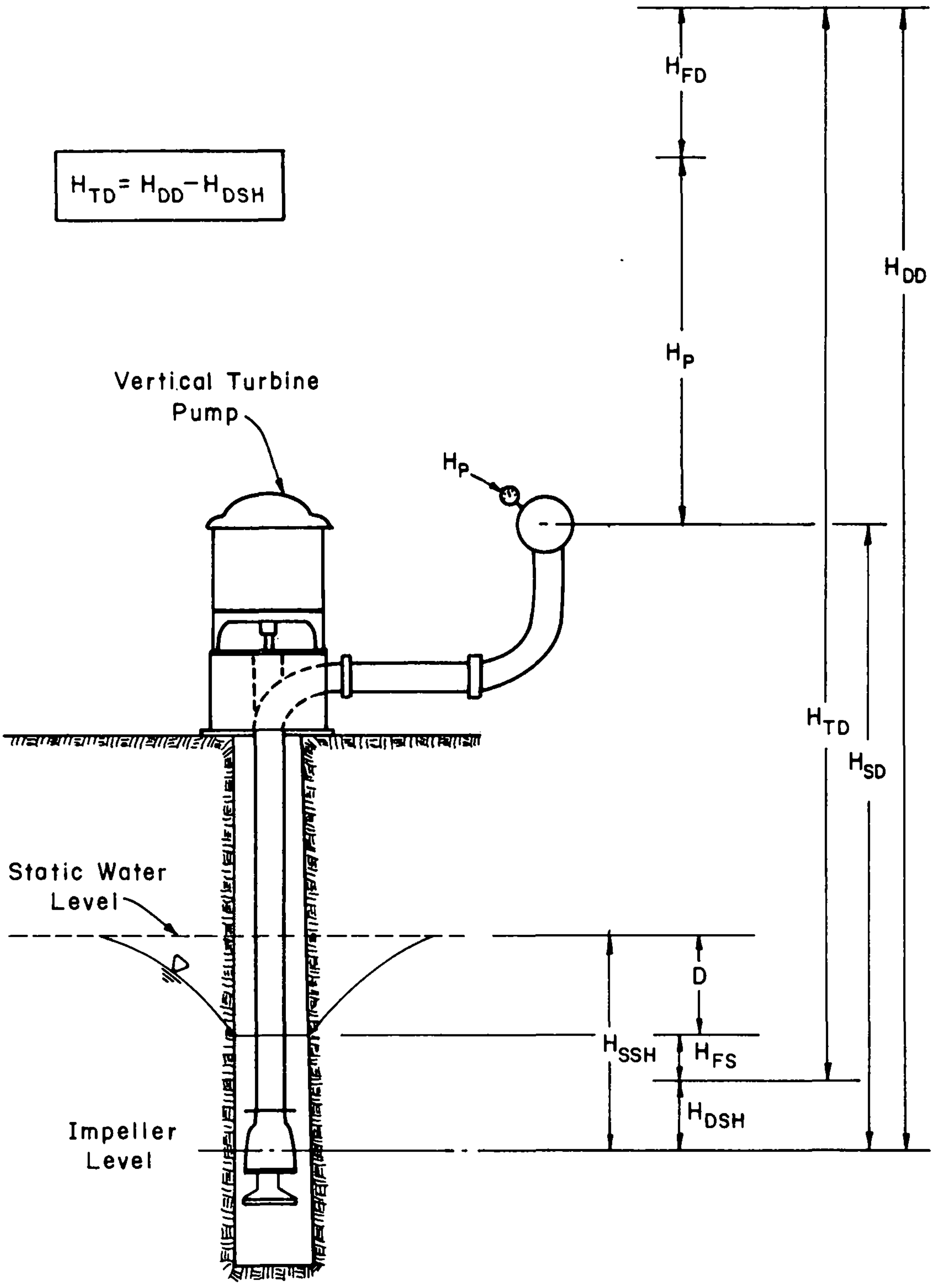


Figure 2.4 Pump with drawdown and pressure discharge

great enough to be significant; e.g., at 8 fps, $H_V = v^2/2g = 1$ ft. For illustration, H_V has been shown in figures 2.1 and 2.2, however it is neglected thereafter. (Note that the subscripts S and D used with the V denote suction and discharge lines, respectively.)

(f) *Friction head* (H_F) is the amount of head needed to overcome the resistance created by the system, including pipe skin, bends, intakes, valves, etc. Tables and nomographs in hydraulic handbooks and texts are best used to determine friction heads (see Hydraulic Institute Standards; Davis, 1942; Schwab, et al., 1966).

(g) *Pressure head* (H_P) need only be considered in systems such as figure 2.4 where the pump discharges into a pressurized system, e.g., sprinkler irrigation. The pressure required by such a system at a given elevation can be converted into an equivalent height of water, e.g., 1.0 psi = 2.31 ft of water.

(h) *Acceleration head* (H_A) is a form of head which need only be considered in high speed reciprocating pumps and, like velocity head, is usually not significant in irrigation or drainage systems. A thorough discussion of H_A can be found in the Hydraulic Institute Standards (any current edition).

(i) *Drawdown* (D) is the vertical distance, if any, which the free surface of a water supply falls while the water lifter or pump is in operation. This usually applies to well sources as in figure 2.4.

(j) *Dynamic (or total) suction lift* (H_{DSL}) is the sum of the static suction lift, suction friction head, and drawdown (if any), minus the suction velocity head (if considered). As shown in figure 2.3,

$$H_{DSL} = H_{SSL} + H_{FS} - H_{VS} . \qquad (2\text{-}3)$$

(k) *Dynamic suction head* (H_{DSH}) is the sum of the static suction head and suction velocity head, minus suction friction head and drawdown. In figure 2.1,

$$H_{DSH} = H_{SSH} + H_{VS} - H_{FS}, \qquad (2\text{-}4)$$

while in figure 2.4 (not considering H_{VS}),

$$H_{DSH} = H_{SSH} - H_{FS} - D . \qquad (2\text{-}5)$$

(l) *Dynamic discharge head* (H_{DD}) is the static discharge head plus the discharge friction and velocity heads, plus any pressure head. In figures 2.1 and 2.3, where velocity head is considered,

$$H_{DD} = H_{SD} + H_{VD} + H_{FD} \qquad (2.6)$$

and in figure 2.4, where a pressure head exists,

$$H_{DD} = H_{SD} + H_{FD} + H_{P} . \qquad (2.7)$$

(m) *Total dynamic head* (H_{TD}), also referred to as *effective head* or just *total head*, is the entire energy potential of the system against which the water lifter or pump must operate. Where a suction head exists, as in figure 2.1,

$$H_{TD} = H_{DD} - H_{DSH} , \qquad (2.8)$$

but where a suction lift is present, as in figure 2.2,

$$H_{TD} = H_{DD} + H_{DSL} \quad . \qquad (2.9)$$

As shown in figure 2.5, the total static head will remain constant for any discharge of the water lifting system. However, because velocity increases with discharge, the velocity and friction heads, being a direct function of velocity, will increase. Similarly, in applications of high capacity pumps in wells, or where a fixed or slow recharging water supply exists, drawdown also increases with discharge. Thus, as the discharge of a pump increases, the total head against which it must operate also increases, as characterized by the example *system head curve* of figure 2.5. As pumping systems become more complex with various combinations of pumps and piping arrangements, their system head curves will vary in shape. Most hydraulic and manufacturer's handbooks explain the basic principles needed to develop such curves--see Hicks and Edwards (1971), Colt Industries (1974), Carter (1949), Finch (1948), Goulds Pumps, Inc. (1973), and Walker (1972). Chapter 5 will discuss the use of these system head curves in selecting efficient water lifters to fit given applications.

Two additional head terms need to be discussed concerning any water lifting device which operates with a dynamic suction lift. They apply particularly (but not limited) to rotodynamic pumps, which cannot displace air sufficiently enough to reduce intake pressure and thus "suck" water.

Net Positive Suction Head Required (NPSHR) is a function of a specific pump's design and is determined by the pump manufacturer. NPSHR is the maximum dynamic suction lift which a pump can handle

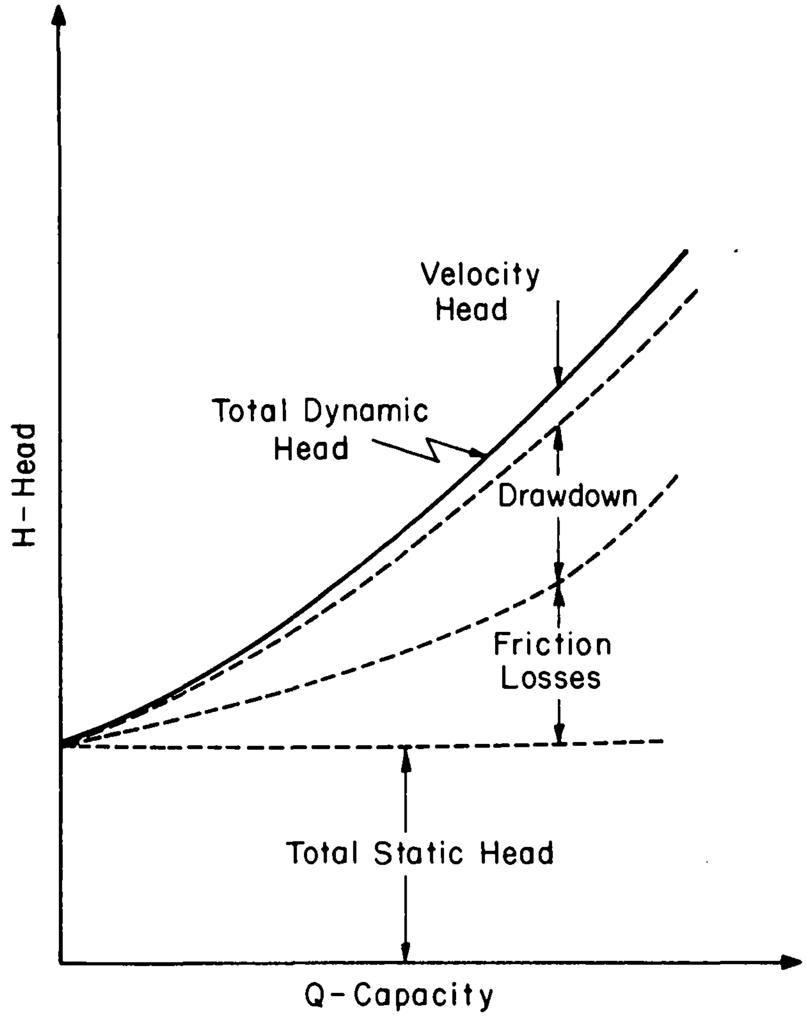


Figure 2.5 Example system head curve showing the change of TDH components with Q

without allowing the head (or pressure) in the pump to drop below the vapor pressure of the pumped liquid. If the pressure anywhere in the pumping system drops below this vapor pressure, *cavitation* will likely occur which can sharply decrease the performance of the pump (see section 4.2.5) and if severe enough can damage the pump and/or piping (Rouse, 1950). To insure that this phenomenon does not occur, the *Net Positive Suction Head Available* (NPSHA) should be determined for any pumping system planned, and should always exceed the NPSHR. From figure 2.6,

$$\text{NPSHA} = P_{atm} - H_{SSL}(\text{or} + H_{SSH}) - P_V - H_F \qquad (2.10)$$

where P_{atm} = absolute atmospheric pressure, and

P_V = vapor pressure of pumped liquid.

P_{atm} must be obtained for the local atmospheric conditions and altitude, while P_V is a function of the liquid's volatility at a given temperature. These pressures can usually be found in pump handbooks or hydraulic texts, e.g., see Walker (1972), p. 13. Of course, all pressure or head terms must be in the same units of measurement, usually feet or meters of water. By also subtracting the velocity head (H_V) from the NPSHA, the "useful NPSHA" which actually exists at the pump (not the pump system) intake can be determined (Walker, 1972). Again, H_V is usually not large enough to be significant and is included here only to clarify terminology often improperly used when discussing head. Table 2.3 is a guide to the theoretical dynamic suction lifts which pumps could be capable of based on atmospheric pressures at different altitudes. However, because of internal losses, pumps--particularly kinetic pumps--are limited to lower lifts. These lifts will vary with individual pump NPSHR, however, Table 2.3 also lists practical values that can be expected at various altitudes.

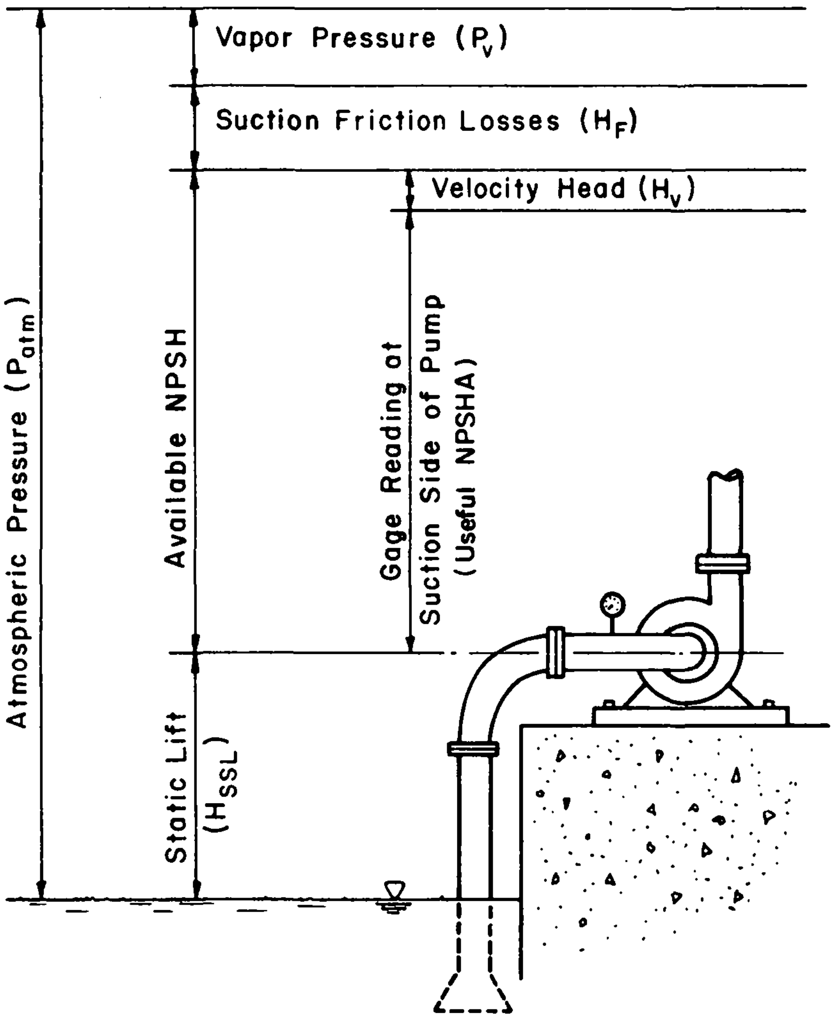


Figure 2.6 Net positive suction head (NPSH)

Table 2.3 Theoretical and practical dynamic suction lifts by altitude

Altitude			Standard Barometric Pressure	Theoretical H_{DSL}		Practical* H_{DSL}	
mi	ft	m	psi	ft	m	ft	m
Sea Level			14.70	33.95	10.35	25	7.6
0.25	1320	403	14.02	32.38	9.88	24	7.3
0.50	2640	805	13.33	30.79	9.39	23	7.0
0.75	3960	1208	12.66	29.24	8.92	21	6.4
1.00	5280	1610	12.02	27.76	8.47	20	6.1
1.25	6600	2013	11.42	26.38	8.05	19	5.8
1.50	7920	2416	10.88	25.13	7.66	18	5.5
2.00	10560	3220	9.88	22.82	6.96	17	5.2

*From Water Well Handbook, K. E. Anderson, 1973.

2.2.3 Power (HP)

Any water lifting device adds energy to the water on which it acts, either by raising it to a higher elevation and/or increasing its pressure, in the case of a sprinkler system. This addition of energy can be expressed by Bernoulli's equation:

$$\frac{P_1}{\gamma_w} + \frac{v_1^2}{2g} + Z_1 + E_p = \frac{P_2}{\gamma_w} + \frac{v_2^2}{2g} + Z_2 + H_F \qquad (2.11)$$

where:
P = water pressure
v = water velocity
γ_w = specific weight of water
Z = water elevation
E_p = energy added by pump
H_F = friction in pumping system
g = acceleration of gravity
1,2 = indicate state of water before and after pump, respectively.

Rewriting equation 2.11 in terms of the head components previously developed,

$$E_p = H_{SD} + H_{SSL}(\text{or } - H_{SSH}) + \Delta H_p + \Delta H_V + H_F \qquad (2.12)$$

$$\therefore \quad E_p = H_{TD} \,. \qquad (2.13)$$

The rate at which the pump adds this energy or head to the water is called the *water horsepower* (WHP) and can be found as

$$WHP = \frac{Q \cdot H_{TD} \cdot \gamma_w}{K} \qquad (2.14)$$

where K is a constant depending on the units of measurement used for the other terms. When Q is in cfs, H_{TD} is in feet, and WHP is to be expressed in horsepower (hp), then K = 550, while if metric units are to be used, K = 75. (See the Appendix for conversions to other units.

Of course, since water lifting devices like any other machinery have losses (e.g., internal friction, slippage, leakage, etc.), in order to add a given WHP to the water, some higher brake horsepower (BHP) will have to be applied to the pump. This BHP will be the energy which must be delivered to the pump by its prime mover. It should be noted here that this parameter of power is not limited to mechanical prime movers, but that manual and animal BHP can be determined to evaluate the performance of water lifters utilizing such means of motivation. For example, since 1 hp = 33,000 ft-lbs/min, if two men lift a bucket and water weighing 100 lbs three feet, eleven times in one minute, then

$$\frac{11 \cdot 100 \text{ lbs} \cdot 3 \text{ ft}}{1 \text{ min}} = \frac{3{,}300 \text{ ft-lbs}}{\text{min}} = 0.1 \text{ hp} .$$

That is, they have put 0.1 hp of energy into the water lifter--the bucket.

2.2.4 Efficiency (Eff)

The *efficiency* of a water lifter is the ratio of energy added to the water over the energy put into the device to obtain the increase in water energy, or put in terms of power,

$$\text{Eff} = \frac{\text{WHP}}{\text{BHP}} . \tag{2.15}$$

Therefore, if in the example of section 2.2.3, the actual energy of water received at the three foot lift equals 0.075 hp (using equation 2.14) then,

$$\text{Eff} = \frac{0.075\ \text{hp}}{0.1\ \text{hp}} = 0.75 = 75\%$$

The amount this efficiency is below 100 percent represents the losses in the water lifter. In this simple example, the energy needed to lift the bucket alone (assuming no leakage) accounts for the other 25 percent. Of course, in more complex devices the previously mentioned factors such as friction, leakage, slippage, etc., will contribute to this loss of efficiency.

Similarly, an efficiency can be calculated for the prime mover which supplies the BHP into the water lifter. For example, 1.0 hp of electricity (= 0.7457 kw) may be applied to a motor, but only 0.8 hp of work is applied to the pump by that motor. It then has an 80 percent efficiency.

Where the method of transmitting the prime mover power to the water lifter is not direct, losses may also occur in the transmission. For example, when belts are used between a motor and pump, slippage and heat losses occur which prevent getting all the motor's output power to the pump. Thus, an efficiency for the transmission can also be calculated.

Multiplying all these efficiencies together produces the overall efficiency (OAE) of the water lifting operation, i.e., the percentage of energy put into the prime mover which will actually be added to the water. That is,

$$\text{OAE} = \text{Eff}_{\text{pump}} \times \text{Eff}_{\text{mover}} \times \text{Eff}_{\text{transmission}}. \qquad (2.16)$$

In systems using electric power, the OAE is often referred to as *wire-to-water efficiency*.

2.2.5 Performance Curves

Using various combinations of the parameters defined above, the performance of any water lifting device can be described graphically in *performance* or *characteristic curves*. Figure 2.5 showed how an H-Q curve is used to describe a pumping system, i.e., what total head must be produced to deliver a given discharge through that system. Likewise, an H-Q curve can be used to show at what head(s) a water lifter will deliver a specified discharge. These curves are not limited to modern pumps. Specific curves are given in Chapters 3 and 4 of various types of devices; however, the simple bucket can again serve as a good example. As the height (i.e., head) increases through which a person must lift a bucket of water, it can be expected that he will be able to deliver less buckets per unit time. So, this water lifter's H-Q curve may look something like figure 2.7. Similarly, the variation of BHP and Eff with Q can be plotted. These performance curves are not only for modern pumps.

These four characteristic parameters are often plotted together for a specific device using Q as the common abscissa, as shown in figure 2.8. (These curves are only an example and represent no actual device.) A fourth curve, NPSHR-Q, is also usually included for any pump which has NPSH limits, e.g., centrifugal pumps. These curves are given for a device operating at a constant speed and size. However, *composite performance curves* such as figure 2.9 combine the characteristics of various sizes of the same specific pump, operating at a constant speed. Such a composite usually shows the respective H-Q curves for each size and then superimposes constant BHP, Eff, and NPSHR lines over them. Similar composites are also used with H-Q

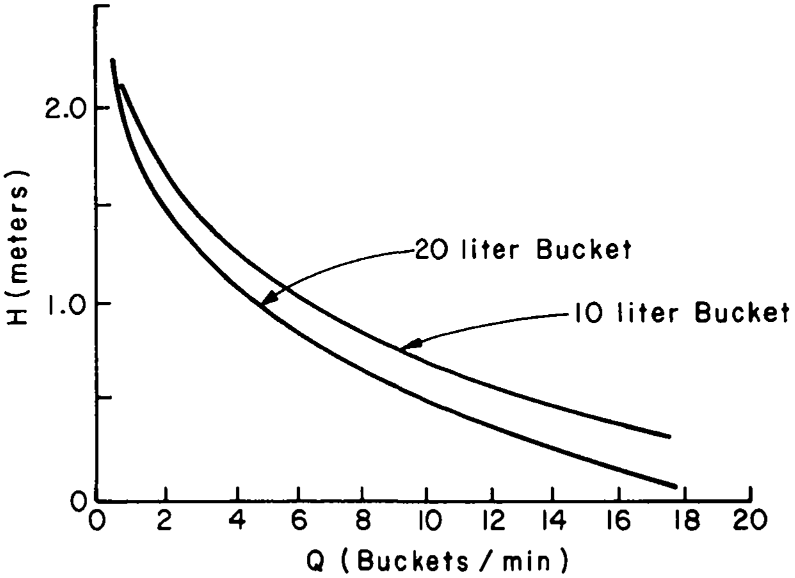


Figure 2.7 Example H-Q curve
(not based on actual data)

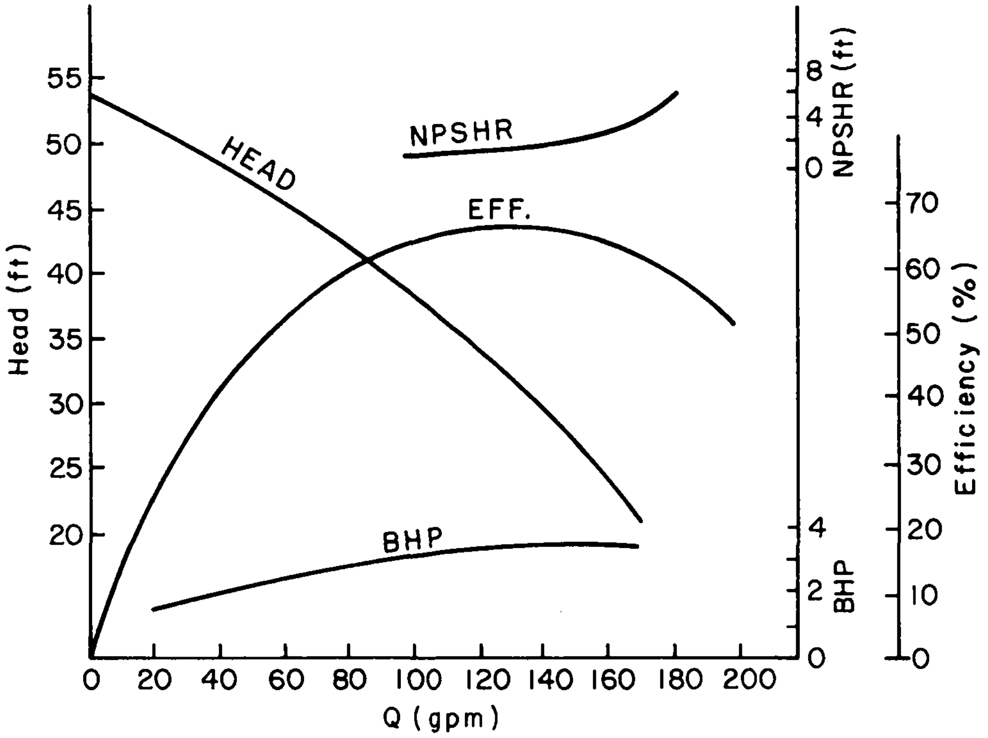


Figure 2.8 Performance curves

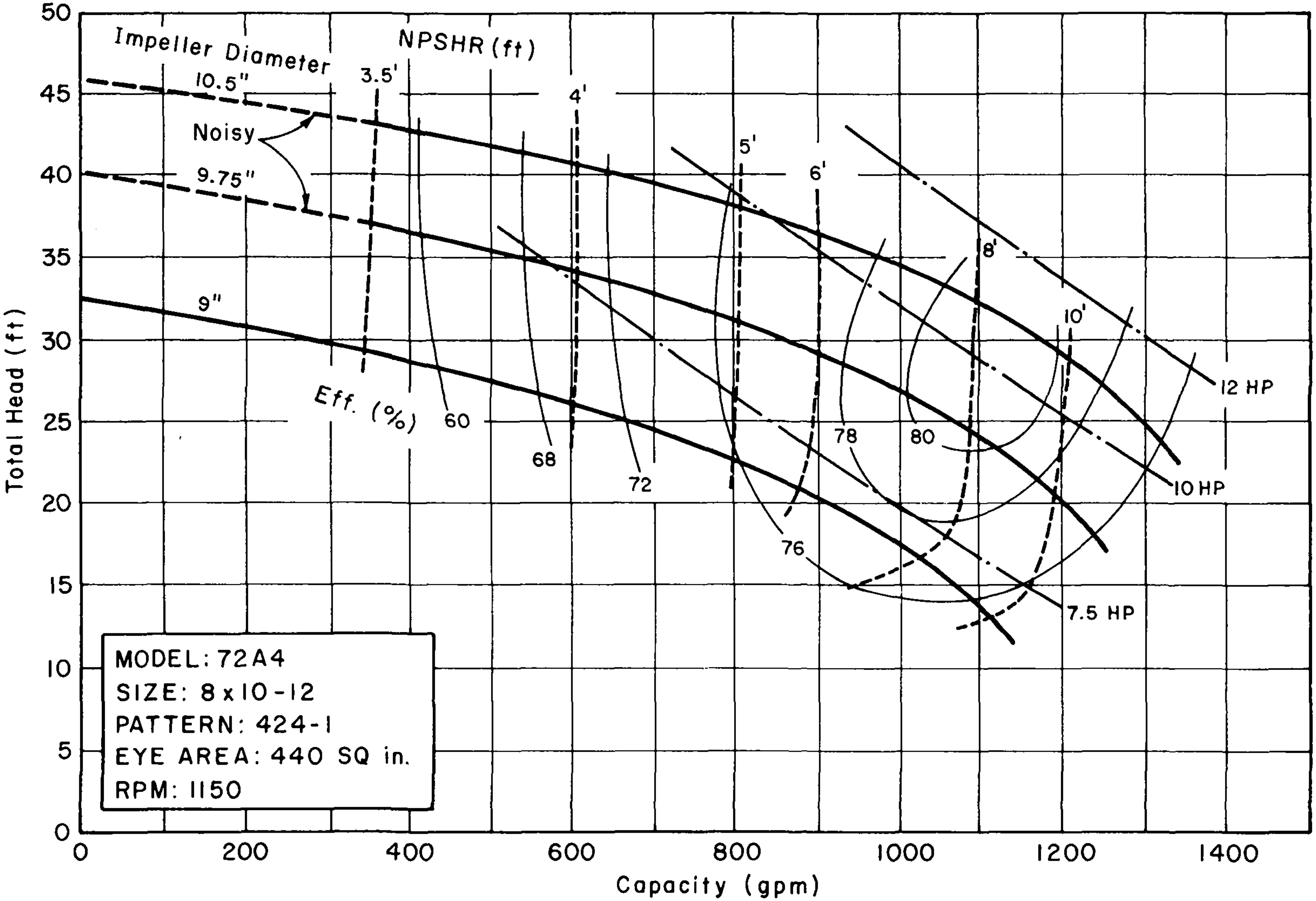


Figure 2.9 Composite performance curve

curves for various operating speeds of a constant pump size (Colt Industries, 1974).

Although the actual performance of any specific pump can be described only by its characteristic curves, a set of relationships called *affinity laws* can be used to closely predict performance changes due to changes in pump speed or size. For a pump of constant size or displacement;

Law 1a - $\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$

Law 1b - $\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$

Law 1c - $\frac{BHP_1}{BHP_2} = \left(\frac{N_1}{N_2}\right)^3$

where N = pump speed in revolutions per unit time (e.g., rpm) or strokes per unit time.

Similarly, for a pump at constant speed;

Law 2a - $\frac{Q_1}{Q_2} = \frac{D_1}{D_2}$

Law 2b - $\frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2$

Law 2c - $\frac{BHP_1}{BHP_2} = \left(\frac{D_1}{D_2}\right)^3$

where D = diameter of impeller.

As can be seen from the above definition, 2a, 2b, and 2c apply only to radial, mixed, and axial flow pumps. Law 1a applies to all rotodynamic, rotary, and reciprocating pumps, while 1b and 1c apply only to rotodynamic pumps (Goulds Pumps, Inc., 1973 and

Colt Industries, 1974). It is recommended that for good approximations, of actual performance, D_2 be within 10 percent of D_1 (Longenbaugh, 1975). Efficiency stays relatively constant for small speed and impeller size changes. Therefore, for appropriate pumps, these laws can be used to find the Q,H, and BHP at operating speeds other than those for the given performance curves, or vice versa, to find at what speed or size a pump must operate to produce a Q or H not on given performance curves.

With these basic terms and principles, a discussion of water lifting methods can follow with the background necessary for a uniform explanation and comparison of the design and operation of the different devices.

Chapter 3

Positive Displacement Methods

3.1 Introduction

As can be seen from table 2.2, the positive displacement class of water lifters comprises a wide variety of methods within the two major subclasses, *reciprocating* and *rotary*, and additionally, several other devices which do not truly fit into either of these subclasses. Unlike the kinetic class, which due to its relatively recent development (see 1.2) is comprised primarily of modern, commercially manufactured pumps, positive displacement devices range from the early bucket and rope to the waterwheel, to the modern direct-acting piston and peristaltic pumps. However, all these water lifers have one thing in common which is the basis for their classification. Each method discharges water in successive isolated quantities. A look at the discharge vs. time curve of a piston pump graphically displays these individual units of water. This can also be easily illustrated with the simple bucket. Each time the bucket is lowered, filled, lifted, and emptied it discharges a given volumetric unit of water. This reciprocating action of the bucket (e.g., up and down the well) is the basis for the reciproacting subclass. If several buckets are attached to a wheel, each one will displace a specific volume of water as it enters the water and is then lifted. The rotary motion of the wheel is the identifying characteristic of the second subclass. Several other miscellaneous methods exist which, although they may be a combination of positive displacement and kinetic principles, exhibit more profound similarities with reciprocating or rotary methods and are therefore considered in this chapter.

Throughout this chapter, devices are mentioned which have several names, depending on the geographic area where in use. Also, the same term is often attributed to entirely different devices. On the basis of extensive literature review, the most common nomenclature is used here for the purpose of classification and to provide a possible standard for future work in this area. However, where possible, an English translation of all names found in the literature and from personal communication is given to serve in referencing the nomenclature in existing publications.

Capacities, efficiencies, costs, and installations vary widely for water lifters in this diverse class, particularly among the handmade devices. However, typical installations of each device will be given and where data is presently available, the costs and performance of each will be reviewed. This will serve to illustrate the operation and application of each device as it is used for irrigation and drainage, and identify those which could be significantly improved with performance analysis and design research.

3.2 Reciprocating Methods

Each of these methods provides displacement of water from one head (elevation and/or pressure) to another by a reciprocating motion between the two heads. It is appropriate that this subclass is the first to be reviewed since it comprises the first devices man developed when he wanted to lift more water than he could hold in his two cupped hands.

3.2.1 Bailing

All the methods in this category are simply based on allowing water to fill a container and raising that container to a desired height.

The means by which this lifting is accomplished is the criteria for further classification and discussion.

3.2.1.1 Bucket/Bag

Utilizing nothing more than a container such as a bag (e.g., of skin or plastic) or solid bucket, a man can raise water to the head and quantity limits of his reach and strength. As illustrated in figure 2.7, the performance of this simple water lifting act can be presented as merely the buckets per minute (Q) which can be lifted between two elevations (H). Or by multiplying Q by the volume of water discharged per bucket, these results can be recorded in more conventional discharge units. One source (Weisbach and Herrmann, 1897) reports that using a 0.35 ft^3 (10 liters) bucket, one man can lift about 15 buckets per minute or 300 cfh to a height of 3.3 ft. This performance requires roughly 1100 ft-lbs of work per minute which is about 0.033 WHP. To obtain the efficiency of the bucket alone, similarly calculate the work performed (in a given time unit) by lifting the combined weight of water and bucket the given height (i.e., BHP) and dividing it into the WHP. Note that only the water actually received at the discharge level is used to compute WHP. This will take into account losses (e.g., splashing and leakage) during lifting and reflect them in reduced efficiencies.

To obtain an estimate of the overall efficiency, the amount of energy put into the man (i.e., calories of food) would have to be measured and divided into the WHP. (Starr, 1971, indicates that man is capable of about 0.08 hp output.) Of course, such measurements will vary considerably depending not only on the person(s) working, but also the type and size of container used, and the conditions at the lifting site. For example, by utilizing a flap valve in a bucket bottom, filling can probably be accomplished faster--however, more leakage may occur. Similarly, temperature, humidity, terrain conditions, etc., will greatly effect the efficiency of a person to transport the water.

(These factors of manual and animal performance are mentioned for this first simple water lifting act since they can be easily visualized here, but they must also be considered for any prime mover/water lifter combination, e.g., heat effects engines and motors as well as man and animal. If real, usable comparisons are to be made between water lifting methods, the measurement of overall efficiencies and performances cannot be restricted to modern machinery. At this point however, socio-economic factors come into consideration (e.g., availability of food for animal or man power versus availability of fossil fuels), and a brief discussion of them is given in Chapter 5.

When the necessary lift exceeds the reach of a single person, he has three alternatives, or combinations thereof, to increase his lift; (a) taking more time to carry the container up an incline (usually using a yoke to carry a pair of buckets), (b) using two or more people in series along which the bucket(s) can be passed, or (c) utilizing a pole or rope (chain, etc.) attached to the bucket. Alternative (a) is a continuation of figure 2.7, sacrificing discharge to increase lift, while (b) requires additional work input. Alternative (c) is the beginning of another category of water lifting devices.

3.2.1.2 Bucket and Rope

Utilizing only a rope or pole (often called a cistern pole and having a hook at one end on which to hang a bucket--see Ewbank, 1876, p. 57) to lower a container into a water source, the lift can be significantly increased. However, since the strength of the human lifter still limits the capacity of the container, as more time is consumed lowering and raising the bucket through greater distances, the discharge again decreases. However, by employing one of several additional devices, the discharge, as well as the lift, of the rope and bucket* can be increased.

3.2.1.3 Bucket, Rope, and Roller

Pulling the rope over a single roller or pulley theoretically requires the lifter to exert the same amount of energy as lifting without the pulley, plus a small amount to overcome friction. However, a simple arrangement, such as figure 3.1a, centers the bucket over the well or water source which prevents dragging it up the well wall (with subsequent splashing and friction) and allows the lifter to pull hand over hand without bending or reaching (figure 3.1a). Also, the lifter can either utilize gravity by pulling the rope down with his weight, or walk away from the pulley with the rope. By using a greater number of pulleys in various arrangements, such as figure 3.1b, the amount of force that must be exerted by the lifter can be significantly decreased, but of course, the distance to pull is increased. This way, the capacity (i.e., weight) of the bucket can be increased. By measuring the pull (e.g., by a spring tension scale) and multiplying it times the

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*This combination will be used throughout further discussion, although other combinations with bags, chains, etc., can often be substituted.

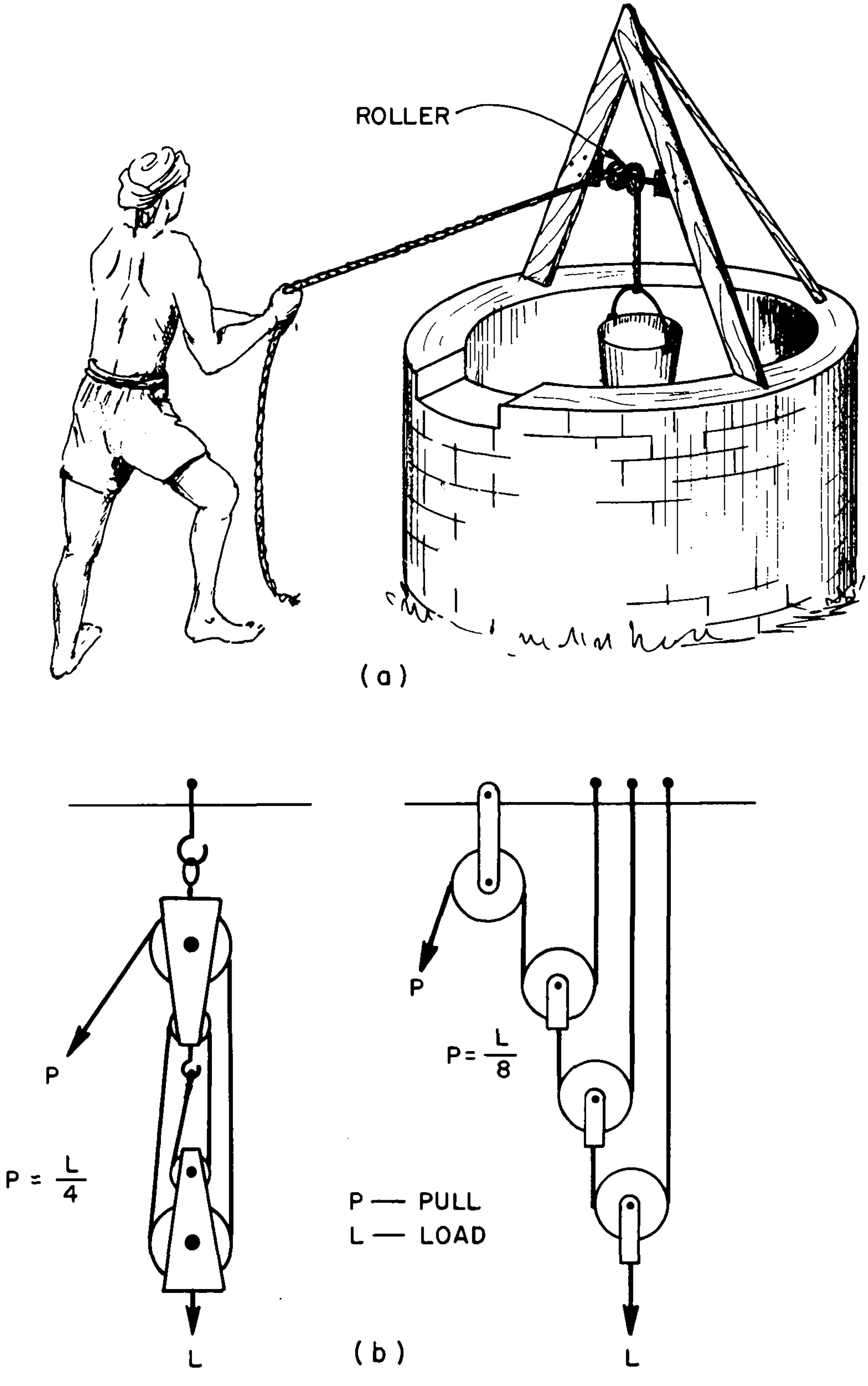

Figure 3.1 (a) Hand-over-hand lifting with bucket, rope, and roller, (b) pulley systems to decrease pull

distance needed to lift a loaded bucket through such a pulley system, the BHP into the water lifter can be calculated.

Of course, with the introduction of such mechanical devices as the pulley, friction losses become a reality and will be refelcted as the difference between the measured pull and that predicted by theory (see figure 3.1b). An additional initial cost for pulleys, supports, etc., has also been introduced, as well as a maintenance requirement, e.g., lubricating the pulley. Costs of rope and pulleys will vary greatly, depending on quality, size, and geographical availability. Although commercially manufactured block and tackle units and pulleys can be purchased to decrease wear and friction, handmade construction can be easily done by the local user--often utilizing "scrap" materials such as wheels, bearings, etc. It is also possible to retain the tripod, pulley, and rope used to construct the well or canal for use in water lifting (see VITA, 1975).

It is interesting to note that devices such as the gaining and losing buckets (figure 1.4) as described by Ewbank, are absent from present day use. It is probable that where surplus water is available to drive such a device, it has been found more efficient to use a ram or watermill. However, a basic idea should not be overlooked here. By using a counterweight, the pull needed to lift the full bucket can be reduced, but of course, effort must also be expended to lower the bucket. By using a second bucket as the counterweight, the discharge can be increased. No data appears available for comparison of optimum two bucket or counterweight operation.

As mentioned, rather than pulling the rope hand over hand, the lifter can move away from the roller to draw the container up from the water source. Utilizing animals such as bullocks or camels to do the pulling, this arrangement, called a *mot*, has been is use in developing countries for centuries. Among the other names found for this device are:

mota
mote
mohte (India)
charsa (India)
ramiokos (Pakistan)
daly (Arabic)
delu (Arabic)
rope and bucket lift .

Several variations of this basic device are often used to improve its efficiency and performance. Where possible, the animal(s) walks down a slight incline (usually 5 to 10 degrees), thereby utilizing its weight (i.e., gravity) to aid in the lifting (figure 3.2). Usually two people are needed for this operation--one to drive the animal(s) and one to empty the bucket. Upon reaching the bottom of the incline, the animal is either backed up or turned around and walked forward up the incline. In the latter case, two animals (or two pair) are often used. While one animal is returning to the top, the rope is detached, the bucket lowered to the water source, and the rope hitched to the other animal which has already returned. Although this scheme can increase the buckets per unit time, it also increases the amount of input power, i.e., more animals, a person to drive them, and another to return the rope hitch.

Another modification to the mot eliminates the need for the person emptying the bucket. As illustrated in figure 3.2, the *self-emptying mot* or *sundio kos* utilizes a bag with a large opening at one end (the top when in the water) and a spout at the other. Two ropes are attached, one each to the top and spout. Each rope passes over a

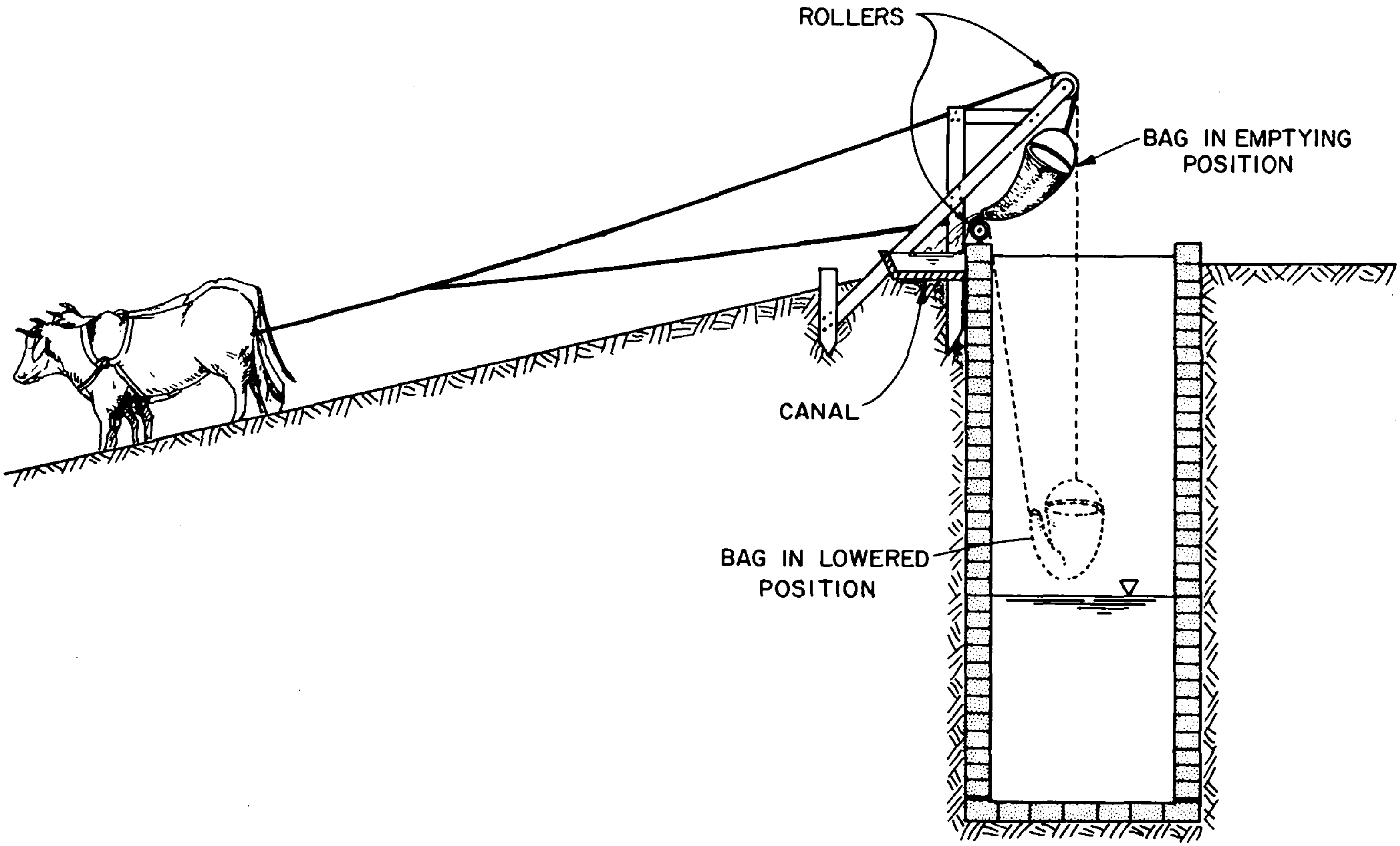

Figure 3.2 Self-emptying mot with inclined tow path

separate roller, but both are attached to the pulling animal. While in the water and being lifted, the spout stays above the bag top, but upon reaching its lower roller, the spout is pulled down and allows the bag to drain. These bags are usually hides attached to an iron or wooden ring and may vary in size from about 24 to 42 gallons (Roberts and Singh, 1951). A bucket with a flexible spout (e.g., a hose) fixed to its bottom is also used. Molenaar (1956) mentions that a bucket is often difficult to submerge for filling without tilting it via the spout rope--thus, still requiring a well attendant. However, by using a flap or ball valve on the bottom, the bucket could easily be made self-submerging. Use of multiple pulleys could again be used to decrease pull, i.e., size or number of animals, or increase capacity, i.e., bucket size. Several units of animals and buckets are often located at one water supply. Lifts usually vary from 10 to 50 feet for mot use (Wilson, 1896). Discharges of 250 cfh have been reported for a 30 foot lift using one pair of bullocks and 600 cfh with two pair at the same head (Molenaar, 1956).

One other variation of the rope-bucket-pulley is shown in figure 3.3. It is referred to as a *two bucket lift, double mot,* or *circular mot.* This figure also illustrates another design for a solid bucket as it could be used in the conventional mot. This water lifter uses two buckets (with bottom flap valves), attached to two parallel guide rails running up a well or shore wall. A rope (or chain) is attached to each bucket and passed through pulleys on poles diametrically opposite each other, with a *circular sweep* in between. An animal is usually used to turn this sweep and thus alternately raise and lower the two buckets. As illustrated here, the circular mot is

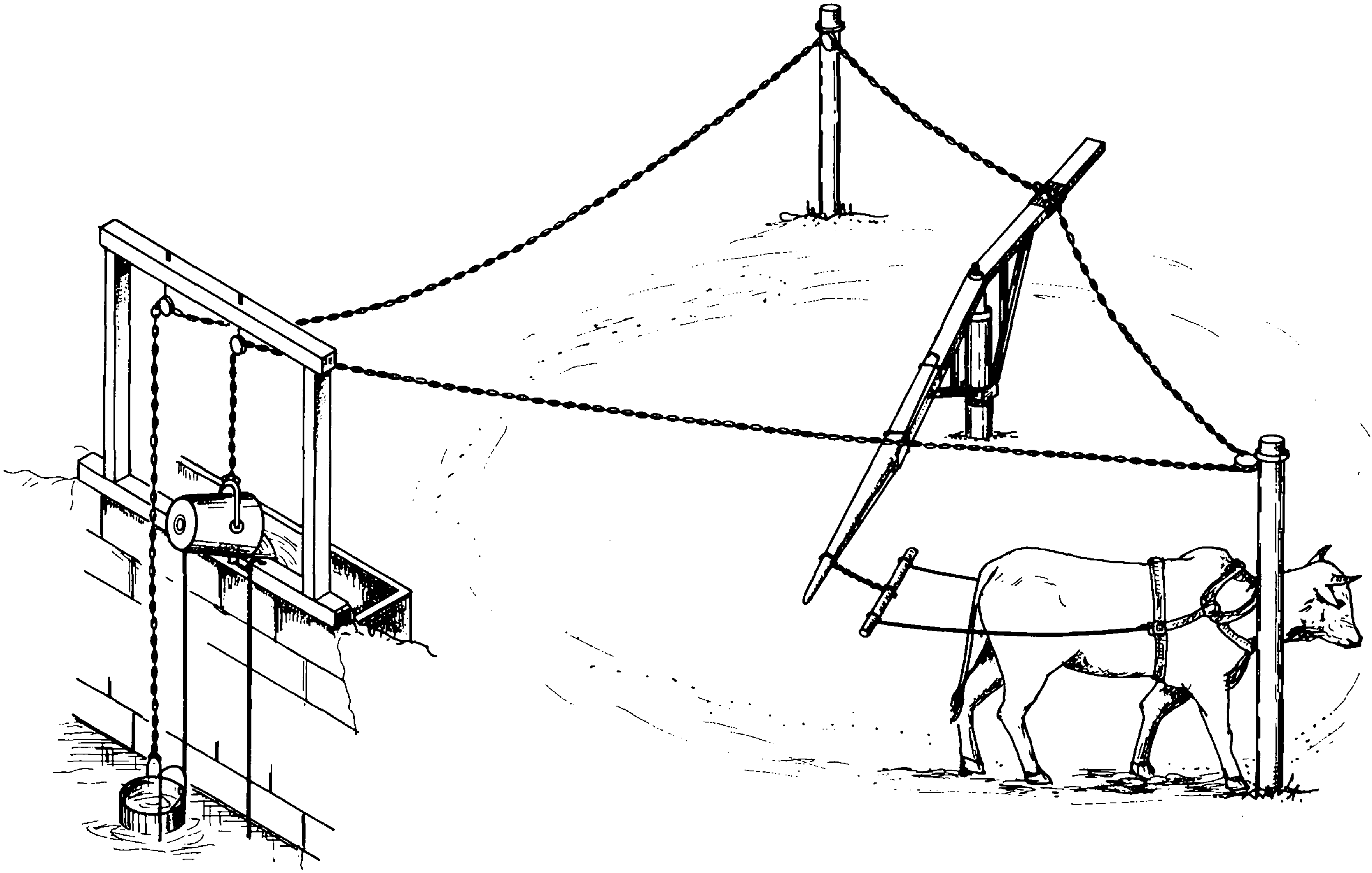

Figure 3.3 Circular mot utilizing two buckets with flap-valves in bottom

usually limited to 5-15 foot lifts, with capacities of around 800 cfh. This data is reported by Molenaar using 16 gallon buckets. However, by utilizing additional pulleys and longer ropes, lifts of 30 feet with discharges of 250 cfh have been accomplished using 12 gallon buckets.

Adjusting* cost estimates reported by Molenaar in 1956, the initial cost of a mot (including rope, pulleys, trough, supports, bucket, and installation) would be about $50.00, with repair costs of a few dollars a year. Of course, the cost of animals (multiplied by the percentage of time used for water lifting) must also be included in initial costs. A typical cost analysis of a mot including labor, depreciation, feed, interest, etc., is given in Chapter 5 along with data on cost per unit of irrigated land.

(It should also be noted here that although the circular mot is only reported in use with animals, its circular motion could readily be adapted to several other prime movers which develop a rotary motion--see Chapter 5).

3.2.1.4 Bucket, Rope, and Windlass (Crank)

As with the use of multiple pulleys, the *windlass* or *crank* provides mechanical advantage to allow increase of the capacity (load) of a bucket and rope. A look at the common domestic well windlass and single bucket will serve to explain this advantage. Figure 3.4 has been given both to illustrate this explanation and to describe a simple method of providing a "sanitary" water supply, i.e., a well and water lifter which are enclosed (see VITA, 1975). The calculations in figure 3.4b neglect friction and the weight of rope, however, if actual efficiencies are to be evaluated, the cranking force exerted will have

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*Costs throughout this paper have been adjusted to 1975 U.S. dollars.

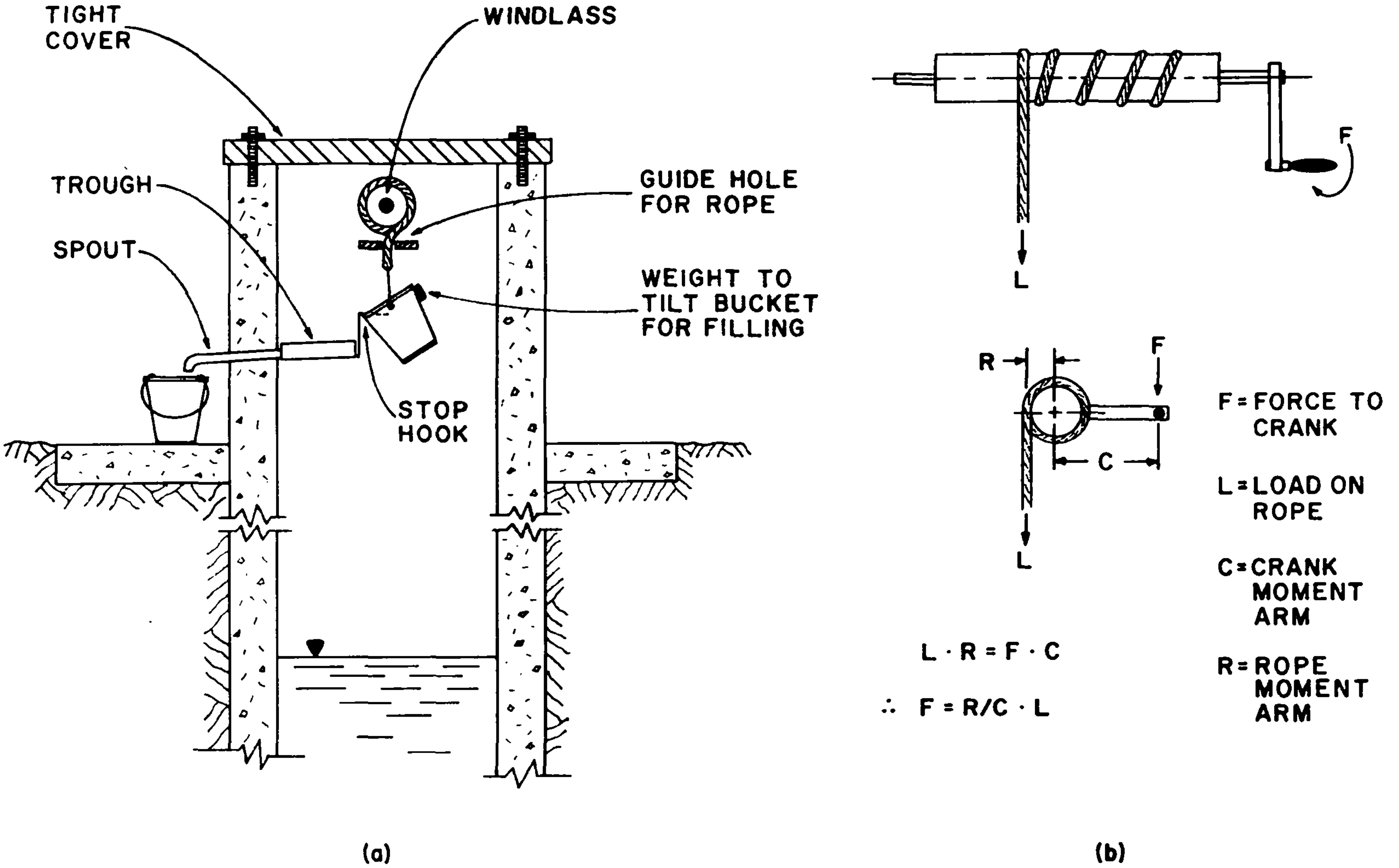


Figure 3.4 (a) "Sanitary" rope and bucket with windlass, (b) lift advantage by windlass

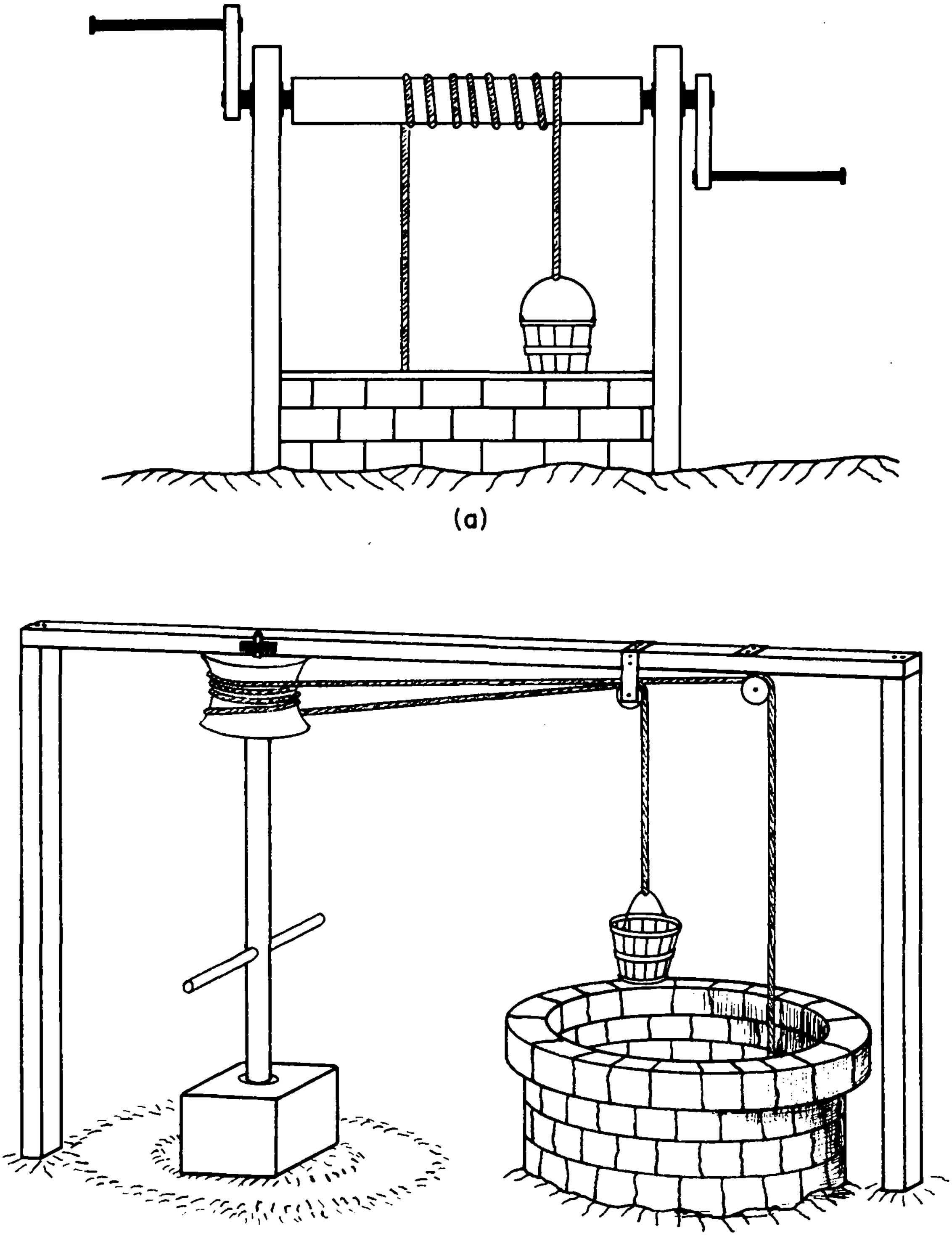
to be measured times the distance cranked through (i.e., BHP), and this compared with the weight of water actually discharged from the spout times the distance from water level to spout.

Many variations of the windlass are possible, including combinations with pulleys, gears, treadmills, etc., as shown in figures 3.5 and 3.6. (Ewbank, 1876, describes many other interesting windlasses which have been used throughout history.) Of course, the most commonly used modification is the utilization of two buckets attached to opposite ends of the same rope which is wrapped around the windlass roller (figure 3.5a). In this way, the buckets counterbalance each other and the BHP must only balance the water weight and friction. The use of these additional devices, such as gears, rollers, and pulleys, can significantly increase the efficiency of the windlass by decreasing the needed BHP. The use of low friction bearings (e.g., ball bearings) with the windlass can also decrease the friction losses.

Again, no data appears available on the performance and cost of this simple water lifter. However, initial cost would probably be only slightly higher than a single pulley system, but the efficiency and capacity would also be higher. With high crank/roller diameter ratios and the two bucket scheme, this water lifting device is very practical for use with the deepest wells or other high lift situations.

3.2.1.5 Counterpoise Lift

The *counterpoise lift* is another variation of the rope/pole and bucket, and was one of the earliest water lifters (see section 1.2). It has been used throughout the world, with many countries reporting several hundred still in use (Franji and Mahajan, 1969, and Dias, 1953).



(a)

(b)

Figure 3.5 Two buckets on (a) two-man windlass, (b) capstan

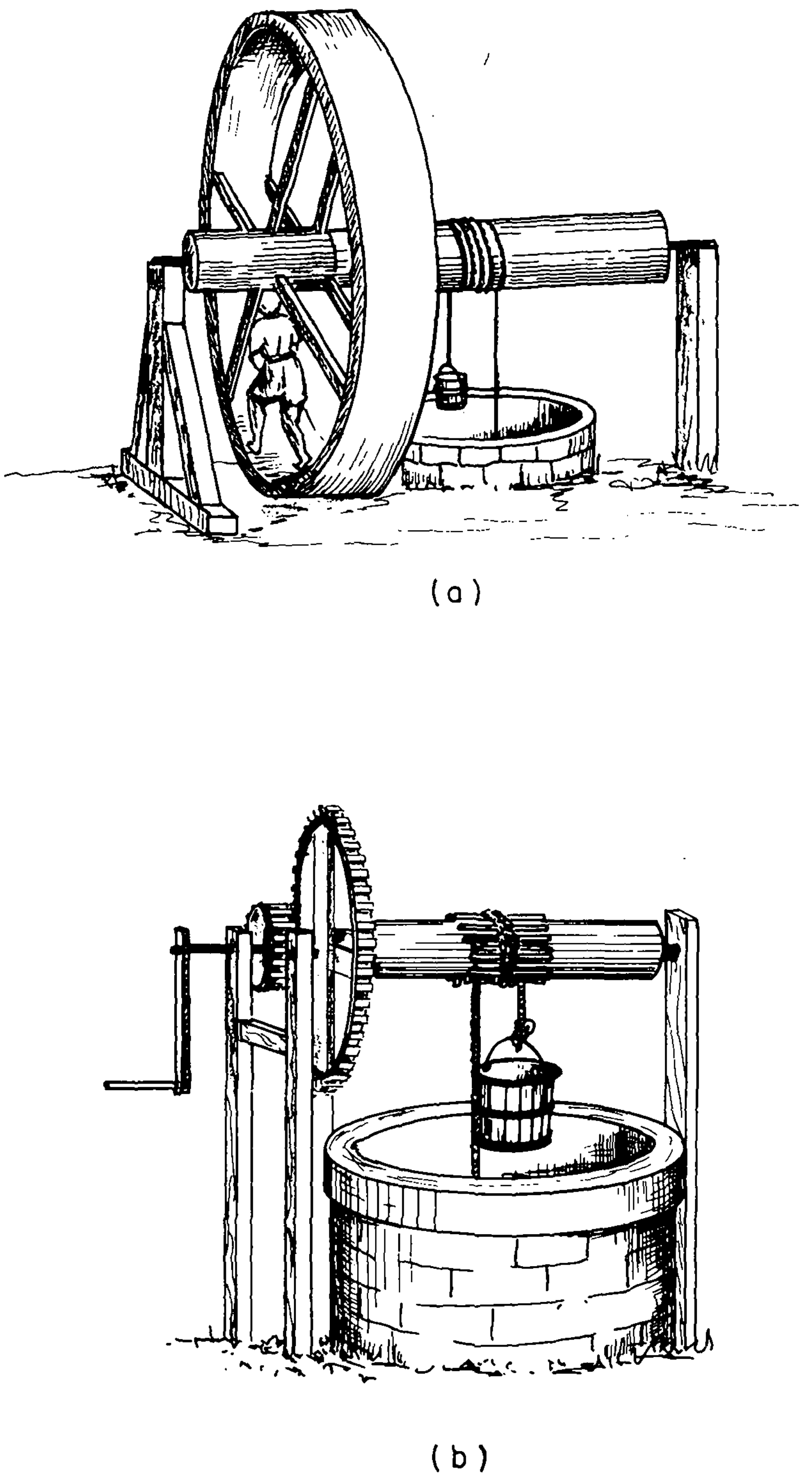


Figure 3.6 Two buckets on windlass (a) with treadwheel drive, and (b) with gearing advantage

Many names have been attributed to this device. A list of the most frequently used are:

shaduf (Egypt)
shadoof
shadouf
chadouf
khetara
kerkaz
kheeraz
guenina
bascule
dhenkali
dhenkli
dhingli
picottah (India)
lat (India)
picotas (Portugal)
sweep
swape

In its most common form today this water lifter consists of a bucket attached to one end of a vertical pole which hangs (freely) from a lever. As can be seen in figure 3.7a, this lever pivots about a horizontal crossbar and is counterbalanced by a weight. This weight is usually sufficient to balance half the weight of the full bucket so that the attendant need only lift half the bucket and water weight. Then, to return the bucket to the water supply, he can use his weight (at least to some degree) to offset the counterweight in order to pull the lever down. However in some cases, the counterweight may be allowed to balance the entire bucket and water weight if the attendant is able to utilize enough of his weight to return the lever. Combinations of weights varying between these two cases are utilized depending on the lift, terrain, and attendant's liking. A pole usually connects the bucket and the lever so that the bucket can be pushed into the water. This is normally done where the lift is 3 to 10 feet. However, if the lift is greater or the water source is in a narrow well (figure 3.7b),

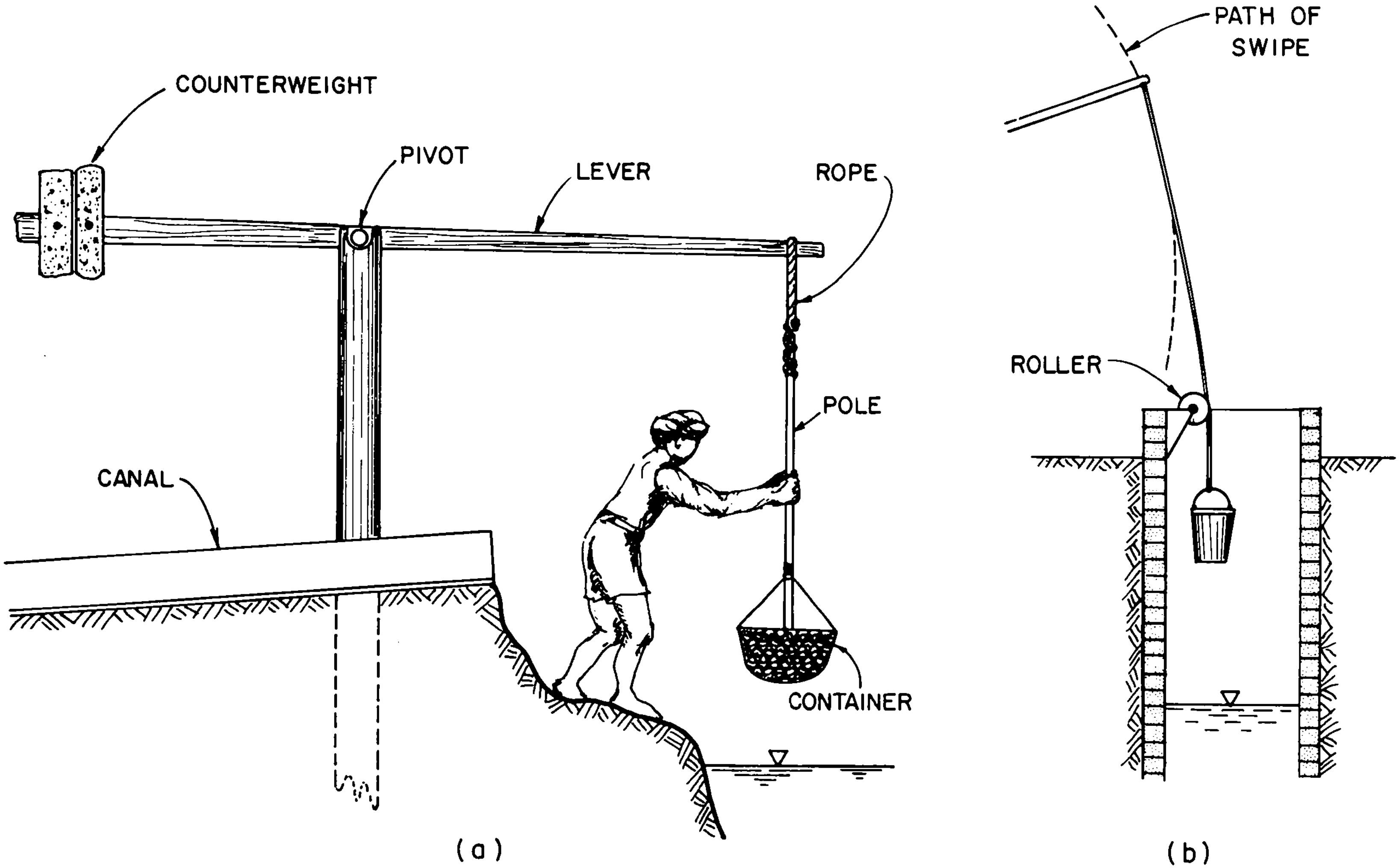


Figure 3.7 (a) Counterpoise lift, and (b) with roller for narrow well

a rope or chain may be used instead of a pole. In this case, the well may be equipped with a roller or pulley to guide the rope and the bucket may have a flap valve to facilitate filling. The terms *sweep* and *swape* are often reserved for counterpoise lifts using ropes rather than poles. Of course, when the lift of a single shadouf is exceeded, a series of them are often employed--one discharging into the supply pool of the one above it.

The lever, pivot, and pivot supports are usually of wood, while counterweights vary in composition; rock, dried mud ball, concrete, can filled with water or sand, etc. The actual water container may be a leather bag fastened to a metal hoop, a used petrol can (Molenaar, 1956), a lined basket, or metal bucket.

Table 3.1 gives the various performance data that have been reported for the shadouf.

Table 3.1 Shadouf performance

Lift (ft)	Discharge (cfh)	Reference	Remarks
8.2	105	Molenaar, 1956	1 man
8.2	180	Molenaar, 1956	2 men working 2 hr shifts each
6.5	210	Molenaar, 1956	2 men working 2 hr shifts each
3-10	210	Garg, 1971	1 man
6.5	180	Schioler, 1973	1 man
1	3300	Buckley, 1905	1 man
1	5760	Buckley, 1905	2 men
6.5	857-1071 cf/day	Framji and Mahajan, 1969	no hours per day given

Here again, initial costs will vary with lift, capacity, and availability of construction materials; however adjusting Molenaar's information to 1975 U.S. dollars, the bucket, rope, and frame can be expected to cost about $12.00.

The term *picottah* (or *paecottah*) is often applied to a specific variation of the counterpoise lift which uses one or two persons as movable counterweights in place of, or combined with, the fixed counterweight (figure 3.8). This device is larger and has a longer lever than a regular shadouf and thus is utilized for higher lifts, usually from 15 to 30 feet. To operate this water lifter, the "counterweight" person(s) walks back and forth along the top of the lever, which has either a notched or plank walkway, and hand rails. As his weight is shifted, the bucket will raise and lower. One additional person is needed to empty the bucket. No data is available on the picottah; however it could be expected to have a slightly higher cost than the shadouf, but capable of higher discharges and heads.

3.2.2 Scooping

In low-lying areas, e.g., Nile River Valley, where lifts from water sources to fields are small (i.e., 2 to 5 ft), man found he could scoop and throw water at a greater discharge than he could fill, lift, empty, and return a bucket or bag.

3.2.2.1 Swingbasket

The *swingbasket* (figure 3.9) operates just as its name implies. A basket is attached with four ropes, two on each side. Two people, each holding two ropes, swing the basket back and forth. In the return motion from the higher elevation, the basket is dipped and filled. Then, on the reverse swing, a twisting of the ropes is

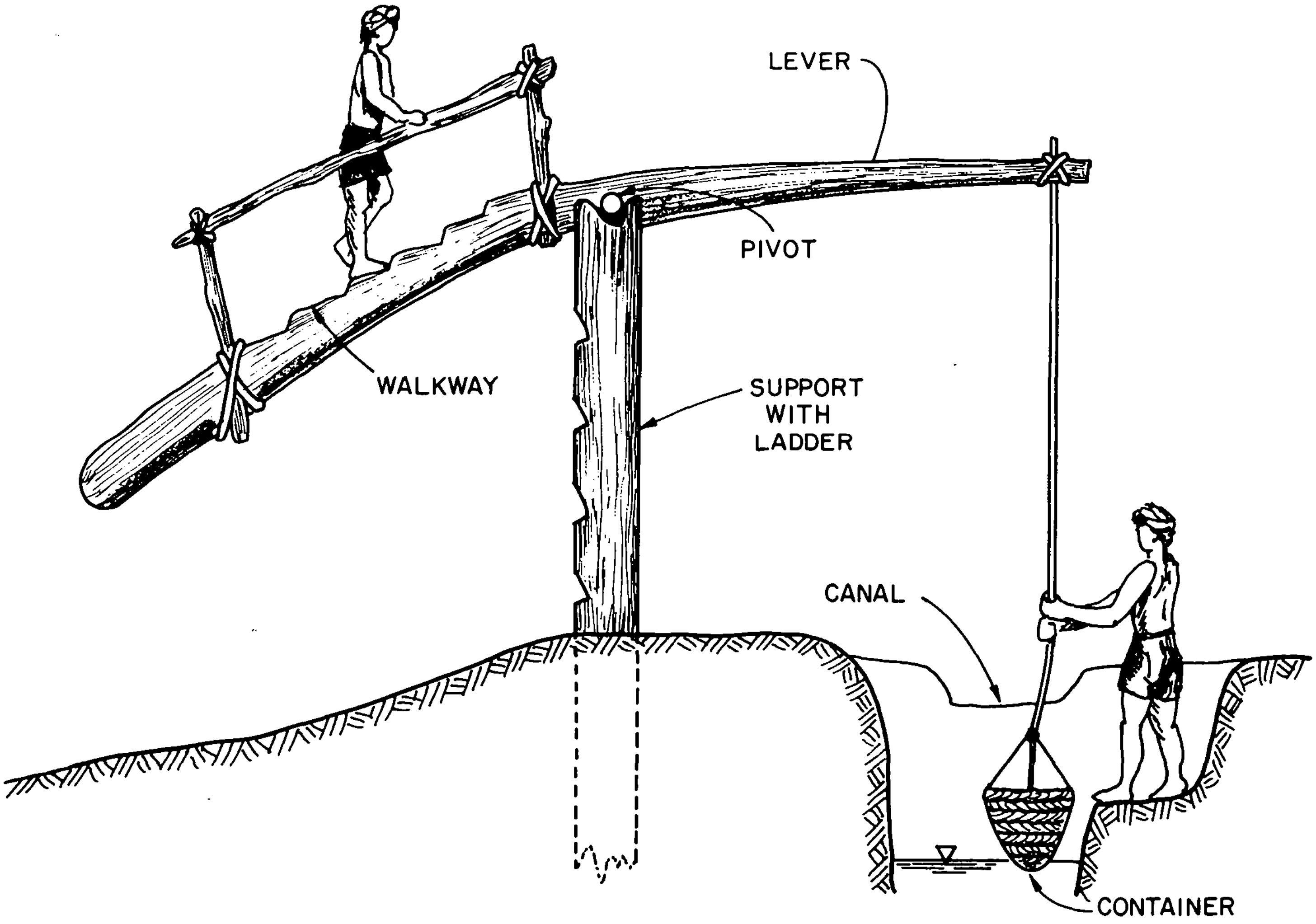
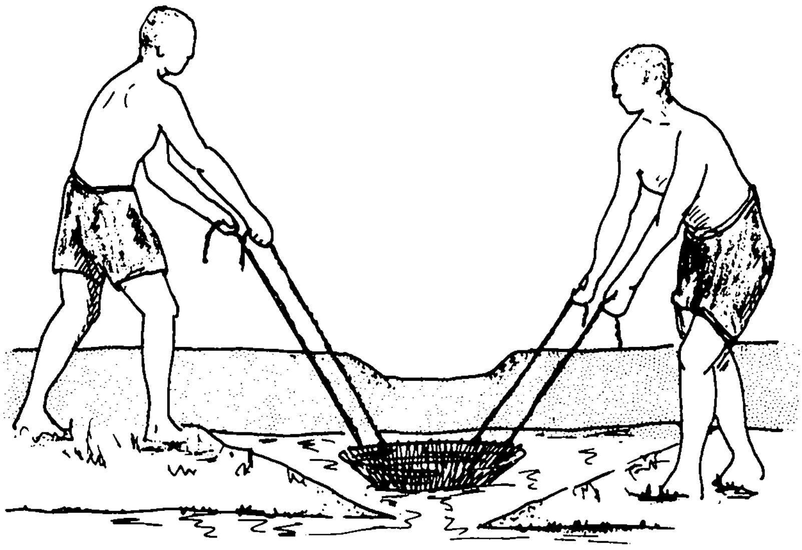
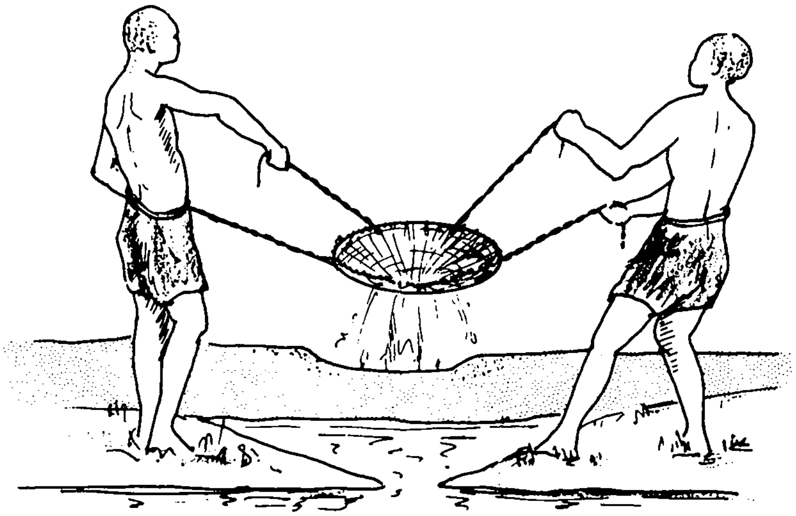


Figure 3.8 Picottah, using man as moveable counterweight



(a) FILLING



(b) THROWING

Figure 3.9 Operation of mental (swingbasket) usually done to throw the water up. This simple device is also referred to as:

latha	*katweh*	*jhatta (Pakistan).*
mental	*basket scoop (India)*	

Reported performance data appears to be rather questionable. Buckley's work in 1905 indicates a discharge of 2000 cfh with a one foot lift, while Molenaar in 1956 reports only 180 cfh for a two foot lift. Based on the performance of a similar device, the shovel (section 3.2.2.2), the former discharge seems high and the latter low.

Of course, the initial cost of the basket and ropes is very little and repairs can be made almost immediately.

3.2.2.2 Shovel or Scoop

By merely using a semi-enclosed shovel, such as the *Dutch scoop* in figure 3.10a, a single person can throw water. However, Weisbach and Herrmann (1897) report that one person can bail water at about the same discharge he can throw it because of the high spillage losses. Therefore, the shovel is usually attached by rope to a tripod and operated as in figure 3.10b. This method reportedly (Molenaar, 1956) produces a discharge of about 300 cfh up a 3 foot lift. Additional ropes may be attached so that one, or usually two, person(s) can pull the shovel as the first pushes. In this manner, roughly 30 cycles can be made in a minute, throwing about 1500 cfh against a head of 4 feet. This would require each of the three lifters to do about 120,000 ft lbs of work per hour.

This device can be quite simply constructed, e.g., using a large can, cut off diagonally on one end and attached with a wooden pole on the other. No cost estimates are available.

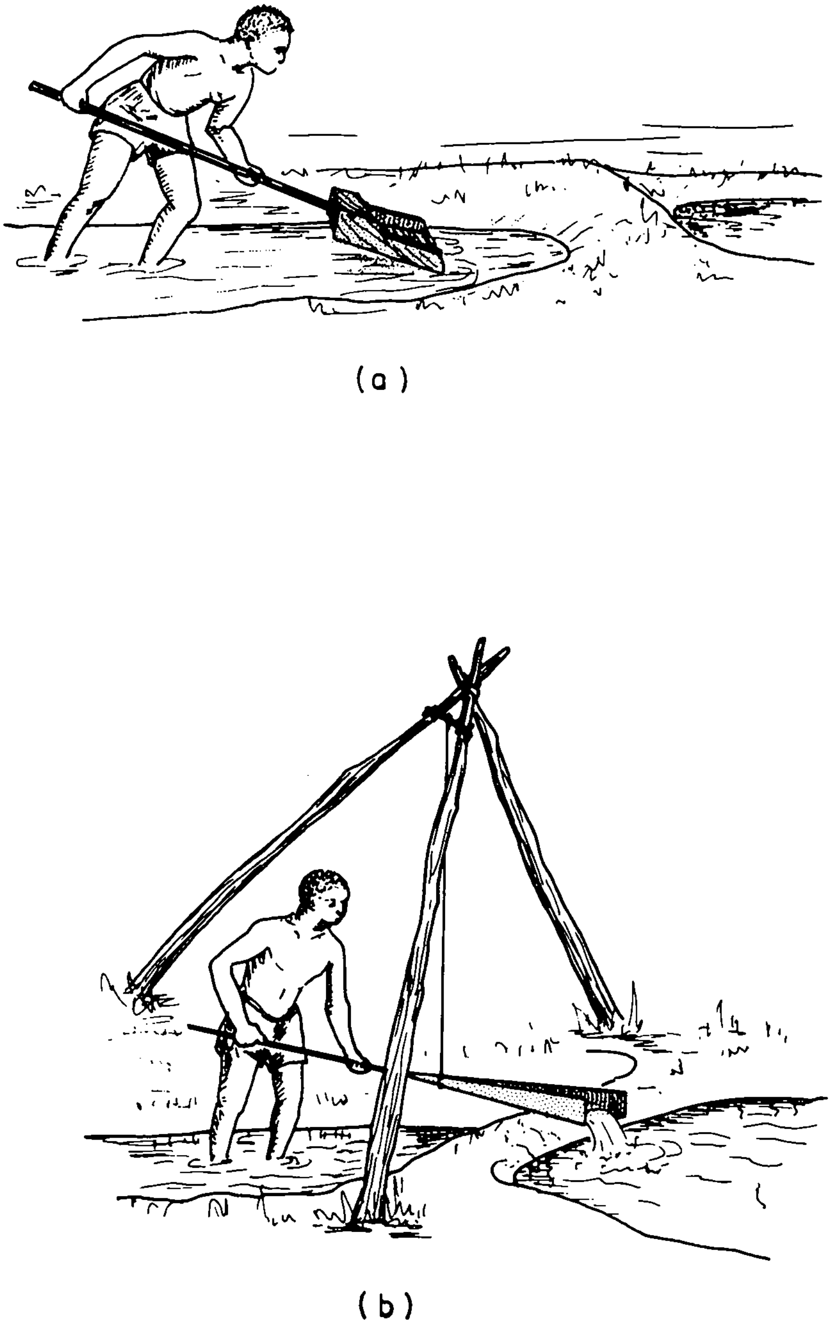


Figure 3.10 Scoop (a) used as shovel, and (b) with tripod

This throwing method can be modified by another device to increase performance. The *water balance* shown in figure 3.11 makes use of a scoop vertically attached to a balance beam which pivots about a centrally supported axis. By alternately pulling on ropes at opposite ends of the beam, one or more pairs of people can push water up the channel in which the scoop travels. The channel profile is circular within the arc of scoop motion. To facilitate the scoop's entry into the water, flap valves are often used which open on the return stroke (see figure 3.11 insert). Although the oscillations per unit time will vary with size of balance and number of operators, Weisbach and Herrmann (1897) report that about 4700 to 5500 cfh can be raised 4 feet.

As constructed in figure 3.11 with finished wood and iron flap-valve frame, the water balance and channel could be expected to cost upwards of $75 to $100. However, utilizing local scrap material for the balance and possibly a concrete channel, this initial cost could be reduced. Again, for example, a used can could be cut with holes and each covered by a leather flap valve to serve as a scoop.

3.2.2.3 Gutter

Rather than pushing water through a channel, as with the balance, and encountering high leakage and friction losses, the *gutter* actually lifts the entire channel. These gutters or troughs were originally hinged at one end to the upper elevation and the other end dipped into the water and lifted, allowing the water to run out. However, the bending and lifting action is very tiring, so gutters are often fitted with handles as in figure 3.12a (also note flap valve). Where this device is used extensively in Portugal, it is called *cegonho* (translated as *swipe*, from Dias, 1953). Another modification

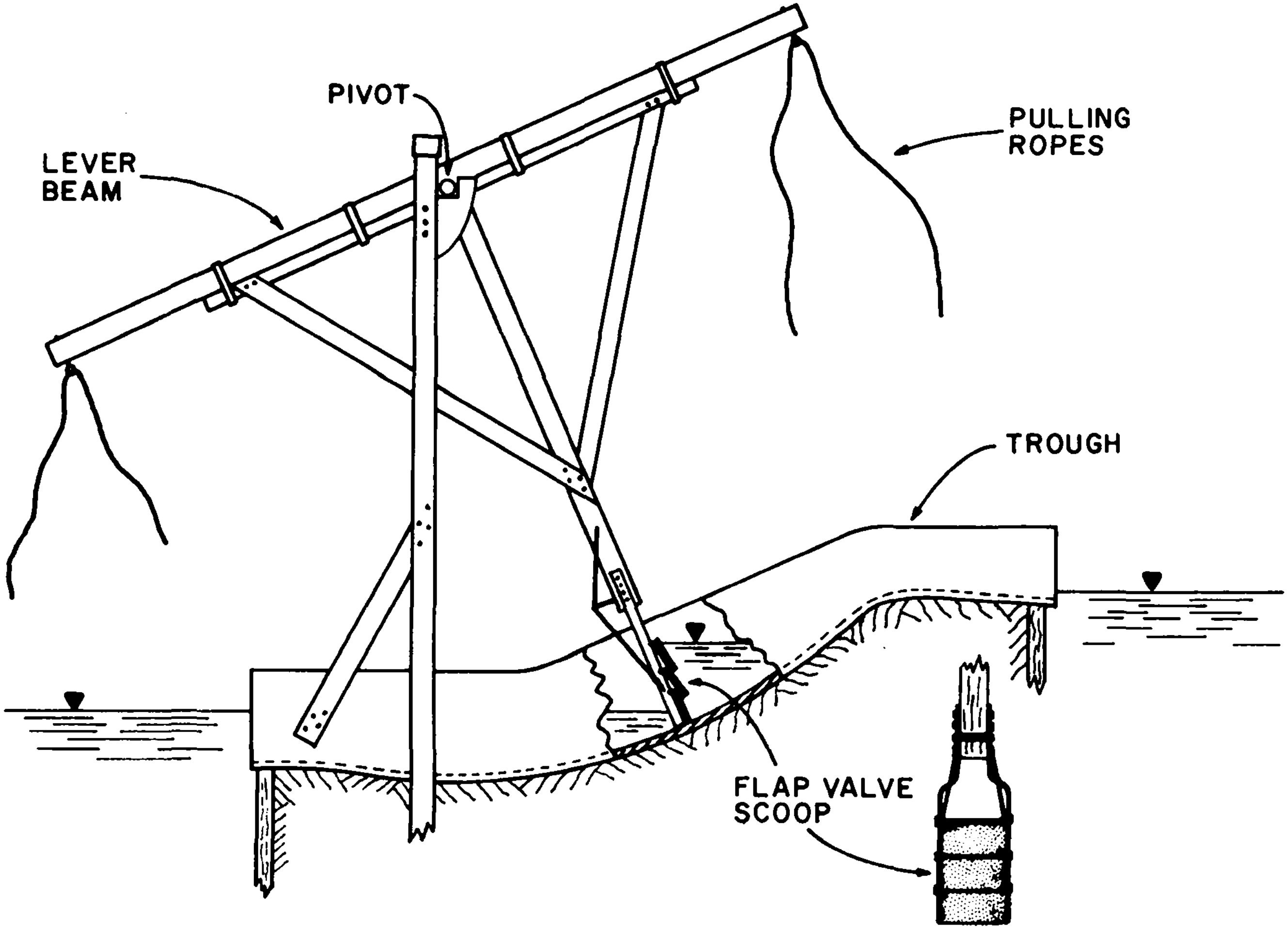


Figure 3.11 Water balance with flap-valve scoop

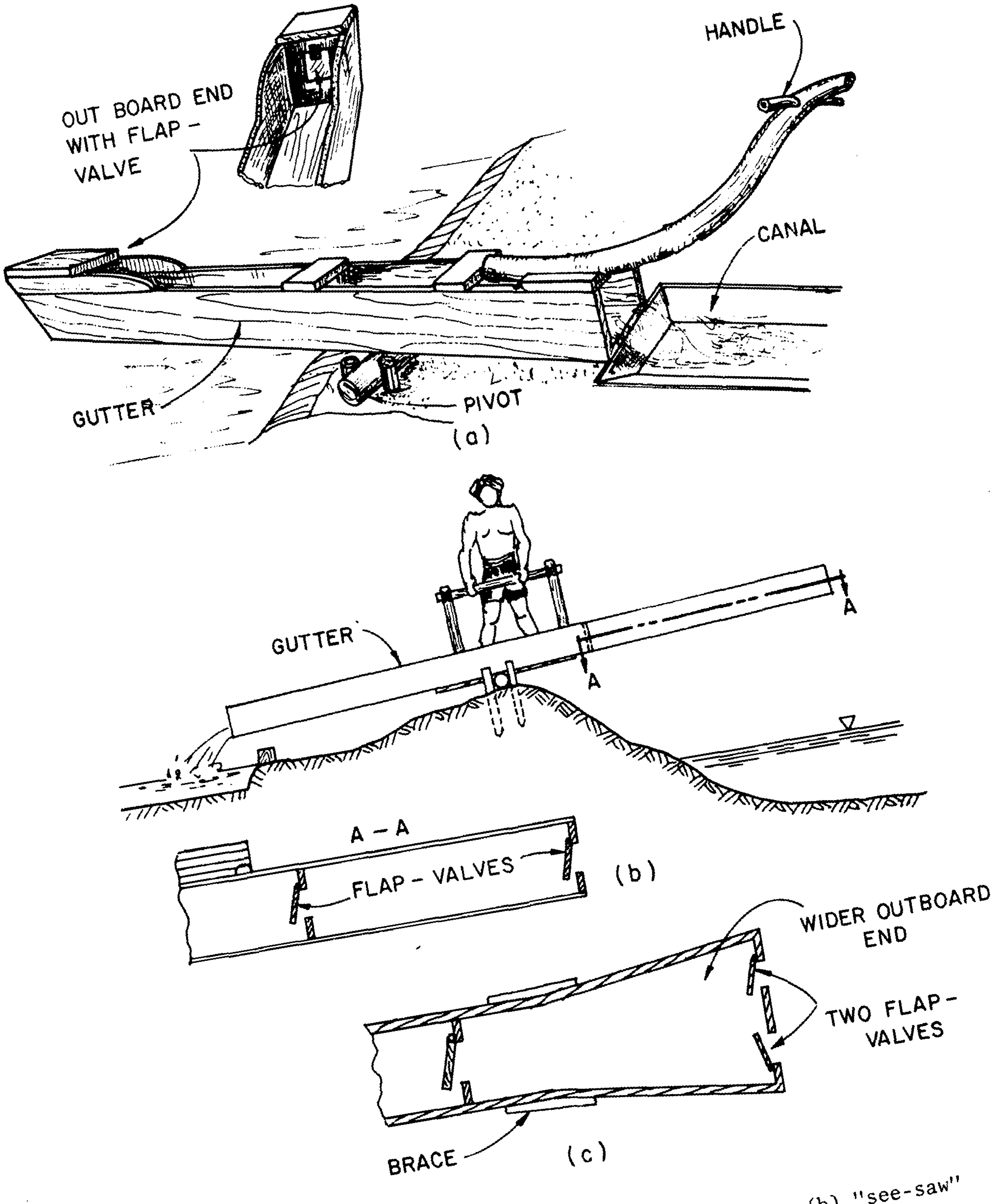


Figure 3.12 (a) Single gutter with handle, (b) "see-saw" gutter, and (c) modifications to increase gutter capacity

is to use the picottah principle and have the operator shift his weight back and forth on a "seesaw" gutter as seen in figure 3.12b. Dias presents this design with the outboard flap valve to ease filling and the inner flap valve (probably) to prevent the return of any undrained water. The capacity of this device could be significantly increased by extending and/or widening the outboard end as in figure 3.12c.

Utilizing overhead levers and ropes, the single or double gutter can be operated either as the above seesaw gutter or as in figure 3.13a, with filling on both up and down strokes and discharging into the center. By using the same circular sweep as in the circular mot, two single gutters can be operated by animal power, as indicated in figure 3.13b. This device, called the *baldeo balti* in the Punjab (Roberts and Singh, 1951), is primarily for lifts up to five feet, as are most gutter devices. Despite the current use and wide variety of these gutter devices, no data on costs or performance is available for comparisons.

Another modification of the simple gutter is the *doon* or *jantu*. As seen in figure 3.14a, it utilizes the counterweight principle of the shadouf. However, as it is used for small lifts, the counterweight is made sufficient to lift the water and gutter. By stepping up on the end of the gutter, the operator can lower and submerge it. As can be seen, the lever and counterweight must be designed to provide a greater moment (i.e., weight times lever arm) than the full gutter, but less than the empty gutter plus operator.

Schioler (1975) has described what he believes to be a rather new modification of the doon (figure 3.14b) which again copies the picottah

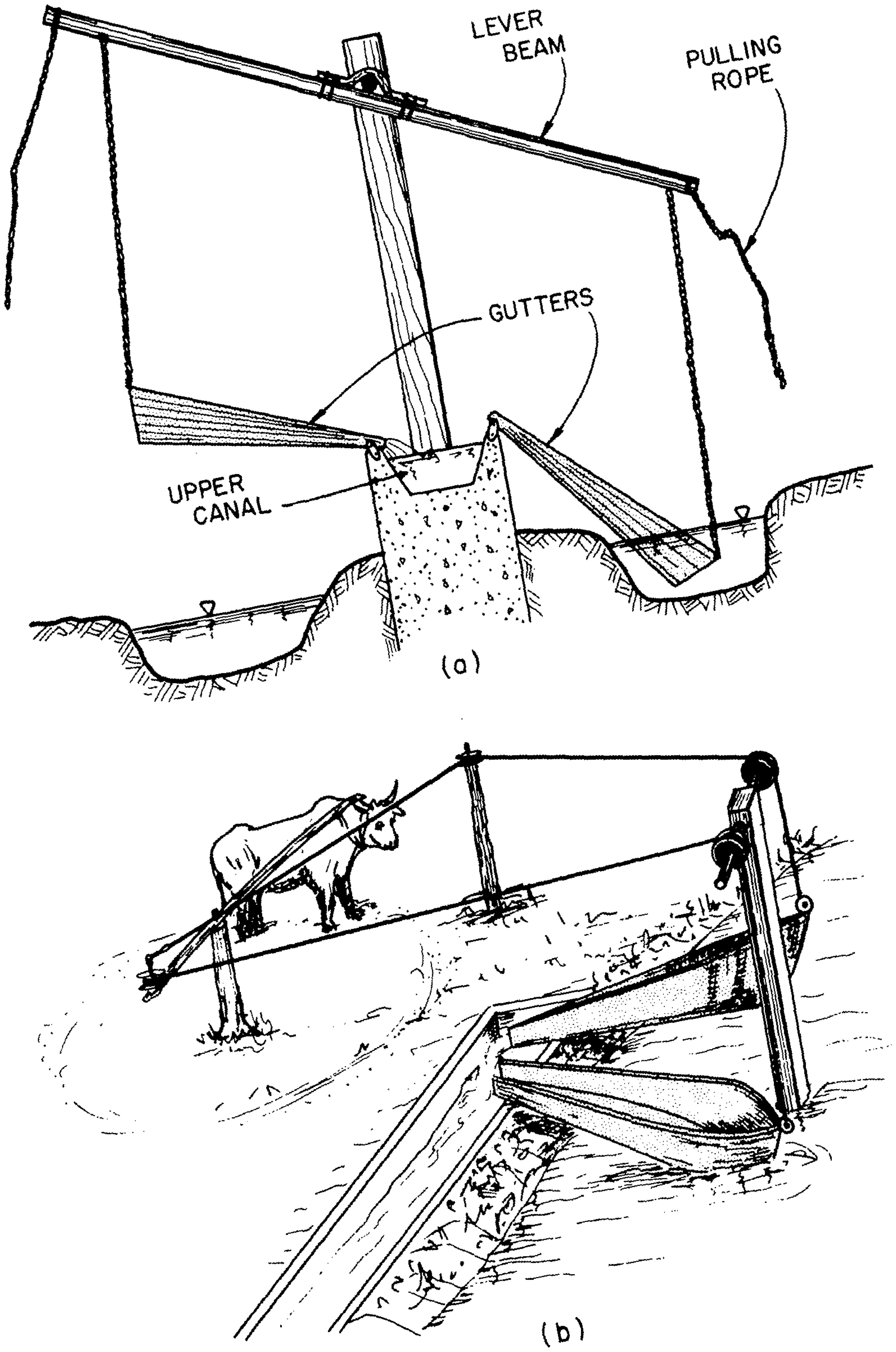


Figure 3.13 Double gutters (a) with lever, and (b) as baldeo balti

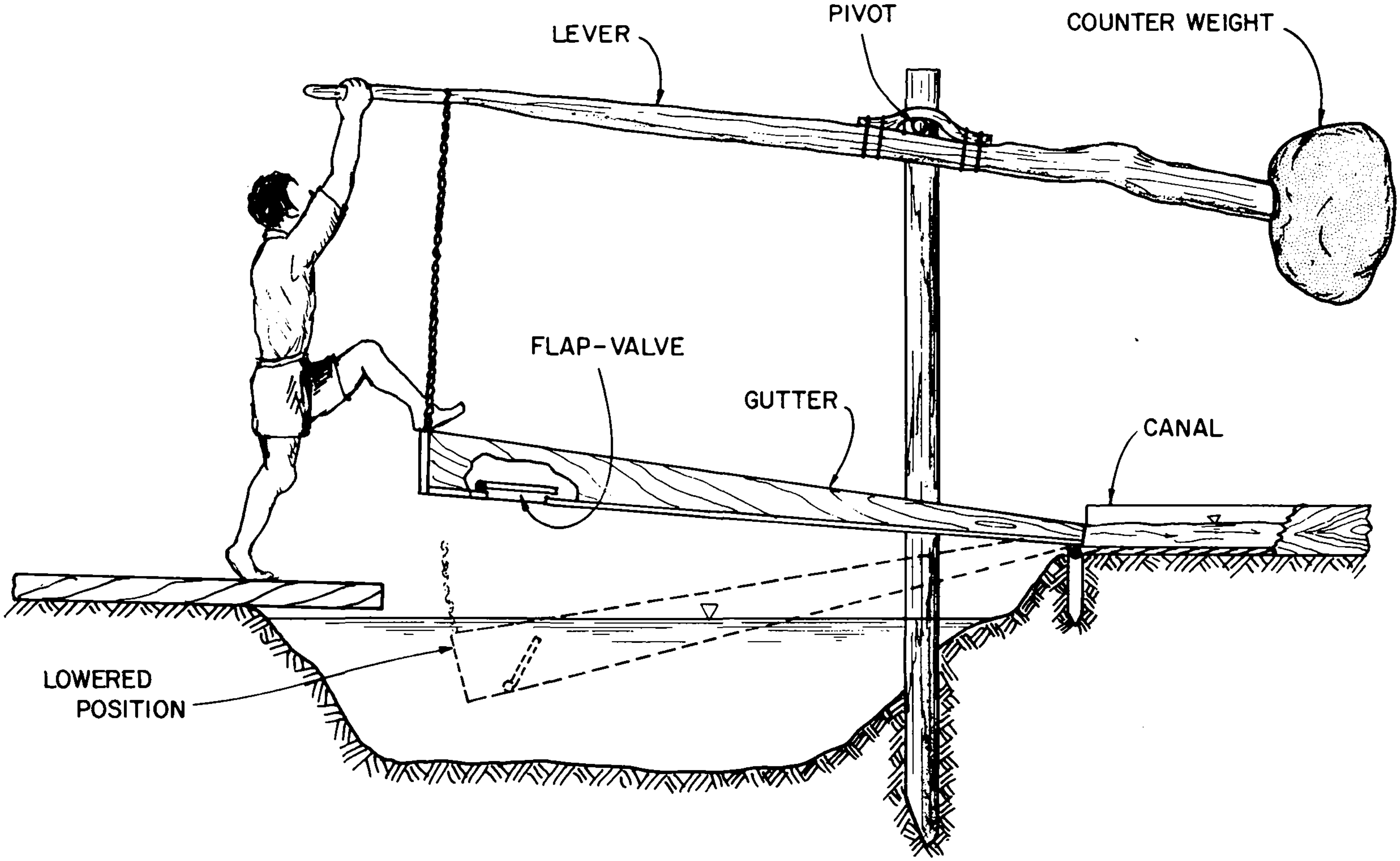


Figure 3.14(a) Doon with flap-valve for aiding submergence

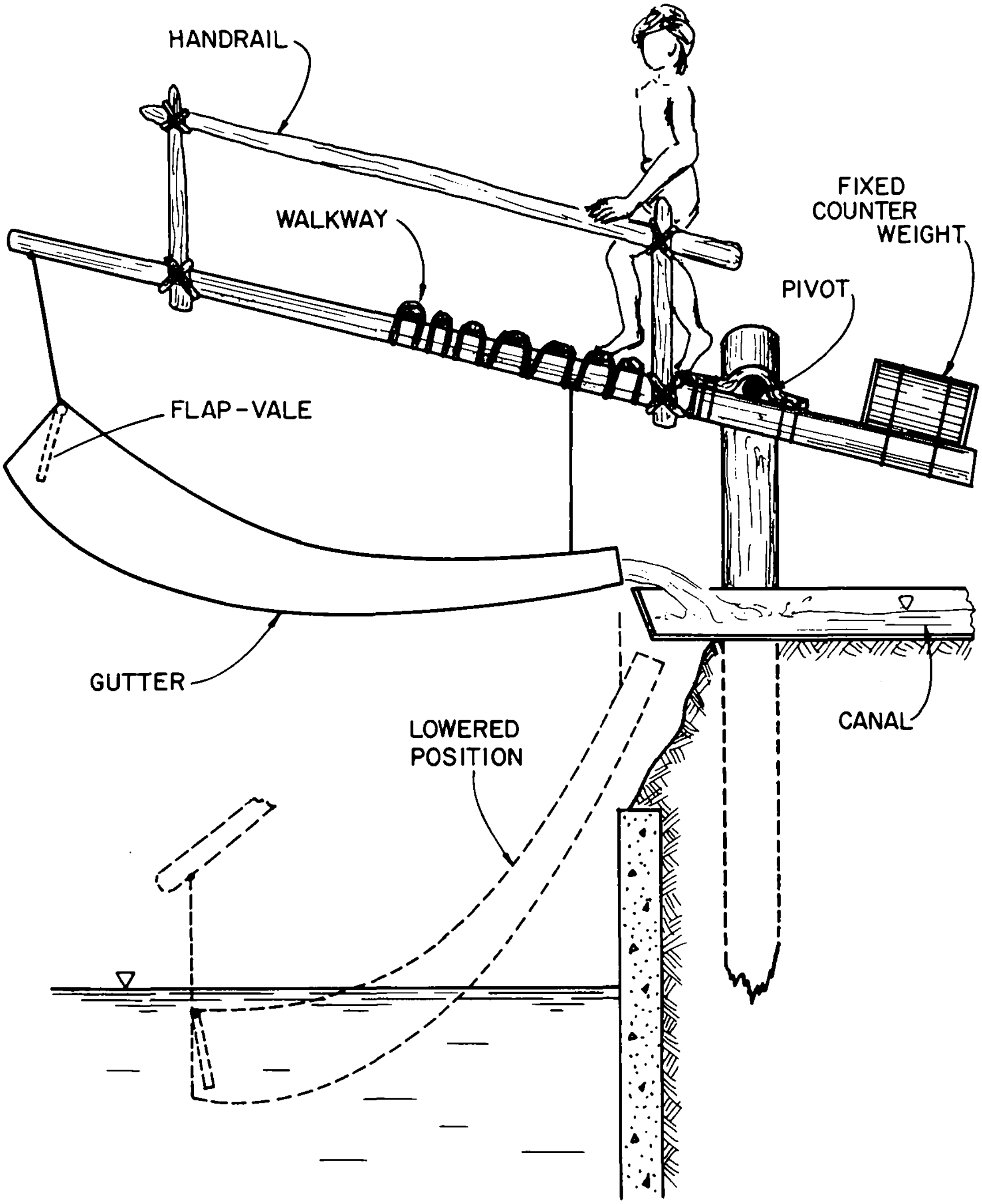


Figure 3.14(b) Picottah-style doon with flap-valve

principle, i.e., the operator walks back and forth on the lever to provide a movable counterweight. Because the gutter is attached at both ends to the lever and rises with it, this picottah-style-doon (no specific name has been reported) is capable of lifts greater than the conventional doon. However, no performance data has yet been made available. Schioler also suggests that with further study gutter shapes could be designed to optimize capacity and lift. He does not mention it, but it would appear necessary to weight the gutter and provide a flapped end to facilitate submergence and filling.

Two more versions of the gutter have been recently introduced. The first, shown in figure 3.15a, utilizes a sealed air container, e.g., a petrol can, to lift the gutter by buoyancy instead of by counterweight. The operator merely steps on the outboard end of the gutter to fill it and steps off to allow buoyancy to lift it. Although no information is available, this device appears cheaper and easier to build and maintain than the conventional doon.

Through recent communication with W. D. Kemper in Pakistan, we have learned of the development of a double-acting, foot-operated gutter. As shown in figure 3.15b, two pans are connected by a rope which passes over a pulley. The operator stands with one foot on each pan and alternately shifts his weight from one pan to the other. By means of a flapped opening in the outboard end of each pan, it fills and is then raised and drained out the shore-hinged end. Kemper reports that a man in good condition can lift 800 cfh (100 gpm) one foot for several hours. Over short periods, a rate of 130 gpm has been reached. It appears that this device is limited to one or two foot lifts, but is

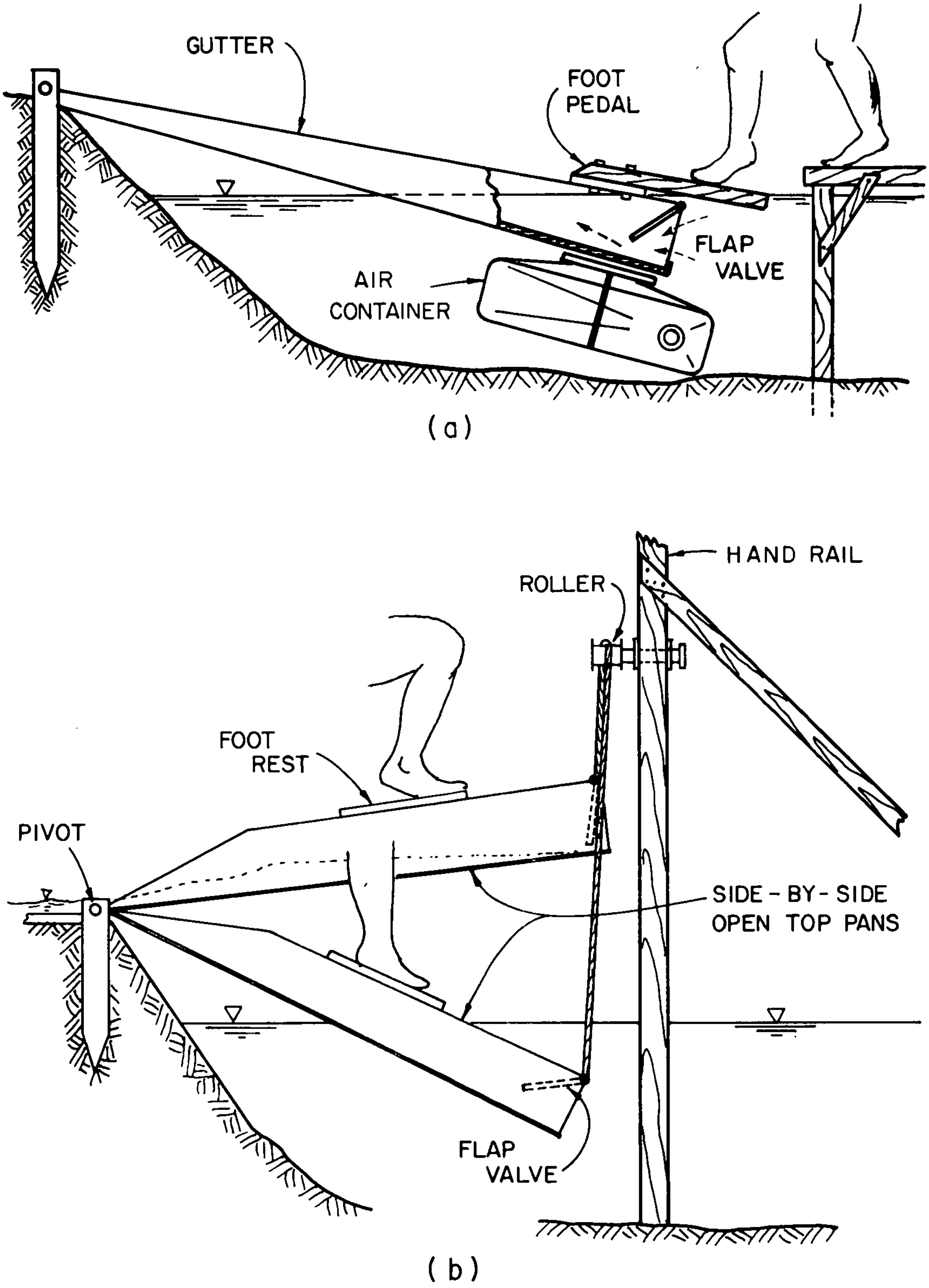


Figure 3.15 Recent modifications of the doon

quite efficient and easy to operate. As this device is still under study, no data on costs or efficiency is yet available.

In all but this most recent gutter device, hollowed-out tree trunks are usually used to build the trough itself. Supports and counterweights are as described in the shadouf.

One additional water lifter belongs in this gutter category, the *zig-zag balance* (figure 1.1). By oscillating the zig-zag frame, water is scooped up by the bottom gutters and caused to flow back and forth through a series of gutters until it reaches the upper level. Although not described anywhere, it would appear that flap valves are located at each gutter junction to prevent backflow. This brief description is given only because of the zig-zag balance's unique design since it no longer appears in use.

3.2.3 Piston-, Plunger-, and Bucket-Pumps

This third subclass of reciprocating methods ranges from the simple, hand "lift pump" to the sophisticated, direct-acting "steam pump." Unlike the reciprocating devices previously discussed, these pumps do not need a suction head to lift water, but instead have the ability to "suck" water from a suction lift (see section 2.2). All pumps in this class utilize as their primary component one of three similar devices to lift the water;

(a) The *plunger-pump* uses a solid or semi-solid cylinder (plunger) to displace the water in a surrounding hollow cylinder. As illustrated in figure 3.16, when the plunger withdraws (upward) from the cylinder it creates a drop in pressure within the cylinder and thus allows water to flow in through a check-valve (e.g. flap, ball, etc.).

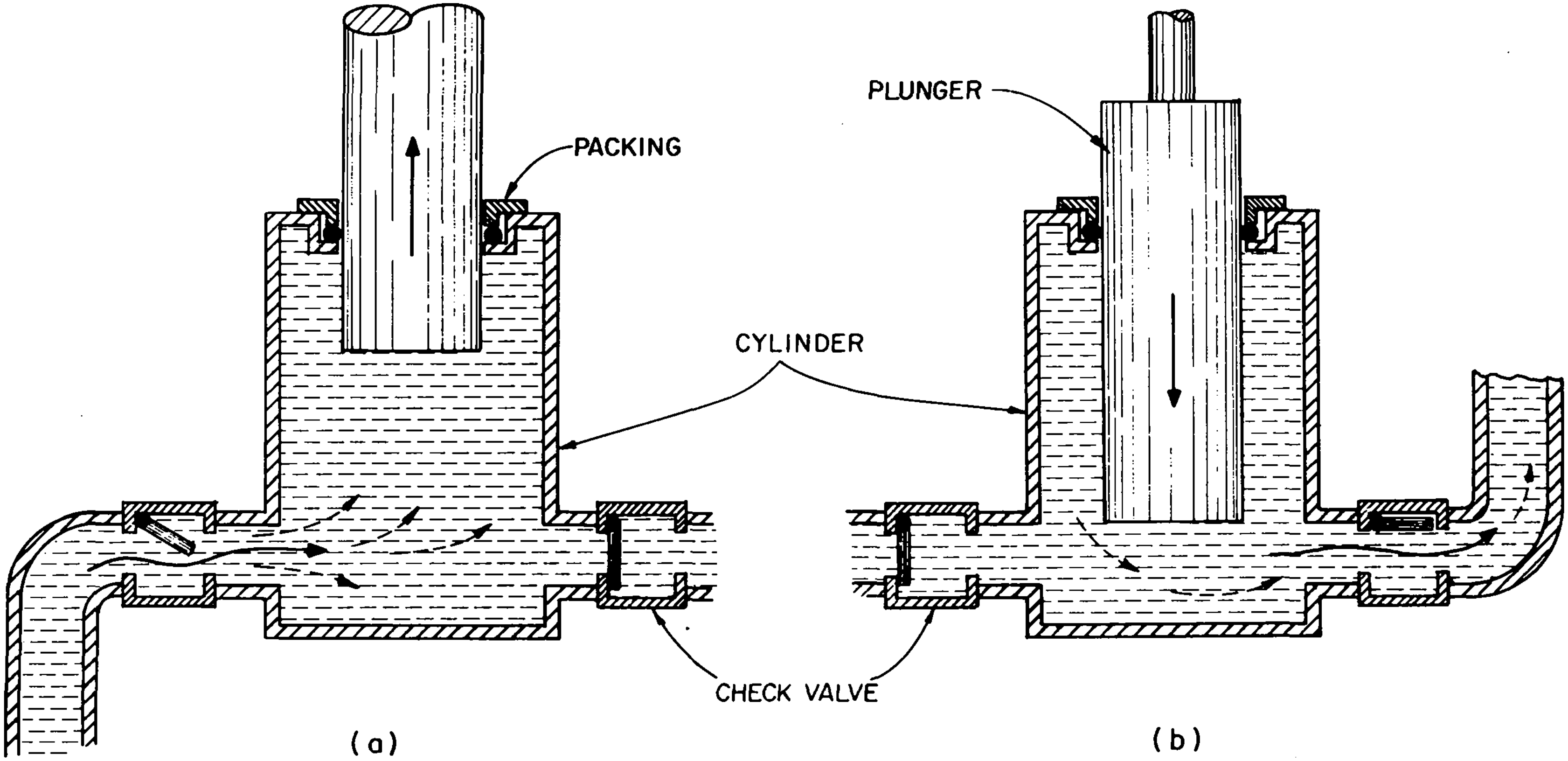


Figure 3.16 Operation of single-acting, plunger-pump; (a) suction, (b) discharge

On the reverse stroke (downward), the plunger forces water out through another, but outward opening, check-valve.

(b) The *piston-pump* (figure 3.17) operates the same as the plunger pump except that it utilizes a solid piston which fits tightly against the cylinder walls.

(c) The *bucket-pump* uses a piston having check-valve(s) which, as in figure 3.18, open on the downward stroke. On the upward stroke, the piston sucks water in through the bottom inlet and simultaneously pushes water out through the upper outlet. Then, on the downward motion, the piston's check-valves open, allowing the water to flow from beneath the piston to above it--ready to be pushed out on the next upward stroke.

All three of these pump types, but particularly the bucket-pump, are often referred to as *lift* or *force* pumps since they can both lift the water to the piston (or plunger) level and force it out of the cylinder. However, as shown in table 2.2, the next normal subdivision of these pumps is into *direct-acting* and *power* categories, depending on the method used to motivate the piston or plunger.

3.2.3.1 Direct-Acting Pumps

Direct-acting piston or plunger pumps are so named because they utilize a driving piston mounted on a common rod(s) with the water-end piston or plunger. As illustrated in figures 3.19 and 3.20, steam (or compressed air) alternately enters both sides of the driving piston, causing it to move back and forth, along with the connecting rod which in turn reciprocates the water-end piston or plunger. In most modern designs, the reciprocating connecting rod also automatically moves the

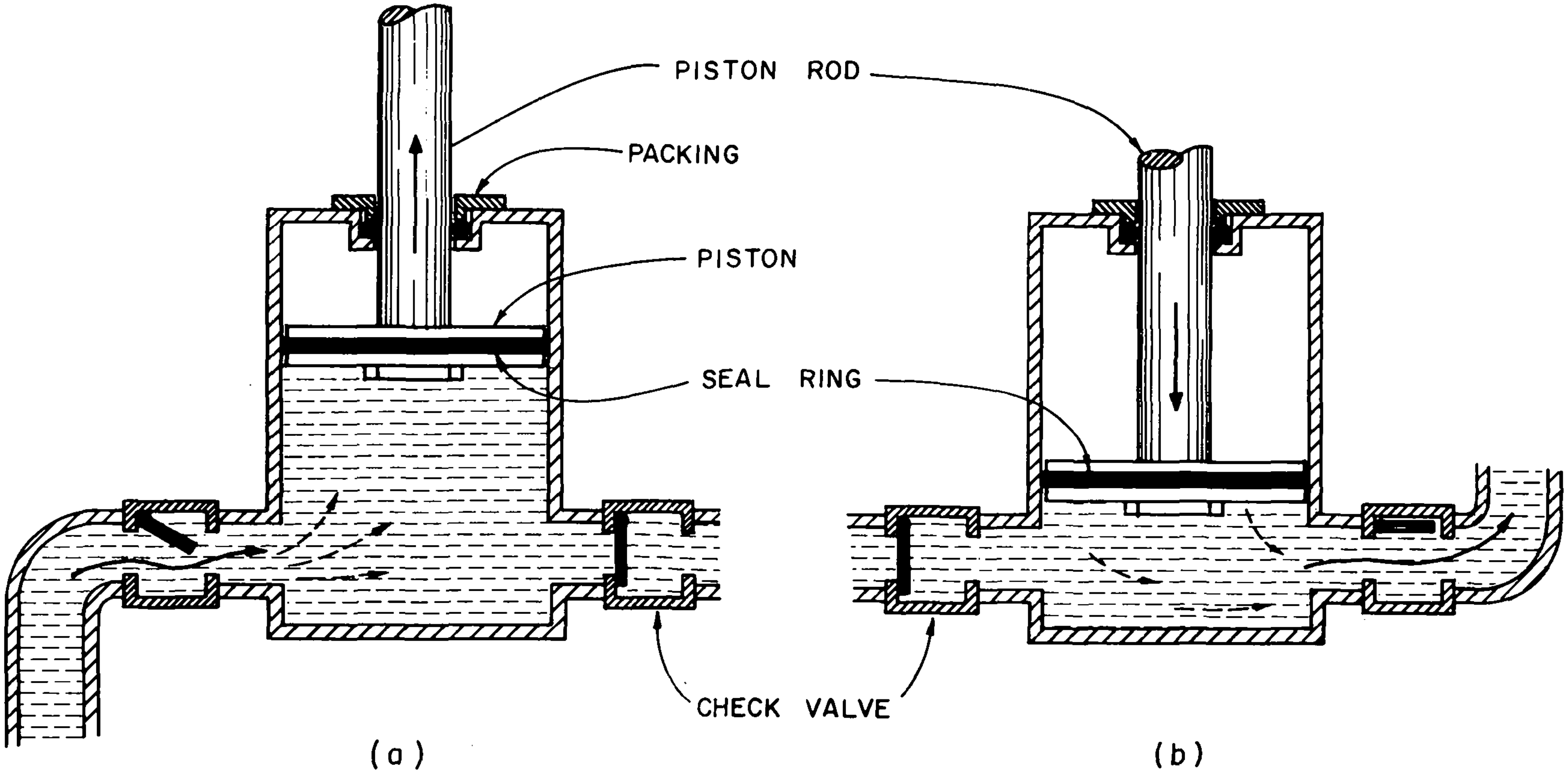


Figure 3.17 Operation of single-acting, piston-pump; (a) suction, (b) discharge

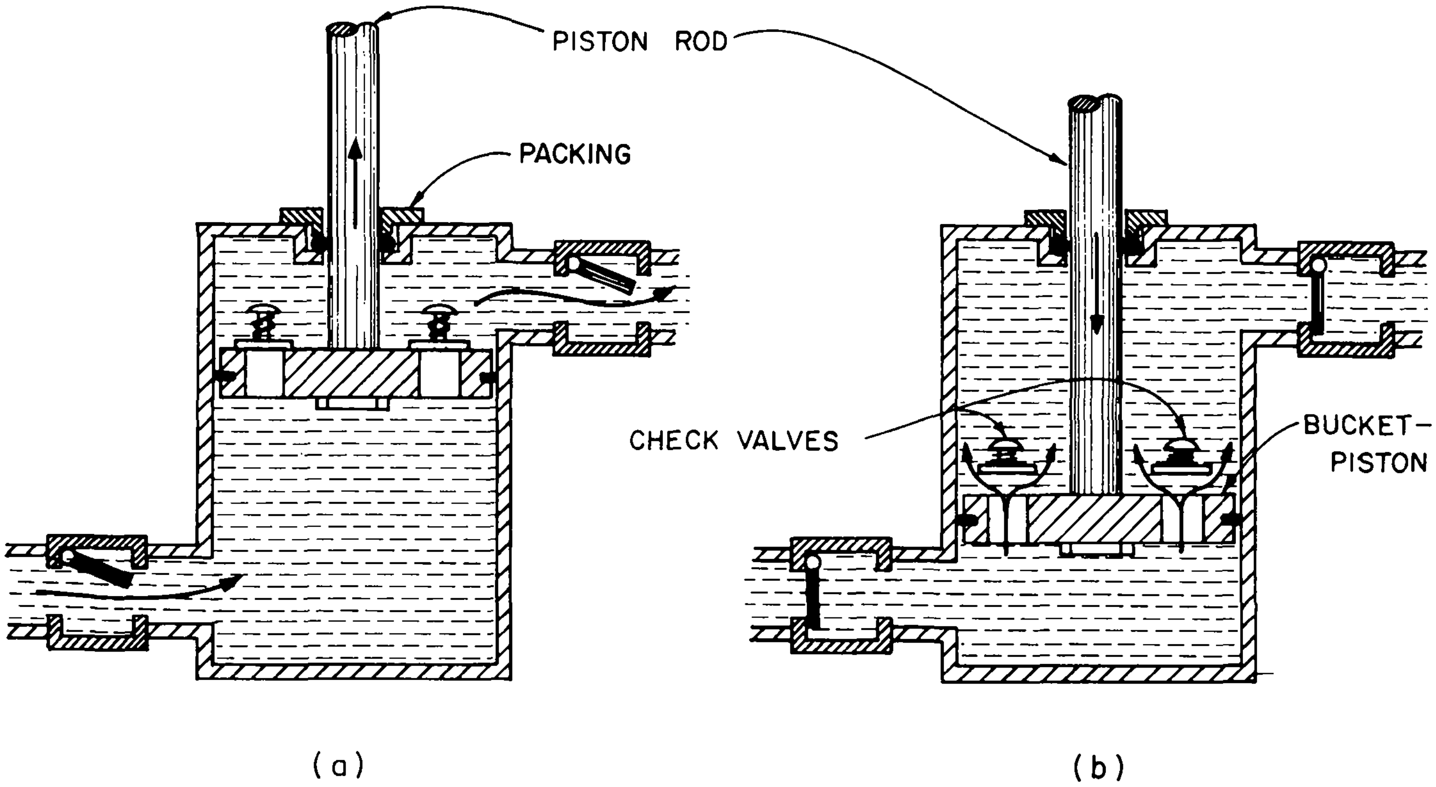


Figure 3.18 Operation of single-acting, bucket-pump; (a) suction and discharge stroke, and (b) return stroke

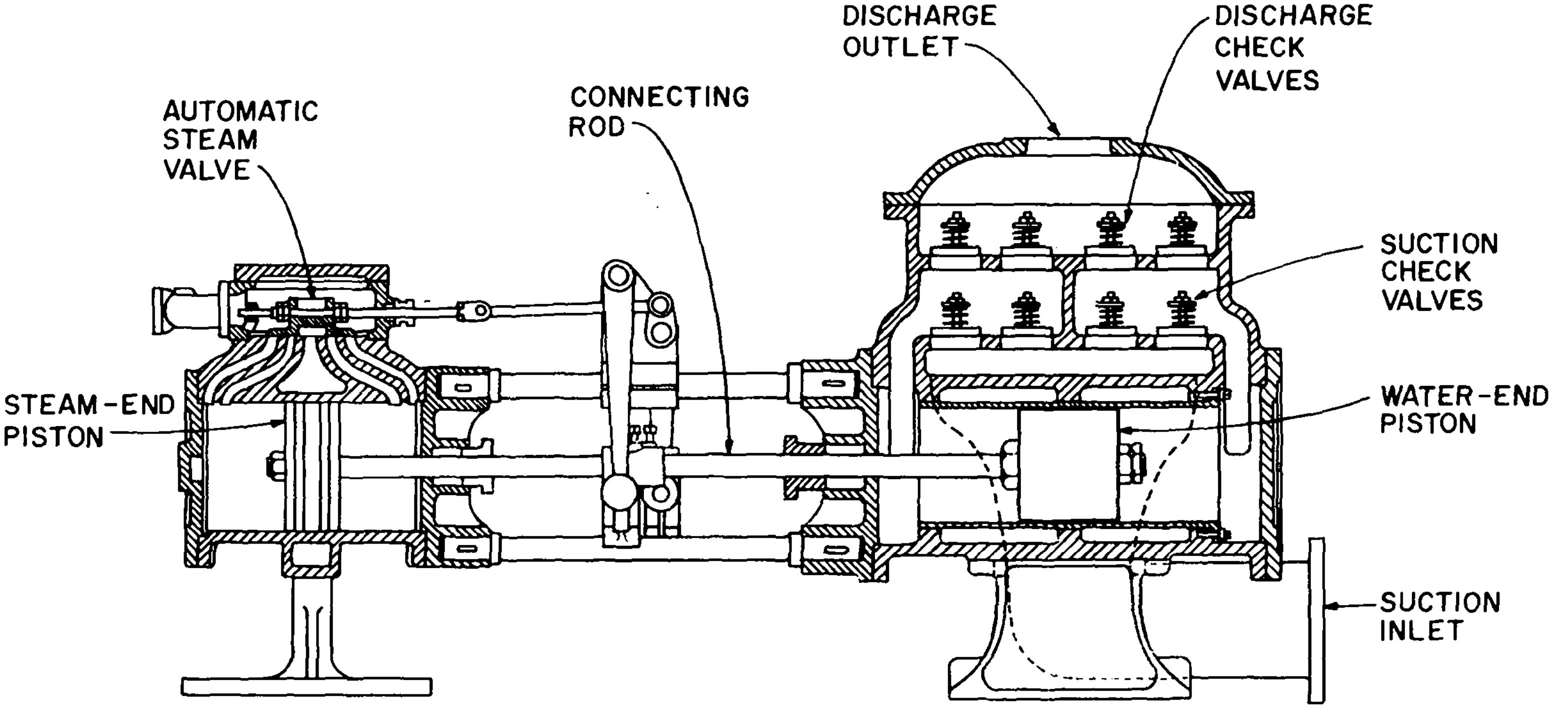


Figure 3.19 Direct-acting, double-acting, piston pump

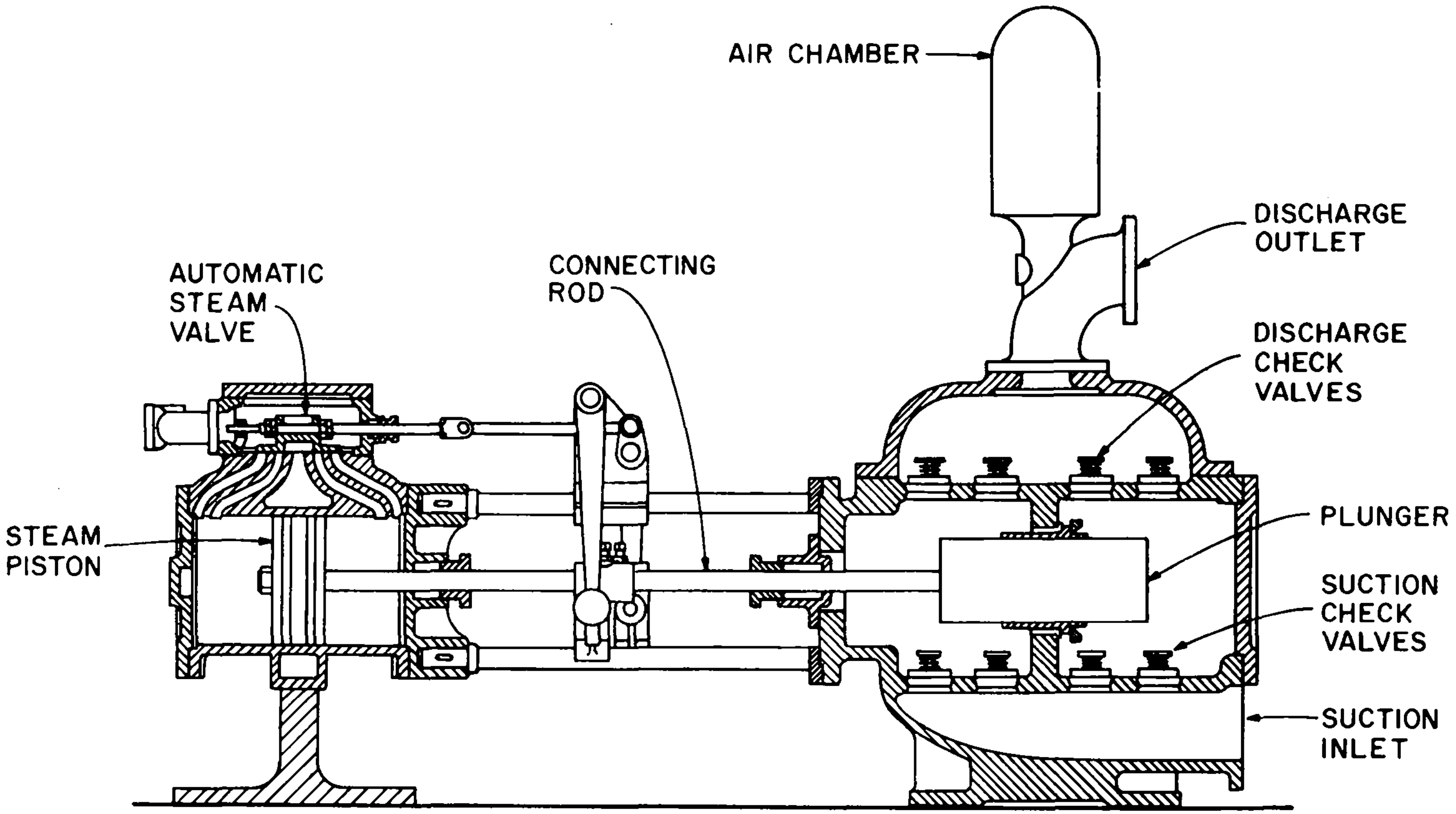


Figure 3.20 Direct-acting, double-acting, inside-packed, plunger pump with air chamber

inlet and exhaust valves for the steam (or air) chamber. Although most direct-acting pumps have one steam piston per connecting rod and are referred to as *simple*, some designs utilize two (or three) *tandem* pistons. With two piston surfaces to push upon, the same steam pressure can apply twice (theoretically) the power to the water piston.

3.2.3.2 Power Pumps

"Power pump" is the popular nomenclature given to any piston-, plunger-, or bucket-pump which is not direct-acting, although of course, all pumps need power to operate. Also, this term usually denotes mechanically driven (e.g. gas engine, electric motor) pumps, however, since the principle is identical, manual-, animal-, and natural-driven piston pumps are included in this category. In addition, steam drivers which use a crank and flywheel instead of direct-action are included (Pumping Manual, 1964, p. 26). Since most drivers produce a circular motion, the power is usually converted to a reciprocating motion by means of a cam or eccentric gear, e.g. the plunger pump in figure 3.21. In addition, a flywheel may be used to store energy not directly used during the nonuniform reciprocating motion i.e. at the end of strokes. Of course, in the basic "hand pump," figure 3.22, the manual power is normally transmitted by means of a reciprocating lever.

Although not normally intended for irrigation or drainage applications, several recent design variations, e.g. induced flow pumps and manifold accumulators (Marlow, 1975), have occurred which have improved the operation of reciprocating pumps in modern applications. However, developments in solar-drivers are leading to new

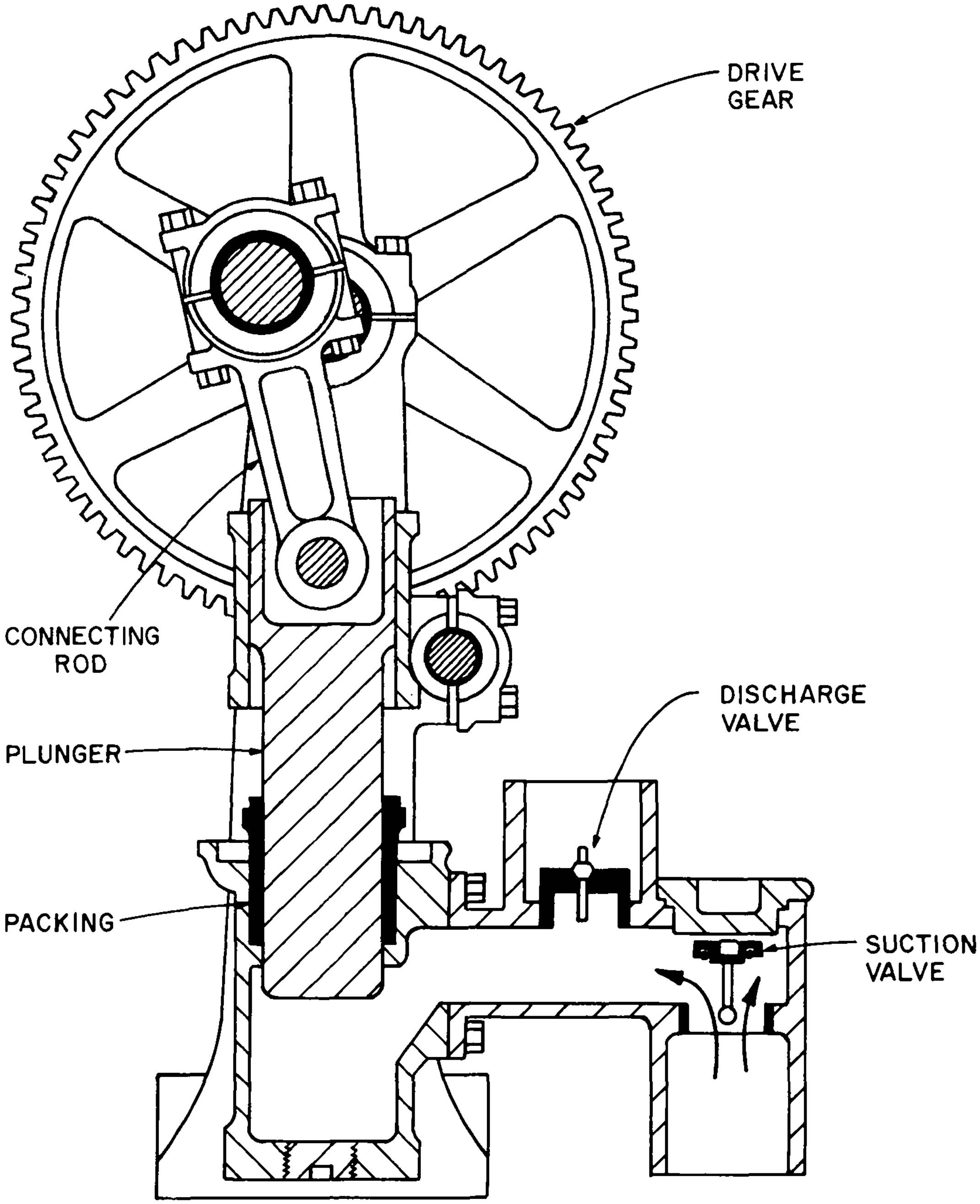


Figure 3.21 Single-acting, power-driven, plunger pump

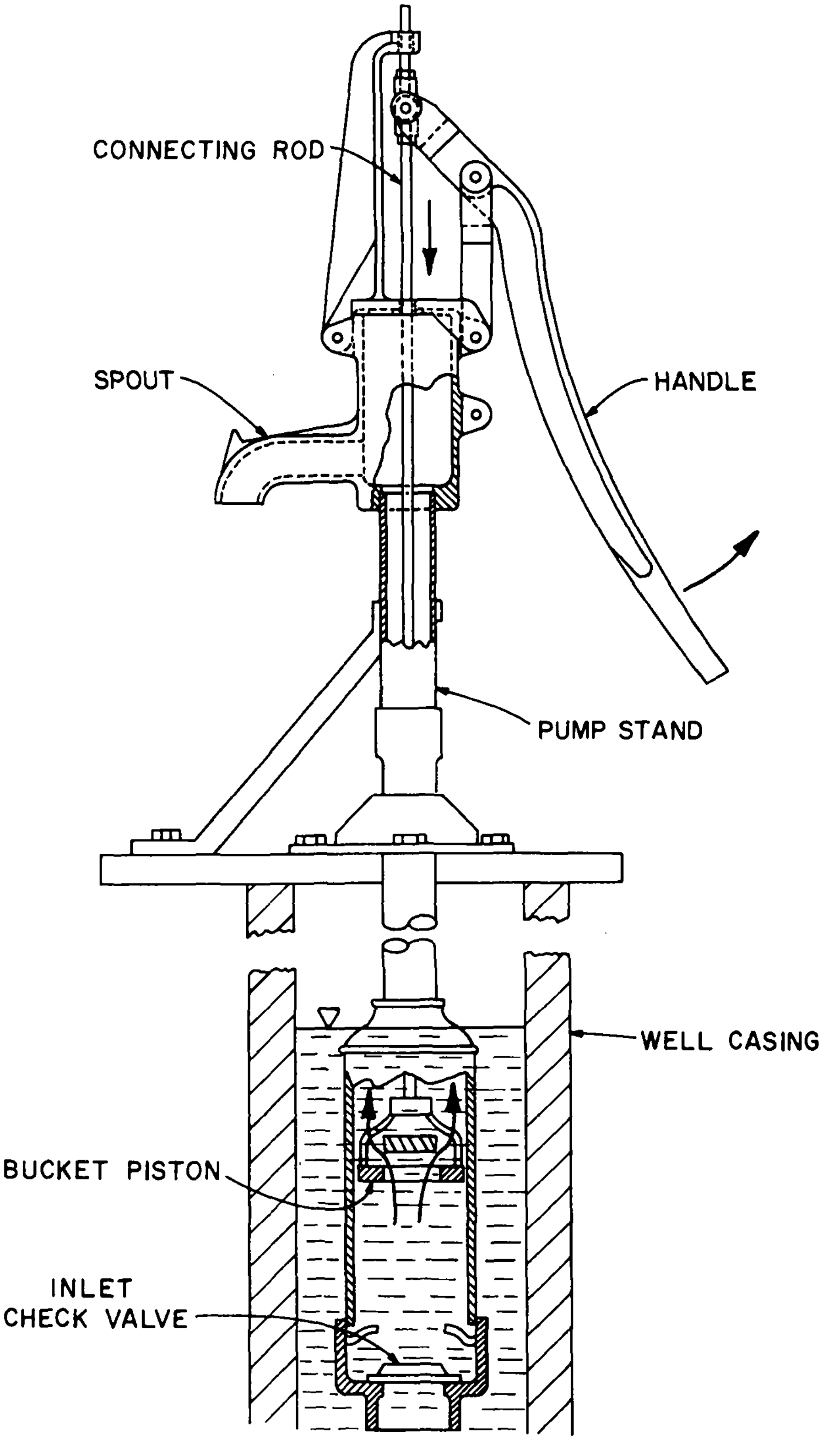


Figure 3.22 "Hand pump" with single-acting, bucket-piston

applications of reciprocating devices for irrigation in arid areas (see Chapter 5).

3.2.3.3 Characteristics

Several differences exist, other than the method of driving, between direct-acting and power pumps. The speed, i.e., strokes per minute, of a steam pump varies with the discharge head and when this head (on the water piston) equals the pressure on the steam piston(s), the pump will stall. The speed of the power pump does not vary significantly with discharge head and will not stall at excess heads. Instead, it may overheat or stall the prime mover, or if not governed, burst the pump cylinder or valves. Therefore, power pumps are usually specified for high head applications and direct-acting pumps for lower heads. Similarly, since a plunger simply protrudes into the water cylinder and need not slide or seal along the cylinder wall as does a piston, plunger pumps are more suitable for high discharge head. However, this sealing at the cylinder wall makes pistons more efficient for high suction lifts.

Another significant difference between direct-acting and power pumps is their discharge per time performance. First, however, two other aspects of pump design and operation must be discussed--single- and double-acting pistons (plungers) and multiple pistons. If reciprocating pumps operate as illustrated in figures 3.16-3.18, the discharge would be in individual time units, with an equal amount of time required to reverse the piston during the suction stroke. This motion is called *single-acting*, and for a single-piston or *simplex* power pump would produce a discharge vs. time curve similar to that in figure 3.23a. Since this makes for an

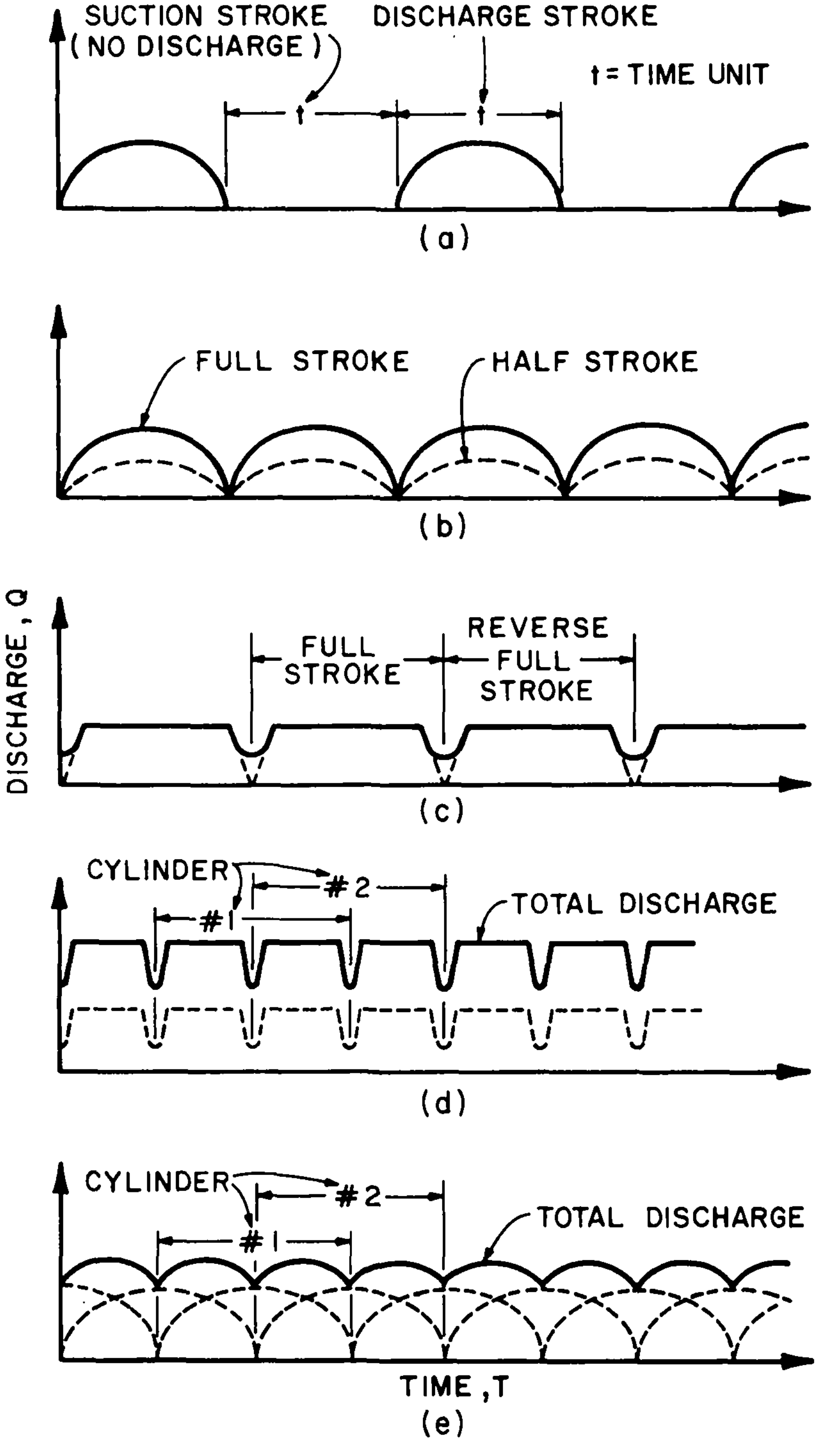


Figure 3.23 Q-T curves for (a) simplex, single-acting power, (b) simplex, double-acting power, (c) simplex, double-acting steam, (d) duplex, double-acting steam, and (e) duplex double-acting power pumps

unsteady discharge, puts a nonuniform load on the driver, and in effect wastes one stroke, most piston- and plunger-pumps are designed to be *double-acting*, as in figures 3.19 and 3.20. In this way, the pump both suctions and discharges with each stroke. (One full stroke is the length of motion in one direction, i.e. two strokes per revolution of a power crank.) Therefore, the time periods of "no flow" are filled by an equal set of "sine wave loops" (Pumping Manual, 1964), producing the curve of figure 3.23b. This sine shaped curve is due to the piston rod following the circular motion of the power driver. The water-piston of a direct-acting pump, however, follows the one-dimensional strokes of the steam piston and thus produces the discharge-time (Q-T) curve of figure 3.23c. This curve is actually that produced when an *air chamber* is used to cut down the variation of discharge head caused by the ending of each stroke. This is normal practice, particularly for direct-acting pumps. Such air chambers are also usually included in the suction line to smooth out the suction flow (Barr, 1903, and Greene, 1913). In order to produce an even more steady discharge, additional pistons can be utilized for each pumping unit. These additional pistons are usually set to end a stroke at the middle of the other piston strokes. Thus, a two-piston or *duplex*, double-acting, direct-acting pump produces a Q-T curve similar to figure 3.23d, while a similar power pump has a curve like figure 3.23e, i.e. the addition of simplex, double-acting curves.

Power and direct-acting pumps are similar in that like other positive displacement devices, they have little variation of Q with H. As shown in figure 3.24a, for each operating speed, the H-Q curve

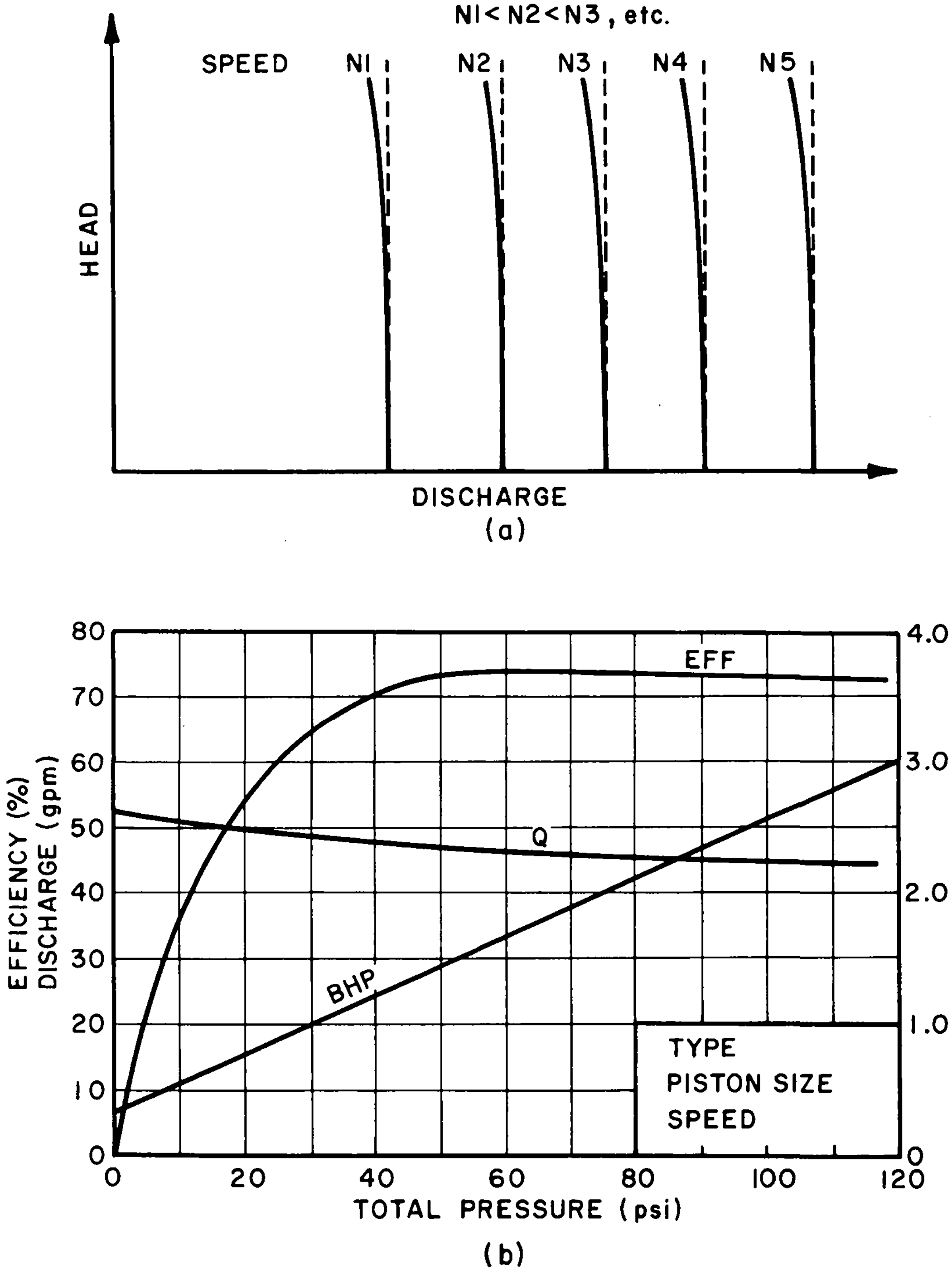


Figure 3.24 (a) Characteristic H-Q curves at various speeds, and (b) sample composite performance curves of reciprocating pump

is nearly vertical. This relationship is also seen in the example composite performance curves of a piston pump in figure 3.24b. Note that because pressure is often the major performance concern in sophisticated, positive displacement pumps, total pressure or head is used as the common abscissa for such curves. However, as previously mentioned, the discharge of steam pumps may show a more appreciable variation with head than power pumps as total head nears stalling pressure.

Another feature of piston-, plunger-, and bucket-pumps is that due to their positive displacement nature, they are self-priming. That is, within the limits of their structural soundness (e.g., cylinder wall strength, air-tightness) and surrounding pressures (i.e. NPSHA), they can displace air in the suction line which causes a pressure drop and thus the suction of water.

Many devices exist to vary the capacity of small direct-acting and power pumps--see Hicks and Edwards, 1971. However, for most pumps, and particularly power pumps, a common method of capacity variation is changing the stroke length. The half-stroke of a power pump is illustrated in figure 3.23b. In addition, a variable-speed driver provides capacity variation quite readily to a power pump. The hand piston-pump serves as a simple example of this--the faster a person "pumps" the handle, the greater the discharge.

3.2.3.4 Applications for Irrigation and Drainage

Since the development of rotodynamic pumps (see section 1.2), mechanically-driven, power and direct-acting pumps have lost popularity for irrigation and drainage where mechanical prime movers are available. This is due primarily to the fact that rotodynamic pumps produce the high Q, low H performance usually needed for irrigation and drainage situations, whereas positive displacement pumps are better suited for high H and low Q applications. Additionally, rotodynamic pumps contain far less moving parts which require less maintenance and cost. Of course, direct-acting pumps need a steam or compressed air source which makes their field use quite impractical. Also, due to the conversion of rotary, prime-mover power into a reciprocating motion for power pumps, much more power is lost in transmission than with rotodynamic pumps which operate in a rotary motion themselves (see section 4.2).

However, when these direct-acting and mechanical-power pumps are used for irrigation or drainage, they exist in three basic forms. In either a vertical or horizontal position, they can be mounted above the water supply with a suction line extending to the water, as in figure 3.25. In this application, the dynamic suction lift must be considered so as not to exceed the NPSHR. Table 2.3 presents a guideline of practical dynamic suction lift limits. When a conventional direct-acting or power pump cannot be installed near enough to the water surface (e.g., in a well or mine shaft), two other forms of these pumps can be utilized. The first is commonly called a *mine* or *sinking pump* and is illustrated in figure 3.26. This device is simply a compact, direct-acting pump which can be lowered into a narrow shaft along with a steam or compressed air hose for power. These pumps were used primarily in mines before the refinement of rotodynamic pumps and have almost no application for irrigation or agricultural drainage. The second alternative for deep well pumping is to lower a bucket-piston with connecting rod to within NPSHR limits

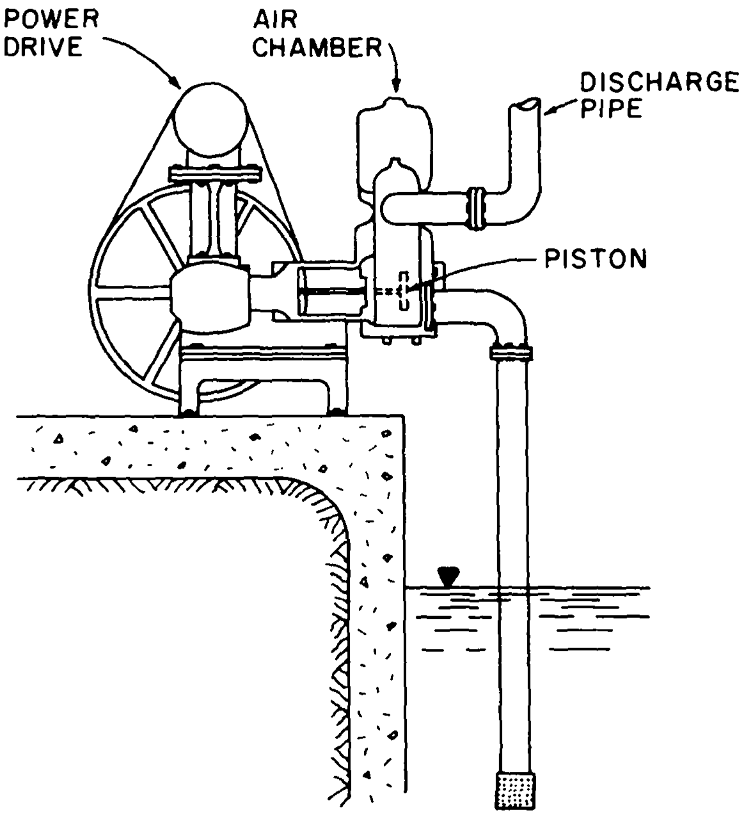


Figure 3.25 Power pump mounted above water supply

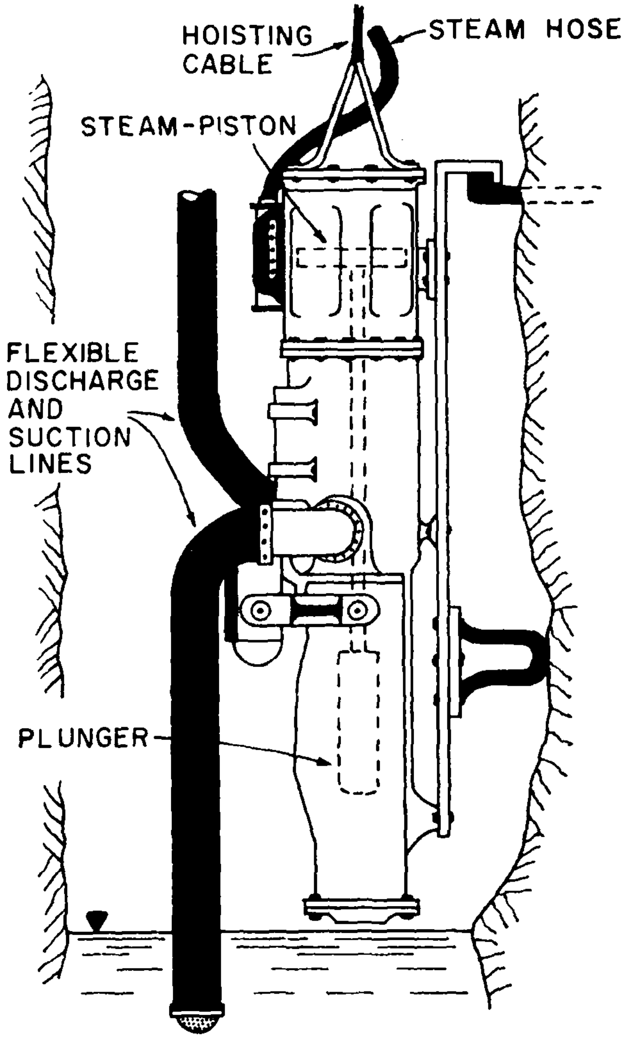


Figure 3.26 Sinking pump in narrow shaft

of the water surface. The rod is connected to a prime mover at the well surface which, due to the long rod length, operates at low speeds (40-65 stokes per minute--spm). These surface prime movers, often referred to as *pump heads*, are usually gas engines, electric motors, or manual levers, however, throughout the early 1900's, steam pump heads were common (Greene, 1913). These bucket-pumps can be single-acting as in figure 3.22 or can utilize double-acting cylinders as in figure 3.27.

Initial costs vary greatly on mechanically driven piston and plunger pumps, depending on size, availability, manufacturer, etc. Manufacturer's catalogs must be consulted for exact prices, however, even the smallest lifter-driver units have "new" prices starting at over $200. Several companies manufacture bucket-pump units similar to the one in figure 3.27, which can be designed to use with several drivers, i.e. the connecting rod can be extended up to a windmill, or it can be attached via a cam gear to a small engine or motor, or a handle can be attached for manual use. Some initial costs on these units would be approximately as follows (for new equipment):

pump head with handle - $50 - $200/each
connecting rod - $75/100 ft
well pipe - $100/100 ft
cylinders with piston - $20 - $70/each
accessories - $20 .

When used with 1/2 to 1 hp engine or motor, additional costs are:

engine (gas or diesel) - $50 - $100
electric motor - $50 - $125
gear attachment - $100 - $200 .

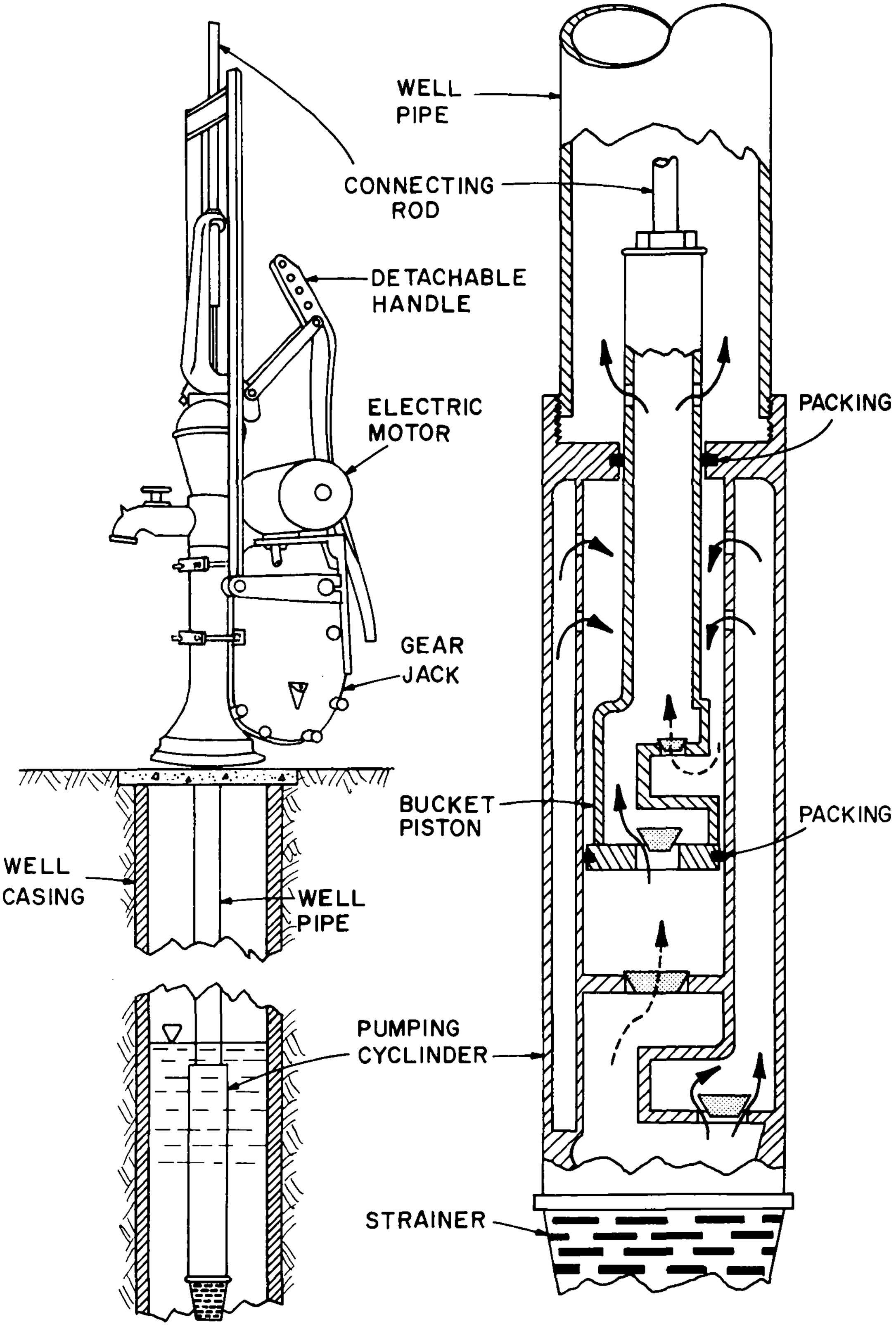


Figure 3.27 Pump head for mechanical or manual power with double-acting, bucket-pump

However, in addition to these commercial bucket-pump units, less sophisticated units are easily constructed by local craftsmen in many developing countries. As Eubanks (1971) describes, the first and simplest bucket (or lift) pumps were made of bored out logs--thus, often called "*wood* or *log pumps*." A wooden piston with leather skirting was attached to a long wooden shaft and inserted into the log cylinder. A lever-handle was optional for reciprocating the shaft. These principles of local manufacture and simple construction have lead several international assistance organizations to develop designs for lift pumps which can readily be utilized in developing countries. Although the primary concern was to provide a pump for domestic purposes, their application can easily be extended to irrigation and drainage.

Among the simplest designs for a bucket-pump is the "inertia hand pump" described in VITA's *Village Technology Handbook* (1975). It is constructed primarily of scrap materials such as used barrel metal and inner tube rubber, and can be made by any craftsmen with the proper tools, e.g. a tinsmith. It is reported to lift 20-30 gpm with a 13 ft head and 60-75 gpm with a 3.3 ft head. Because this design uses scrap material, no cost estimate is given.

Rev. George Cotter, at the Buhangija Mission in Tanzania, reports on a locally developed bucket-pump called the "Shinyanga lift pump." It uses metal rods, pipes, bolts, etc. which can be obtained from "any sizable hardware store," and plastic pipe and steel-ball, check valves, which Rev. Cotter supplies in his locale. He reports that this device is capable of 7 gpm at a 5 ft head. The initial cost, including a 5 ft cement block well, is about $20.00.

The only normal maintenance is replacing the rubber bucket-seal about twice a year.

A Peace Corps volunteer, Steve Simmons, reports the use of a commercial ABI pump in the Congo. In addition to its $300 initial cost, several problems were encountered in its operation which made this pump undesirable for local use (Peace Corps, 1975). Because of such problems, the Peace Corps, working through such agencies as AID, the Battelle Memorial Institute, UNICEF, and CARE, saw the need for a simple, inexpensive, and dependable hand pump. Specifically, they were looking for a pump design with the following features (Peace Corps, 1975);

(a) low production cost,
(b) long life under severe conditions,
(c) easy maintenance with simple tools and unskilled labor,
(d) suitable for shallow- or deep-well applications,
(e) manufacturable in developing countries,
(f) easily operated by small people, including women and children, and
(g) able to discourage pilfering and vandalism.

With these objectives, a pump--shown schematically in figure 3.22--was developed which had a strong cast-iron cylinder, stand, and handle. In an effort to eliminate poor-wearing leather seals, several synthetic materials were suggested as good substitutes, e.g. nylon, Corfam, Rek-Syn, etc. However, an effort was also made to allow the standard design to be adaptable to locally manufactured parts if imported, commercial materials were unavailable. Pumps of several different component materials were tested with up to the equivalent of 10 years of hard use and the various materials evaluated for performance and wear--see Fannon and Frink (1970). No costs were available on this "AID pump," however, the above report lists many agencies and businesses which are cooperating in its manufacture.

In another AID paper, Nizam Ahmed (1975) reports on irrigation by "hand pump tubewells" in Bangladesh. Locally-manufactured, commercial bucket-pumps are used with either mechanical drivers or manual power. The mechanical version allows irrigation of an average of 47 ac per pump, while manual power allows only about 0.6 ac per pump. Ahmed reports that hand pumps with 20 ft of pipe and a strainer can be bought for $45 - $53 or rented for upward of $28 per 4 month season. Maintenance costs average about $2.00 per year for replacement of valves, valve-seats, etc. This report also gives a good cost analysis of irrigation by this method which will be described, in part, in Chapter 5. Additionally, Ahmed observed that continuous hand pumping caused blisters and rapid tiring. Therefore, many farmers have attached bamboo poles and/or ropes to the pump handle with which they can push the handle down by foot and then pull up by hand. They do this either sitting or standing.

W. K. (Tim) Journey, working with UNICEF and the World Bank, has also suggested improvements to the piston pump such as using PVC instead of cast iron in down well components to cut friction and corrosion. Additionally, he has developed a simple, counterweight pendulum apparatus to conserve manual energy during pumping (see section 5.2.1).

These hand pump developments have been included as examples of efforts being made to improve the design of these pumps and to promote their use.

3.2.4 Diaphragm Pumps

Diaphragm pumps are often considered another form of the piston pump since many designs utilize a piston as an operational component. However, because *bellows pumps* are also a diaphragm device, this subclass is appropriately considered apart from piston pumps. The major feature of diaphragm pumps is that the reciprocating piston has been replaced by a pulsating, flexible membrane which operates in basically one of three ways.

In bellows devices, the diaphragm comprises a portion of a chamber which can thus expand and contract. As can readily be seen in the *double lantern bellows pump* in figure 3.28, the expanding bellows draws water in past an inlet check-valve just as a retracting piston or plunger does. Then, as the bellows is contracted, the water is forced through an outlet check-valve.

Although such lantern-style bellows are not commonly used for water pumping, this principle, combined with foot-operation (an idea originally used by ancient blacksmiths for venting forges--Rouse and Ince, 1963) has been developed into a low-cost, low-lift pump by the International Rice Research Institute (IRRI) under a contract with AID. As seen in figure 3.29, the bellows in this "foot pump" are made of canvas with metal reinforcing inserts and a wooden frame. The operator stands on the two foot rests above the bellows and shifts his weight from one foot to the other. This alternately expands and contracts each bellows and thus lifts water.

The IRRI design has a handle bar which serves as both a support while pumping and a handle for carrying the 45 lb pump. It is easy to repair and simple enough for small machine shops to construct.

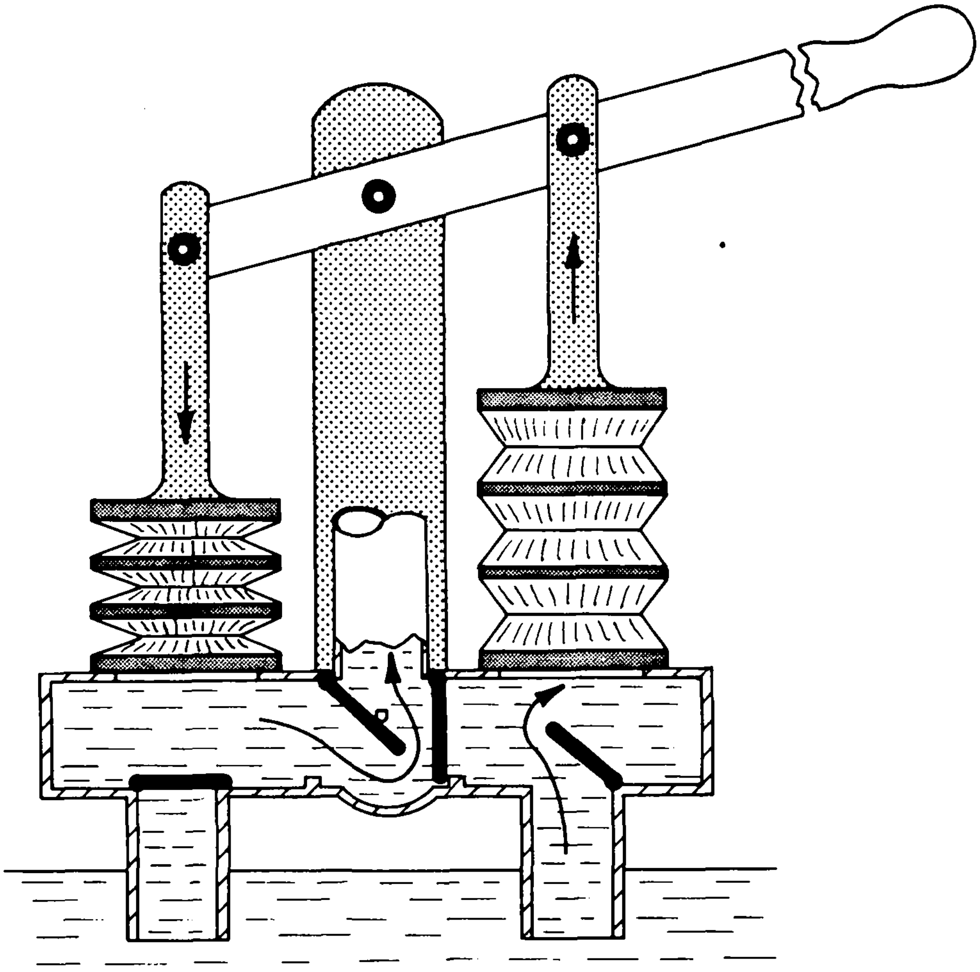


Fig. 3.28 Double "lantern" bellows for pumping water

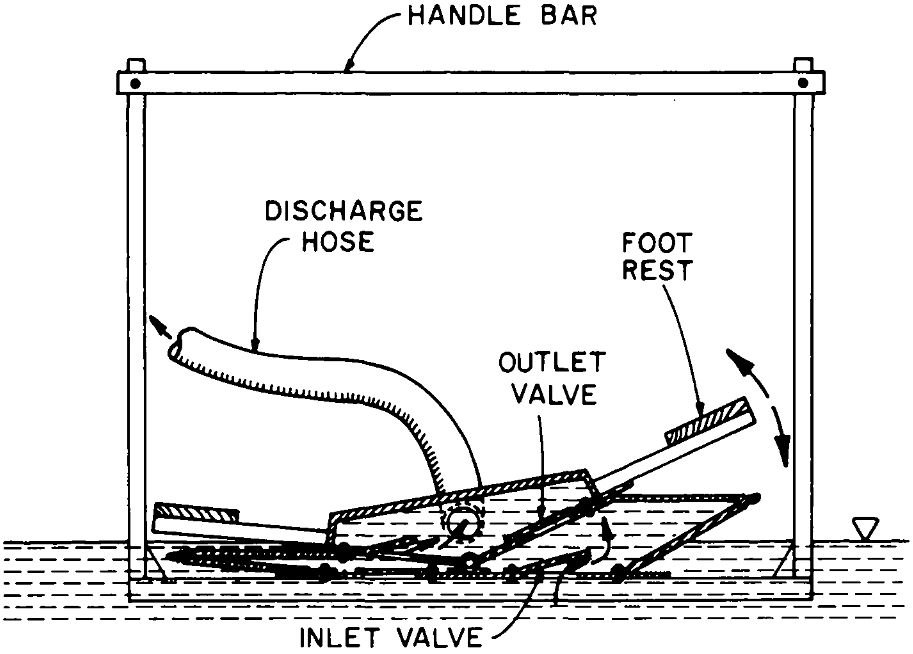


Fig. 3.29 Foot-operated bellows pump
(Courtesy of IRRI)

Design drawings are given free of cost to manufacturers who agree to IRRI conditions. Although this design is expected to be rugged for a long service life, additional work is being done to improve its present durability (Kuether, 1975). Cost is about $25 (Shuler, 1976). Normal maintenance consists of canvas repair after about 175 hours of use. The performance of this pump is reported (IRRI, 1975) as:

40 gpm at 1.6 ft head
32 gpm at 3.3 ft head
29 gpm at 5.0 ft head .

This, of course, will vary depending on the operator.

The second form of diaphragm pumps is similar in operation to the piston pump, however, as shown in figure 3.30, the diaphragm is attached to both the piston and the cylinder. This has the advantage of removing the sliding friction between piston and cylinder wall. In addition, since the piston only serves to reciprocate the diaphragm, abrasive fluids, e.g. sandy water, can be pumped without wearing the piston and cylinder walls. The common forms of diaphragm-piston pumps are operated in either of two ways. As in figure 3.31, the piston is reciprocated by a mechanical driver (e.g. gas or diesel engine), or for smaller capacities by hand or foot lever mechanisms (figure 3.30). The other method, illustrated in figure 3.32, is to utilize compressed air or hydraulic pressure on one side of the diaphragm to push it down and then allow a spring loaded piston to pull it up. The pneumatic or hydraulic pressure is automatically regulated to provide the reciprocating motion (e.g. by a solenoid valve and regulator).

These diaphragm-piston pumps are commonly designed to handle 10-150 gpm at heads ranging upwards of 200 ft. The pneumatic/hydraulic

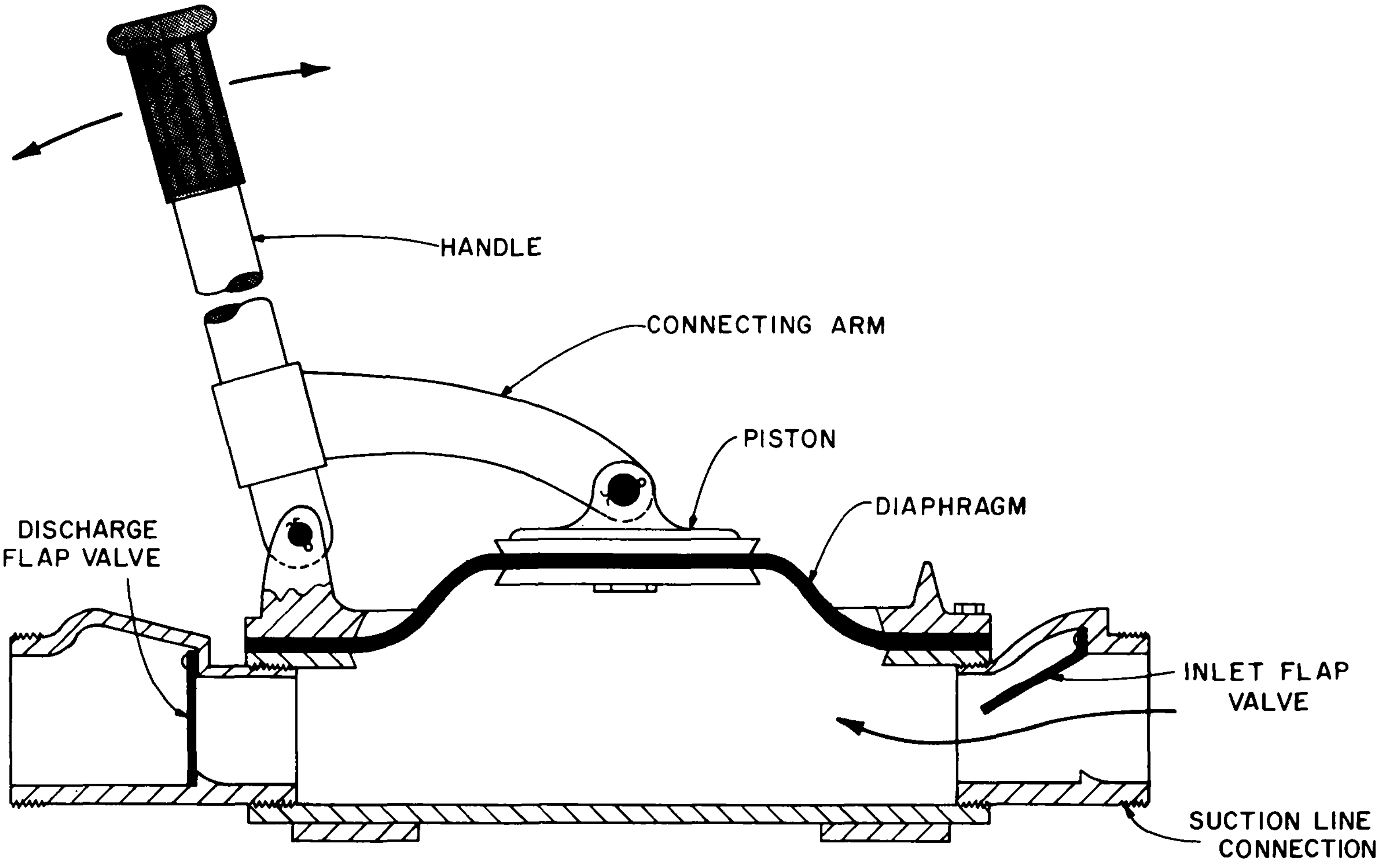


Figure 3.30 Diaphragm pump with handle-lever for manual operation

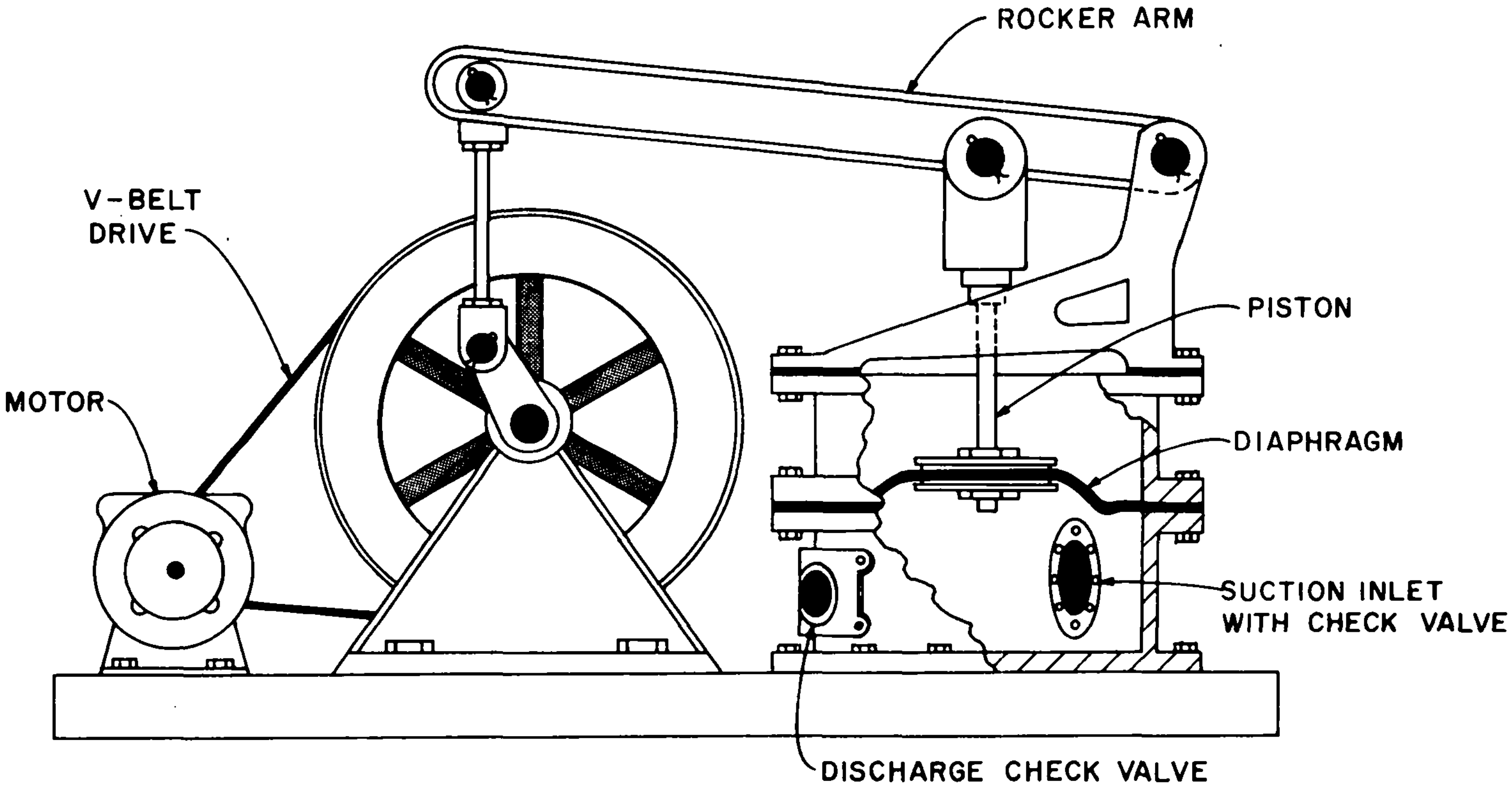


Figure 3.31 Diaphragm pump with mechanical drive--typical "heavy duty" unit

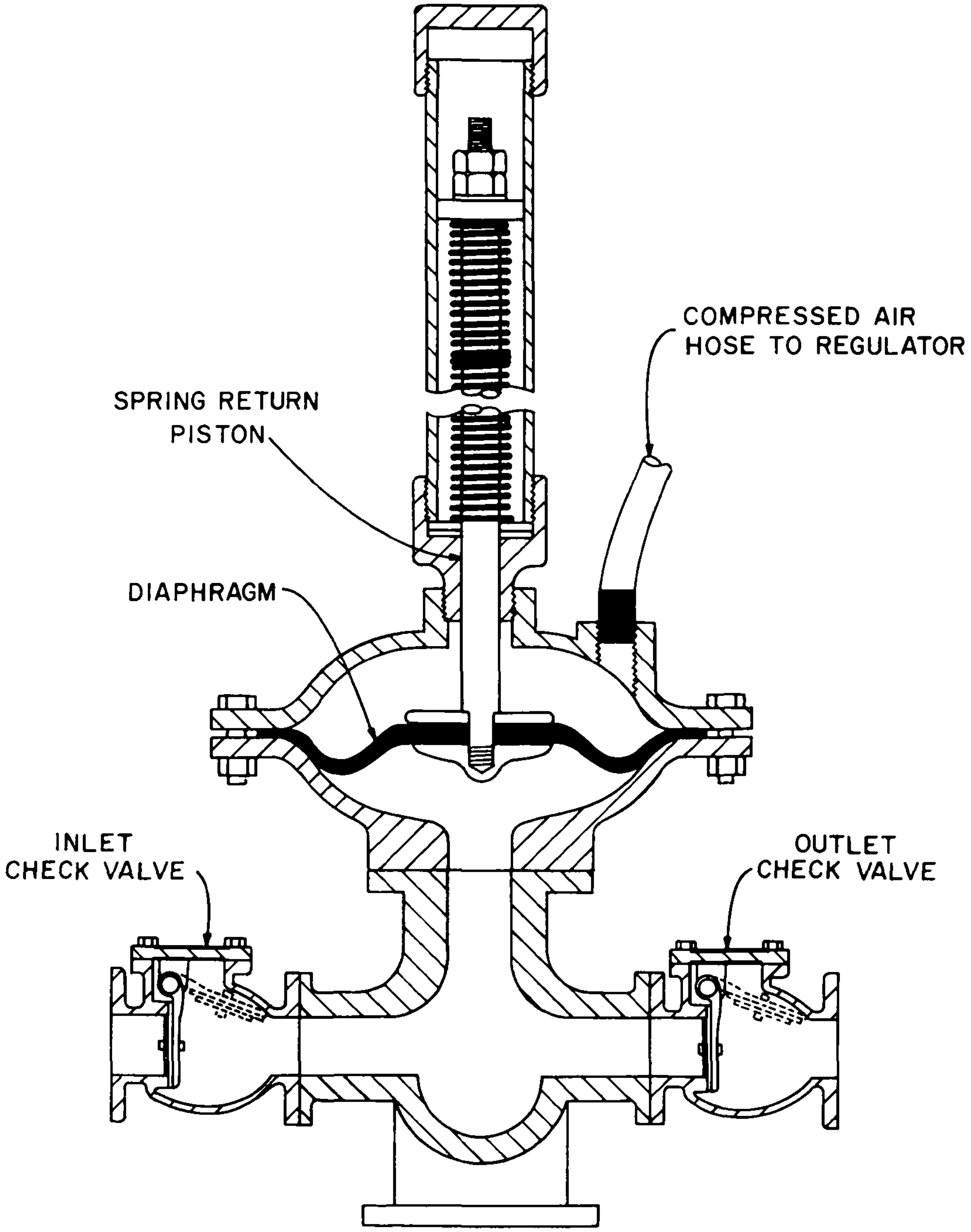


Figure 3.32 Pneumatic/spring operated diaphragm pump
(Adapted from Dorr-Oliver)

operated pumps, in large-capacity sizes, range in price from about $1000-$4000, while mechanical-driven units (including driver on single frame) are in the $500-$3500 range. Small-capacity, manual diaphragm pumps are available commercially in the $30-$200 range, however, similar devices can easily be manufactured by small machine shops.

The third method of diaphragm pump operation is similar to the hydraulic-driven device mentioned above. The only difference is that the piston is not attached to the diaphragm, but instead is utilized as a type of secondary pump above the diaphragm. As shown in figure 3.33, the piston alternately forces the "working fluid" in and out of the cylinder, pulsating the diaphragm, which in turn pumps another fluid. This method has the advantage of providing even pressures across the diaphragm membrane as opposed to mechanical stroking which produces nonuniform stresses with stretching or fatigue near the piston (Pumping Manual, 1964). This type of diaphragm pump is usually confined to small-discharge, industrial uses, however, it is mentioned to illustrate the use of secondary, working fluids. As with power pumps, capacity regulation of diaphragm pumps is normally accomplished by varying the driver speed.

3.3 Rotary Methods

The devices in this subclass increase head by displacing (positively) water in a rotary motion. They should not be confused with rotodynamic pumps which also use a rotary motion (see section 4.2), but utilize primarily high-speed, kinetic energy to increase head. Rotary devices, however, can operate even at very slow speeds and still increase head. As will readily be seen in several of the early devices, (e.g., noria, paddle-wheel), rotary water lifters "trap" the water

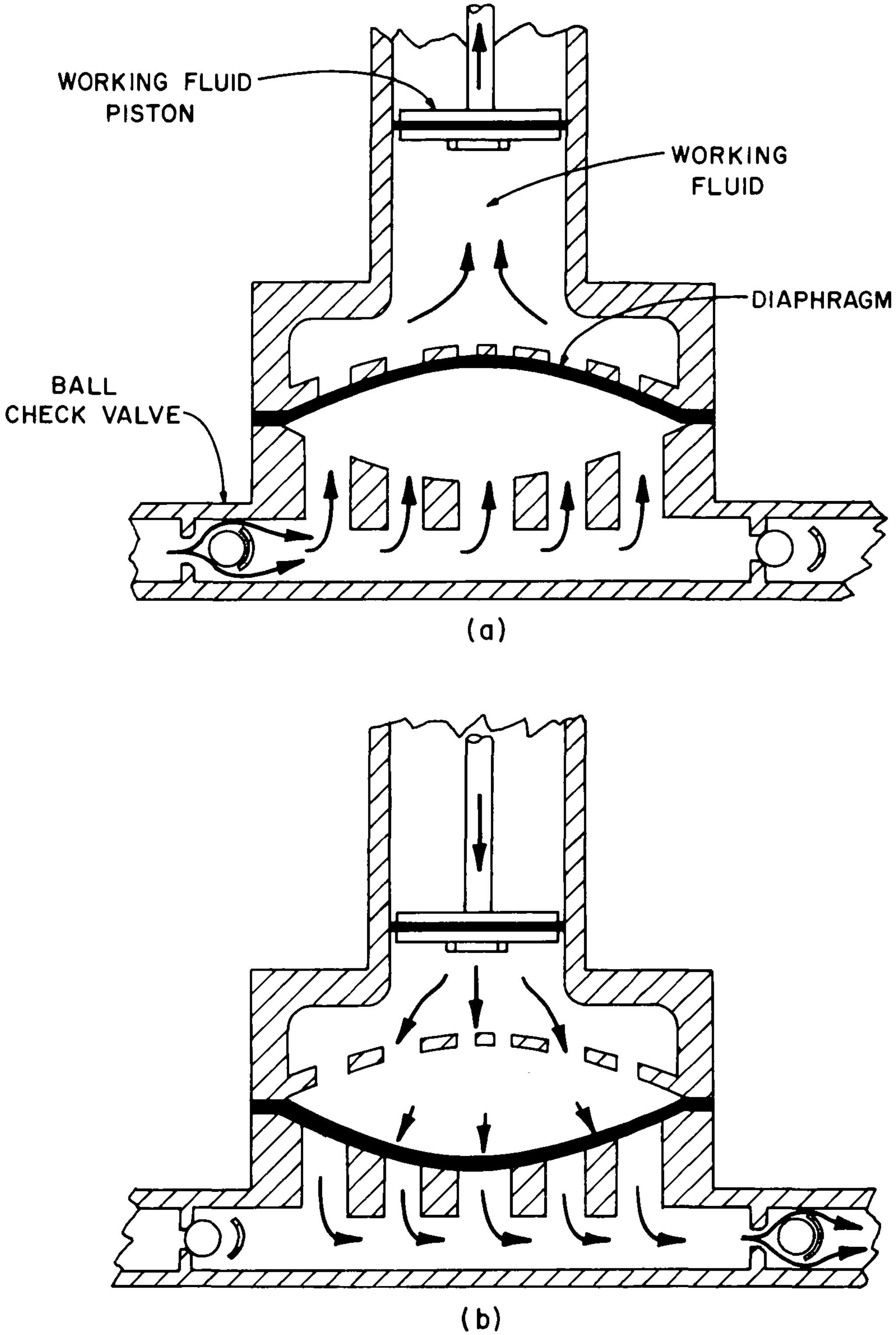


Figure 3.33 Fluid-operation diaphragm pump; (a) suction, (b) discharge

and push it from one elevation (or head) to a higher one. Although, like reciprocating devices they displace isolated units of water, rotary methods normally discharge a more continuous flow (i.e., at a given speed) because several water pushing components (e.g., blades, buckets, pistons) rotate one behind another.

3.3.1 Wheel

After many of the early reciprocating devices were developed, it was eventually discovered that by mounting several of them on a wheel, a more continuous flow could be obtained, i.e., less time waiting to return the one (or two) lifter(s) back to the water supply. The first device to be discussed is a good example of this development.

3.3.1.1 Paddle-Wheel

This wheel type device utilizes the basic idea of lifting water by scooping it, just as was done with the water balance (figure 3.11). However, instead of one scoop or paddle moving back and forth, several paddles are attached to the periphery of a wheel and by rotating the wheel, each paddle pushes a unit of water up a channel.

A typical small-capacity, paddle-wheel is shown in figure 3.34, operating with manual power. In this example, the operator "pedals" the tips of the paddles, however in other versions, the axis of the wheel is attached to a shaft which can then be turned (often via gearing) by some other prime mover, e.g., a windmill, an animal-powered circular sweep, etc. The device shown in figure 3.34 has widespread use in low lift applications such as rice paddies. In order to minimize losses, a wooden channel is usually provided for the paddle-wheel to rotate inside of. In table 3.2, Molenaar (1956)

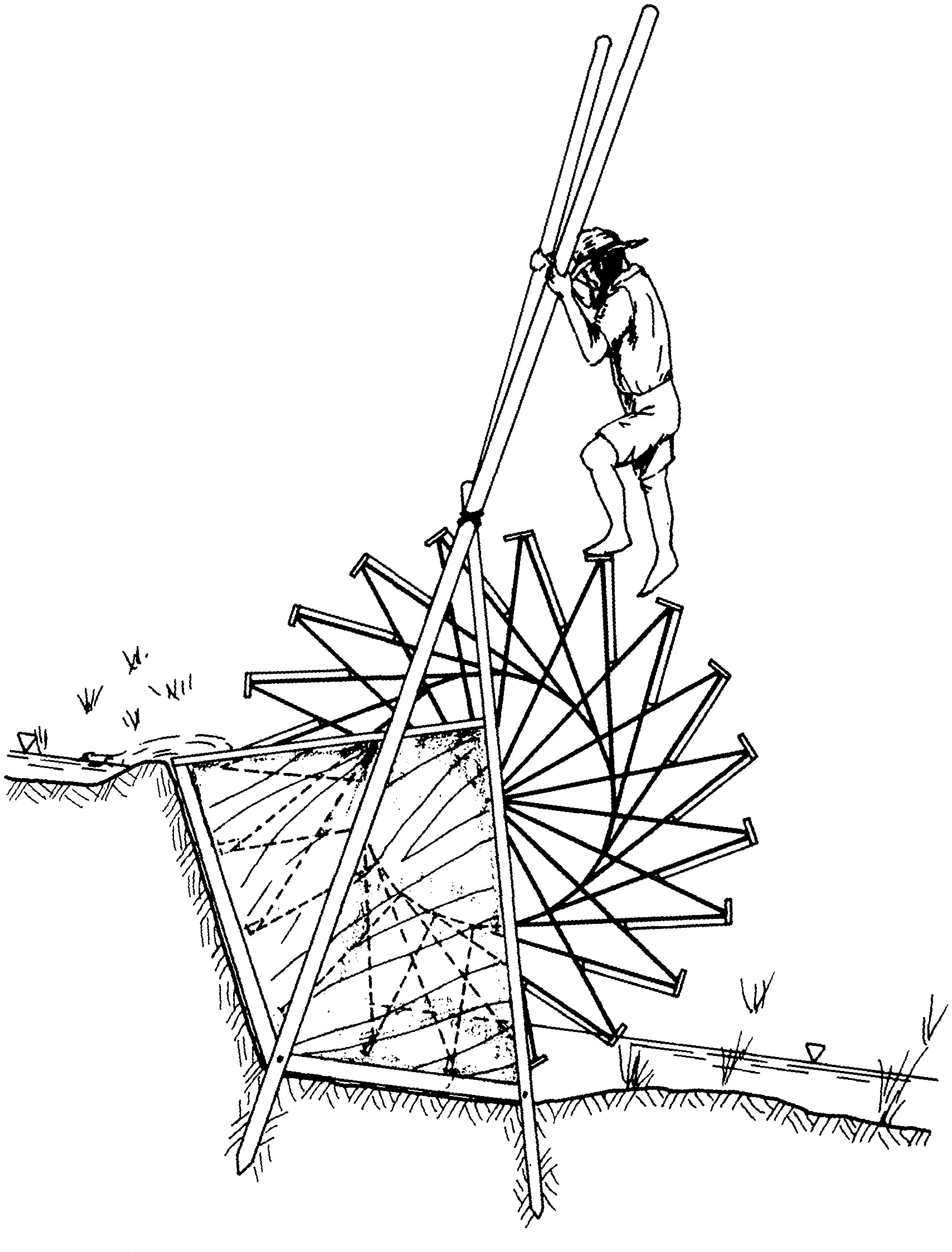


Figure 3.34 Paddle-wheel operated as treadmill

reports the performance of various size paddle-wheels with such a channel.

Table 3.2 Manually-operated paddle-wheel performance

Wheel diameter (ft)	Number of paddles	Man Power required for 1-hr. operation	Height lifted (ft)	Discharge (cfs)	Discharge (cfh)
4	8	1-2	0.5-1.5	0.12	443
8	12	6-8	1.0-2.0	0.18	664
10	16	8-12	1.5-2.5	0.31	1106
12	24	12-16	2.0-3.0	0.50	1770

Paddle-wheels are also commonly referred to as *paddle-pumps*, *chackrams* (India), *kharbauwys*, *flash-wheels*, and *scoop-wheels*, however, the latter two names usually infer large wheels of the size and design used with high-power, mechanical drivers. Such scoop-wheels (figure 3.35) were used extensively in low-lying areas, such as Holland, around the turn of the 20th century. Although windmills originally drove these large scoop-wheels (Starling, 1892), steam engines were later utilized as lifts up to 8 ft and discharges of 250 cfs per wheel (at 2.0 ft heads) increased the power demand (Slichter, 1910). An analysis by W. Airy in the 1910 *Engineering* provides several methods for improving the efficiency of scoop-wheels, as illustrated in figure 3.35:

(a) Paddles, curved (or at least inclined) backward from the direction of rotation, prevent excess lifting of water above the upper water level and ease paddle entry into the lower water body.

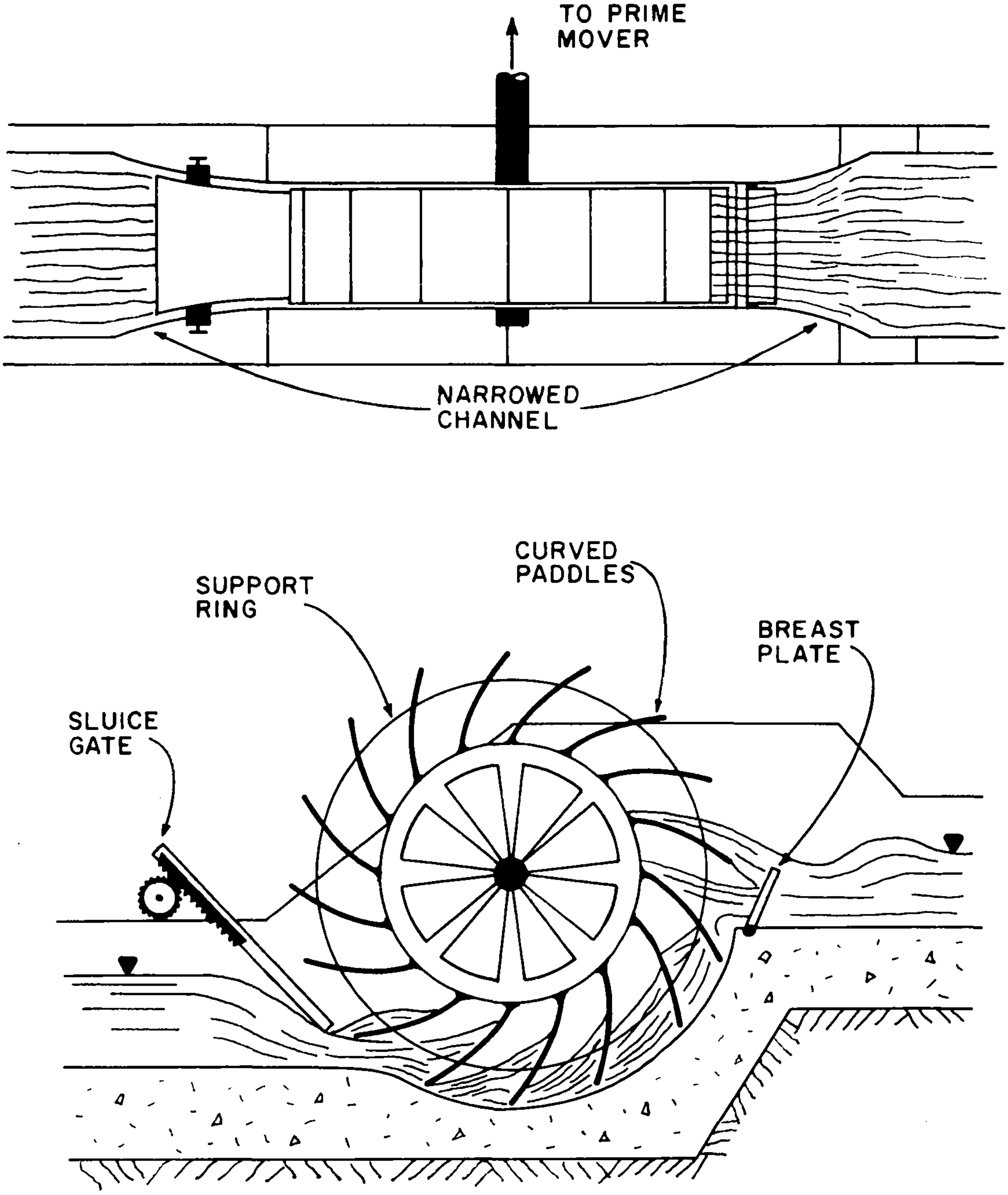


Figure 3.35 Scoop-wheel with accessories for improving performance

(b) A hinged "breast plate" at the upper channel, tangent to the wheel will prevent excessive back flow.

(c) A sluice gate, tangent to the wheel, at the lower level can convert elevation head into a velocity head (e.g., 1 ft head produces 8 fps). Therefore, the water will in effect enter the wheel rather than the wheel entering a relatively still body of water, which creates friction losses.

(d) Inlet and outlet channels of the same width as the wheel increase the velocity of water adjacent to the wheel, and thus reduce friction as in (c).

(e) Shrouds can be used to enclose the paddles and thus reduce leakage losses and wear on paddle sides.

These modifications can also be made to small paddle-wheels, however they are more effective for permanent installations. Of course, these additions will increase the initial cost, but they may increase efficiency and cut maintenance. No cost data is available on paddle-wheel construction or operation.

3.3.1.2 Water Ladder

The water ladder is another rotary scooping device which is also referred to in various forms as:

rahad (Thai)

dragon wheel (China)

chain pump

link-belt box elevator

paddle pump.

It consists of an inclined trough and a chain of paddles which is pulled through it by a sprocket at the upper end--see figure 3.36. The entire device can be made of wood, which allows for construction in developing areas and ease of maintenance. The driving sprocket is

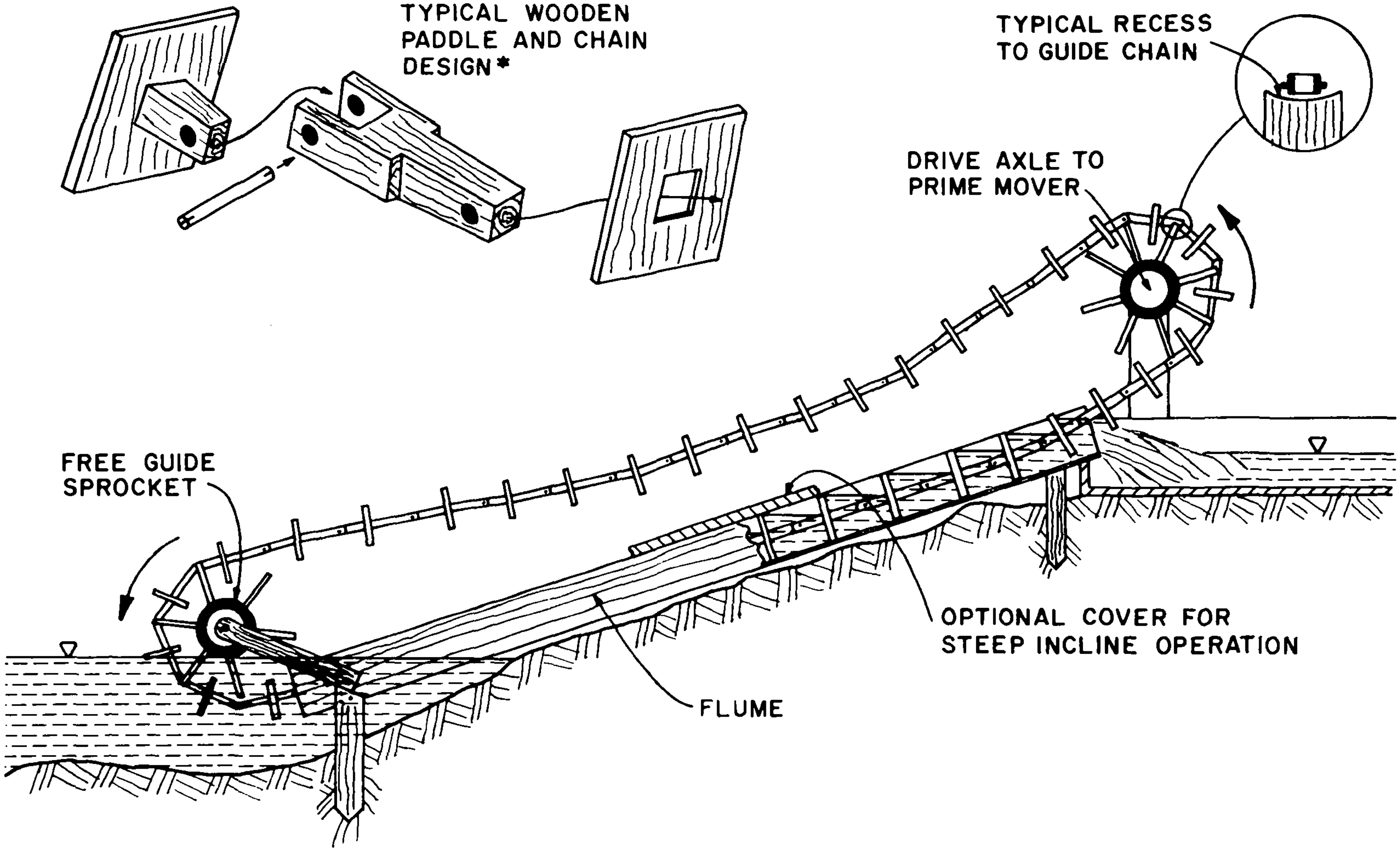


Figure 3.36 Water ladder with open flume (Note: enclosed-flume water ladder is essentially a "chain pump.") (After Schioler, 1975)

attached to a shaft which can be driven by several prime movers. Older designs used the same direct pedaling power as the paddle-wheel (section 3.3.1.1) or animal-power via a circular-sweep and gearing (Schioler, 1975). Later designs incorporate windmills and small internal combustion engines. Using a small engine (2-3 hp) as the prime mover, performance testing was done by Subin Pinkayan at the SEATO Graduate School of Engineering (Bangkok) on a water ladder similar to those used throughout much of Asia. The device was almost entirely of wood, including the chain connecting the paddles, and was operated at 80 rpm (sprocket speed). The trough was 19 cm in depth. The paddles were spaced 20 cm apart and were 18 cm high and 15 cm wide. As should be noted here, these dimensions allow 4 cm of play between the paddle and sides. As the water ladder was found to average about 40 percent efficiency, reduction of this clearance could be expected to increase the efficiency. This testing was conducted primarily to study the effects of *inclination* (i.e., angle between trough and water supply) and *submergence* (i.e., depth to which paddles at intake are submerged) on Q, Eff, and HP. In general, the results showed that (Pinkayan, 1961);

(a) Q varies with submergence and is a maximum when the intake is submerged to the top of the trough's lower end (i.e., 100 percent).

(b) A paddle spacing to paddle depth ratio of approximately 1.1 provides the maximum water volume per paddle and a minimum of losses. For this size device, Q is therefore independent of inclination from 22° - 46°.

(c) For an all wooden pump, the sprocket speed should be less than 80 rpm to prevent excessive wear and breakage.

The recommendation was also made that other variables, e.g., operating velocity, be studied in future tests. This pump, with a 2-3 hp engine driver, delivered about 0.8 cfs at a 3 ft head. Molenaar (1956) reported that a water ladder powered by 4 men could lift 0.23 cfs 3 ft. Wilson (1896) reported that a "link-belt box elevator" constructed with a metal chain and powered by a 7 hp driver was capable of lifting 5 cfs 10 ft. He also recorded that "the highest practical lift of these machines is 20 feet, and one of this capacity costs $50 (1896) per second-foot," which would be about $150 per cfs today (U.S. Department of Commerce, 1975). However, the more common type of water ladder, as tested by Pinkayan, is normally limited to 3 ft lifts and for operation by two men (i.e., with foot treadle) would cost about $35-$40 (Molenaar, 1956).

3.3.1.3 Chain Pump

The *chain pump* is very similar in design and operation to the water ladder. In fact, the names are often used interchangeably. Additional names for this device include:

chain-disc pump	*Liberation waterwheel (China)*
pater-noster pump	*chaplet pump.*

In essence, the chain pump is a water ladder with an enclosed trough which allows its use on steep inclines or vertically, as in figure 3.37. This enclosed trough eliminates the spacing/depth ratio limit on the capacity of water ladder paddles, i.e., except for leakage losses, the entire space between paddles or discs can be filled with water.

A length of circular pipe commonly serves as the enclosed trough, while the circular discs pulled through it are often fitted with rubber or leather perimeter rings to reduce leakage between

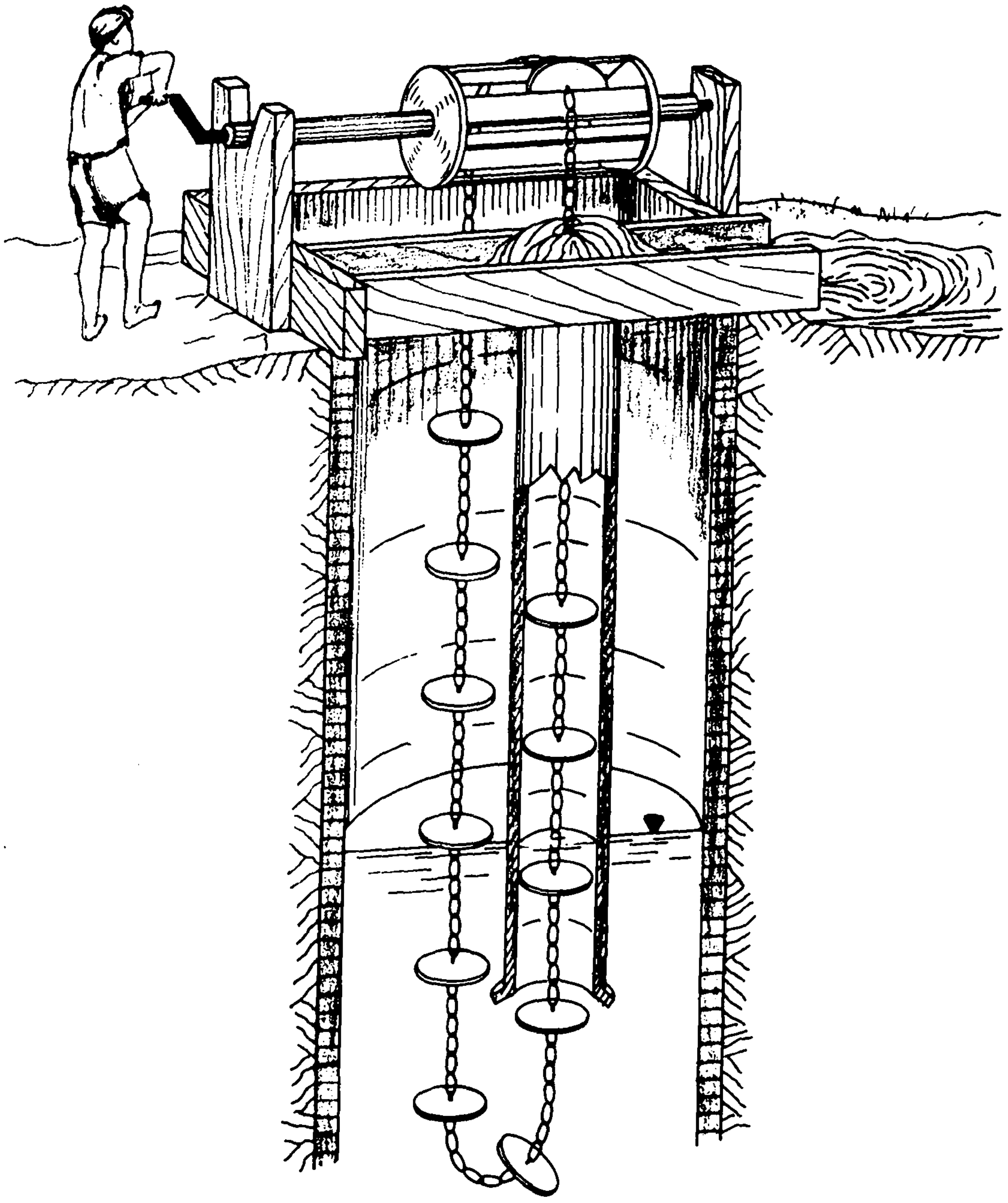


Figure 3.37 Chain pump with manual windlass

them and the pipe. As in the water ladder, a driving sprocket or notched wheel engages the endless chain at the upper level to pull it around. In vertical installations such as figure 3.37, the chain is long enough to allow it to hang free below the pipe bottom. This lower pipe end is usually flared to facilitate entry of the discs into the pipe. Several chain pumps are often driven off of the same horizontal shaft where sufficient power is available. Capacity of a chain pump will vary with its size, speed of operation, and water tightness. Roberts and Singh (1951) suggest that lifts greater than 20 ft are usually impractical due to the amount of leakage within the pump. Table 3.3 records some of the performance data available on the chain pump.

Table 3.3 Chain pump performance

Lift (ft)	Discharge (cfh)	Reference	Remarks
20	40	Molenaar, 1956	4 men, 4 in. pipe
10	72	Molenaar, 1956	4 men 4 in. pipe
5	110	Molenaar, 1956	4 men 4 in. pipe
20	330	Roberts and Singh, 1951	4 in. pipe, ? hp
240	("low lift")	Framji and Mahajan, 1969	3 in. pipe, ? hp

No cost data is available on chain pumps, however they should compare closely with water ladders. The use of commercial pipe (if not scrap) will increase the initial cost, while using natural material, such as hollow bamboo, can reduce it. Dias (1953) also recommends using metal catches on the driving sprocket to reduce wear on wooden wheels.

3.3.1.4 Persian Wheel

Probably one of the most extensively used water lifters, particularly with animal power, is the *Persian wheel*. In some areas, the term "Persian wheel" refers to any water lifting wheel device which is animal powered. However, as most commonly used, the Persian wheel is a variation of the chain pump--another name to which it is also referred. It consists of a series of containers (e.g., buckets, pots, bags) attached to two parallel loops of rope or chain which pass over a driving wheel, as in figure 3.38. As the buckets pass over the open-rim wheel, they empty into a trough below it and then return down to the water supply for refilling. Many combinations of gears and shafts are in use to connect the wheel to the driver, however they generally fall into three basic designs;

(a) A vertical-axis pinion gear meshes directly with the gears of the driving wheel and the driving animal(s) walk around the entire device to turn the pinion gear, as in figure 3.39a.

(b) The pinion gear is connected to the driving wheel via a long horizontal shaft and the animal(s) walks only around the vertical pinion gear as with the noria in figure 3.42.

(c) A horizontal shaft connects the driving wheel directly to a prime mover which produces a vertical rotation, e.g., a treadmill (refer to the "donkey-wheel" in Schioler, 1975) or engine.

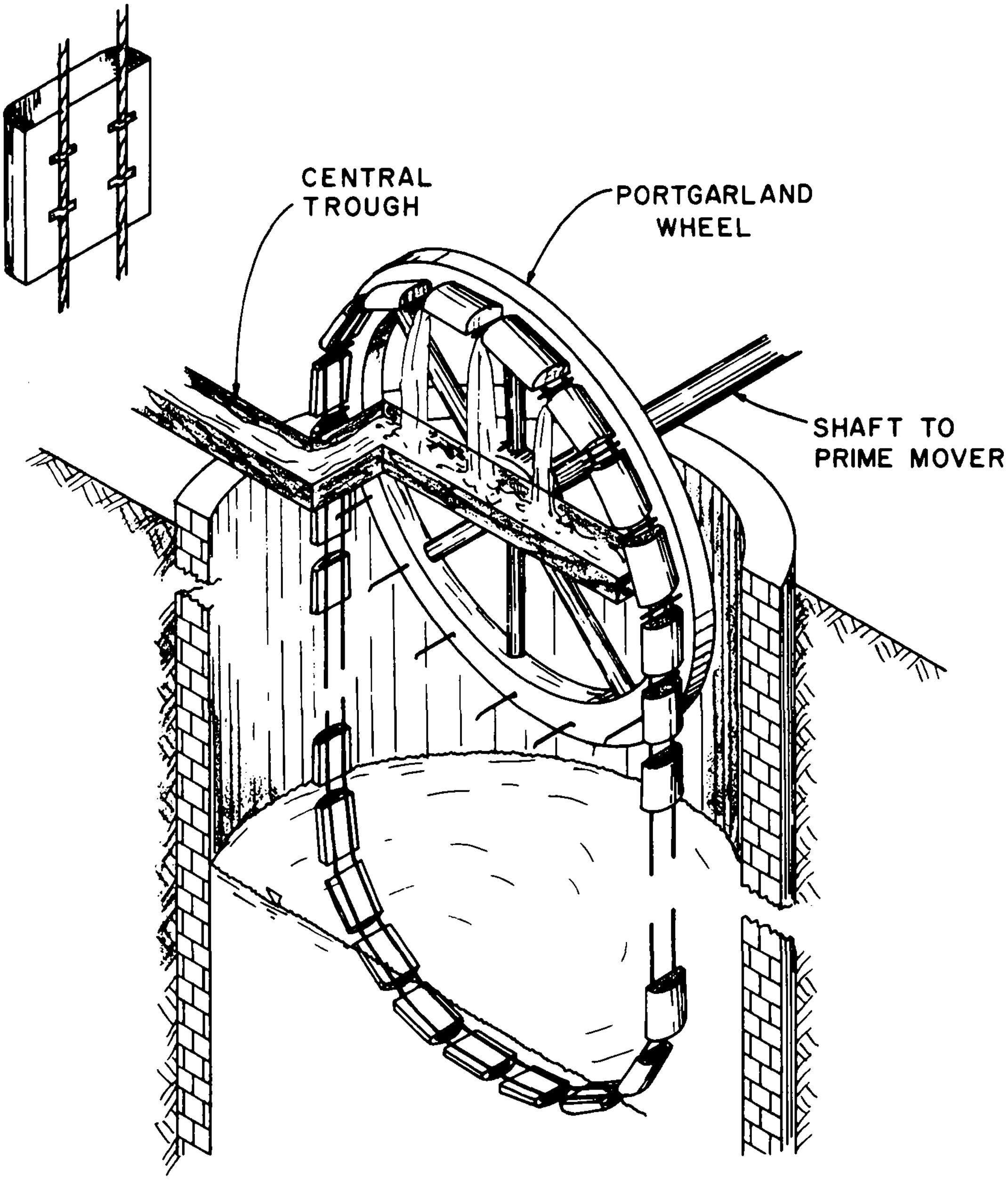


Figure 3.38 Persian wheel with portgarland drive wheel and horizontal drive shaft

Several names which are also applied to the Persian wheel are:

chain-bucket pump	*chain-of-pots*
bucket wheel	*paternoster wheel*
Egyptian sakia	*rahat (Pakistan)*
Egyptian noria	*scoop wheel.*

Other names which refer to specific variations of this device are *taboot*, when bags are used instead of buckets, and *potgarland*, when a wheel with horizontal "carrier-pegs" drives the bucket loop (as in figure 3.38). Until about 70 years ago, the name *sakia* was also used for the Persian wheel but is now applied to the tympanum (see section 3.3.1.6).

By lengthening the chain of buckets, this device can lift water from greater depths. Two Persian wheels in series (i.e., one below the other) were the lifting mechanism for Joseph's Well (see section 1.2) which was approximately 300 ft deep. They are usually constructed entirely of wood, except for the containers, however modern versions have begun to use more metal parts. Roberts and Singh (1951) report that Persian wheels with metal gears, bearings, etc. are about 28 percent more efficient than with wooden components. Ball bearings in axles can also improve efficiency and are almost mandatory when engines or electric motors are supplying the power. Schioler (1973) reports the efficiency of a wooden Persian wheel with metal bearing surfaces to be about 60 percent. Other than friction the major loss of efficiency in Persian wheels is that power is consumed lifting the buckets, rope, and water higher than the desired upper water level in order for the buckets to empty. As will be seen in the next two sections, other devices eliminate this excess lift. The Persian wheel, however, claims its major advantage in being capable of much greater total lifts. Table 3.4 lists available performance data on some typical wooden Persian wheels.

Table 3.4 Persian wheel performance

Lift (ft)	Discharge (cfh)	Reference	Remarks
30	325	Molenaar, 1956	? hp some metal parts
20	395	Molenaar, 1956	? hp some metal parts
10	580	Molenaar, 1956	? hp some metal parts
5	760	Molenaar, 1956	? hp some metal parts
25	510	Roberts and Singh, 1951	2 bullocks metal bearings

The cost of constructing a Persian wheel comprised primarily of wood, with some metal fasteners and wearing surfaces, could be expected to be about $60. (This cost estimate reflects the use of inexpensive labor and materials in developing countries.) Thorkild Schioler's *Roman and Islamic Water-Lifting Wheels* (1973) gives some excellent details of the construction of Persian wheels and other wheel devices, e.g., gears, bearings, fasteners, etc.

A modified version of the Persian wheel is the *zawafa* or *Egyptian jhallar*. Most zawafas today are constructed entirely of metal, as in figure 3.39a, although original designs were wooden. Rather than each bucket dumping water into the same central trough within the driving wheel diameter, troughs between the spokes of the driving wheel (figure 3.39b) receive the dumped water and channel it to a

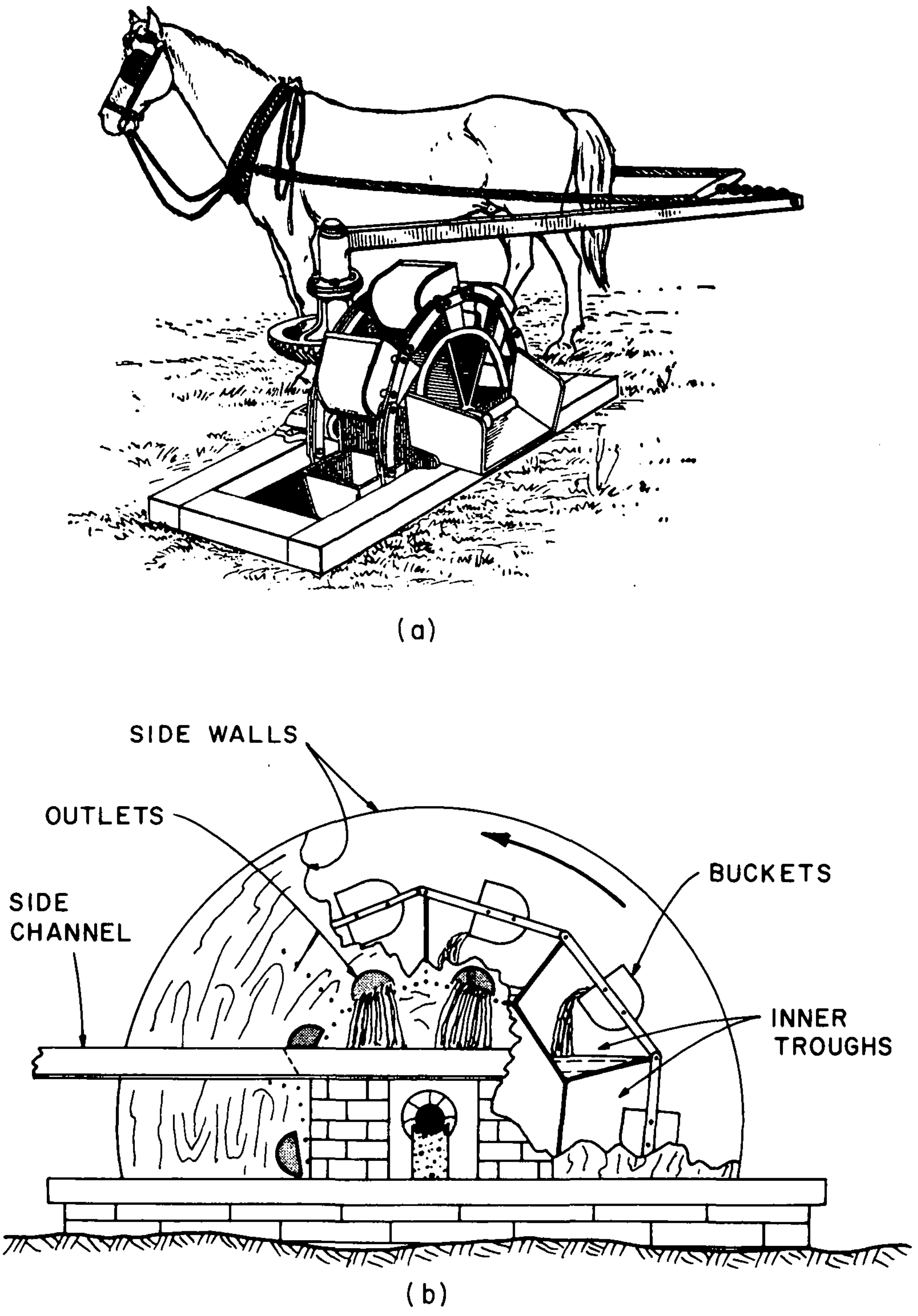


Figure 3.39 Modified Persian wheel or zawafa; (a) metal design, (b) wooden design with side walls

common trough alongside the wheel. In this way a stronger, double-rim wheel can be utilized for deep, heavy lifts or where all metal construction is used, and the water need not be lifted much above the desired upper water elevation. Table 3.5 gives some typical performance data of metal zawafas.

Table 3.5 Zawafa performance

Lift (ft)	Discharge (cfh)	Reference	Remarks
6.5	1300	Molenaar, 1956	1 animal
13.0	850	Molenaar, 1956	1 animal
20.0	425	Molenaar, 1956	1 animal
20	2000	Wilson, 1896	4 horses
2.5	5400	Roberts and Singh, 1951	Eff = 76%

The cost of metal zawafas varies greatly with the prices of metals in various geographic areas, however by adjusting the costs given by Roberts and Singh (1951), in a developing country initial costs will probably range from $120-$600.

Small versions of the Persian wheel called *continuous-belt bucket pumps* are designed for use with a hand crank. These pumps utilize many closely-spaced buckets of only a few inches in height, width, and length (see Wagner and Lanoix, 1959). They are primarily for domestic purposes with low lift and capacity.

3.3.1.5 Noria

Another wheel-type water lifter is the *noria* which has containers (e.g., buckets, pots, etc.) fixed to a driven wheel. Since the containers do not loop below the wheel, as in the Persian wheel, the noria wheel must have a diameter slightly larger than the total static head. There are a large variety of noria designs and installations and it is probably for this reason that almost no performance or cost data is available on this device.

Although norias can be driven by almost any type of prime mover, the name "noria" has often been used when referring specifically to wheels that are driven by water. Such water-driven norias have paddles which are pushed by the swift flow of a water source, e.g., figure 3.40a. Of course, the power supplied to the paddles must be sufficient to lift the water and overcome friction. Therefore, the size (and weight) of the noria and the discharge and head it must supply need to be matched to the available water source's velocity and the paddle surface area. If for instance, the small paddles in figure 3.40a do not afford enough surface area to receive sufficient power from the streamflow to equal the required WHP plus friction of the noria (f_n), i.e.

$$(\gamma_w\ Q\ H_{TS}) + f_n = \text{WHP} + f_n = \rho_w\ A_p\ v_w^3$$

where: ρ_w = mass density of water

A_p = surface area (one side) of submerged paddles

v_w = velocity of streamflow,

then, the size of the paddles may have to be increased--possibly utilizing a design more like figure 3.40b. Two alternatives to increasing paddle size (which increases weight and therefore friction) are; (a) increase the water supply's velocity by decreasing its channel's cross-sectional area as was done with the sluice gate and narrowed channel for the paddle-wheel (see section 3.3.1.1), or (b) supply a fall (i.e., head) for the water source so that it can power the

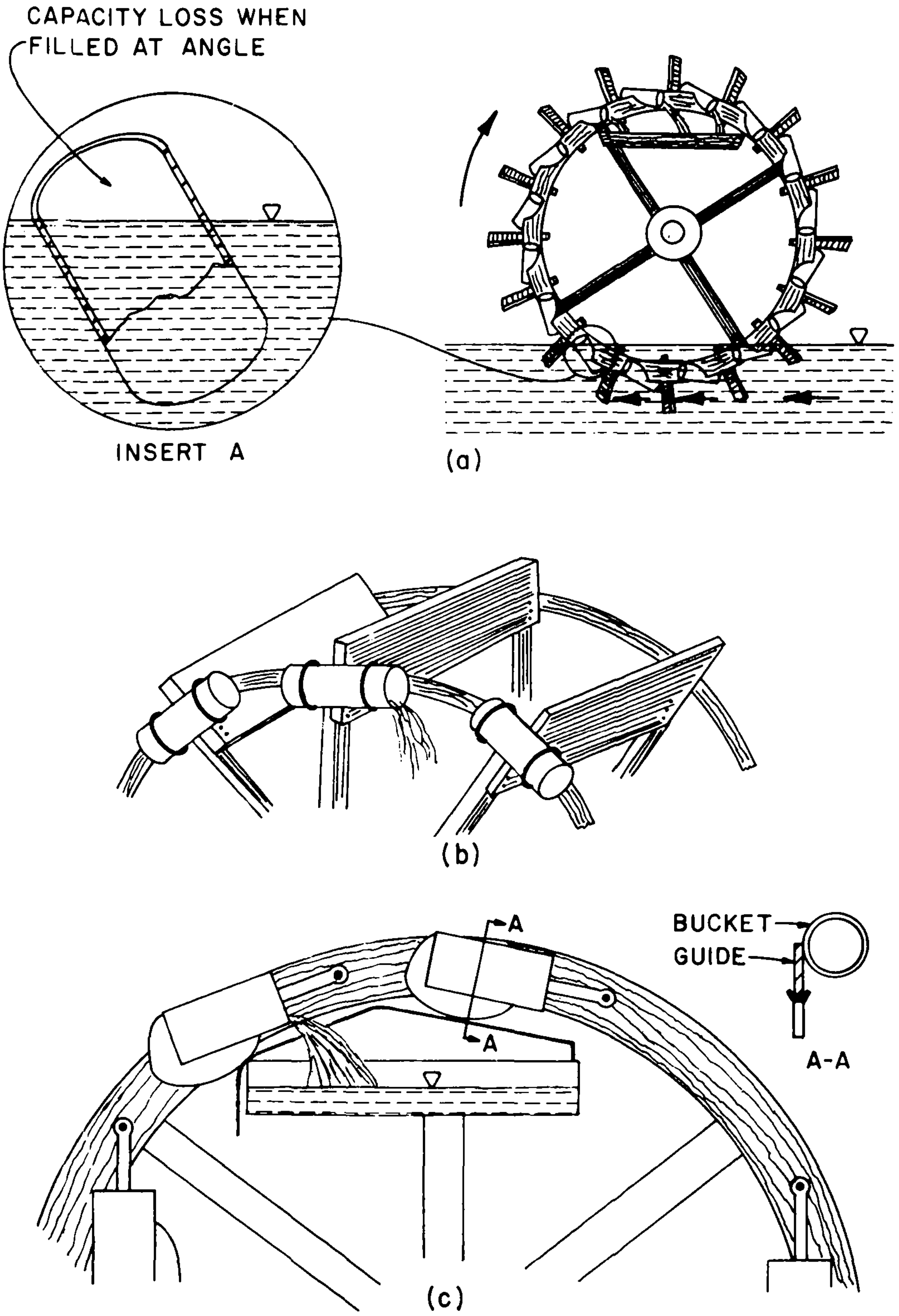


Figure 3.40 Noria; (a) with fixed buckets, driven by current, (b) with larger paddles, (c) with moveable buckets

noria as an undershot wheel (see section 5.2) as in figure 3.41. Of course, a separate driving wheel (i.e., watermill) can be placed apart from the noria (e.g., in a swifter width of the river) and connected to it by a horizontal shaft, as would be done for other types of drivers, e.g., figure 3.42.

A few other common modifications to the noria which are utilized to improve efficiency and/or adapt it to a given installation include:

(a) Use of deep, small diameter containers as in figure 3.40a to decrease spillage.

(b) Use of movable buckets, e.g., figure 3.40c, to allow complete filling (i.e., as opposed to fixed containers which fill at an incline--see figure 3.40a, Insert A) and prevent emptying until the bucket reaches the upper level trough. This allows the trough to be nearer to the top of the noria's arc, i.e., a movable-bucket noria can be used for the same head as a larger, fixed-bucket noria.

(c) An enclosed noria with compartments built into it and appropriate inlets and outlets utilizes practically the entire wheel circumference and width for increased capacity, e.g., figure 3.42. The enclosed circumference can also be utilized as a treadmill so that manual power can be directly applied without the use of gears, shafts, etc.

(d) In a design such as figure 3.41, the water can flow into the containers from a side channel just as they leave the lower water source elevation. This way, power is not wasted pushing the containers through the water source. In a water-driven noria, such as in figure 3.41, this elimination

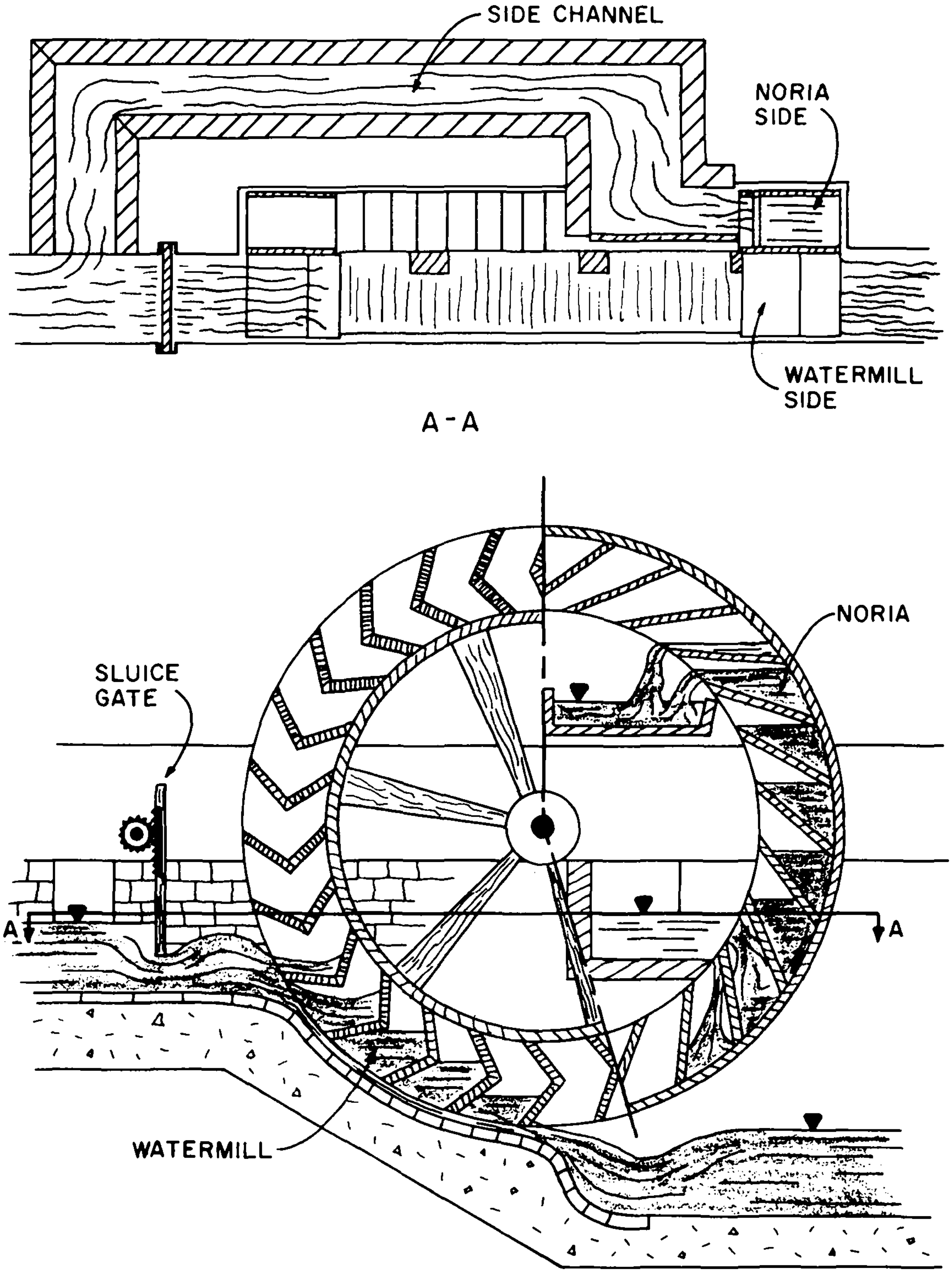


Figure 3.41 Water-driven noria with side channel and sluiceway to increase efficiency

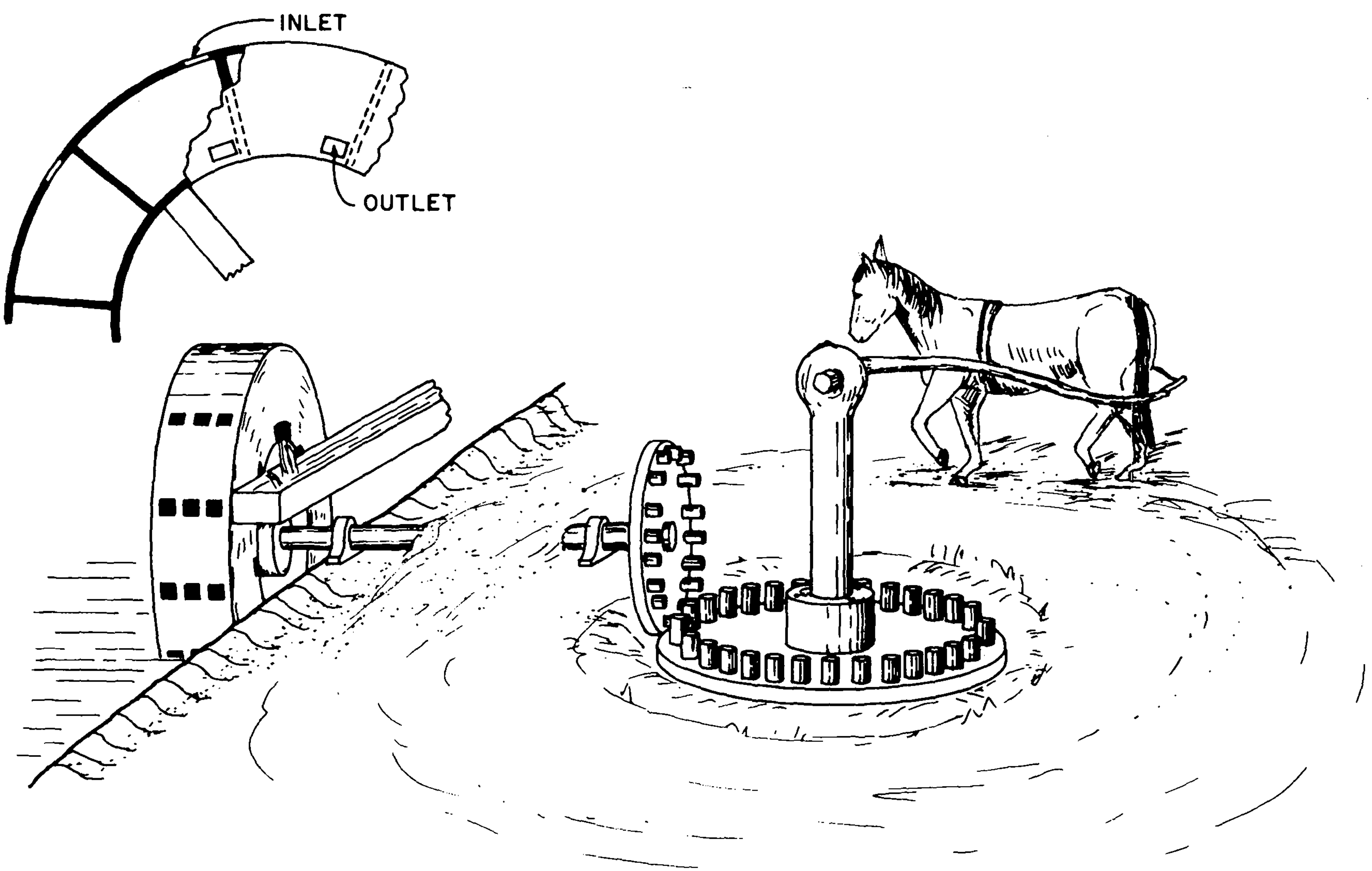


Figure 3.42 Noria with enclosed compartments driven via long shaft and pinion gears by animal

of drag can be a considerable factor in matching available water power to lift and capacity requirements. Note however, that the fall of water into the containers cannot be allowed to be so great as to create a significant reversing force.

Several other names have been found in use for the noria such as:

scoop-wheel
bucket-wheel
sakia (Egypt)
dawlab (Persian)
waterwheel elevator (Algeria)
Persian wheel
tanbusa
tabliyya
tulunba.

3.3.1.6 Tympanum

The *tympanum* is a wheel device which consists of several individual, enclosed compartments, similar to the enclosed noria of figure 3.42. However, in tympanums, each compartment has an inlet on the wheel circumference and an outlet adjacent to the wheel hub. Therefore, it is not necessary to lift the water above the required elevation. Of course, for the same head, a larger diameter tympanum-wheel is needed than noria-wheel, i.e., the tympanum diameter must be slightly more than twice the head. Due to this size requirement, tympanums are usually limited to lifts of less than 10 ft. It is interesting to note, however, that Wilson (1896) describes a 39 ft diameter wooden tympanum with iron compartment partitions and bearings which lifted water 14 ft from the Chesapeake and Delaware Canal. It required 350 hp to turn the wheel at 1.7 rpm and discharged 300,000 cfh (83 cfs).

Several other names which are applied to this device include:

sakia (Egypt)
sagia
sagiya
sakiyeh
tablia
taboot
tanabish (Egypt)
drum-wheel
waterwheel
spiral wheel
scoop-wheel.

Most early tympanums were of the easy-to-construct design labeled HRES-D_2 in figure 3.44. However, early in the 17th century, La Faye noted that that design kept the water at the periphery of the compartment and thus maintained the maximum moment arm about the axle due to the pull of gravity on the water. This would obviously require more input power to overcome. Therefore, La Faye suggested the spiral-wheel design in figure 3.43 which kept the water almost vertically in line, beneath the axle and thus created a smaller moment arm (Ewbank, 1876). Several other designs, such as the logarithmic and Archimede's spiral curve (figure 3.44) are also widely used today, as seen in figure 3.45.

Recognizing that compartment shape effects the performance of a tympanum, the Hydraulic Research and Experiment Station (HRES) of the United Arab Republic's Ministry of Irrigation conducted a program for testing various designs. Using 6 x 75 cm plastic models of the shapes in figure 3.44, they determined that the D_2 design was capable of higher discharges at a given head than the others (figure 3.44) and that its simple, "straight-line" design afforded easy construction by users in developing countries. They also found that utilizing individual outlet compartments, such as are shown in the D_1, D_2, and

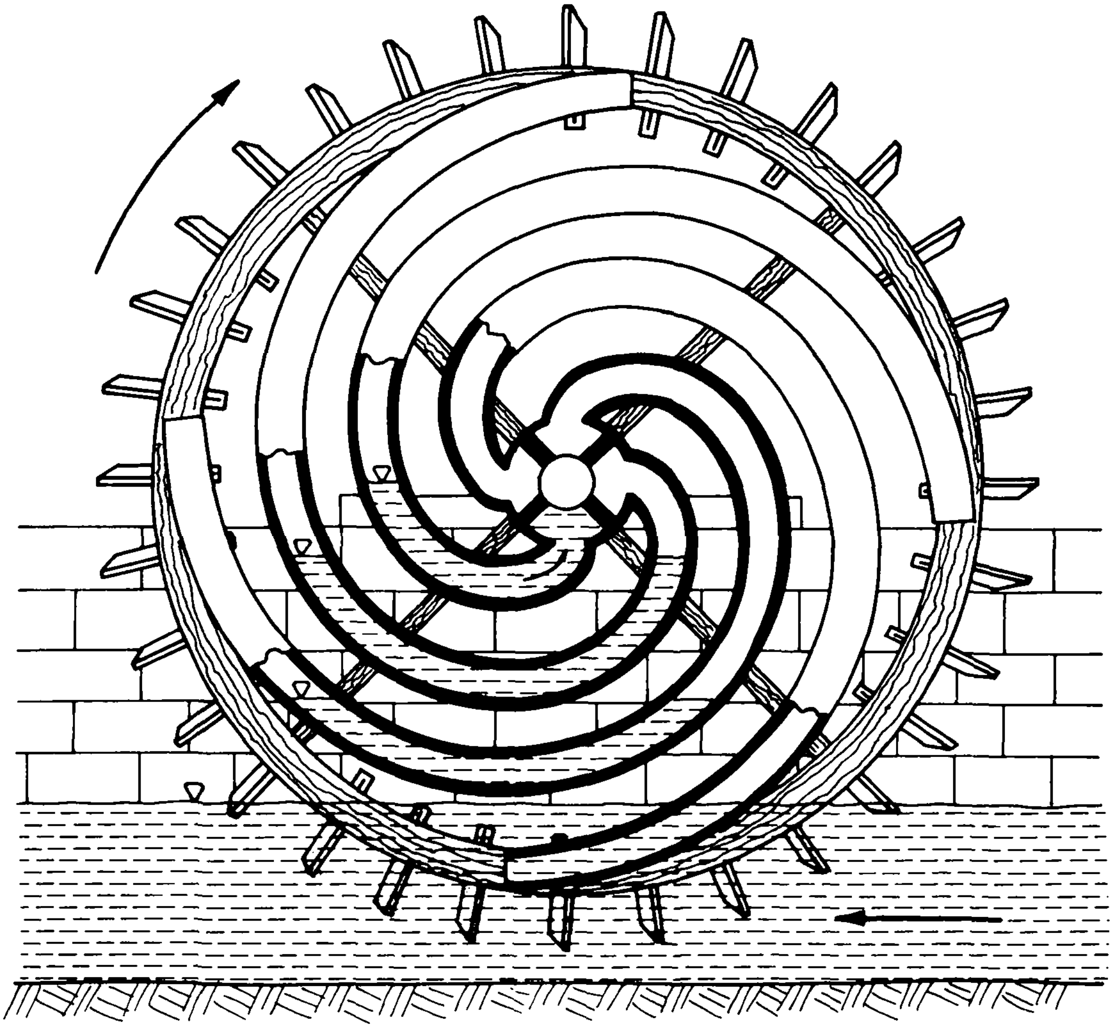


Figure 3.43 Tympanum with spiral troughs equipped with paddles to be current-driven

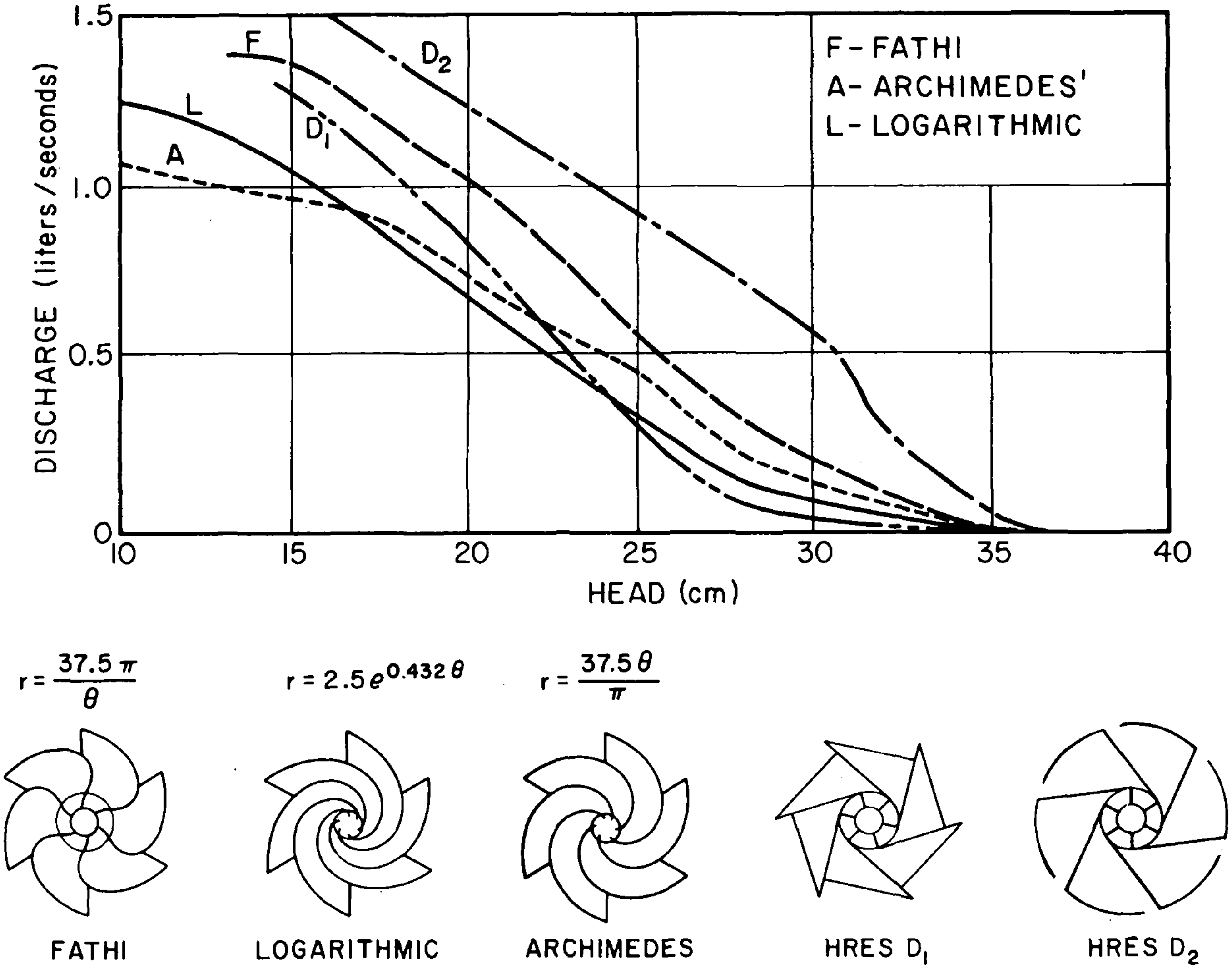


Figure 3.44 Comparison of various tympanum designs (HRES, 1965)

Fathi designs in figure 3.44, improve the efficiency of a tympanum by preventing discharge from one compartment leaking back into the compartment(s) below it. This separation of discharges can also be accomplished by having the discharge outlets in the sidewalls, as in the enclosed noria. The term *tablia* is used to specify this type of tympanum. In addition, HRES concluded that:

(a) At constant head and speed (rpm), discharge increases with the number of compartments.

(b) Depending on inlet size and shape, a maximum number of compartments and speed is reached after which filling is incomplete and begins to decrease discharge.

(c) For wheels operated in the 2 - 15 rpm range, 6 - 8 compartments provide optimum discharge.

Although ease of construction and maximum discharge are normally the primary concerns of users in developing countries, similar tests could also be made to determine the power requirements and efficiencies of various designs within a common range of sizes and speeds. This would be particularly useful for tympanums which are driven by mechanical prime movers, e.g., gas engines. Normally, animal-driven tympanums operate at 2 - 4 rpm, while engine-driven ones operate at 8 - 15 rpm.

Tympanums, such as the one in figure 3.45, are commonly constructed of galvanized sheet metal and utilize second-hand roller bearings in the axle. Typical performances of such tympanums are given in table 3.6. No data is available on construction costs of tympanum devices. Operation costs are included in a comparison of various devices in Chapter 5.

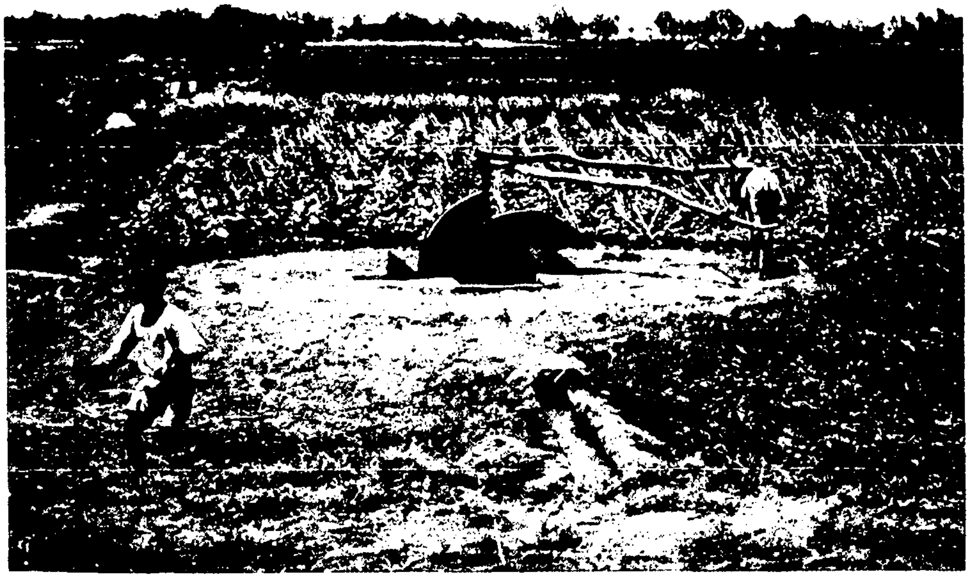


Figure 3.45 Tympanum operated with animal-drive

Figure 3.46 Archimedean screw operated manually

Table 3.6 Tympanum performance

Diameter (ft)	Lift (ft)	Discharge (cfh)	Remarks	Reference
16.4	5.9	1274	1 animal	Molenaar, 1956
13.1	4.3	1805	1 animal	Molenaar, 1956
9.8	3.0	2655	1 animal	Molenaar, 1956
6.6	1.0	4036	1 animal	Molenaar, 1956
9.8	4.9	708	1 animal; tablia	Molenaar, 1956
13.2	8.2	425	1 animal; tablia	Molenaar, 1956

3.3.2 Screw

The basic *screw* (figure 3.46) is merely an incline surface rotating around a central axis and when used as a water lift, it in effect pushes the water up the incline--see Weisbach and Herrmann (1897).

One of the earliest designs for a water-lifting screw utilized a flexible tube wrapped around and secured to an inclined axle, as in figure 3.47a. This design is often referred to as a *water snail*, *Egyptian screw*, or *cochleon*, however it is rarely used today. Instead, the commonly referred to *Archimedean screw*, which has been in use for centuries (see 1.2), is the more popular screw-device presently in use. Several other names are applied to this water lifter:

screw pump
water-screw
Roman-screw
screw mill
tambour.

As illustrated in figure 3.47b, this device can be easily constructed primarily of wood with a few basic tools. A typical design utilizes

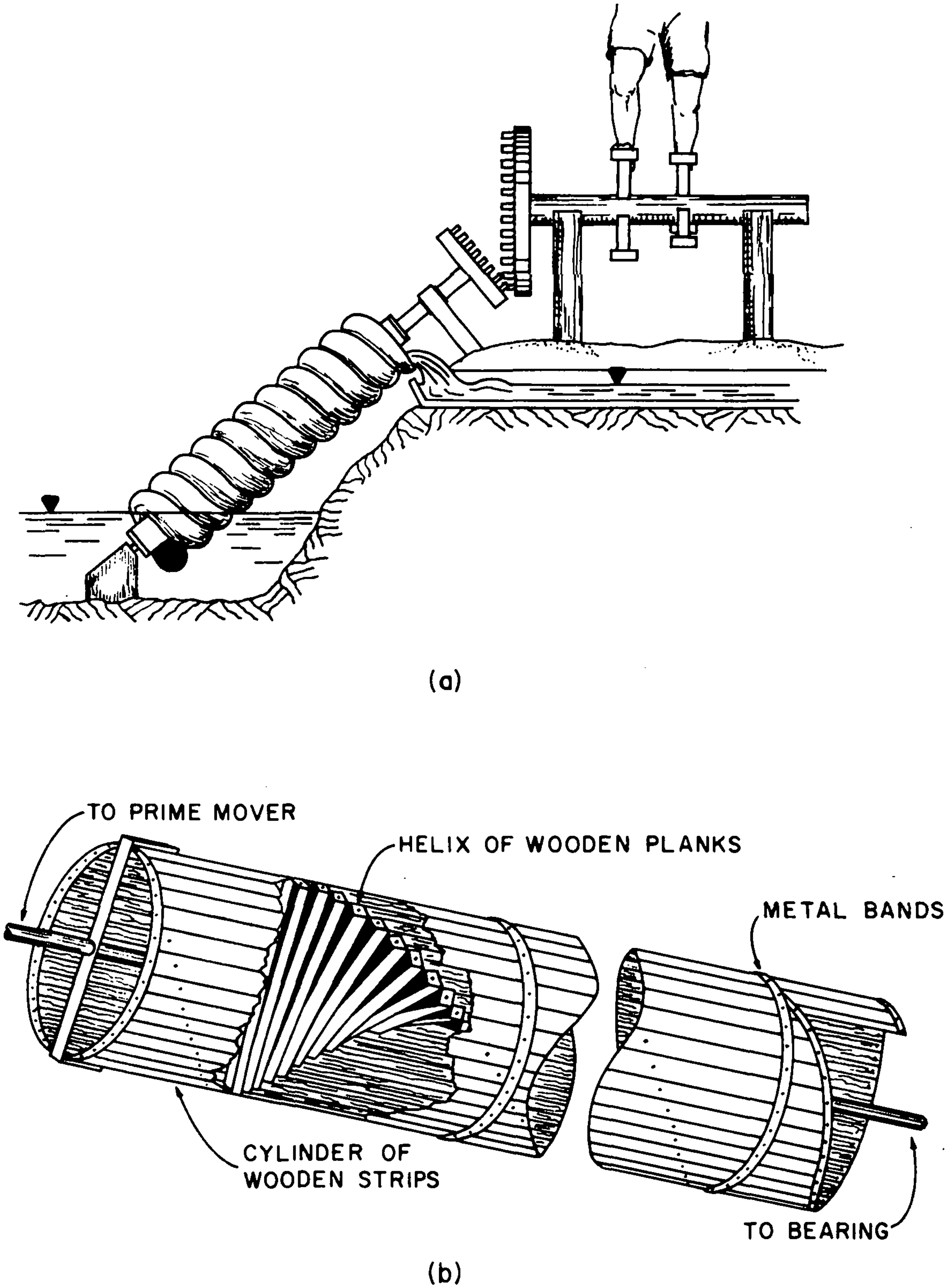


Figure 3.47 (a) Pedal-power water-snail, and (b) construction of simple, wooden Archimede's screw

about 70 blocks each cut to 1.5 x 2.5 x 17 inches, and made with a hole at mid-length. A rod (normally iron when available) is then fitted through the hole in each block and the blocks adjusted to form a helix (or screw) by overlapping about 0.5 in. Strips of wood are then fastened to the periphery of the screw and secured with metal bands to form the outer cylinder. A bearing must be provided in the water supply to support the lower end of the axle rod, while the upper end of the cylinder is connected to an appropriate driver (e.g., hand crank, treadmill, engine) which then rotates the entire device. Figure 3.46 shows such a screw with manual operation. This type construction is sufficiently compact and lightweight so as to allow it to be easily transported, e.g., on the back of an animal such as a donkey--see Molenaar (1956). A screw of this basic construction, with necessary bearings and handle for manual crank-operation, would cost about $20 - $35, depending on available materials (Molenaar, 1956). Typical performances of such devices are listed in table 3.7, part A.

A variation of this basic wooden design utilizes instead a metal auger which turns inside an outer metal cylinder, as in figure 2.2. Such auger pumps can be produced by light industry in developing countries. In Thailand, such a device, called a "Debbharid," is produced by some 25 factories at the rate of 47,000 per year (Kishida, 1971).

In a 1966 Colorado State University thesis, Rider reports on the development of a small auger to improve the performance of a commercially produced Powerdike. The Powerdike is a gas-engine powered carriage which drags a check dam down an irrigation ditch

Table 3.7 Screw performance

Lift (ft)	Discharge (gpm)	Power	Remarks	Reference
A.)				
1.6	65	1 man	6 x 1.3 ft	Molenaar, 1956
2.5	65	2 men	8.3 x 1.3 ft	Molenaar, 1956
1.6	100	2 men	6.7 x 1.6 ft	Molenaar, 1956
0.8	130	2 men	5 x 1.8 ft	Molenaar, 1956
B.)				
-	30	engine; 0.75 hp	4 in. diameter; @ 1500 rpm	Rider, 1966
-	65	engine; 1.1 hp	4 in. diameter; @ 1900 rpm	Rider, 1966
10	30	engine	4 in. diameter; @ 2000 rpm; at 90° to horizontal	Rider, 1966
7	75	engine	4 in. diameter; @ 2000 rpm; at 45° to horizontal	Rider, 1966
6	325	engine; 4 hp	6 in. diameter; @ 1350 rpm	Rider, 1966

to provide surface irrigation. Rider's "screw conveyor pump" lifted water from behind the check dam into an adjacent field. His thesis investigated the performance of a screw as it is effected by variables such as:

(a) inclination of device

(b) speed of operation

(c) pitch of flighting (i.e., helix)

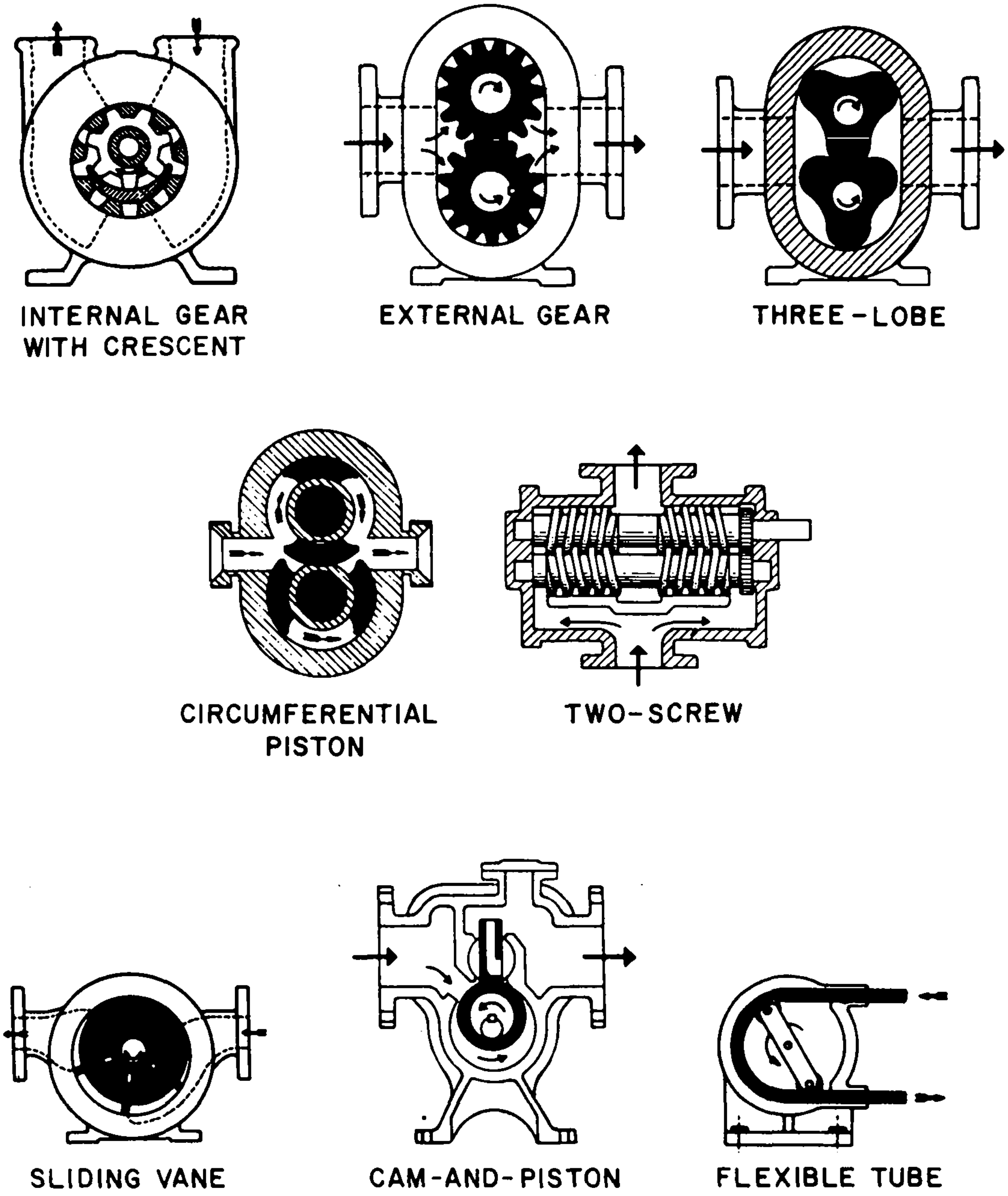
(d) diameter of cylinder.

He also mentions the work of H. Klueter (unpublished) who investigated the use of a screw conveyor to lift liquid manure. Included in this work is the performance of various screws in lifting clear water--see table 3.7, part B.

Another variation of the screws, as discussed above, is the use of more than one helix within the same cylinder. This is another variable which effects the capacity of this device but does not appear in available literature. For low lifts, the Archimedean screw provides a simple, durable device with few moving parts and easy maintenance. It is interesting to note that screws, up to 6.5 ft in diameter, were driven by large windmills in Holland to drain polder land (Starling, 1892).

3.3.3 Rotor

Another subclass of rotary water lifters are those which employ a high speed *rotor* within a fixed casing (or stator) and are commonly called *rotary pumps*. A wide variety of rotor designs and combinations have been developed--a few are illustrated in figure 3.48. R. Hadeckel presents an interesting--and lengthy--history on the development of many rotary pumps in two volumes (157 and 158) of *The Engineer*. All rotary pumps operate in basically the same manner--the rotor (or rotors) traps water between itself and the stator and then pushes it from the inlet to a higher head outlet. An interesting feature of rotary pumps is that they can pump in either direction, i.e., the suction or discharge line can be attached to either orifice, if, of course, the driver is connected appropriately. Although the discharge is separated into individual masses by the appendages of the rotor(s), the high speed operation of these pumps (normally 40-3600 rpm) presents an



INTERNAL GEAR WITH CRESCENT

EXTERNAL GEAR

THREE-LOBE

CIRCUMFERENTIAL PISTON

TWO-SCREW

SLIDING VANE

CAM-AND-PISTON

FLEXIBLE TUBE

Figure 3.48 Various types of rotary pumps (after Hydraulic Institute) almost continuous flow of water. Of course, as mentioned in the affinity law discussion (see 2.2.5), Q varies directly with speed. This is also shown in the rotary pump performance curves in figure 3.49. These example curves also show that rotary pumps, like reciprocating pumps, maintain an almost constant Q for varying H, and that because pressure is usually the major concern in their application, pressure (e.g., psi), rather than Q, is often the common abscissa.

Because rotary pumps must trap the water with relatively no leakage in order to be efficient, only very small clearances (0.001 - 0.002 in.) must be allowed between rotor and stator. Therefore, with only two exceptions, rotary pumps cannot handle abrasive fluids without excessive wear. Thus, they have no practical application for lifting most irrigation or drainage water. They have been found to be used most advantageously in pumping high viscosity fluids at low Q and high H--however, they are not limited to those applications. Rotary pumps have been developed to handle discharges to 3000 gpm or pressures to 5000 psig. Depending on such variables as material, size, and design, rotary pumps--such as some of the more common designs shown in figure 3.48--may range in price anywhere from $50 to $14,000 (Holland and Chapman, 1966).

The two rotary pumps which are capable of handling abrasive fluids are the single helical-screw and the flexible impeller designs. As shown in figure 3.50, the *helical rotor pump* consists of a helical-shaped rotor which turns inside a molded rubber stator which has a similar inner shape. As the rotor turns, it traps water along the stator walls and "squeezes" it toward the discharge outlet. Helical pumps are commonly used in a horizontal position and close-coupled

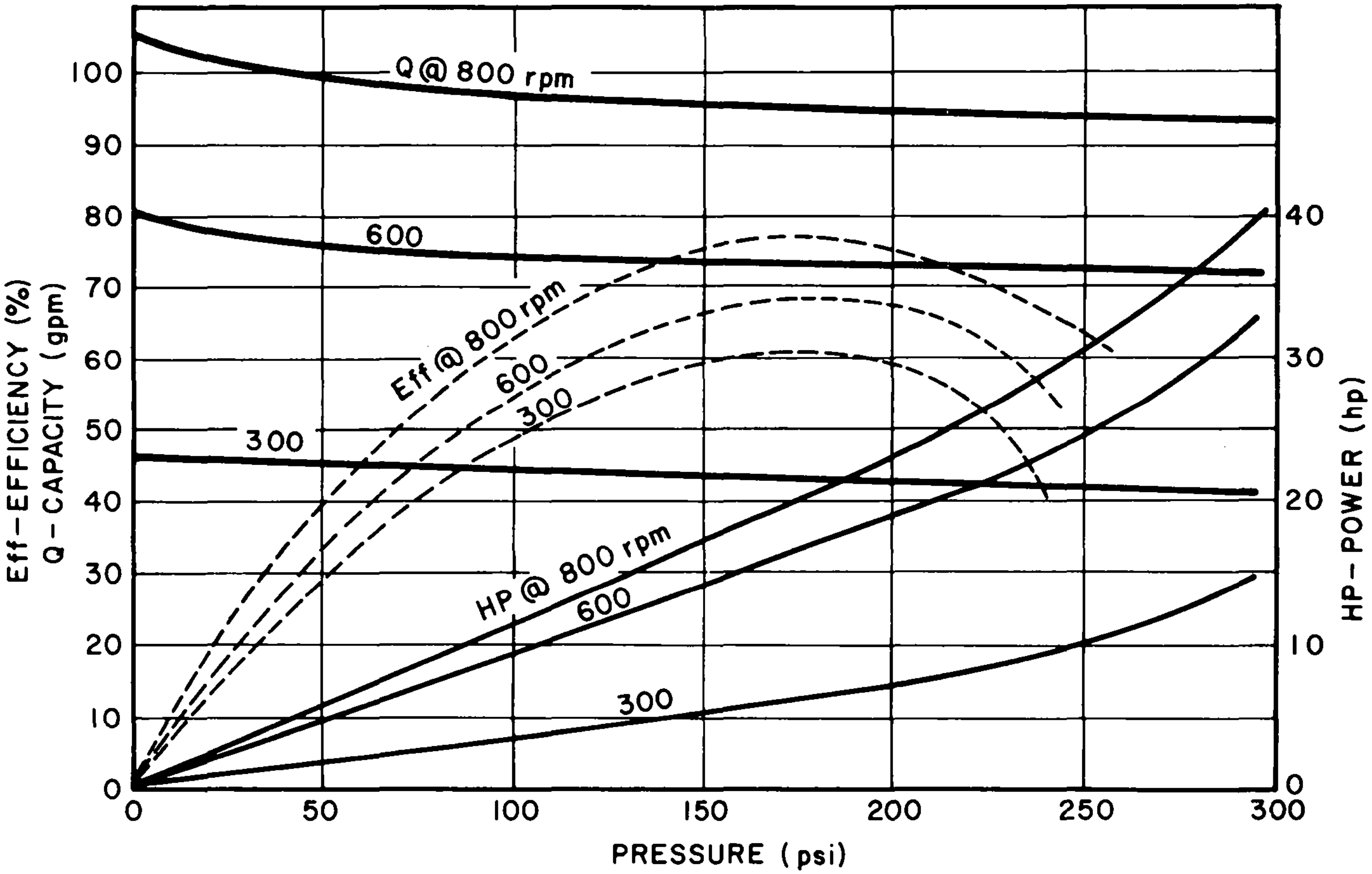


Figure 3.49 Example of rotary pump performance curves (not based on actual pump)

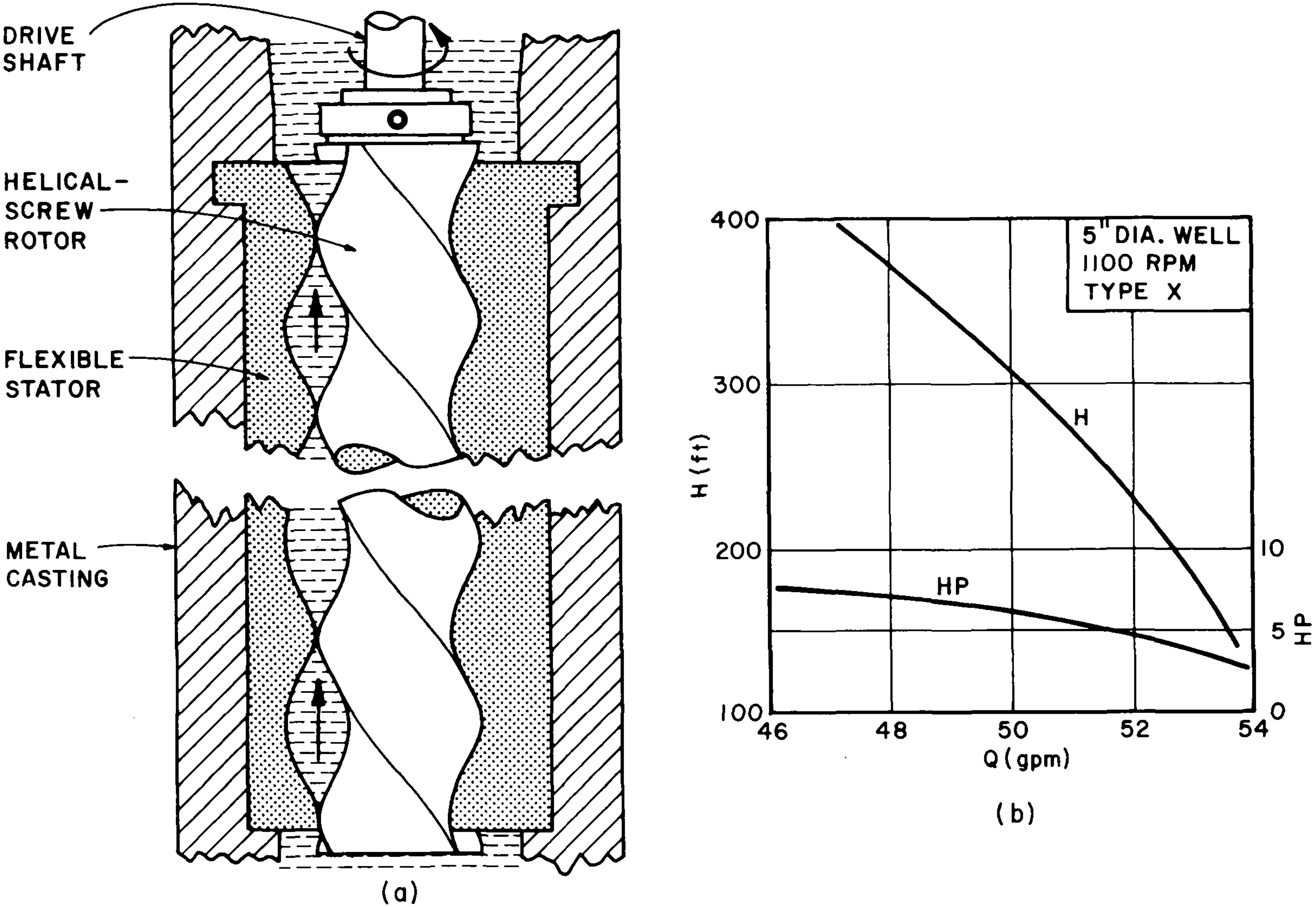


Figure 3.50 (a) Helical-screw rotary, and (b) typical performance curve of "vertical helical" pump

to an electric motor for pumping from shallow wells, i.e., they have NPSHR limitations just like any other pump. In such installations, they handle moderate heads and small discharges--typical of domestic applications. However, larger, vertically-mounted helical pumps can be installed in narrow (e.g., 4-5 in.) wells with the same type shaft and pump head arrangement used with vertical turbine pumps (see figure 4.17). Such deep-well helical pumps are capable of heads up to about 1000 ft. Between these two types of helical pumps, they cover a range of discharges from 5-75 gpm. Close-coupled units may vary in price from about \$100 to \$2000, including motor, while the vertical units will vary with horsepower, at a slightly lower rate than vertical turbine pumps (see section 4.2.6).

The *flexible-impeller* or *-rotor* pump utilizes a flexible, paddle-wheel-like rotor to trap and lift water, as shown in figure 3.51. Because of the flexible impeller, this pump--unlike most rotary pumps--can operate against a closed discharge without building up damaging pressures. However, since the flexible vanes stay in contact with the casing, high friction losses occur which lower efficiency. Also, at high pressures, these vanes tend to slip, creating leakage losses within the casing. Most flexible impeller pumps are in the \$20 to \$600 range. They can be made to handle from 0.5 to 100 gpm and with heads up to about 110 ft.

Although not (yet?) practical for irrigation and drainage applications, one additional rotary pump was learned of during the research for this paper which should be mentioned. Originally developed as a steam expander, the KROV pump is powered by a saturated steam power plant using methane, coal, peat, lignite or wood as fuel.

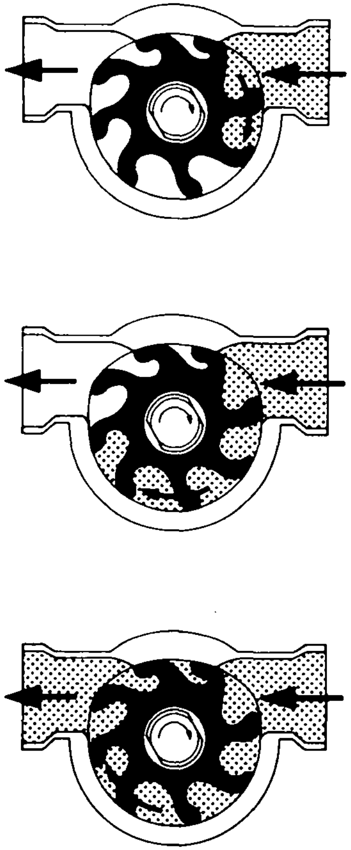


Figure 3.51 Operation of flexible-rotor pump (Courtesy of Jabsco Pumps)

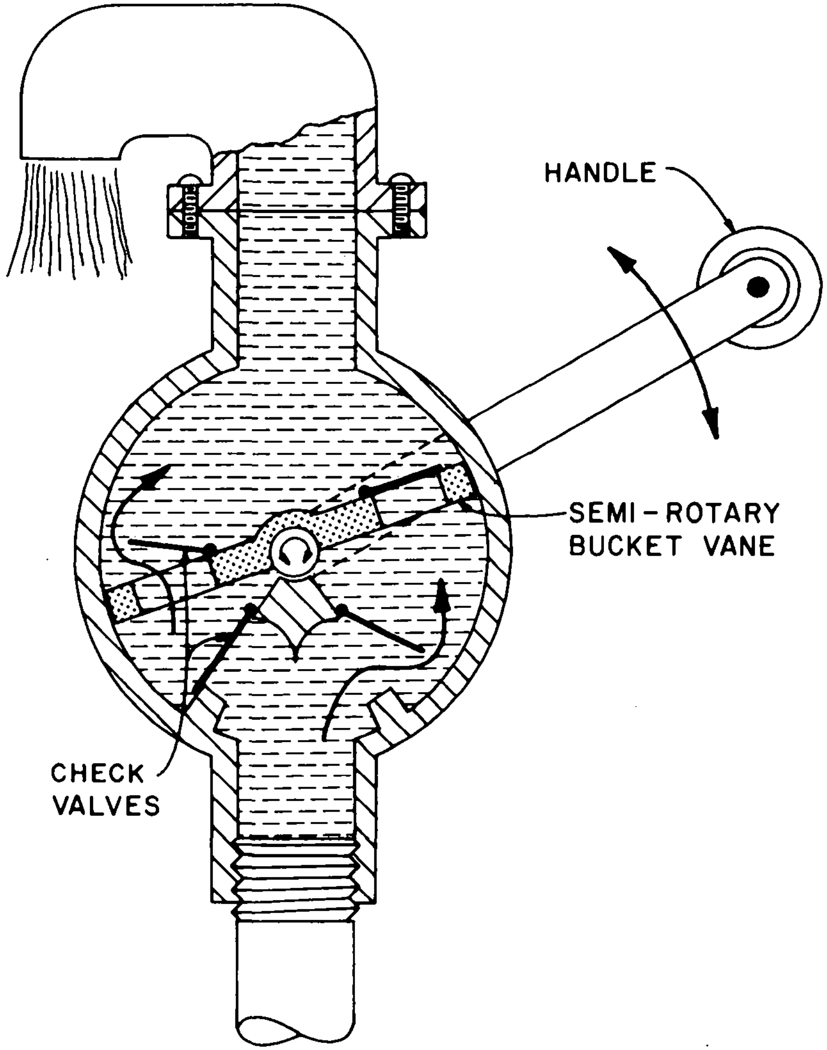


Figure 3.52 Manual, double-acting, semi-rotary pump

It is basically a rotor, made up of several vanes which are free to vary the space between them. It is stated to be theoretically capable of up to 5 million gpm at sizes of 12-20.5 ft diameters. This recent development will probably be used primarily in power plants and large pipe lines (Keller, 1975 and 1973).

The *semi-rotary pump*, shown in figure 3.52, is a half-breed device which utilizes both rotary and reciprocating motions. A vane, very similar to the bucket-piston (i.e., with flap valve(s)) is rotated through an arc in a circular casing which also contains a check valve(s) fixed to the casing. As the vane is alternately rotated in opposite directions, each set of fixed- and vane-check valves suctions and discharges a unit of water. To avoid wasting energy, most semi-rotary pumps are double-acting, as in figure 3.52, and several such pumps may be attached to the same driving shaft. This pump is usually limited to small-capacity, domestic applications and is normally operated by manual power.

3.4 Miscellaneous Methods

As previously mentioned, a few water lifting methods exist which do not fit, either individually or collectively, into any of the established classes. However, since they exhibit primarily positive displacement characteristics, they are appropriately considered in this chapter.

3.4.1 Hydraulic Ram

When a pumping site is available which has an excess water supply with sufficient potential energy (i.e., elevation head), the *hydraulic ram* can be used to make water power lift water. Although such ideal topographic locations are not common, where they do exist, the ram is a very economical water lifting device. After the initial cost and installation, it can operate 24 hours per day with little attention and is almost maintenance free.

As illustrated in figure 3.53a, the ram utilizes a flow of water from a source above it to drive a smaller discharge of water to an elevation above the source. In figure 3.53b, water flows down the drive pipe, into the ram and out the waste valve until the water velocity is sufficient to provide enough momentum to close the waste valve. The water is then forced through the check-valve and into the air chamber. This rush of water continues into the chamber until the air pressure within it exceeds the force of the inflowing water. The check valve is then forced shut, causing the water above it to flow up the delivery pipe, while the falling water again flows through the waste valve. This cycle occurs rather rapidly--25 to 100 times per minute. The valves can normally be adjusted to vary the strokes per minute (spm) which in turn regulates the discharge. More water is needed to operate at slower spm's, but a higher percentage of water is also driven up the delivery pipe. This variation in performance is a function of the size and type ram used, as well as the ratio between driving head and delivery head. Table 3.8, part A, lists some ram sizes by pipe diameters, and typical minimum driving (or falling) discharges (Q_f) necessary for them to operate.

The efficiency of a ram is normally taken as

$$\text{Eff} = Q_r \times H_r = \frac{Q_d}{Q_f} \times \frac{H_d}{H_f} \quad ,$$

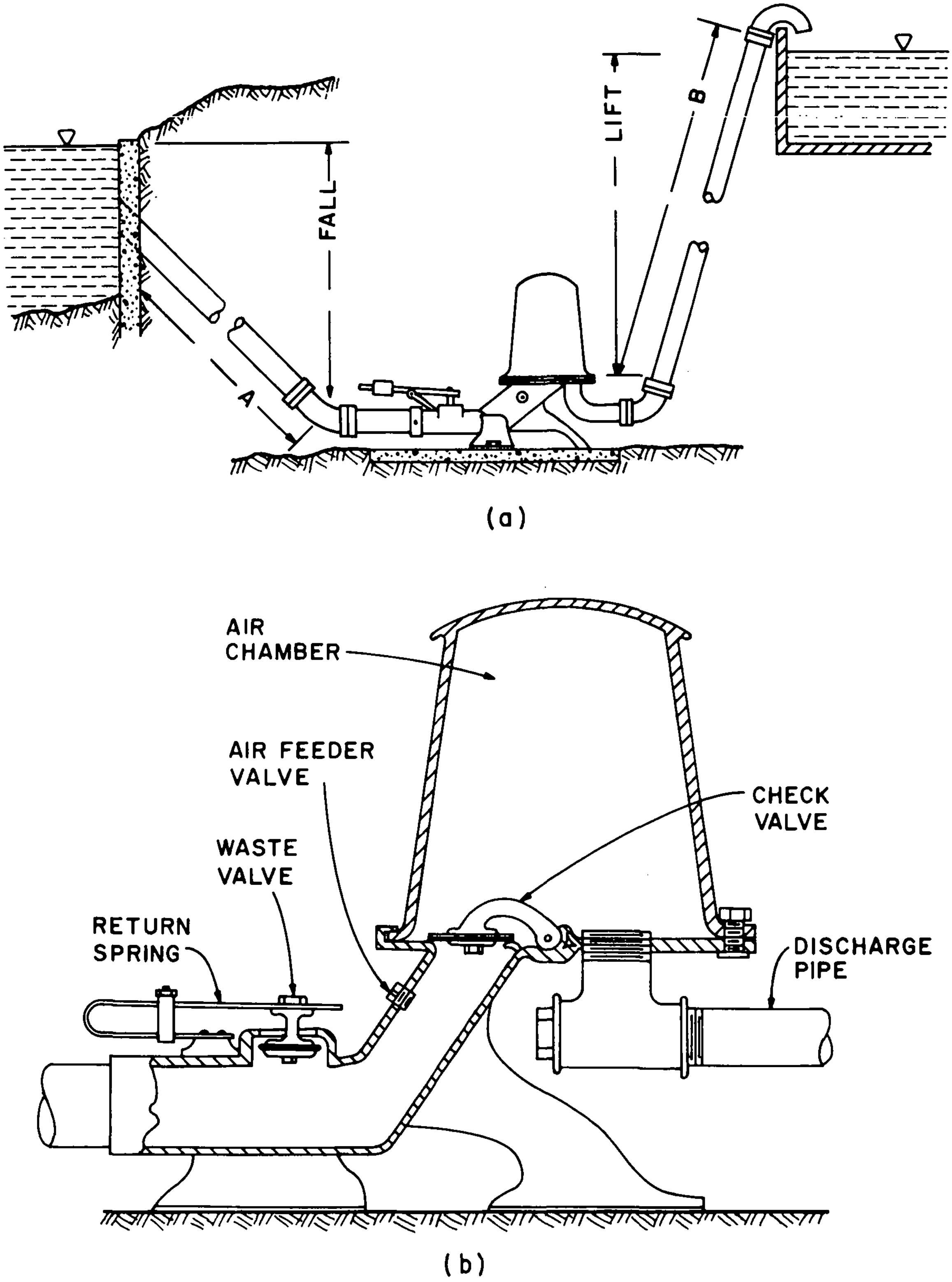


Figure 3.53 (a) Installation, and (b) typical design of hydraulic ram

where:

Q_r = discharge ratio or discharge efficiency

H_r = head ratio or head efficiency

Q_d = discharge in delivery pipe

Q_f = discharge in fall pipe

H_d = head from ram to delivery point (also H_{DD})

H_f = head of falling water from source to ram (also H_{DSH}).

The efficiency of rams is usually about 60 percent. Some typical combinations of Q_r and H_r are given in Table 3.8, part B. Rams

Table 3.8 Ram performance

A. Typical capacities for various size rams:

Drive Pipe (in.)	Delivery Pipe (in.)	Minimum Q_f (gpm)
1	½	4
2	1	15
4	2	45
6	3	90
9	4	200
12	5	300
18	8	600
24	10	1000

(after Anderson, 1973)

B. Typical discharge ratios (Q_r) for various head ratios (H_r):

H_r:	2	4	6	12	20
Q_r:	.35	.16	.10	.05	.03

(after Weisbach and Herrman, 1897)

usually need a minimum H_f of 18 inches to operate. With sufficient H_f, some rams are capable of H_d's up to 500 feet. Discharges (Q_d) vary from less than 1 gpm to about 1600 gpm.

In order to obtain efficient operation, the ram must be installed so that the drive pipe length (A) is 5 to 10 times greater than H_f, while the delivery pipe (B) should not be more than 20 times H_d (Kaufman, 1948; and Mother Earth News, 1974).

Double-acting rams are also available which utilize the fall of one water source to drive water from a second supply. Such rams are used primarily for domestic purposes where a "clean" water supply either has insufficient potential head or cannot be wasted, but a "contaminated" supply does exist above the clean water. These double-acting rams are not usually required, nor is their additional cost justified, for irrigation or drainage purposes.

Ram-action devices have also been adapted to work in siphon pipelines for drainage applications, as was illustrated in figure 1.8. Possibly because they operate with a suction lift, need to be primed, and fit very few appropriate installations, their use is not mentioned in current literature. However, another ram-type device, called the *hydrostat*, is in current usage. Instead of water directly driving water, the hydrostat utilizes a set of cylinders which are driven by water and in turn, drive a smaller quantity of water. Their use is limited primarily to assisting the operation of domestic water mains.

Rams vary in cost, depending on size and make, from about $200 to $3000. This usually includes a drive pipe strainer, but does not include pipe or other plumbing accessories. Double-acting rams are

$80 to $300 more. Because the ram is a rather simple device (i.e., has few moving parts, no high-speed drive connection, no close tolerances, etc.), several designs have been made available which only need materials that can be obtained in most plumbing or hardware stores; e.g., metal rod, concrete, pipe, bolts, rubber washers, etc. (Kaufman, 1948). A similar, easy-to-construct design has been set forth by VITA for use in developing countries (Kindel, 1975).

Other names which are often used when referring to hydraulic rams are:

water-ram *impulse pump*
hydraulic engine

3.4.2 Air-Lift Methods

Compressed air can be used in two different methods to lift water. The first method, using an eductor pipe, is the one commonly referred to by the general term *air-lift pump*.

3.4.2.1 Eductor Method

In this air-lift method, compressed air is forced down into a well through a pipe. At a point below the water level, the air is allowed to escape into an eductor pipe which extends from below the water level up to the well surface or a discharge pipe. As shown in figure 3.54, these pipes can be arranged in one of three ways; (a) the air pipe can be a small pipe inside the eductor, (b) a small air pipe can parallel the eductor on the outside and then connect to it near the bottom, or (c) the air pipe can be larger than the eductor and fit around and below it. However, in all three schemes, the air will mix with the water, creating a lighter fluid in the eductor pipe than the water in the surrounding well. The heavier fluid will thus force the

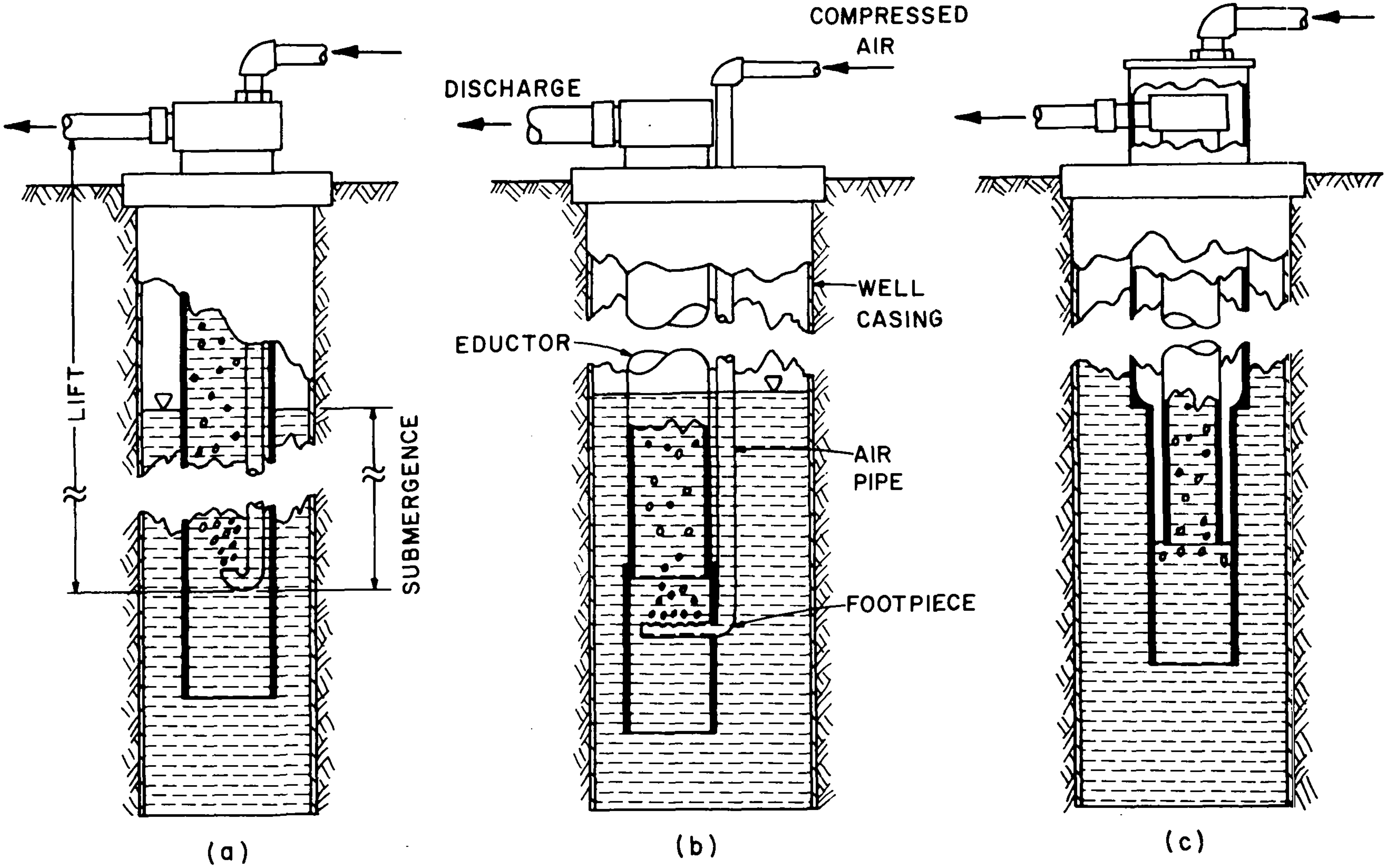


Figure 3.54 Eductor air-lift methods; (a) air pipe in eductor, (b) air pipe outside eductor, and (c) eductor inside air pipe

air-water mixture up and out of the eductor pipe. Because the water pressure at the bottom of the eductor must exceed the weight of air-water in it, the air and eductor pipes must be submerged sufficiently to produce this pressure. Table 3.9, part A, gives some typical degrees of submergence necessary to produce a given lift. As in this table, submergence is expressed as the percentage or ratio of the length of air pipe below water to the total lift (i.e., air pipe

Table 3.9 Air-lift operation

A. Submergence required for various lifts:

Lift (ft):	25	50	100	200	500	700
Submergence (%) range:	55-70	50-70	45-70	40-60	35-45	35-40
optimum:	68	65	60	52	-	-

(after Anderson, 1973; Kill, 1973)

B. Component sizes for various discharges:

Q (gpm)	Minimum Well Casing Diameter (in.)	Eductor Pipe Diameter (in.)	Air Pipe Diameter (in.)
30-60	4	2	1/2
60-80	5	3	1
80-100	6	3-1/2	1
100-150	6	4	1-1/4
150-250	8	5	1-1/2
250-400	8	6	2
400-700	10	8	2-1/2

(after Kill, 1973)

bottom to discharge elevation). The amount of necessary submergence can vary within the given range, depending on the available well depth, velocity of air flow (v_a) into the eductor, and efficiency of any foot piece, however, an optimum submergence will exist for each installation near the valve given. If v_a is too low, the discharge may surge, or if too high, the discharge will create high friction losses. In either case, efficiency will drop. Therefore, the air and eductor pipe sizes, well casing size, and v_a must be matched to the desired discharge. Table 3.9, part B, gives typical sizes of plumbing which will give acceptable values of v_a and thus good efficiency when a small air pipe is used outside the eductor. (This is probably the most common arrangement for irrigation pumping.) In very deep wells, it is often necessary to increase the eductor pipe diameter toward the top to keep the air-water mixture's velocity (v_{aw}) below about 45 fps. Above that velocity, friction losses are too high.

The volume of air (V_a) required to create the proper air-water mixture depends on the amount of lift and submergence. V_a can be determined by tables or formulae, such as the commonly used one by Rix and Abrams:

$$V_a = \frac{L}{C \times \log\left(\frac{S + 34}{34}\right)}$$

where: V_a = ft^3 of air per gallon of water

L = total lift in ft

S = submergence in ft

C = a constant depending on lift.

The values of the constant, C, are given in many handbooks and pumping texts, however, they were not included here because considerable disagreement exists among available literature--see Escritt (1972), p. 188; Ivens (1920), p. 133; Anderson (1973), p. 120. A foot piece at the end of the air pipe is helpful in improving the efficiency by breaking up the airstream into small bubbles which mix more thoroughly with the water.

Since air-lift pumps have no moving parts they require no other maintenance than is required for the air compressor. They are very applicable to lifting abrasive or dirty water, thus one of their most common usages is in sewage works. In irrigation and drainage they are confined mainly to testing new well installations since they are not efficiently used in conditions of fluctuating water supply levels. Also, they cannot pump any considerable distance horizontally without a booster pump. The major cost of this type air lift installation (other than the well sinking) is the air compressor (see Chapter 5). The only other initial costs are for piping and the foot piece, all of which can be improvised from second-hand materials.

3.4.2.2 Displacement Method

As mentioned in Chapter 1, the displacement method of lifting water was discovered by Heron, who used it to create the fountain in figure 1.2. Referring to that figure, Heron used the head of water in A to compress the air in B. This air created a pressure on the surface of the water in C, which then flowed up the pipe to elevation D. Using a mechanical air compressor instead of a compressing water head, this principle has been adapted for modern applications. As illustrated in figure 3.55, air is withdrawn from container A which allows water to flow into it. Air is then forced back into the container, displacing the water and forcing it up the discharge pipe. In the example figure,

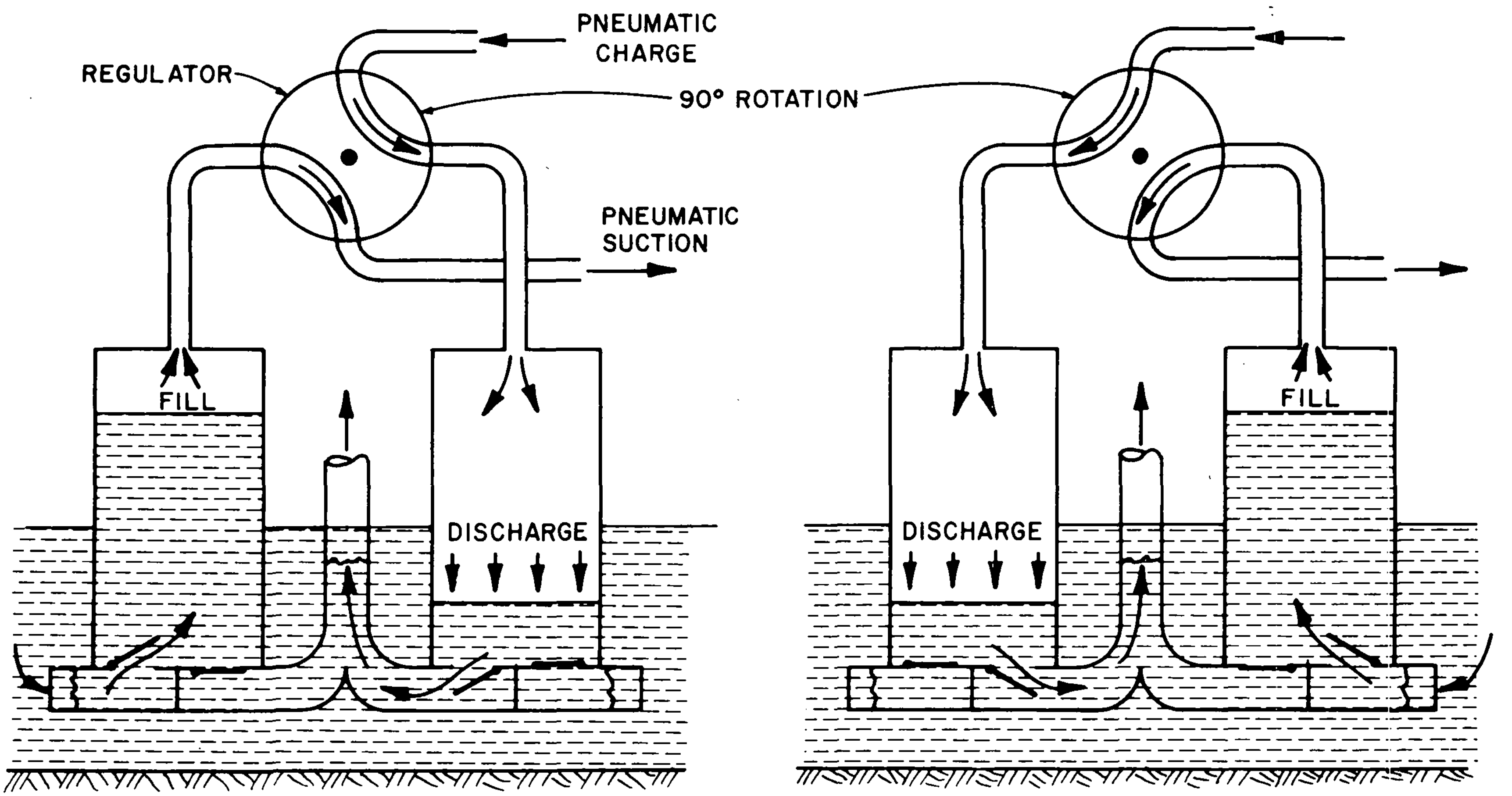


Figure 3.55 Operation of displacement air-lift system

a second container, B, is utilized to make the discharge continuous and prevent wasting compressed air. A series of small, such double units may be used with short cycle times to increase efficiency.

Since the development of the eductor air-lift methods, displacement-type installations have rarely been used for irrigation and drainage purposes. They require much more plumbing and have several check valves and switches (e.g., the regulator) which must be maintained. However, two recent developments have found new applications for the displacement air-lift principle.

The current "energy shortage" has created an incentive for the development of water lifters which can utilize natural energy. Among them is the solar water pump designed by D. P. Rao and K. S. Rao at the Birla Institute in Pilani, India. They have developed two types of systems--air cooled and water cooled.

In the water cooled arrangement shown in figure 3.56, the system consists of a solar collector, flash tank, and cooling tank located above ground, and a pair of water tanks located in the water source. Water enters these water tanks by an inlet check valve under atmospheric pressure. A working fluid--pentane or some other petroleum fraction--flows by gravity from the flash tank into the solar collector where it vaporizes at about 35°-40°C. It then flows through the flash tank and into one of the water tanks. As in the pneumatic-operated displacement container, this vapor will create a pressure within the tank sufficient to push the water up a discharge pipe. The water being discharged from the one tank passes through the cooling tank and condenses the vapor in the other water tank. As that vapor is condensing and returning to the flash tank, water is flowing into the second tank

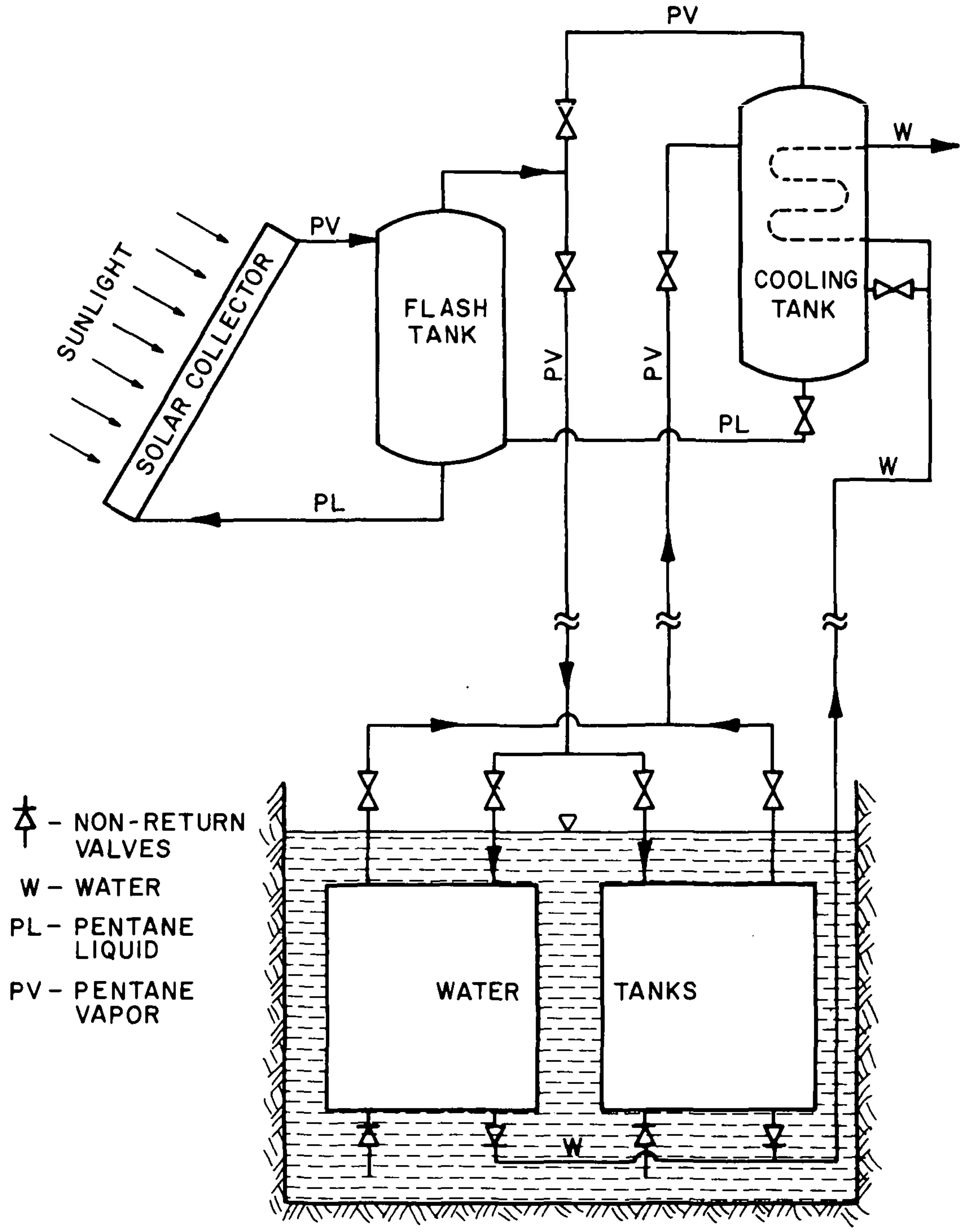


Figure 3.56 Schematic operation of water-cooled solar pump

because of the decrease in pressure. Upon completion of these two simultaneous filling and discharging operations, the vapor is switched into the other tank and the cycle repeated.

A similar air-cooled system utilizes only one water tank which is emptied during the daylight heating hours, and filled during the cooling night. This arrangement requires the water tank to be large enough to handle one entire day's pumping requirement.

Early morning sunlight, from about 7-10 A.M., is required to bring the working fluid to vaporization temperature, so that actual pumping can only take place from about 10 A.M. to 4 P.M. With this time limitation in mind, the collector and tanks must be sized to produce the desired daily discharge. Table 3.10 gives some of the results achieved by Rao and Rao (1975) for various size systems. Theoretically, discharge is limited only by the size tanks available and lifts up to 300 ft should be within practical operation capabilities.

Table 3.10 Solar pump performance

	Air-cooled system with 10 x 12 ft water tank		Water-cooled system with two 3 x 5 ft water tanks	
Lift (ft)	Discharge (ft^3/day)	Collector Area (ft^2)	Discharge (ft^3/day)	Collector Area (ft^2)
30	880	250	7,805	1,000
60	880	400	5,406	1,000
90	880	550	3,607	1,000

Because the components are not yet commercially produced as a unit, these pumps are still rather expensive for use in developing countries. The air-cooled system which produced the results in table 3.10 cost about $1,420 for the tanks, plumbing, and insulation, and \$4.50 per ft^2 for the collector. The water-cooled system cost about \$2,100, plus the \$4.50 per ft^2 of collector, i.e., about \$6,400 total. Of course, the operating cost is almost nil--only an occasional recharge of the working fluid. With further development to cut initial costs and improve efficiency, the lack of moving parts (except check valves) and ease of operation by unskilled labor, make this system a feasible solution to reducing pumping costs in a time of rising fuel costs.

The second recent development of the displacement method is the foot operated device in figure 3.57. It is being manufactured commercially by a French company for use primarily in developing countries. As shown in the figure, a foot pedal reciprocates a small air-piston which is connected to a displacement cylinder in the water supply via a flexible hose. As in the other displacement methods, the charge and exhaust of air by the piston causes discharge and filling of the cylinder, respectively. The discharge flow is through another flexible hose which is connected at the surface to appropriate plumbing. In a design for 4 in. diameter wells, this device is reported to deliver 53 cfh at a 66 ft head, and 18 cfh at 200 ft (Mengin, 1976).

3.4.3 Pulsometer

Although the *pulsometer* probably cannot be found in use anywhere today, as mentioned in Chapter 1, it was commonly used for drainage purposes around the turn of this century. It utilizes the principles of both the steam and air-lift pumps. Referring to figure 1.5, steam (under pressure) from connection B, is alternately directed by the ball check-valve (C) into the adjacent displacement chambers (A). The

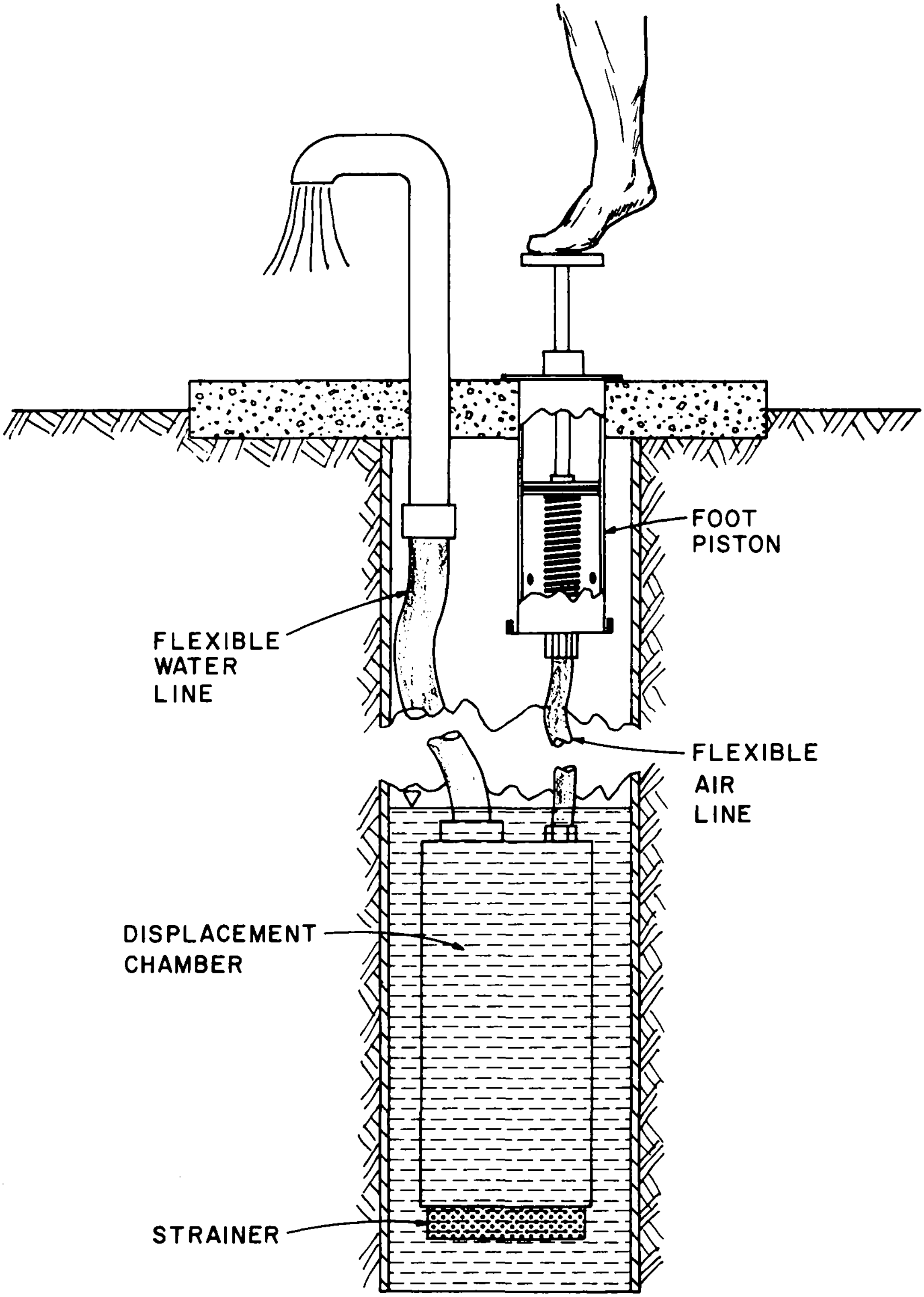


Figure 3.57 Displacement air-lift method operated by foot piston

steam pressure forces water out of one chamber through check valve D and up pipe E, while in the other chamber, the steam is condensing, creating a pressure drop, and thus drawing water in through suction pipe F. The oscillation of this action between chambers (from about 12 per minute in larger pulsometers to 130 per minute in smaller sizes) causes quite a vibration and was the origin of its common name, pulsometer. Although not practical for irrigation or agricultural drainage, it is included here for its unique operation (see also Rogers, Vol. 2, 1905, pp. 269-280; Weisbach and Herrman, 1897, pp. 286-291).

3.4.4 Explosion Pump

Another unique, but obsolete, water lifter is the *explosion pump* of Humphrey. As shown in figure 1.9, its operation is quite simple and was originally claimed to be more efficient than conventional steam pumps (Greene, 1913, pp. 128-129). A charge of coal gas is brought in through valve A and exploded in chamber B. This will drive water in pipe C (obtained from the supply D in the previous cycle) up the discharge pipe (E) to the reservoir (F). The spent gases are exhausted through valve G and a new unit of water is drawn from D through inlet ports (H). The rebound of water in pipes C and E is the method for exhausting the gases and compressing the new charge of coal gas. Ignition of the explosion is by electric spark. A rather extensive analysis of this device was reported by W. C. Unwin in the 1909 *Engineering* (see Unwin, 1909). Although the reasons for the explosion pump's obsolescence are not available, its unique operation was once thought to be an important breakthrough in water lifting--see *Engineering*, 1909, pp. 512-514.

Chapter 4

Kinetic Methods

4.1 Introduction

The *kinetic class* of waterlifters comprises a smaller variety of subclasses than positive displacement devices, but is presently the most widely used class (where available) for irrigation and drainage. This is primarily due to its adaptability to most applications and prime movers. The term centrifugal is commonly used, but erroneously, to denote this entire class--probably because centrifugal pumps were the first devices to develop in this class (Chapter 1). As the term kinetic implies, this class of pumps adds energy to the water by the motion of an impeller or, in the case of jet pumps, the motion of another fluid mass. Jet pumps are often included with centrifugal pumps which are commonly used to pump the driving fluid of an ejector. However, since the jet subclass also encompasses injectors utilizing steam and recent ejectors use rotary and reciprocating pump drivers, a separate subclass of jet devices is included.

"Centrifugal" is also commonly used to classify the group of pumps we have more appropriately labeled *rotodynamic* (table 2.2), which includes true centrifugal pumps as well as three other types. *Peripheral* pumps are often given a distinctive subclass (as in the Hydraulic Institute Standards) since they, like *propellers*, are not true centrifugal devices. However, the use of this rotodynamic subclass (more commonly used in Europe) can be used to classify all pumps which utilize a high speed rotary (as opposed to positive displacement rotary) motion. The terms *velocity*, *impeller*, and *rotokinetic* are also used occasionally instead of rotodynamic (Lazarkiewicz and Troskolanski, 1965; and Wagner and Lanoix, 1959).

4.2 Rotodynamic Pumps

All rotodynamic devices consist of two primary parts; an *impeller* which imparts energy by its rotary action, and a *casing* which guides the fluid to and from the impeller and confines the energy transfer. Several hundred different designs have been developed by an almost equal number of manufacturers for various applications and mechanical requirements. This paper can only cover the general operation and characteristics of the basic subclasses and suggest a few of numerous references available on the details, theory and design of kinetic pumps.

4.2.1 Radial Flow

Radial impellers give the fluid a true centrifugal action, i.e., the fluid enters at the eye or axis of the impeller and is thrown radially--at 90° to the shaft axis--outward to the enveloping casing by the impeller vanes (figure 4.1). This creates a partial vacuum at the eye which draws in additional water from the suction line(s). As the water is expelled from the vanes, it is guided by the casing in one of two manners. In a *volute casing*, figure 4.2a, the water is discharged by the vanes into a widening spiral casing, which converts velocity head into pressure head. Since this creates greater pressures near the discharge side of the casing, double (figure 4.2b) or triple volutes are often used to equalize the pressure distribution. In a *diffuser casing*, figure 4.3, a ring of guide vanes, curved backward to the impeller vanes, perform much as multiple volutes--expanding outward to make the pressure conversion. In

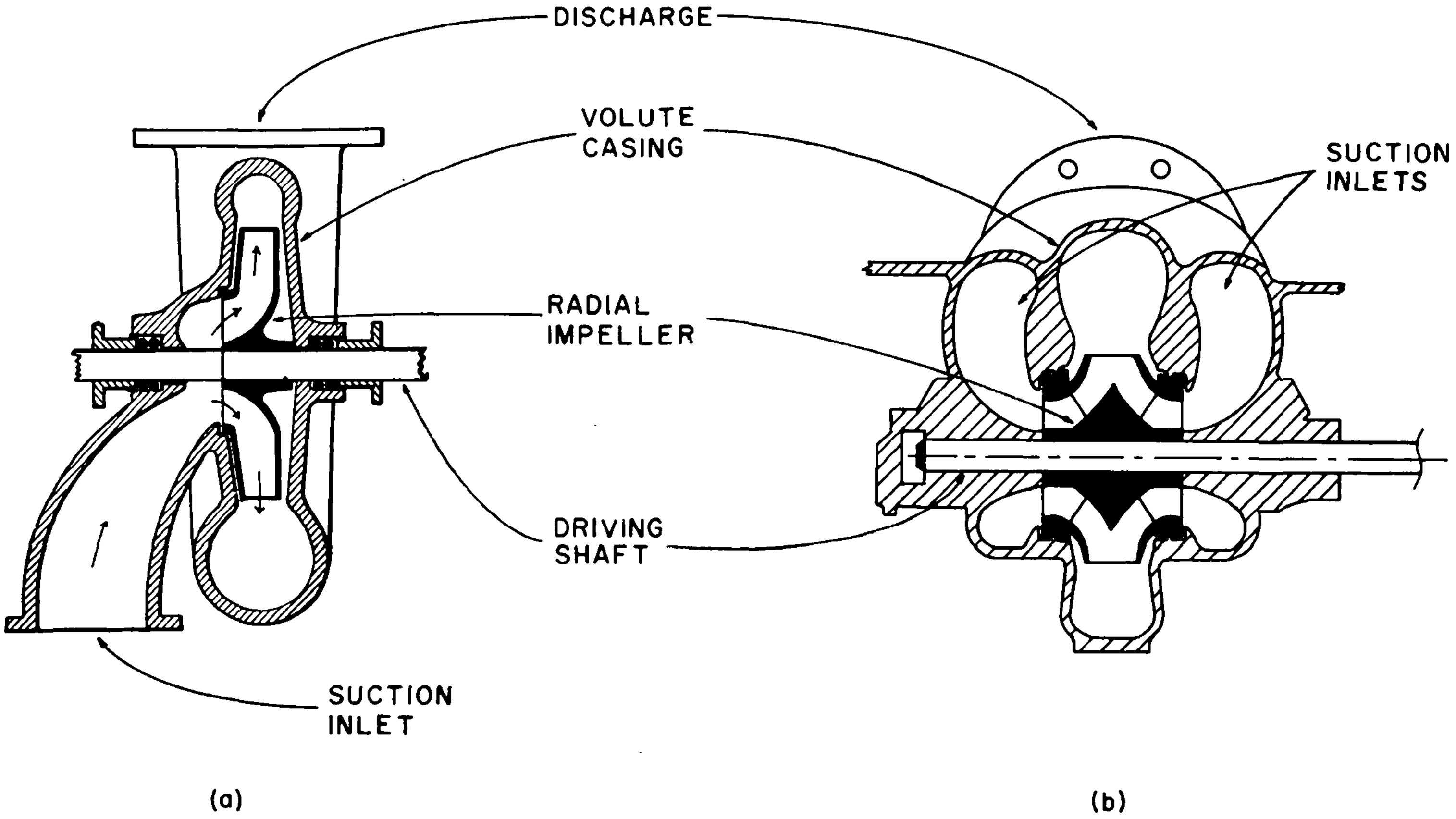


Figure 4.1 Radial impellers: (a) single suction, (b) double suction

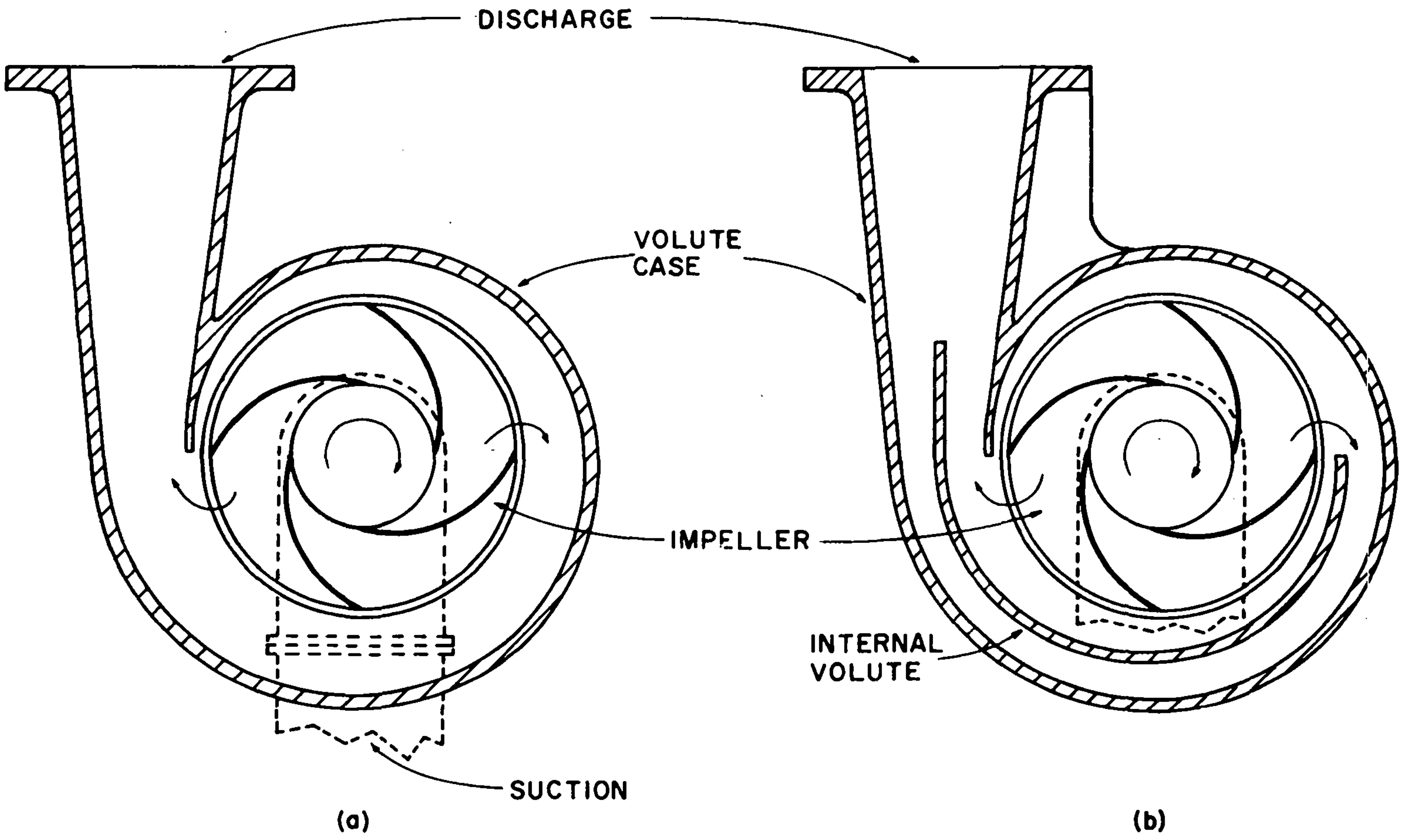


Figure 4.2 Volute casings: (a) single, (b) double

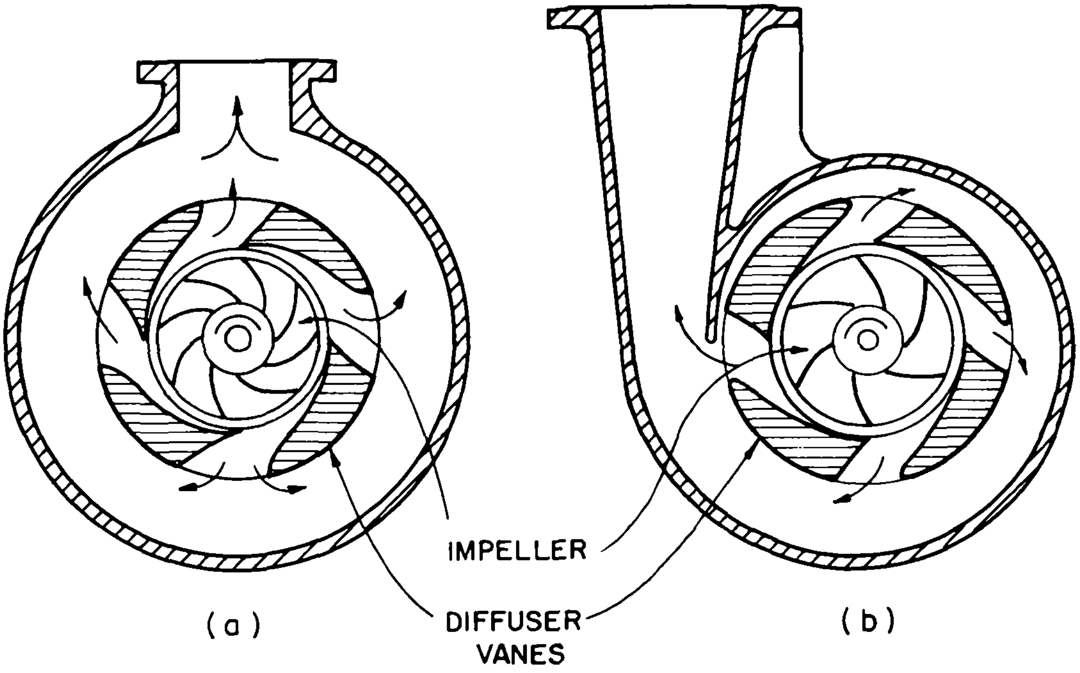


Figure 4.3 Radial diffuser pumps with (a) circular casing, (b) volute casing

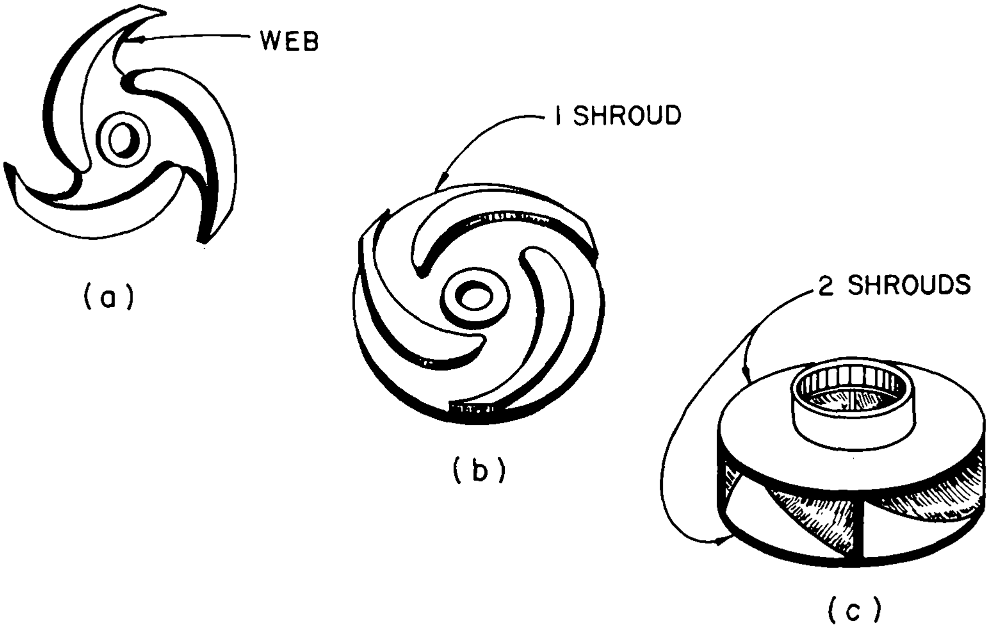


Figure 4.4 Impellers: (a) open, (b) semi-enclosed, (c) enclosed

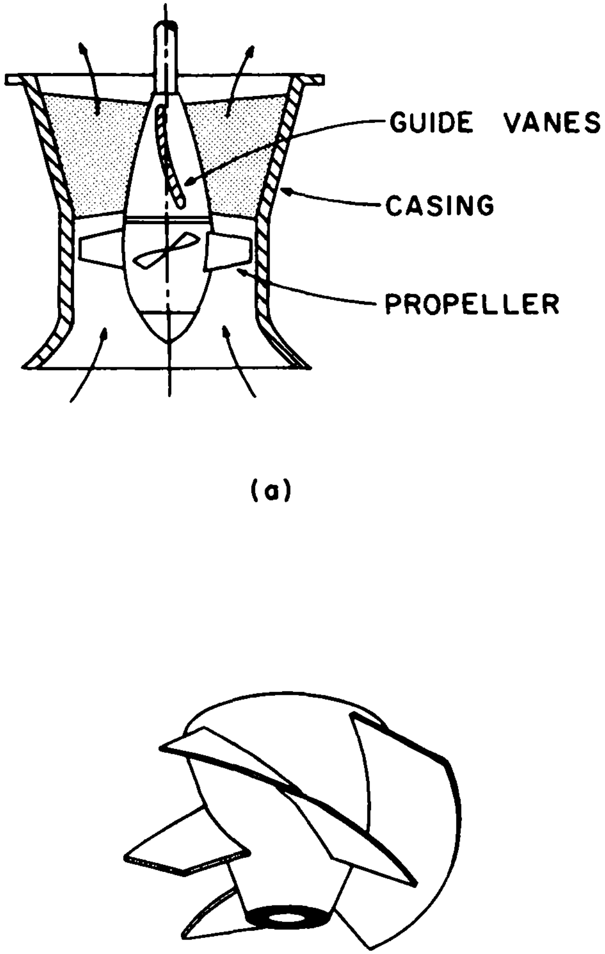
multiple stage pumps, e.g. submersible well pumps (figure 4.16), these diffusers also guide the water into the eye of the next stage. Impellers can additionally be classified as *enclosed*, *semi-open* (or *semi-enclosed*), or *open*. As shown in figure 4.4, the enclosed impeller has a *shroud* on both sides of the vanes, the semi-open has a shroud only on the upstream side, and the open has essentially no shrouds, only the webbing needed to support the vanes. If the vanes have a double curvature, i.e., normal to both the shaft axis and shroud(s), the impeller is often referred to as a *Francis impeller*--having the same design as a Francis turbine blade, but working in reverse.

4.2.2 Axial Flow

Axial flow impeller pumps, or as they are often called *propeller pumps*, increase the head on a fluid by the lifting action of the vanes. The fluid flow is parallel to the pump shaft as shown in figure 4.5. In most designs, guide vanes are provided immediately after the impeller to convert excess rotational velocity of the fluid to pressure head. The impeller vanes may be fixed parallel to, or at any angle to, the shaft axis, or they may be adjustable for changes in application conditions. To improve lifting capabilities, some curvature is also usually provided along the axis, as illustrated in figure 4.5b.

4.2.3 Mixed Flow

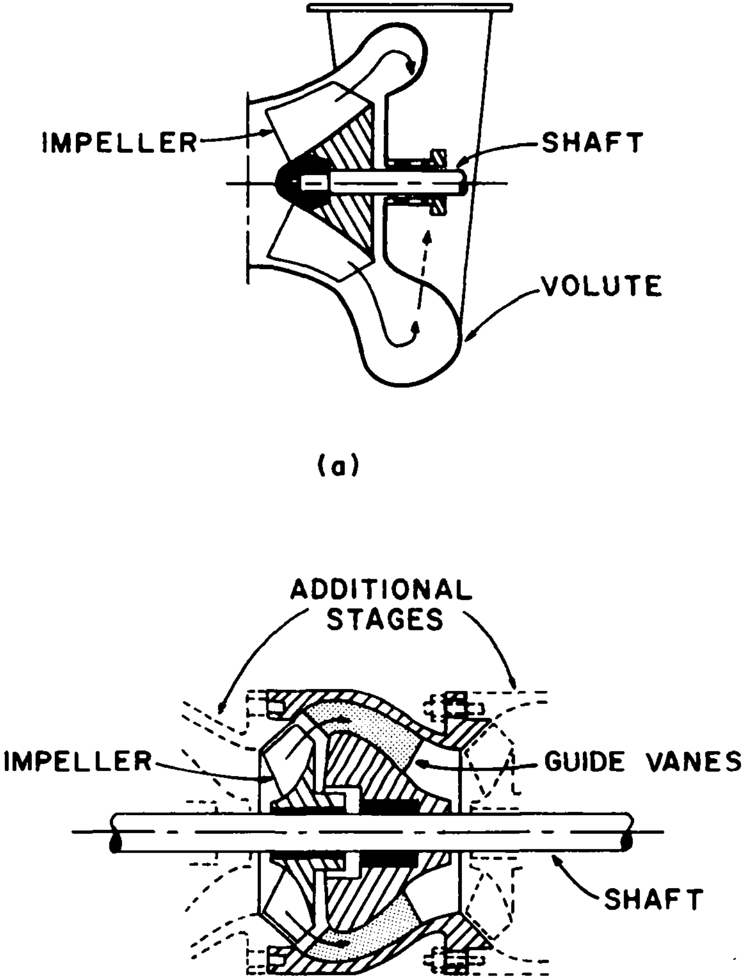
Mixed flow pumps have impellers which impart to the water both axial and radial motion, i.e., the vanes discharge at some angle between 0° and 90° from the axis. Mixed flow impellers are used in two basic pump designs; the *helical* flow (figure 4.6a) which utilizes



(a)

(b)

Figure 4.5 Axial-flow impellers (propellers)



(a)

(b)

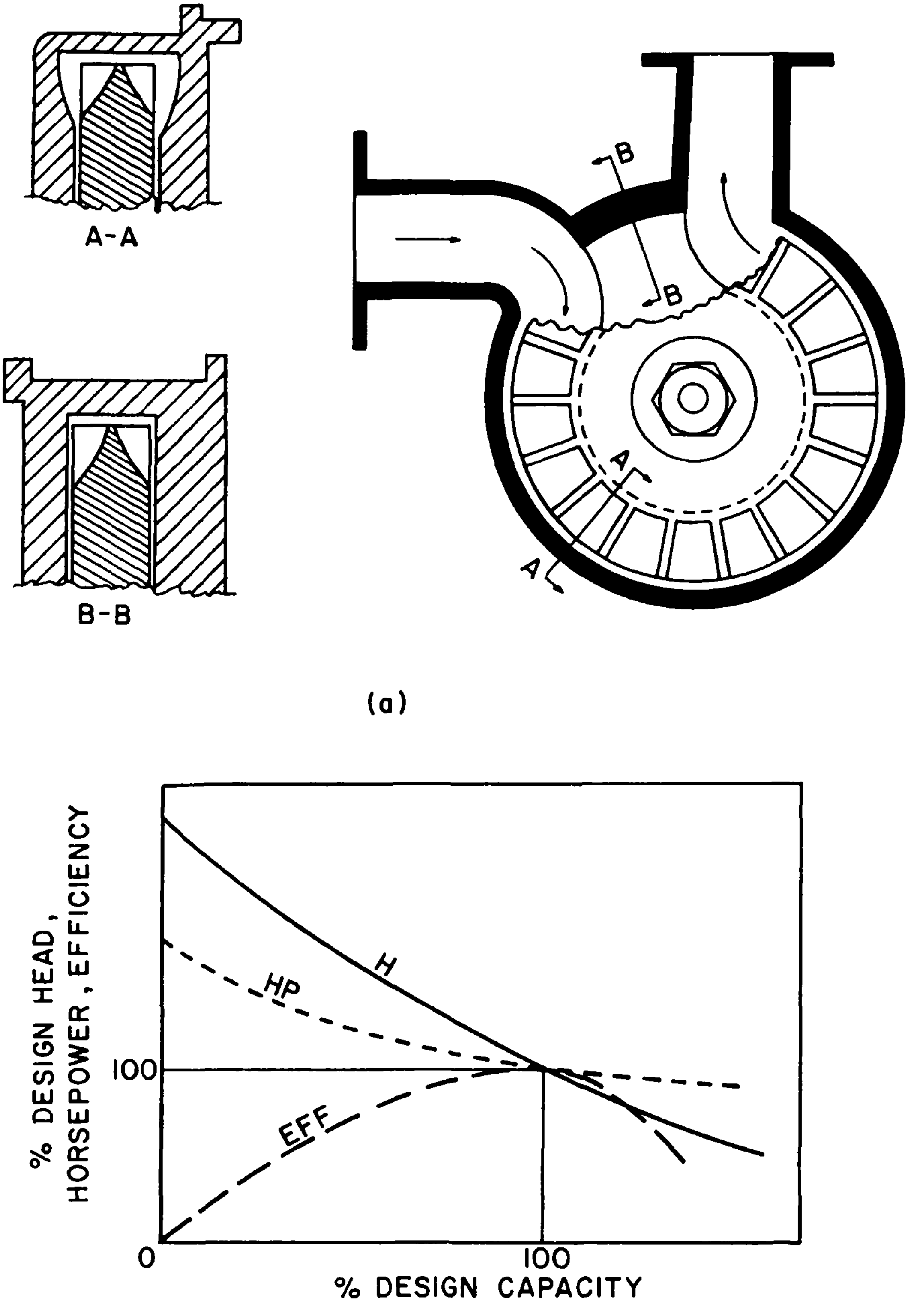
Figure 4.6 Mixed-flow impellers: (a) helical, (b) diagonal a volute casing, and the *diagonal* flow (figure 4.6b), as used in the bowl construction of vertical well pumps.

4.2.4 Regenerative Flow

Regenerative pumps are also referred to as *vortex*, *peripheral*, *side channel*, and *turbine* pumps--the latter name often leading to confusion with vertical "turbine" pumps (a misnomer itself). Although the basic principle is the same, a fine distinction exists between peripheral and side channel pumps. A peripheral pump has a volute casing at the impeller tip which decreases in cross sectional area in the direction of flow (i.e., opposite of a volute pump). The side channel pump casing has wider side passages to retard fluid flow. The principle of both can best be illustrated with the peripheral pump. Referring to figure 4.7a, a peripheral impeller receives the water, as its name implies, at its periphery and recirculates the water several times about its short, double-sided vanes before discharging. This recirculation is produced by the decreasing volute (or side channel) design which causes reverberation of the water back toward the suction inlet. This reverberation or vortex action allows the impeller to impart additional energy to the water. A regenerative pump can develop heads several times greater than a volute pump with the same size impeller and speed, thus making this type pump useful for high pressure requirements. At the outlet port, the casing narrows to a clearance just sufficient to pass the impeller (figure 4.7a, section B-B), thus forcing the water out.

4.2.5 Characteristics

Since the operation principle of radial, mixed, and axial flow pumps is the same, a discussion of their basic characteristics can



(a)

(b)

Figure 4.7 (a) Regenerative pump, and (b) typical performance curves be made jointly. Because of their unique operation, regenerative pumps are included only where specifically mentioned.

Along with its performance curve, several other parameters can be used to describe a pump's operation. Many are used in design work, as described by Addison (1966), and Lazarkiewicz and Troskolanski (1965), however a few, more descriptive terms are commonly used in pump selection, installation, and operation.

The first such parameter is called *(nominal) specific speed,* or more properly, *kinetic specific speed* since another term, *dynamic specific speed,* is also used in design work. It is defined as

$$N_s = \frac{N\sqrt{Q}}{H^{3/4}}$$

where N is shaft speed in rpm, Q is discharge in gpm, and H is head in feet. Table A.8 gives the conversion of N_s to other commonly used measurements. Specific speed is used as a "type" number which is constant for similar pumps. It is indicative of impeller shape and varies uniformly with changes in the impeller diameter ratio, D_2/D_1, another characteristic parameter. (Two similar parameters, true specific speed and shape number also exist, but are used primarily for design purposes (see Addison, 1966, pp. 65-70).) Figure 4.8 shows this relationship between N_s, D_2/D_1, and impeller type. The Hydraulic Institute has also developed a set of curves which recommend N_s upper limits for given heads at which cavitation, vibration, etc. can become a problem. These curves can be found in the Hydraulic Institute Standards and many pumping publications, however the effect of increasing suction lift is illustrated in

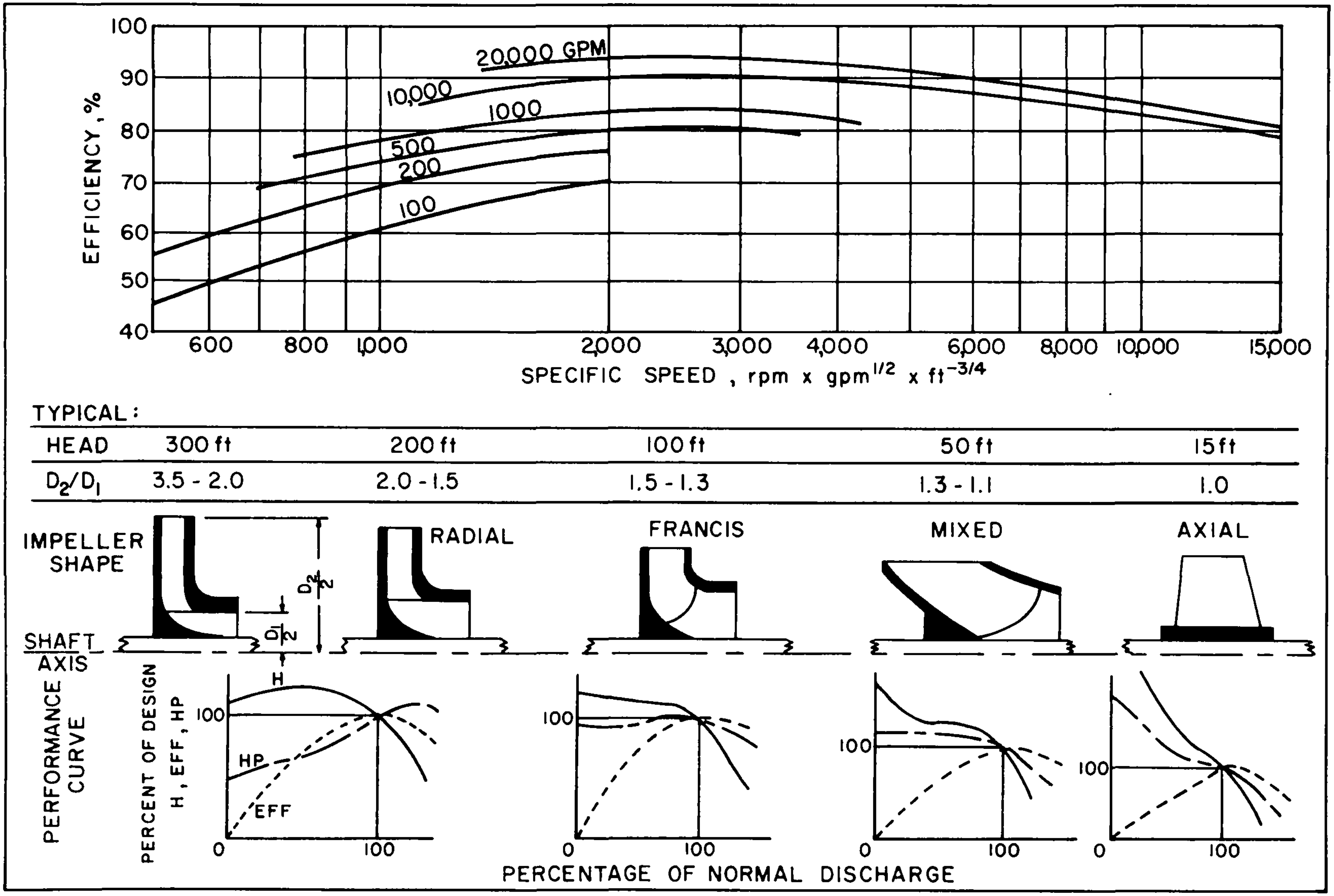


Figure 4.8 Approximate relationships of rotodynamic pump characteristics

figure 4.9. Thus, by utilizing N_s as a selection tool, optimum installation conditions can be designed.

Another parameter, *suction specific speed* is defined as

$$S = \frac{N\sqrt{Q}}{NPSHR^{3/4}} .$$

(Note that for double suction impellers, Q equals half the total discharge through the pump.) This number is used primarily for indexing the cavitation performance of a pump.

Also included in figure 4.8 are typical shapes of pump performance curves as they vary from radial to axial flow impellers. By reviewing these curves, some of the different performance features of various rotodynamic pumps can be observed. For example, as impeller type changes from radial to axial, the H-Q curve steepens, so that while the discharge of a high N_s pump varies greatly with head, a lower N_s design will operate in a more narrow head range. It can also be seen that for an axial pump, power is a maximum at shutoff (Q=0) and decreases with increasing discharge, while for radial designs, power is at a minimum for shutoff. And as figure 4.8 illustrates, efficiency is high over a wider range of Q for lower N_s pumps, however, higher maximum efficiencies can be obtained for high N_s pumps (Rouse, 1950).

A still closer look at these same curves will indicate some of the characteristics of various pumps. A head curve which falls steadily with increasing discharge represents *stable* performance, i.e., the pump will operate at only one discharge for a given head. However, an H-Q curve which rises and falls is called *unstable* since the pump can operate at more than one discharge for a given

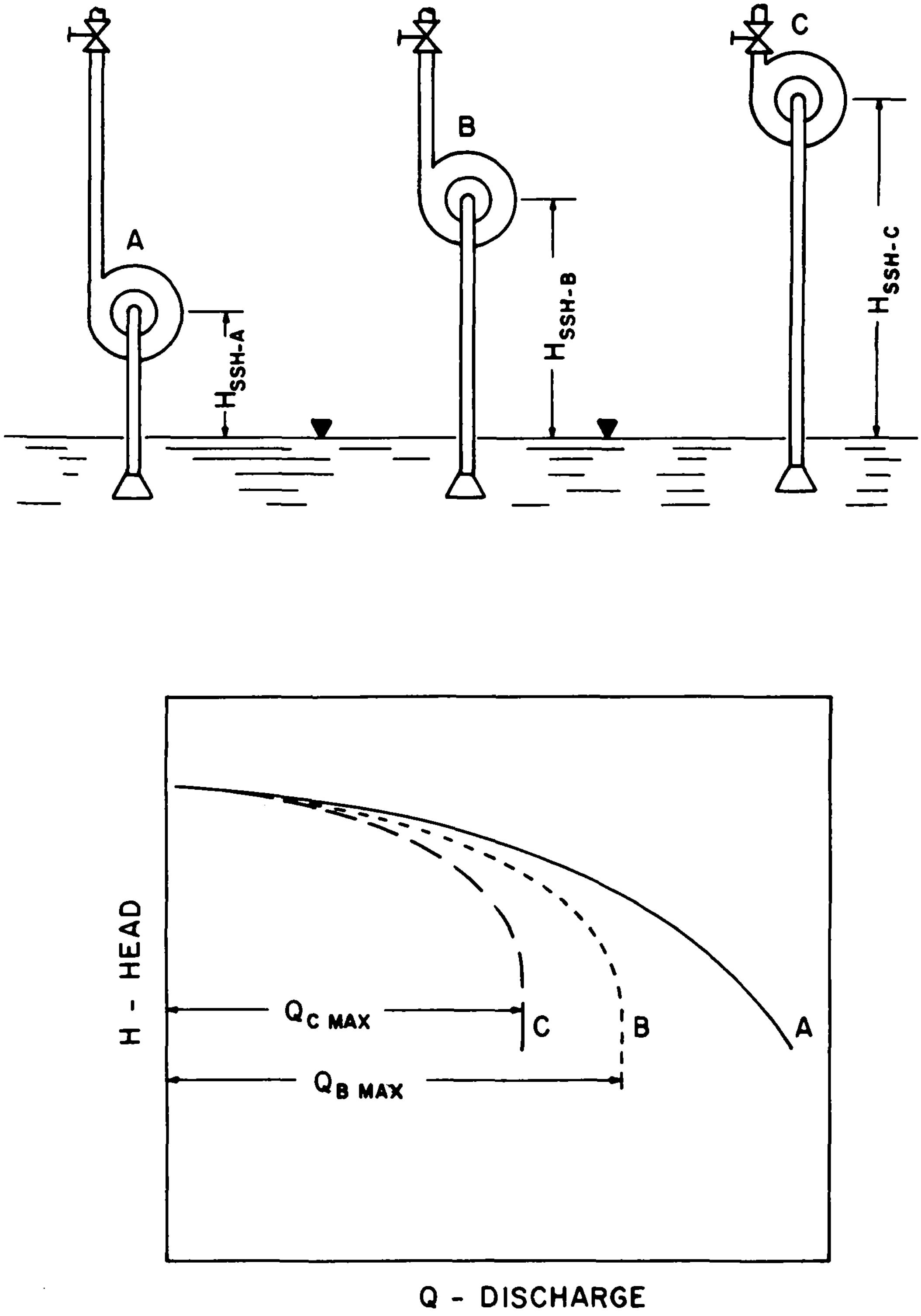


Figure 4.9 Effect of excessive suction lifts on pump performance

head, thus creating discharge fluctuations and poor efficiency. Figure 4.10 illustrates the following relationships between impeller shapes and H-Q curves:

(a) a wide impeller produces a flatter curve than a narrow impeller,

(b) an impeller with more vane curvature will result in a steeper curve than with flatter vanes,

(c) an impeller with more vanes will exhibit a flatter curve than with fewer vanes.

These relationships cannot be taken to extremes, since for example, absolutely straight vanes result in poor efficiency (see section 1.2).

Although the regenerative pump is not in the radial/mixed/axial family of rotodynamic pumps, it also has distinctive curves. As illustrated in figure 4.7b, the performance curves resemble, in shape only, those of an axial flow pump. That is, power and head are both a maximum at shutoff. However, regenerative pumps usually have a discharge range of 1-200 gpm and single stage heads of up to about 500 feet, while propeller pumps have been built to handle upwards of 100,000 gpm but are limited in head to about 30 feet (Pillai, 1969). Specific speeds of regenerative pumps are the lowest of the rotodynamic class, ranging from 500-1300.

Comparison of several characteristics should be noted for various rotodynamic pumps as they relate to selection and application. At a specific horsepower, a closed impeller will yield a higher efficiency and head than will a semi-open impeller of the same size. Although this additional head may be only a few feet, in a multi-stage pump, this could add up to significant savings (Longenbaugh, 1975). Open

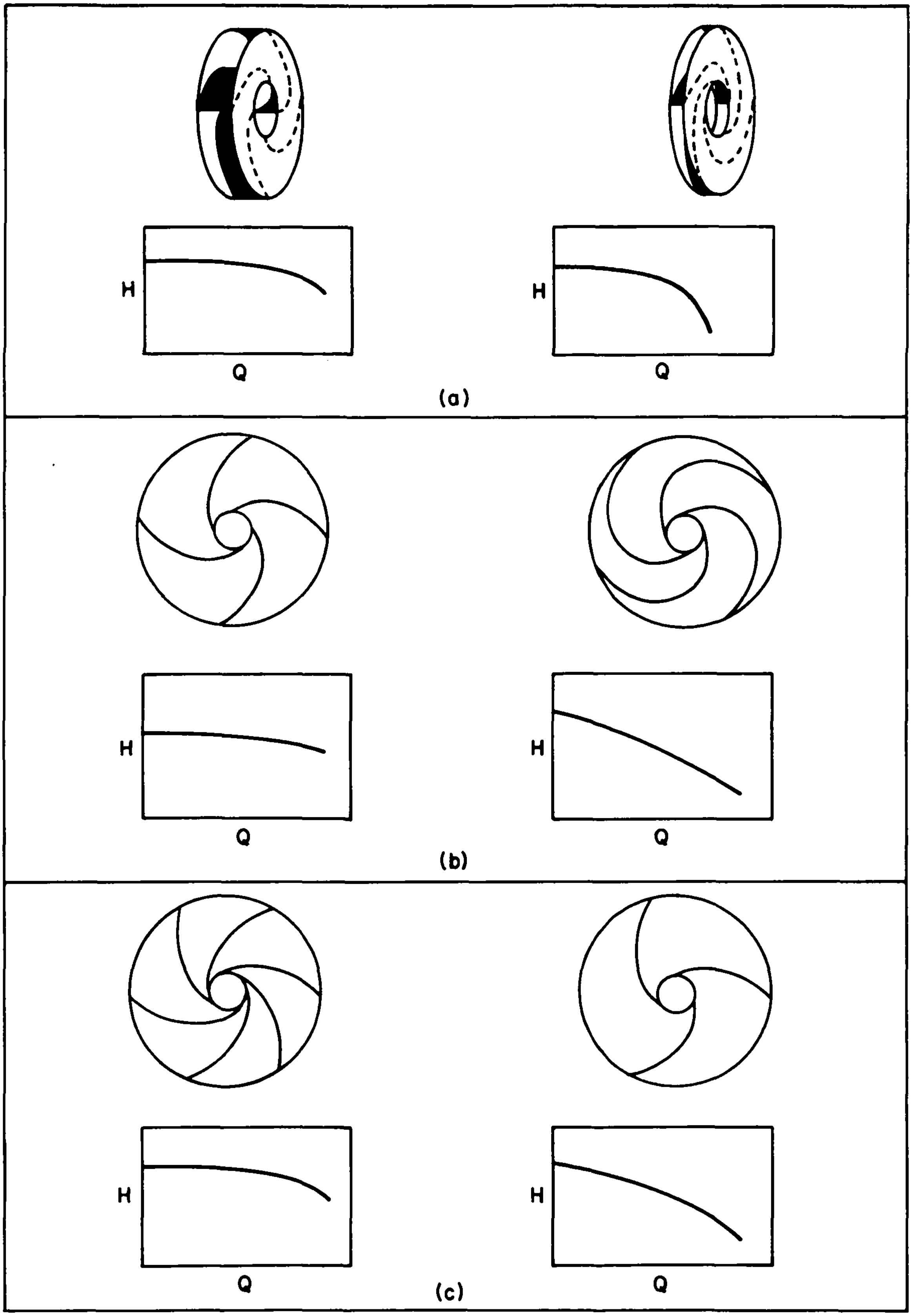


Figure 4.10 Impeller shape effects on H-Q curves

and semi-open impellers allow wear between vanes and casing, which increases the clearance, and thus the amount of "leakage," between them. Consequently their capacity and efficiency will drop over time. However, the vanes in a closed impeller are protected on both sides. Thus, the wearing surfaces of a closed impeller are less critical to the capacity of a pump which should therefore maintain its original efficiency longer. The open or semi-open impeller can however be adjusted (by axial shaft displacement) to maintain high efficiency, but at a sacrifice to capacity (i.e., wide versus narrow impeller--figure 4.10). A common practice has long been to recommend open or semi-open impellers wherever pumping fluids could clog the impeller--although not a major concern with irrigation water, this is a significant problem in drainage. However, recent tests have shown that well-designed, closed impellers will clog infrequently and maintain a much better efficiency life than open impellers when pumping abrasive fluids (Doolin, 1972). Such generalized comparisons should be used with caution since the ever increasing number of new designs has produced a wide range of performance characteristics and applications. Performance curves should be the primary resource in making pump selection for any installation.

Two additional aspects of rotodynamic pump operation are important to their application; *capacity regulation* and *priming*. Variability of capacity is not usually of concern for irrigation and drainage since the pump is ordinarily selected to match its head and discharge at maximum efficiency to field requirements (Chapter 5). However, if the pump is used in situations of variable demand, e.g. different crops or fluctuating drainage level, regulation of discharge can save on energy consumption. Unlike positive displacement devices, head may vary significantly with changes in the discharge of a rotodynamic pump. As Smeaton found in the 18th century, discharge, head, and power vary by definite proportions for small charges in pump speed or impeller diameter. These affinity laws can be used to estimate performance points other than those given by a curve such as figure 2.9. Replacing the constant impeller size curves in that figure with constant speed curves, it can be seen that increasing or decreasing the speed at a constant head will increase or decrease, respectively, the capacity. However, two interdependent changes will also result from such speed changes. Depending on the type pump, the power consumed may increase or decrease, thus providing additional savings or cost. Also, as in most mechanical devices, higher speeds will increase wear. When pumping abrasive fluids, such as most irrigation and drainage water, this wear can be quite severe. Walker (1972) states that doubling the speed of rotodynamic pumps can result in four times the wear.

As also indicated by the affinity laws, a change in impeller size will vary capacity. Except for permanent demand changes, disassembling the pump and exchanging or altering the impeller(s) is not usually practical. However, in propeller pumps, blades with adjustable pitch are available and in centrifugal and mixed flow pumps, adjustable diffusers or guide vanes can be utilized. These adjustable devices have the effect of changing impeller size and capacity by permitting a broader high-efficiency range (Rouse, 1950).

Capacity regulation can also be accomplished by throttling the discharge. (Throttling the suction line is not recommended since this decreases the NPSHA and thus increases the probability of cavitation.) This will increase the total head against which the pump must operate by increasing friction and therefore lower the discharge. Unlike most reciprocating pumps, this throttling will not cause excessive pressures within a rotodynamic pump. However, in some axial- and mixed-flow pumps, the accompanying power increase (see figure 4.8) may overheat the driver.

Of course, various schemes of by-passes, storage reservoirs, and parallel pumps can also be designed into the pump system to regulate flow. However, the pump manufacturer should be consulted on any major deviation from normal pump operation.

The second feature of rotodynamic pumps yet to be considered is their need to be primed. Unlike positive displacement pumps, when first started, they cannot displace air to create the pressure differential necessary to "suck" water. Also, since rotodynamic pumps utilize the water they lift to lubricate all or some of their rotating parts, running dry--even for just a few seconds--can cause excessive wear on wearing surfaces which can in turn cause significant efficiency losses.

Various methods are used to prime rotodynamic pumps, depending on pump type and application. They include:

(a) foot-valve and filler method,

(b) providing a dynamic suction head,

(c) removal of air from suction line and pump by air pump,

(d) self priming by recirculation chamber or auxilary positive displacement pump.

Where automatic operation of a pump is required, methods (b) and (d) are used. The use of a foot valve does not sufficiently insure against loss of the prime water and is often considered an unnecessary friction loss.

4.2.6 Applications for Irrigation and Drainage

Due to the wide range of head/capacity situations over which rotodynamic pumps can be used and the flexibility with which they can be combined to various prime movers, this subclass of water lifters has become the most popular for irrigation and drainage when available. At this point, regenerative pumps will again be excluded from consideration since their close clearances prohibit efficient use in liquids with abrasives--a common occurrence in irrigation and drainage. In such applications, regenerative pumps have about one-third the life of other rotodynamic pumps (Pillai, 1969 and Carter, 1949). They are better utilized for "clean," domestic water lifting. Multi-stage centrifugal pumps are better qualified to handle abrasive fluids in the high head--low discharge situations where regenerative pumps could normally be used.

Table 4.1 lists and describes some of the more commonly used irrigation and drainage installations for rotodynamic pumps. The selection of these installations is determined by the water source available and the type of pump and driver required or available. (The selection of pump and driver is discussed in Chapter 5.)

In all installations, care must be taken to stabilize the pump and driver to insure efficient transmission of power and to prevent damage due to movement and misalignment. Manufacturers' manuals should be consulted for proper installations. Numerous references

Table 4.1 Typical rotodynamic pump installations

A. RADIAL FLOW AND LOW N_s MIXED FLOW PUMPS

Position of shaft	Installation	Figure	Remarks
Horizontal	1) On shore with pipe suction line	2.1, 2.6	Usually for permanent installation on foundation; with suction head or lift.
	2) On shore with flexible suction line		Usually for portable use on frame.
	3) On ground surface over shallow well		Depth to water level limited by NPSHR.
	4) In pit over shallow well	4.11	Allows increase of NPSHA.
	5) On float or boat in water supply with pipe or flexible suction	4.12	Good for greatly fluctuating water level in pond, river, drainage ditch, etc.
	6) In combination with ejector	4.22	For shallow or deep wells.
Incline	7) On trailer, submersed in water supply	4.13	Can be run directly from tractor's PTO.
Vertical	8) Over well with pipe or flexible suction line		Same as for horizontal.
	9) In dry pit	4.14	Allows suction head to prime.
	10) Submersed volute on frame		Same as in dry pit, but open to water; long shaft or close-coupled.
	11) Lightweight, portable submersible	4.15	Close-coupled with submersible motor.
	12) Single stage, mixed flow bowl assembly	2.4	Uses diagonal impellers; commonly called *vertical turbine pump*.
	13) Multi-stage, mixed flow bowl assembly	4.17	Same as (12); driven from above via shaft or by submersible motor; for deep water sources where well is too narrow for vertical volute (down to 6 in. diameter); water or oil lubricated.
	14) Multi-stage, radial flow assembly	4.16	Used for deepest wells (up to thousands of feet); used with submersible electric or hydraulic motors; sizes down to 4 in. diameter.

B. AXIAL FLOW AND HIGH N_s MIXED FLOW PUMPS

Position of shaft	Installation	Figure	Remarks
Horizontal	1) In siphon arrangement	4.18a	Used in large pumping stations--not practical for small agricultural uses due to low efficiency and priming difficulties.
	2) At vertical wall of pit	4.18b	Self priming; for high discharges.
Incline	3) Fixed on shore		Good for installation on levee or canal bank.
	4) On portable frame on shore	4.19c	Allows for use at various heads and locations.
	5) On portable frame on boat	4.19b	Utilizes boat motor and propeller.
Vertical	6) Mounted in well		Only for shallow wells.
	7) Fixed on shore	4.20	Can be used with siphon, as shown, to decrease power consumption.
	8) On portable frame		Same as inclined (4) (5).

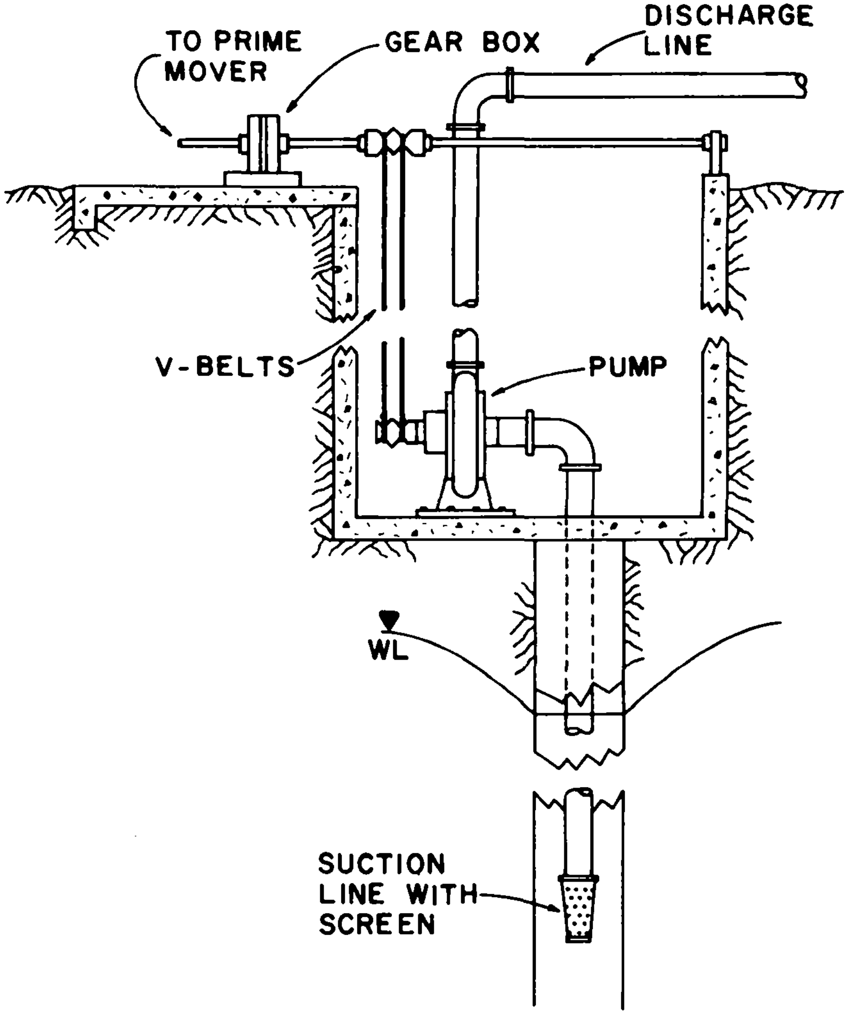


Figure 4.11 Horizontally-mounted volute pump in pit

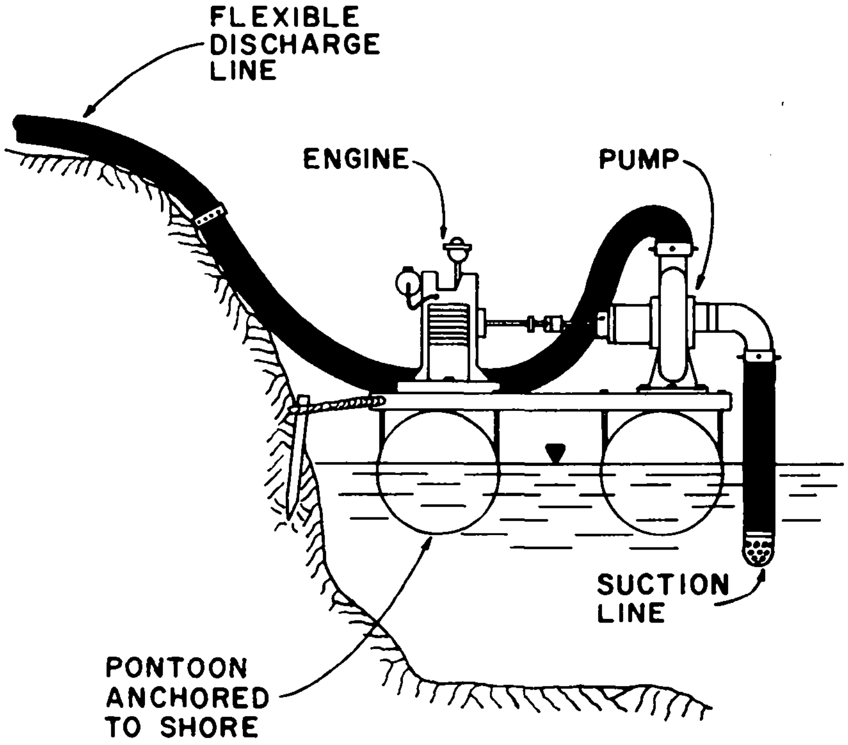


Figure 4.12 Pump and driver mounted on pontoon in water supply

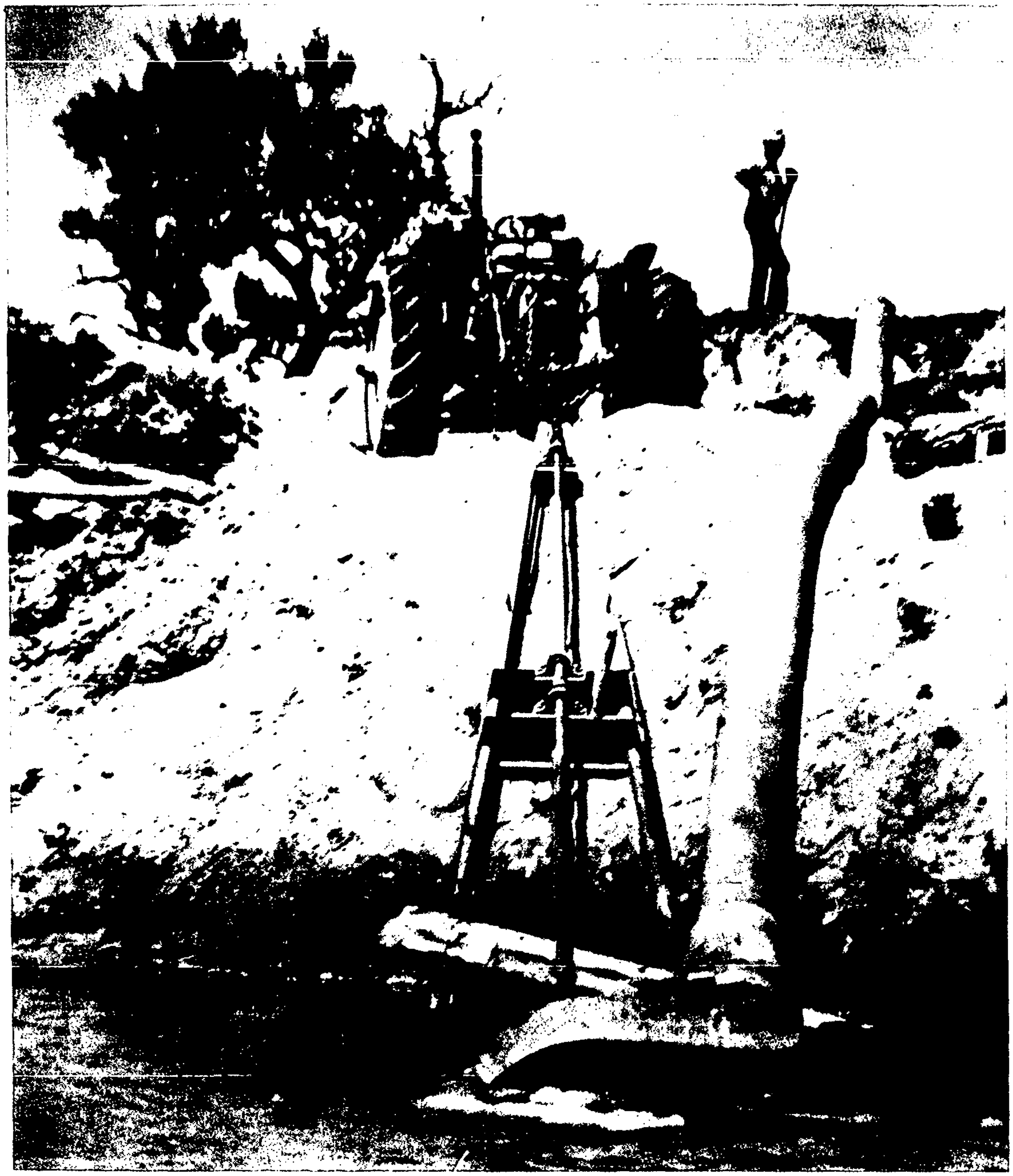


Figure 4.13 Centrifugal pump on portable trailer (Courtesy of Crisafulli Pump Co.)

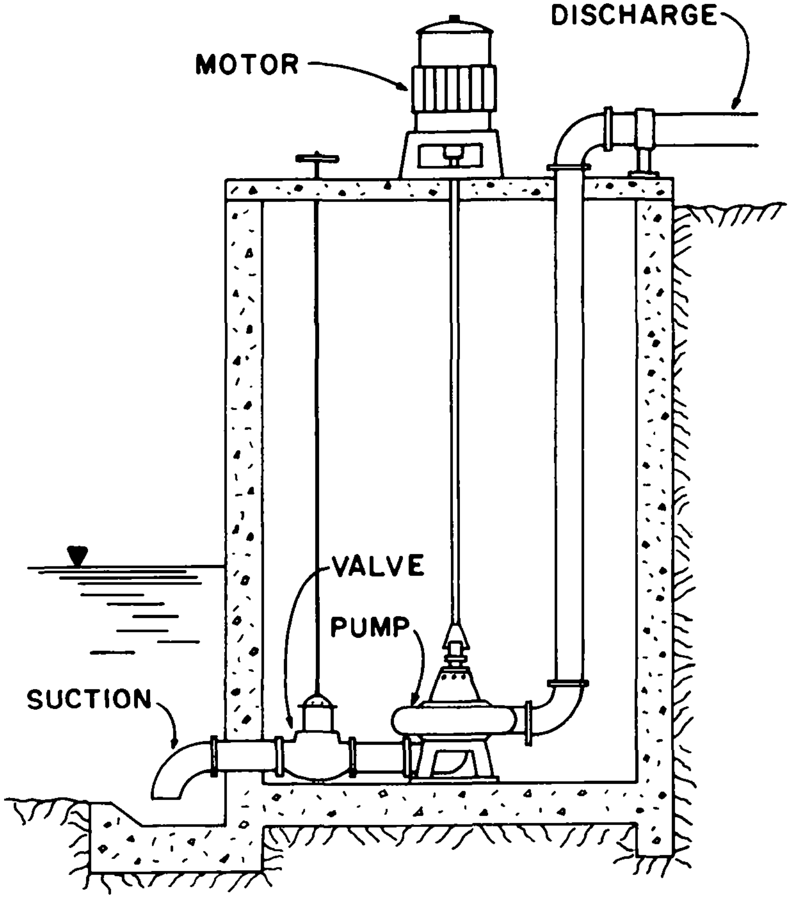


Figure 4.14 Vertical volute in dry pit

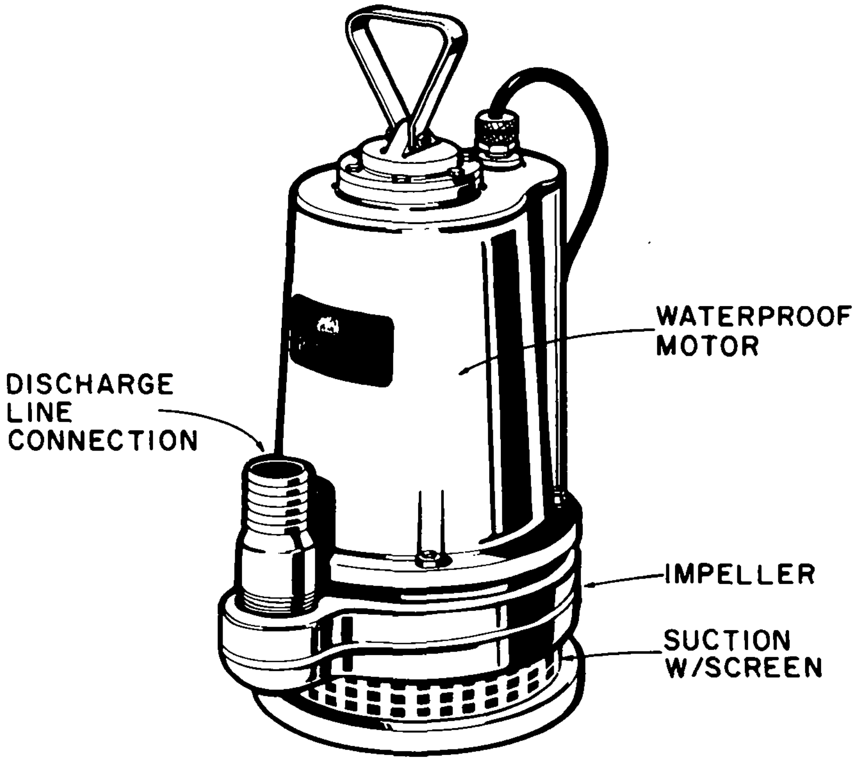


Figure 4.15 Submersible, portable volute pump (courtesy of Peabody Barnes Pump Co.)

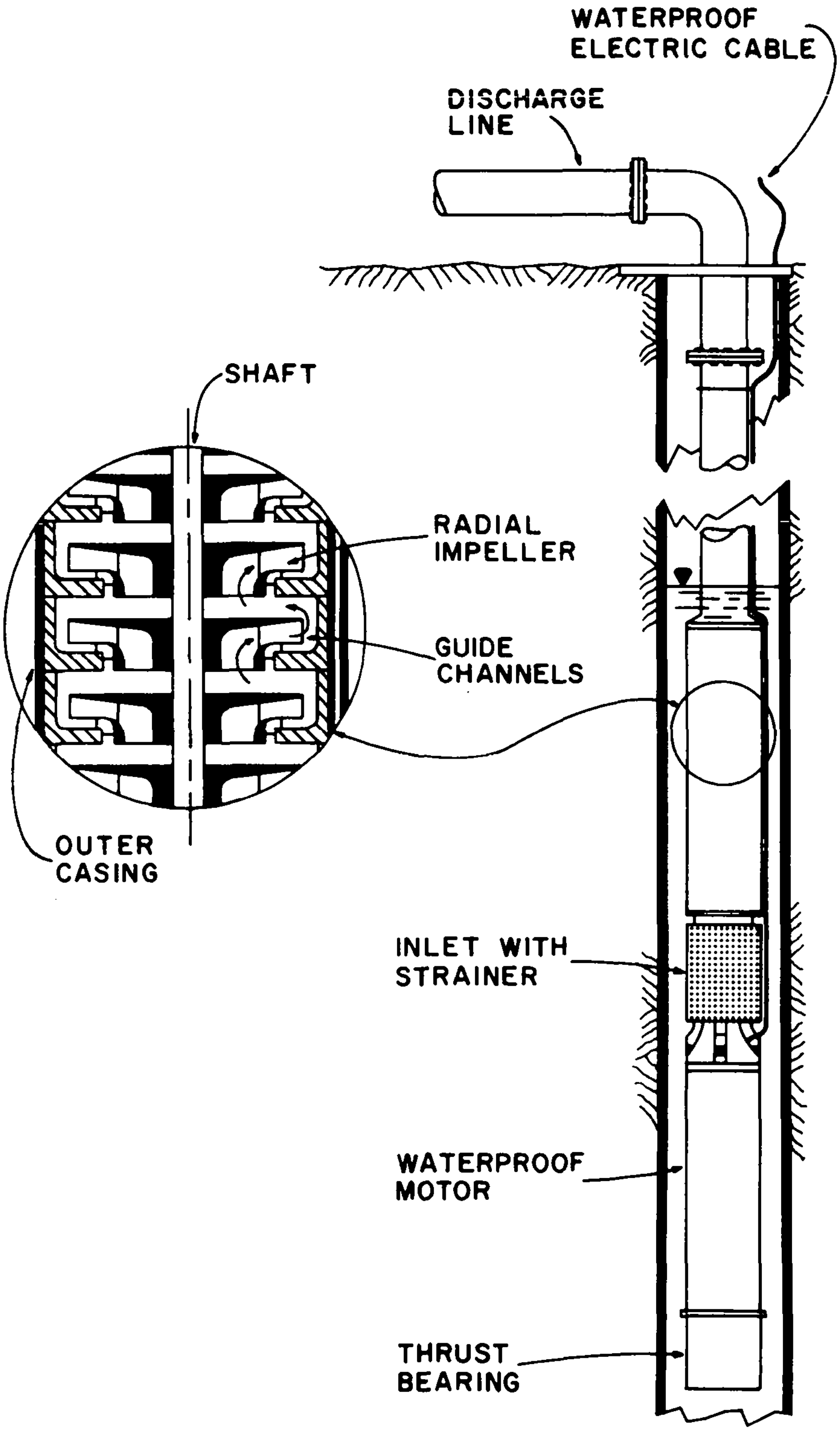


Figure 4.16 Radial-flow, vertically-mounted, "submersible" pump

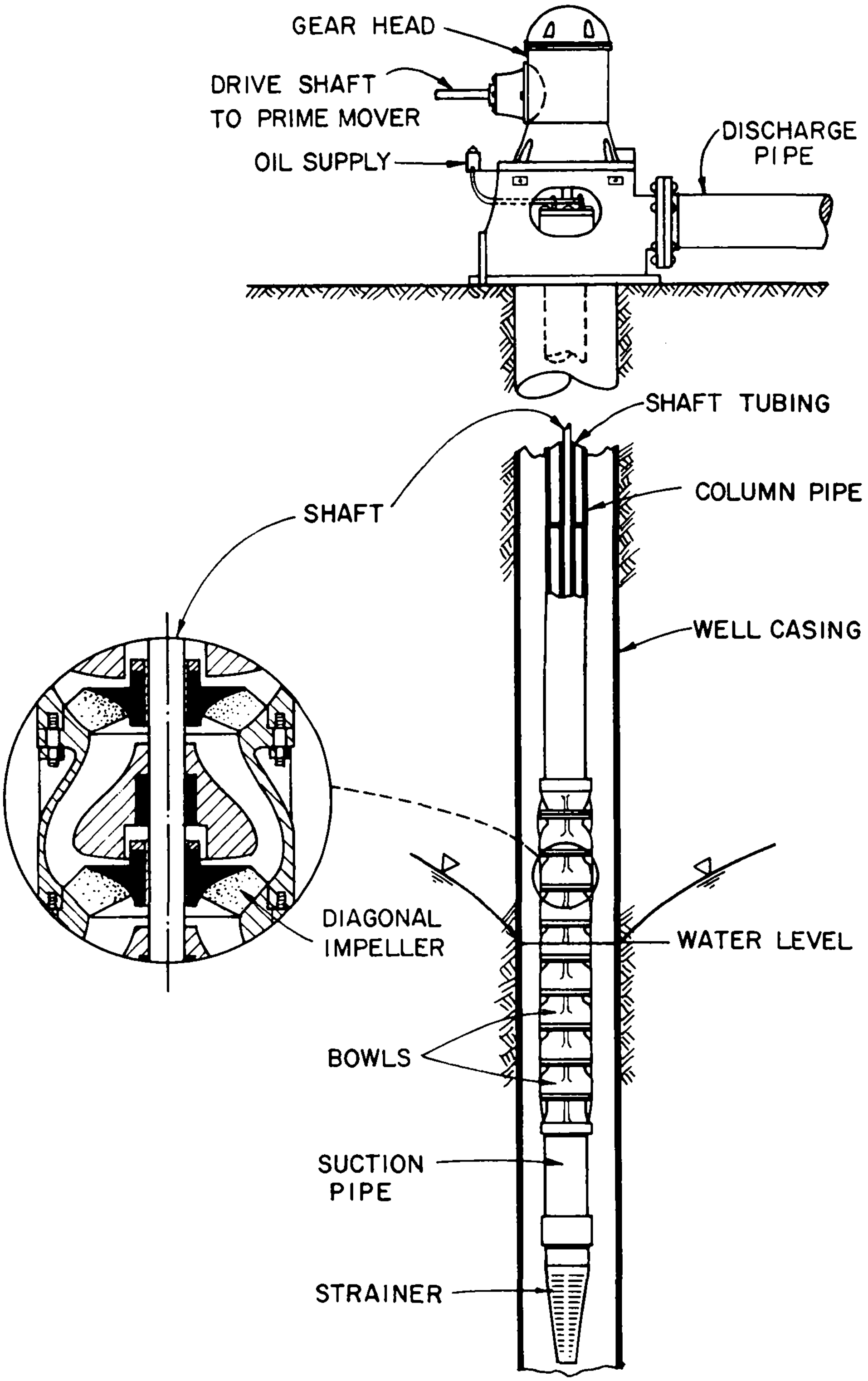


Figure 4.17 Mixed-flow, vertically-mounted, "turbine" pump

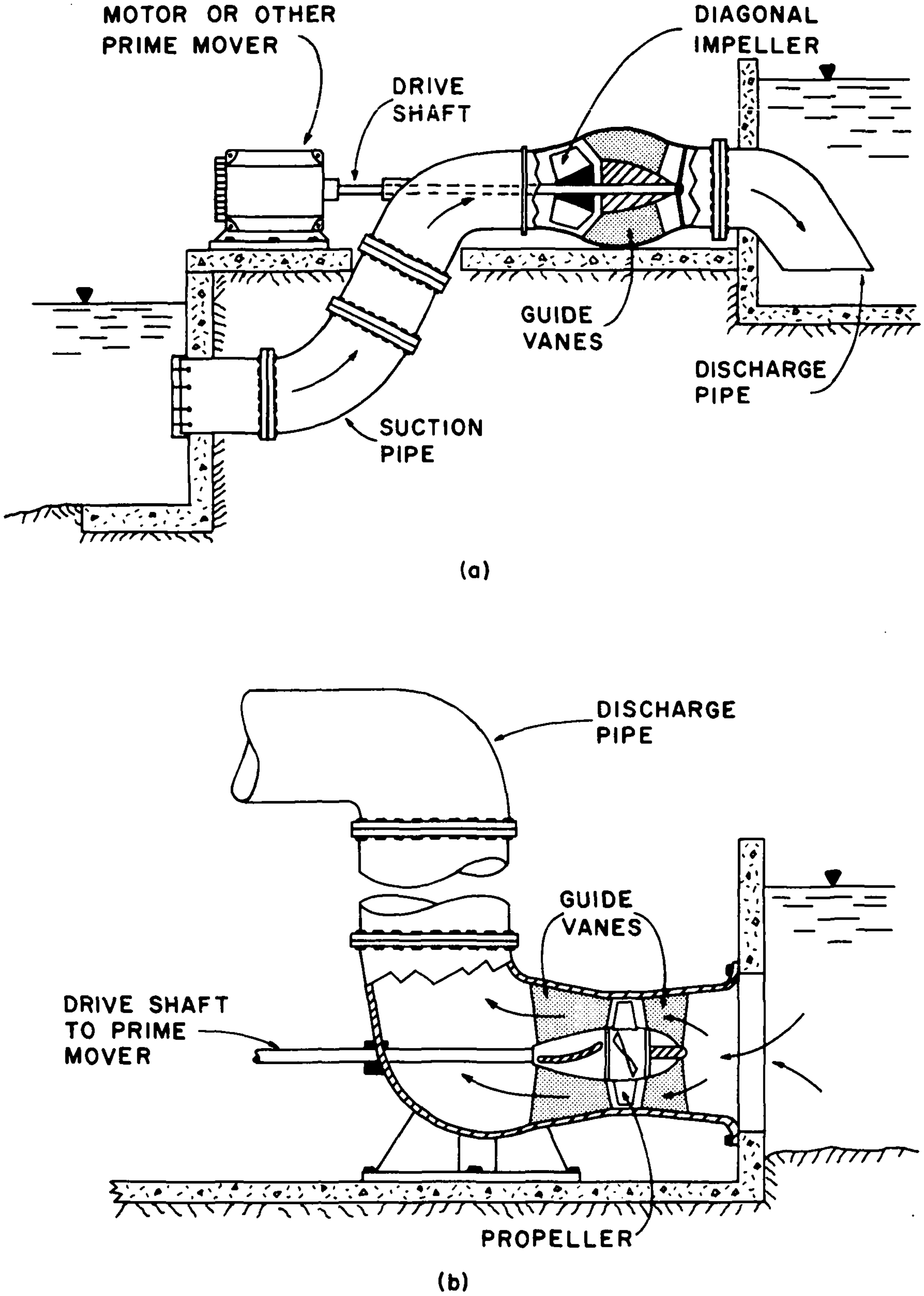


Figure 4.18 Horizontally-mounted, (a) mixed-flow pump in siphon arrangement, and (b) propeller

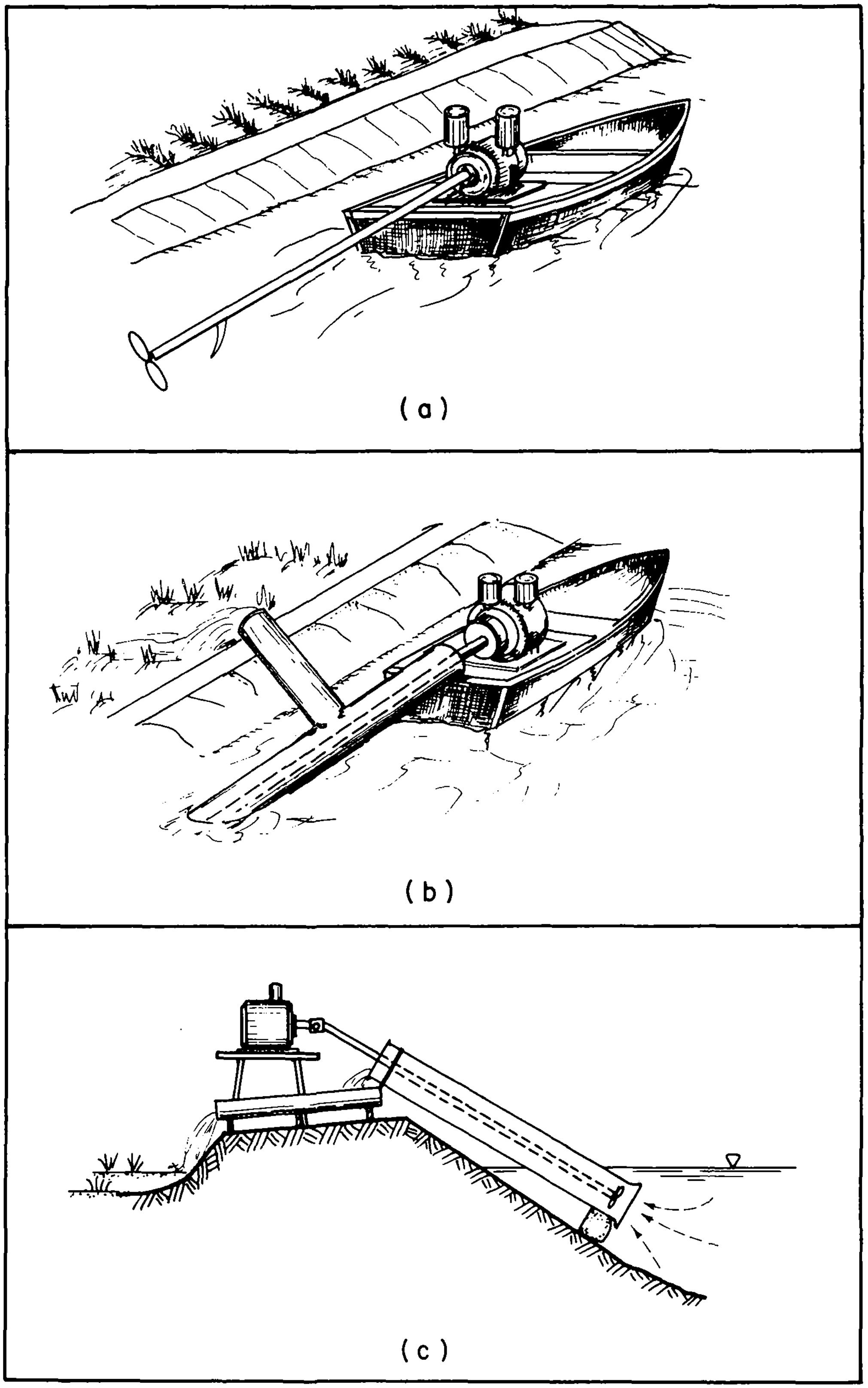
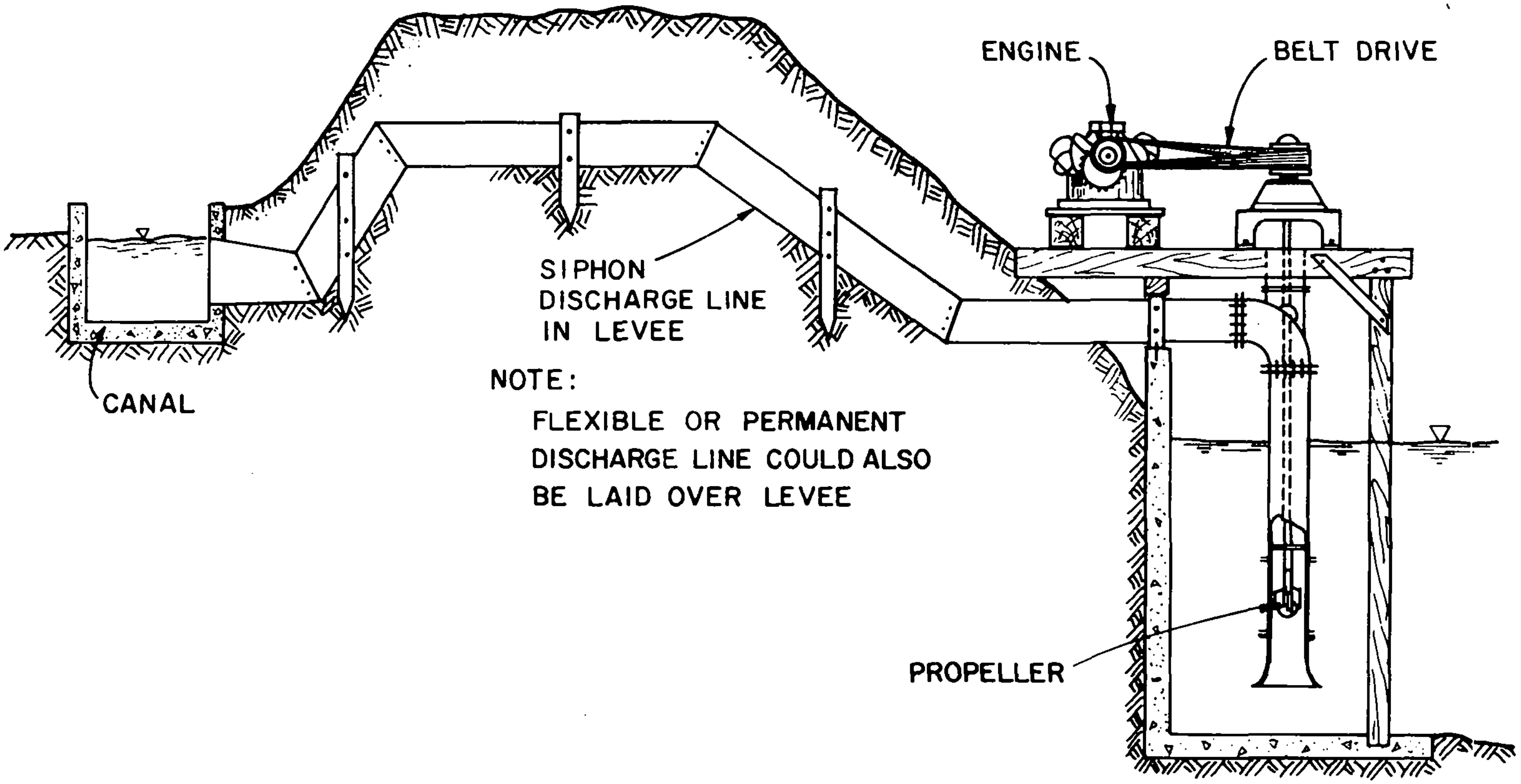


Figure 4.19 (a) Thai-style outboard engine and propeller used (b) for pumping from boat, and (c) from shore



NOTE:
FLEXIBLE OR PERMANENT DISCHARGE LINE COULD ALSO BE LAID OVER LEVEE

Figure 4.20 Vertically-mounted, axial-flow pump fixed on shore are also available which provide general installation guidelines. They include: Ahmad (1969), *E.E.U.A. Handbook #30* (1972), Finch (1948), Holland and Chapman (1966), *Hydraulic Institute Standards* (any edition), Jindal (1974), and Pillai (1969). A strong, level foundation is especially important to the support of a vertical turbine pump where the alignment of the long drive shaft is critical in maintaining efficient performance and preventing wear.

As with all machinery, moving parts of pumps require lubrication. In rotodynamic devices, this lubrication is usually accomplished in one of three ways, or combinations thereof. Some bearings, e.g., thrust bearings, are *grease-packed.* Surfaces between impellers and casings usually depend on the water being pumped to provide lubrication. In low-abrasive water, the shaft of a vertical "turbine"* pump may be left exposed to the water for bearing lubrication. However, where gritty water may wear or clog the bearings of a vertical turbine pump and in most other rotodynamic pumps, oil is utilized for lubrication of shafts. In the oil-lubricated, vertical turbine pump (figure 4.17), a shaft tubing surrounds the shaft and provides a key way for oil flow. Of course, this entire matter of long shaft lubrication has been eliminated with the development of electric and hydraulic driven "submersible"* pumps, because the motor of these submersibles is located in the well, close-coupled under the impellers. This also eliminates the need for complex bearings to support the shaft. However, while most multi-stage submersibles are limited to about 400 gpm, multi-stage vertical

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*Throughout this paper we will use the popular nomenclature for various specific pump applications to avoid confusion--see table 4.1.

turbine pumps can deliver flows in the 30,000 gpm range (Hicks and Edwards, 1971).

Manufacturers produce a wide range of basic rotodynamic pumps covering many specific head/discharge/application requirements. By modification of such variables as impeller size, number of stages, drive speed, etc., these basic designs can be made to fit any intermediate conditions. While the manufacture of the complex vertical turbine and submersible pumps is presently limited to several companies in industrial nations, volute and propeller pumps are easily manufactured by the basic industries (e.g. foundries) in developing countries (Ahmad, 1969). In fact, a 1961 SEATO thesis by Srisakdi Charmonman explains the design, construction, and performance of an axial-flow pump made quite simply by encasing the propeller of a Thai-style outboard boat motor (3½ - 7 hp.) with a cylinder. As illustrated in figure 4.19, this design permits dual use of the motor for both boat and pump motivation. This pump can be utilized with the anchored boat as a foundation (figure 4.19b) or dismounted and used on shore (figure 4.19c). This improvisation provides the simple low head, high discharge pump required for the irrigation and drainage of crops such as rice in lowland areas. Commercial units of this design are reported to be manufactured in Japan for about $300 (Bowers, 1975).

Initial costs of rotodynamic pumps vary greatly, depending on the type, size, power, materials of construction, and manufacturer. Many pumps also require numerous accessories and/or sophisticated foundations and installations. For exact prices of rotodynamic pumps and costs of installation, manufacturers' catalogs and/or well contractors must be consulted. However, as a rough guide, a buyer can expect to pay (for pump only) up to $500 for sizes under 1 hp, $100-500 per hp up to 10 hp, and $100-400 per hp above 10 hp, with cost per hp decreasing for increasing horsepower (based on 1974-75 U.S. manufacturers' catalogs of new pumps). Of course, used pumps can be obtained for less, depending on condition. Typical economic analyses of pump costs, including pump and driver prices, installation and operating costs, etc. are given in Chapter 5.

4.3 Jet Pumps

A *jet pump* is a device which uses the kinetic energy of one fluid (i.e., the driving fluid), rather than an impeller, to pump another fluid. Depending on their application, jet pumps are known by several names; *injector*, *jet heat exchanger*, *ejector*, and *eductor*. The first two utilize a gas (usually steam) to drive another gas or a liquid, while the latter two devices utilize a liquid (usually water) to drive another liquid or a gas (Engineering, 1968, and Kneass, 1903). The term, eductor, also applies to air-lift pumping (Chapter 3) which is a positive displacement method and should not be confused with the jet principle. Injectors and exchangers are primarily used in conjunction with boilers. Therefore, in irrigation and drainage applications, the use of a "jet pump" usually implies an ejector.

An ejector utilizes a driving pump* to force the driving water at a high pressure into a venturi tube or suction box. There it

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*This pump is usually a centrifugal device, however, recent developments are incorporating positive displacement pumps--see Walkden, 1967, p. 318-319.

entrains additional water to deliver a discharge of higher volume and lower pressure. This principle can be used in either of the two methods shown in figure 4.21. For ease of operation and installation in wells, the sequence of figure 4.21b is normally utilized in irrigation and drainage systems, although it is the design in figure 4.21a that is often used to add fertilizer to irrigation water. The arrangement of figure 4.21b can increase the capacity of a centrifugal pump, however, at the expense of total head and efficiency. Although ejector efficiencies rarely reach 40 percent, this is an effective way to increase the suction lift capability of a centrifugal pump. As mentioned in section 4.2, rotodynamic static suction lifts are limited (by NPSHR) to about 15-25 ft, so that for smaller depths, ejectors are of little advantage. However, if the suction lift is greater than allowed by the NPSHR and the pump cannot be conveniently located nearer to the water source, an ejector can effectively increase the suction lift--usually up to a limit of about 120 ft. Units are available in sizes capable of handling up to 10,000 gpm (Eier and Schoenleber, 1942). In the case of a well supply, this also allows all moving parts to remain above ground for easy maintenance. Figure 4.22 illustrates the common arrangement of ejectors for shallow and deep wells.

Because the centrifugal-jet arrangement of figure 4.21a was not available commercially for irrigation and agricultural drainage applications, work was undertaken at the International Rice Research Institute (IRRI) to develop such a design (Samuel, 1975). This sequence utilizes the entire discharge of the centrifugal pump to lift an additional quantity of water through the ejector. Such systems

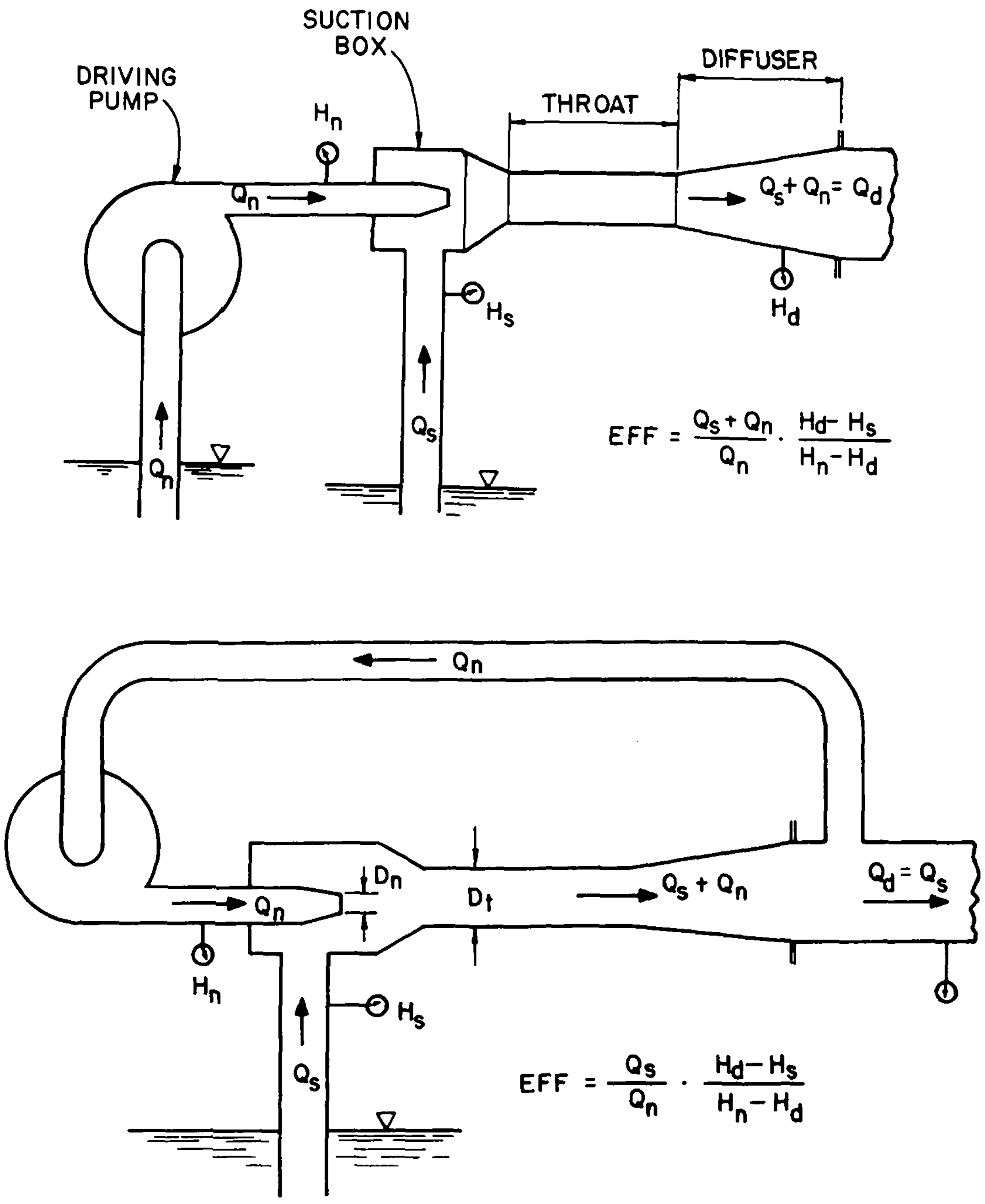

Figure 4.21 Two ejector arrangements: (a) $Q_d = Q_s + Q_n$, (b) $Q_d = Q_s$, with Q_n recycled

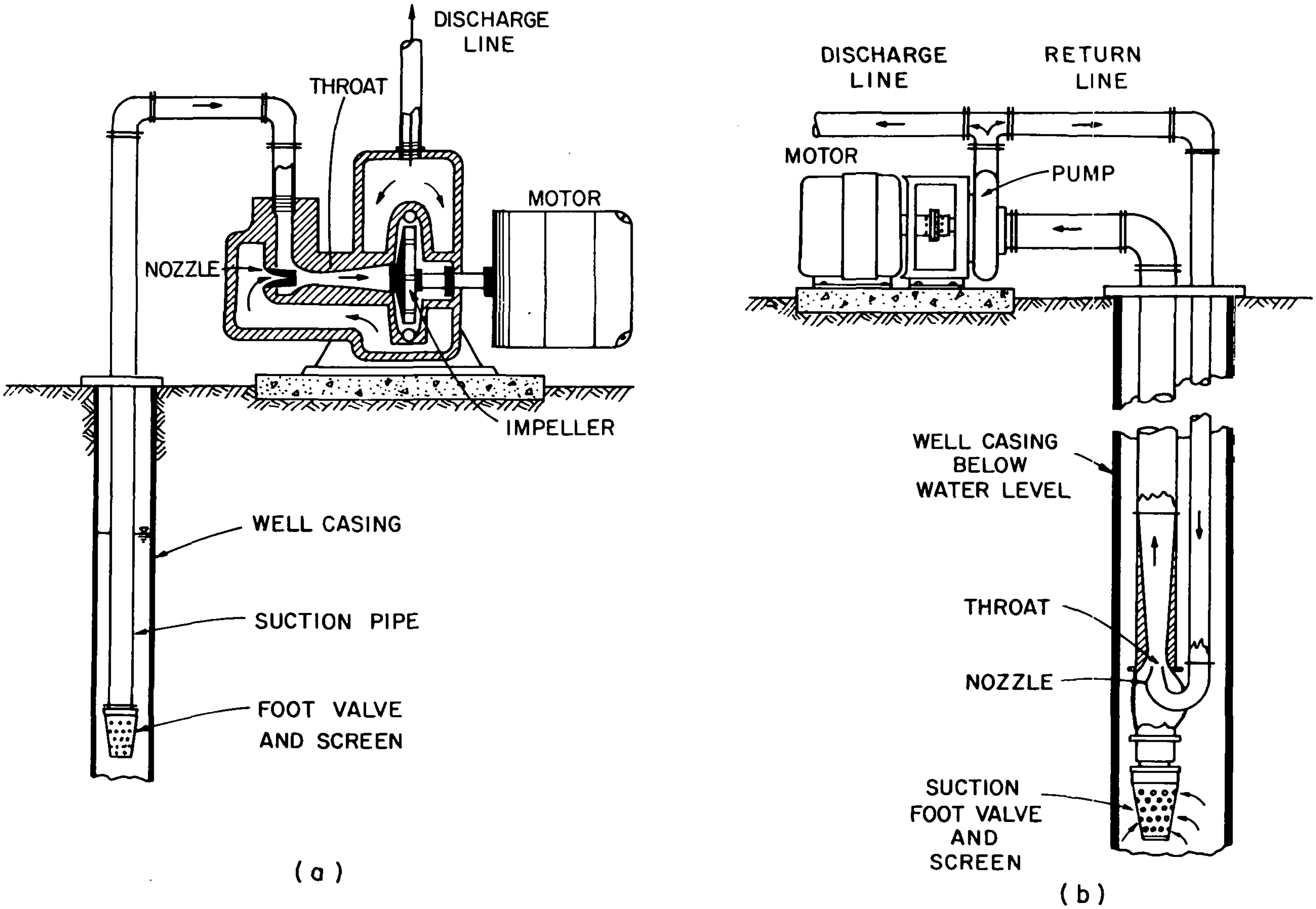

Figure 4.22 Jet pumps for (a) shallow well with ejector/impeller combination unit, (b) deep well with ejector in the well

were primarily used to lift sewage or other fluids which were not desirable to be passed through the pump. In these cases, a clear driving fluid was drawn from another source. Now, the IRRI design makes this system applicable for low lift agricultural pumping situations, e.g. between canals and paddies.

Efficiency is the characteristic of primary concern for an ejector. Of course, its size (i.e., diameter) must be matched to the driving pump by remembering that smaller flow areas increase velocities, which in turn, increase friction. However, since an ejector does not actually pump water, i.e., it does not have a prime mover power input, but rather transfers velocity head into increased discharge (momentum law), the efficiency at which it performs this transformation is the major characteristic of the ejector. This efficiency is primarily a function of the following dimensionless parameters:

$$\text{Area ratio} = A_r = \frac{A_n}{A_t} = \frac{\text{nozzle area}}{\text{throat area}}$$

$$\text{Discharge ratio} = Q_r = \frac{Q_s}{Q_n} = \frac{\text{suction discharge}}{\text{nozzle discharge}} \text{ (figure 4.21b)}$$

$$\text{or} \quad = \frac{Q_d}{Q_n} = \frac{Q_s+Q_n}{Q_n} = \frac{\text{total discharge}}{\text{nozzle discharge}} \text{ (figure 4.21a)}$$

$$\text{Head ratio} = H_r = \frac{H_d-H_s}{H_n-H_d} = \frac{\text{net jet pump head}}{\text{net driving head}}$$

Although efficiency can be expressed using any of these ratios, or combinations thereof, the most common expression for efficiency is work in over work out, or Q_rH_r. As can be seen, for the arrangement of figure 4.21a,

$$\text{Eff} = \frac{Q_s}{Q_n} \frac{H_d-H_s}{H_n-H_d} ,$$

while for figure 4.21b,

$$\text{Eff} = \frac{Q_s+Q_n}{Q_n} \frac{H_d-H_s}{H_n-H_d} .$$

The higher efficiency in the second case reflects the greater overall discharge which is produced with the same head ratio.

By adjusting the three variables, head, discharge, and flow areas, different performance curves can be produced. Figure 4.23 illustrates a typical set of H-Q curves for an ejector of constant A_r and size as it performs with variable net driving head (H_n-H_d) and nozzle discharge (Q_n). Note that in regard to such performance curves, jet pumps follow the same affinity laws as rotodynamic pumps for head and discharge. Instead of using constant area ratios, some performance curves use diameter ratios, D_r. Figure 4.24 shows the interrelationship of efficiency, H_r and Q_r as a function of D_r. From figure 4.24a, it can be seen that higher head ratios are obtainable with lower size ratios. Also, the locus of maximum efficiencies in figure 4.24b shows that the geometrical proportions of an ejector (as reflected by D_r) greatly influence efficiency. Of course, changes in ejector size (with constant A_r) or length of piping within the system will alter the efficiency, primarily as a function of friction (Stepanoff, 1948).

Priming of a centrifugal-jet pump system is necessary to begin operation. This is usually accomplished by the use of a return feed storage tank, supplied by the system during the previous operation.

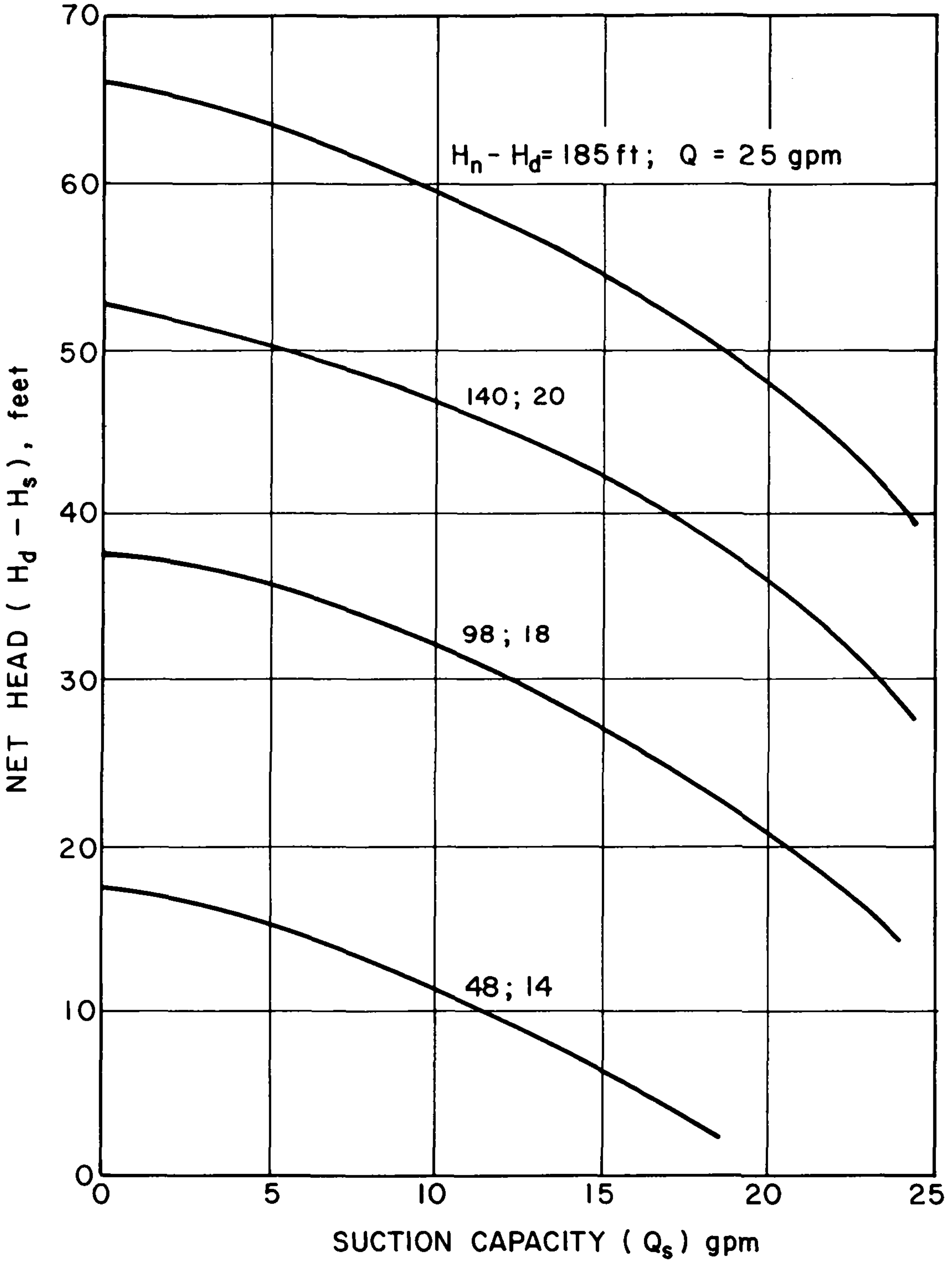

Figure 4.23 Typical jet pump performance curves

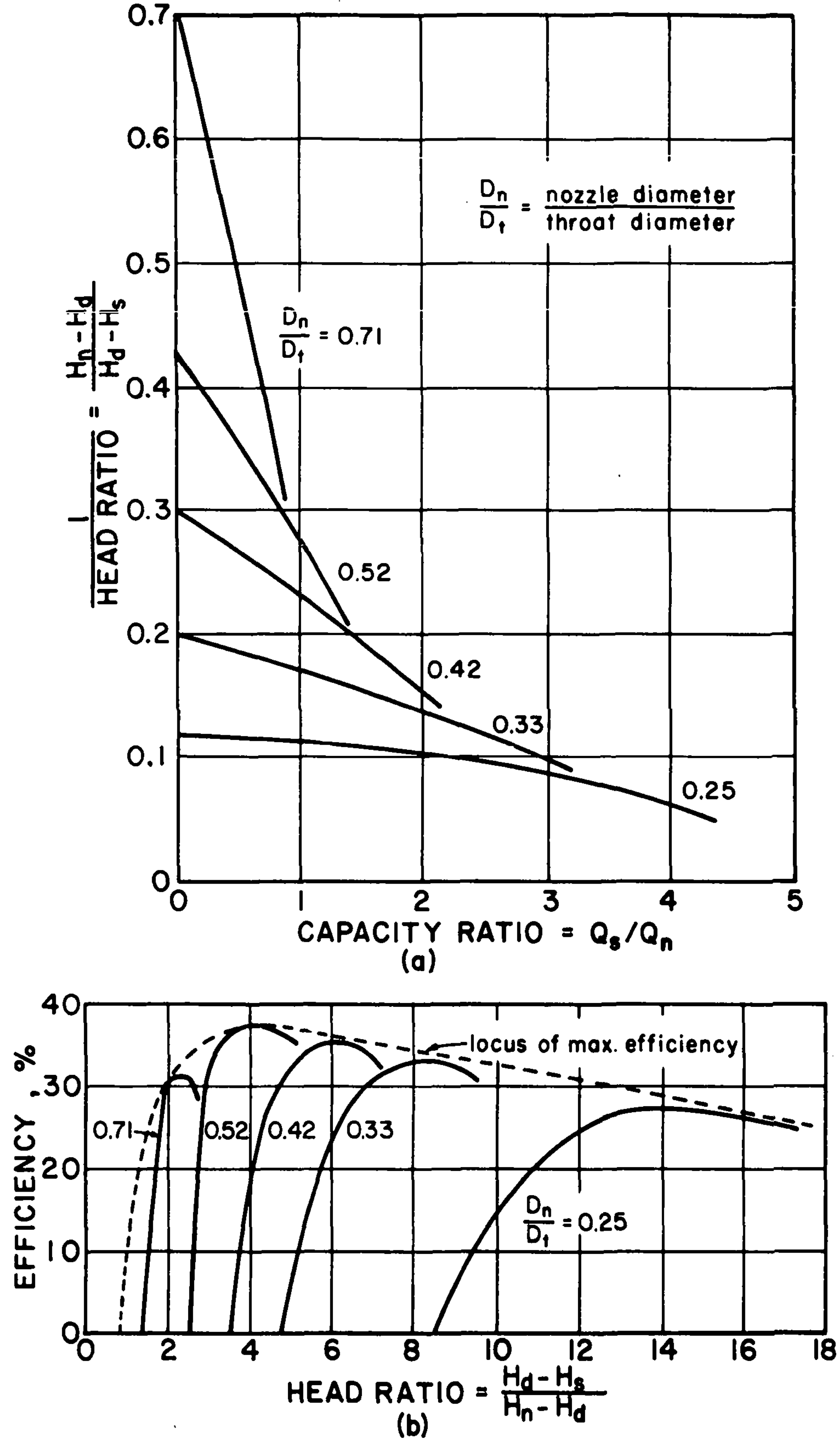

Figure 4.24 Size ratio influence on jet performance (adapted from Engineering, 1968)

However, another application of an ejector (i.e., jet nozzle) is to remove the air and thus prime a rotodynamic pump. This application is usable only where there is an available source of compressed air or steam, or water at a higher head (Pumping Manual, 1964).

These general characteristics and the performance curve of a specific ejector should be considered when selecting a jet pump for a particular application. Initial costs of ejectors vary with size and construction, however, the nozzle/throat assemblies alone (i.e., not including driving pump, pipes, fittings, and accessories) are usually in the $15 to $75 range.

Chapter 5

Applications

5.1 Introduction

In the preceding chapters, the operation and construction of water lifters and pumps have been discussed with only illustrative mention of the various prime movers that can be used to drive them. The following section will review briefly the operation, construction, and cost of the driving devices which can be used to power water lifters and some of the common methods of transmitting this power (i.e., gears, belts, shafts, etc.). In addition, the criteria for matching prime mover and water lifter to a given installation will be considered in light of availability, water requirements, and cost analyses.

5.2 Prime Movers

Although many water lifters and pumps are commonly described and utilized with only one or two prime movers, this section will illustrate how most water lifters can be adapted to a variety of drivers. With the current world energy situation, previously uneconomical pump/driver combinations are becoming competitive with traditional applications.

5.2.1 Manual

Manual power is an easily transported prime mover which can be used to provide a variety of motions, e.g., circular, reciprocating, twisting, etc. One of the major benefits of utilizing manual power in developing countries is that it helps to alleviate the high unemployment and underemployment rates in these areas. Because human power can be utilized to perform other tasks (e.g., seeding, cultivating, etc.), the cost of maintaining manual power for water lifting can be shared among several duties. When labor must be employed to operate a water lifter, the prime mover cost will be the wages and/or benefits paid to the laborer. These wages vary widely depending on the economic situation in a specific locale. In some developing areas, \$.10/hr or \$2.40 plus food per month is not uncommon (Molenaar, 1956), but may range up to a few (i.e., 1-2) dollars per hour. When wages include food, or family members are utilized, the cost of food must be considered. Allison (1975) reports that in a season requiring 120 man-days of water-lifting labor, 30 kg of rice were eaten by the labor, which, at \$.20/kg, cost \$6.00.

As mentioned in Chapter 2, prime movers have an efficiency just like water lifters, i.e.,

$$\mathrm{Eff}_{\mathrm{pm}} = \frac{\text{Work out}}{\text{Work in}} \quad .$$

Of course, the efficiency of individual humans varies with their physical condition and environment, however, a general approximation is that humans can convert 20 percent of the caloric potential of food energy into usable work (Allison, 1975).

Physical condition is also a factor which makes manual labor a variable power source. If the labor being depended upon to drive a water lifter is tired from previous work or is sick, his output will decrease or be nonexistent. Even if in good condition when starting his water lifting duty, he will gradually tire with continued work. This decline in manual output is often relieved somewhat by utilizing two or more shifts of operators, usually in one or two hour shifts. More exact physiological information can be applied to specific body movements, however, available literature relating to water lifting reports that a grown man is capable of about 0.06 - 0.08 hp (or 2000 - 2700 ft-lb/min) of output energy over a sustained period, i.e., about 5 hours, not including rest periods (Allison, 1975 and Starr, 1971).

Human power also varies depending on the type of motion performed. More power can be obtained from leg motion than by the arms. During short time periods (10-15 minutes), the legs can develop about 0.25 hp while the arms can provide only about 0.10 hp (Mengin, 1976). Of course, a task requiring movement of the entire body (i.e., arms, legs, torso) would normally be expected to require more energy than one needing only arm motion. Therefore to conserve human energy, manual driving devices should be designed to minimize body movement.

Several adaptions and additions to basic water lifter designs have been utilized to also reduce energy output per each motion. The doon and counterpoise lift (see 3.2) with counterweights to reduce lifted loads are two examples of such designs.

A recent development by Tim Journey (formerly with UNICEF in Bangledesh) has produced another energy conserving device which could be used with several reciprocating water lifters. However, Journey has specifically applied it to the manual piston pump. An overhead, horizontal bar has the pump connecting rod attached to one end and a pendulum to the other end. The pendulum can simply be a vertical pole with a sand bag attached to the bottom. For heads between 10 and 17 ft, a horizontal push on the pendulum of about 15 to 22 lbs is needed to maintain the pendulum swinging, which then utilizes its weight to conserve the manual energy applied to it--see Allison, 1975.

Drs. Sant Garg and Radhey Lal have developed a system by which manual power can be used to drive a centrifugal pump--a water lifter previously restricted to high speed drivers. By means of a 4-bar linkage (called a "crank and rocker mechanism"), the reciprocating motion of two men is converted into a rotary motion. Then, a gear train of six spur gears, with an overall gear ratio of 1 to 120, increases the first driving gear's 10-20 rpm to a final 1200-2400 rpm which is usable for a centrifugal pump. For a range of lifts between 3.3 ft to 7.5 ft, the small centrifugal used supplied from 330 to 25 cfh, respectively. The use of worm gears and/or fewer gears with higher ratios to reduce friction are among the recommendations made to increase efficiency. (A detailed description of this work is given in a 1967 thesis by Garg.)

Other such devices can be concocted to make manual power applicable to fit several water lifters. For example, by using the pedal, chain, and rear axle of a bicycle, rotary leg-power can be applied to any of the rotary water lifters. A discarded bicycle can be permanently fixed into the pumping system, or a bicycle, still used for transportation, can be fitted with a stand and treadmill type apparatus for mounting when needed to pump water. If, in addition, a gear train (such as used by Garg) is included, the pedaling action can supply sufficient rpm and power to drive a centrifugal or rotary pump.

Table 5.1 outlines the basic motions which can be provided by manual power and some of the typical water lifter/transmission combinations with which they can be utilized.

Table 5.1 Manual power applications

Performed with	Transmission	Water lifter	Remarks
	A. Reciprocating motions		
arms and/or upper torso	rope (may also include pulleys, etc.)	bucket	figure 3.1
	rope	swing basket	figure 3.9; may require some leg movement; for 2 persons
	rope	water balance	figure 3.11; can also operate with one person and counterweight
	rope and pole	counterpoise lift	figure 3.7
	rope and pole	shovel	figure 3.10; may require some leg movement
	handle	gutter	figure 3.12a
	handle	diaphragm pump	figures 3.28 and 3.30
	handle and connecting rod	piston pump	figure 3.22; can also incorporate counterweight or spring return devices
	crank and rocker mechanism, gear train	centrifugal pump	see Garg (1967)
legs and lower torso	connecting rod, foot pedal and return device (e.g., spring or counterweight)	piston pump	see Schioler (1975), p. 10
	pedal and spring return	diaphragm pump	adaptation of figure 3.30
	pedal	air diaplacement pump	figure 3.57
	rocking foot rests	bellows pump	figure 3.29
	direct	doons	figures 3.14a and 3.15
	walkway	picottah	figure 3.8
	walkway	gutters	figure 3.12b
	walkway	picottah-style doon	figure 3.14b
	B. Circular motions		
arms and/or upper torso	crank	screw	figure 3.46
	crank	water ladder	figure 3.36; small capacities
	crank and small gear train	rotary	see Eubanks (1971), and Hadeckel (1939)
	lever	semi-rotary	figure 3.52
	crank and windlass	bucket	figure 3.5a
	crank and shaft	chain pump	figure 3.37
	crank and cam	piston pump	utilizes eccentric type gearing similar to figure 3.21
legs and lower torso	horizontal axis treadmill or pedals (on lifter or separate with connecting shaft)*	paddle wheel noria Persian wheel tympanum	single unit (i.e., lifter and mill) cut transmission losses; see Schioler (1975) pp. 5-6; for standing support, require arm rest as in figure 3.34; pedaling usually done in sitting position
	horizontal axis treadmill or pedals connected via shaft	screw water ladder chain pump	see figure 3.47b; as above
	horizontal axis treadmill and windlass	rope and bucket	figure 3.6a; needs human ability to turn and reverse rotation
	horizontal axis treadmill (or pedals) and cam	piston pump	as in eccentric gear in figure 3.21
	horizontal axis pedals and gear train	centrifugal pump	similar to Garg's (1967) device

*Vertical axis mills and pedals can be used, but require pinion gears to convert to vertical rotation.

5.2.2 Animal

Like manual power, animals provide a relatively mobile source of driving energy which can be utilized for several duties, e.g., plowing, transportation, water lifting. Thus, if an animal can be used for tasks other than just water lifting, the price and maintenance costs of that animal can be "time-shared" by each task for economic purposes.

Although draft animals constitute a common and vital source of power in many developing countries, their upkeep can be particularly difficult in areas where water is scarce, rainfall is variable, or livestock disease is common (Merrill, W., 1976). If an operator does not want to, or cannot, provide for the care and feeding of an animal, or he only needs the animal(s) for a short period of time, he can rent or lease the animals. In this case his prime movers cost for water lifting will be the rent (time-shared if used for other duties). However, when an operator owns his own animal(s), he will have an initial purchase cost plus maintenance. Initial costs will vary greatly depending on the type, size, and condition of the animal, and the geographic area. For the purpose of establishing a relative cost comparison (and for later cost analyses), by adjusting Molenaar's (1956) costs, a single bullock could cost about $100-150 and be expected to have a 10-year usable life. He also allots about $.05 per bullock for feed cost per each hour of utilization. This feed cost can also vary considerably depending on the method of farm operation. In some traditional systems where various fields are allowed to lay fallow for given time periods, the grass cover of these fields can often supply sufficient feed requirements. However, it may be necessary to supplement this grazing with grain, grain by-products, and/or foods not used for human consumption. In areas where such fallow land is not available (with modern technology and high demands for tillable land, this is often the case), an opportunity cost to allow land for grazing, feed, and shelter must be attributed toward maintenance of animals (Merrill, W., 1976). Of course, the cost of any manual labor which must be employed or allotted (i.e., family member) to maintain and drive the animal(s) must also be considered when making an economic analysis of using animal power (see section 5.3). Svendsen reports that the AgBank's* economic information indicates that, in many developing areas, animal power is cheaper than motorized units--particularly in light of the current world energy situation. Non-dependence on imported fuels and spare parts is another factor making animal power more practical for developing farm areas.

Animals, like humans, vary in their ability to convert food energy into usable work depending on size, condition, and species. However, in general, they are about the same, or slightly higher, in this conversion efficiency as humans, i.e., 20-25 percent (Lewis, 1976). Likewise, depending on the individual animal, usable power from animals can be expected to be about 0.6 hp (Merrill, W., 1976). Starr (1971) reports more specifically that a horse will develop about 0.7 hp, and an ox can provide about 0.3 hp. Tests at the Indian Agricultural Institute in Pusa have shown that the average size bullock is capable of providing 120 lbs of sustained drawbar pull, while a camel is capable of about twice that (Molenaar, 1956).

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*The AgBank is a common term for the Agricultural Development Bank of Afghanistan which is funded by a branch of the World Bank.

Such power capacities, plus the ability of an animal to work in a given situation (i.e., size, climatic conditions, training necessary), must be considered when matching animal power to a specific water lifting device. Animals are usually allowed to work in 3 hour shifts since, like humans, they tire and produce less work.

Table 5.2 suggests some of the typical water lifting applications for animal power, including common transmissions. In general, animals are limited in such applications to pulling with a harness or pushing with their feet by means of a treadmill. However, a wide variety of mechanical systems to connect this power to water lifters are utilized. Traditional wooden and/or metal circular sweeps are arranged so that the animal(s) walks either around the entire lifter/sweep combination, as in figure 3.39a, or just around the sweep which is connected to the water lifter by a shaft and gears (figure 3.42) or ropes (chains) and pulleys (figure 3.3). Where available, scrap materials from old machinery and vehicles are often utilized to provide more efficient transmission systems. The AgBank, for example, is marketing a Persian wheel, partially constructed of old truck differentials (Svendsen, 1975). Schioler makes one additional suggestion for improving two-animal sweeps. When two animals are harnessed side-by-side and connected to a single sweep arm, the outside animal must walk faster than the inner one, thus they tend to impede each other. If, however, the two animals are harnessed individually to two separate arms placed diametrically across the sweep, they will not interfere with each other and can walk at the same pace--see Schioler (1975), p. 22.

Table 5.2 Animal power applications

Motion of animal	Transmission	Water lifter	Remarks
A. Reciprocating	rope and roller	mot	figure 3.2; this requires wasting energy on a non-lifting return trip
B. Circular	sweep, rope, pulleys	two-bucket lift	figure 3.3; method to convert circular motion to reciprocating action
	sweep connected to lifter by gears and shaft (i.e., animals walk only around sweep and must go over or under shaft)	paddle wheel tympanum Persian wheel noria water ladder chain pump screw centrifugal pump	figure 3.42 shows this arrangement with a noria; required where sweep tow path cannot surround water lifter, e.g., at shore of lake, canal, etc.; use of high ratio gear train can allow use with centrifugal pump
	sweep directly connected to lifter (i.e., sweep gears mesh directly with lifter and animal walks around sweep and lifter)	paddle wheel tympanum Persian wheel noria chain pump	figure 3.39a shows this system with a Persian wheel; elimination of shaft and gears, as above, cuts transmission losses
	horizontal axis treadmill connected by shaft and/or gear(s) to lifter	paddle wheel tympanum Persian wheel noria chain pump water ladder screw	similar to arrangement of human treadmill in figure 3.6a; see donkey-wheel in Schioler (1975) p. 14; normally limited to smaller animals

5.2.3 Natural

"Natural" prime movers are the forces of nature which, without being converted to a different form, can provide energy to drive a water lifter, i.e., as opposed to mechanical drivers (see section 5.2.4) which require the consumption and/or conversion of combustible fuels or electricity. Except for possibly having to pay a "users right" for some water and geothermal sources, the natural forces of wind, water, sun, and geothermal heat provide free forms of energy. This can allow applicable water lifters to operate with relatively low running costs.

5.2.3.1 Wind

Windmills are currently in the upward stage of another, in a long series, of rise and fall cycles of popularity. As mentioned in section 1.3, this present increase in usage is due primarily to the existing world energy situation. Although many designs have been developed throughout the ages, only a few basic ones are still in use. However, many major improvements have been developed, primarily to make the output power usable for electricity generation.

One of the simplest and oldest windmills is of the type shown in figure 5.1. Normally, it is constructed by placing 8-12 poles (often bamboo) radially into a hardwood axle and fastening wire or rope between the outer tips of the poles. Cloth is then attached between the pole spokes to form a wheel of sails, usually about 17 ft in diameter. The sails are usually attached so that they can be furled about the poles when not in use or in high, damaging winds. Most "sail" windmills are permanently fixed to face into the prevailing wind direction as the one in figure 5.1. However, a rotating mount,

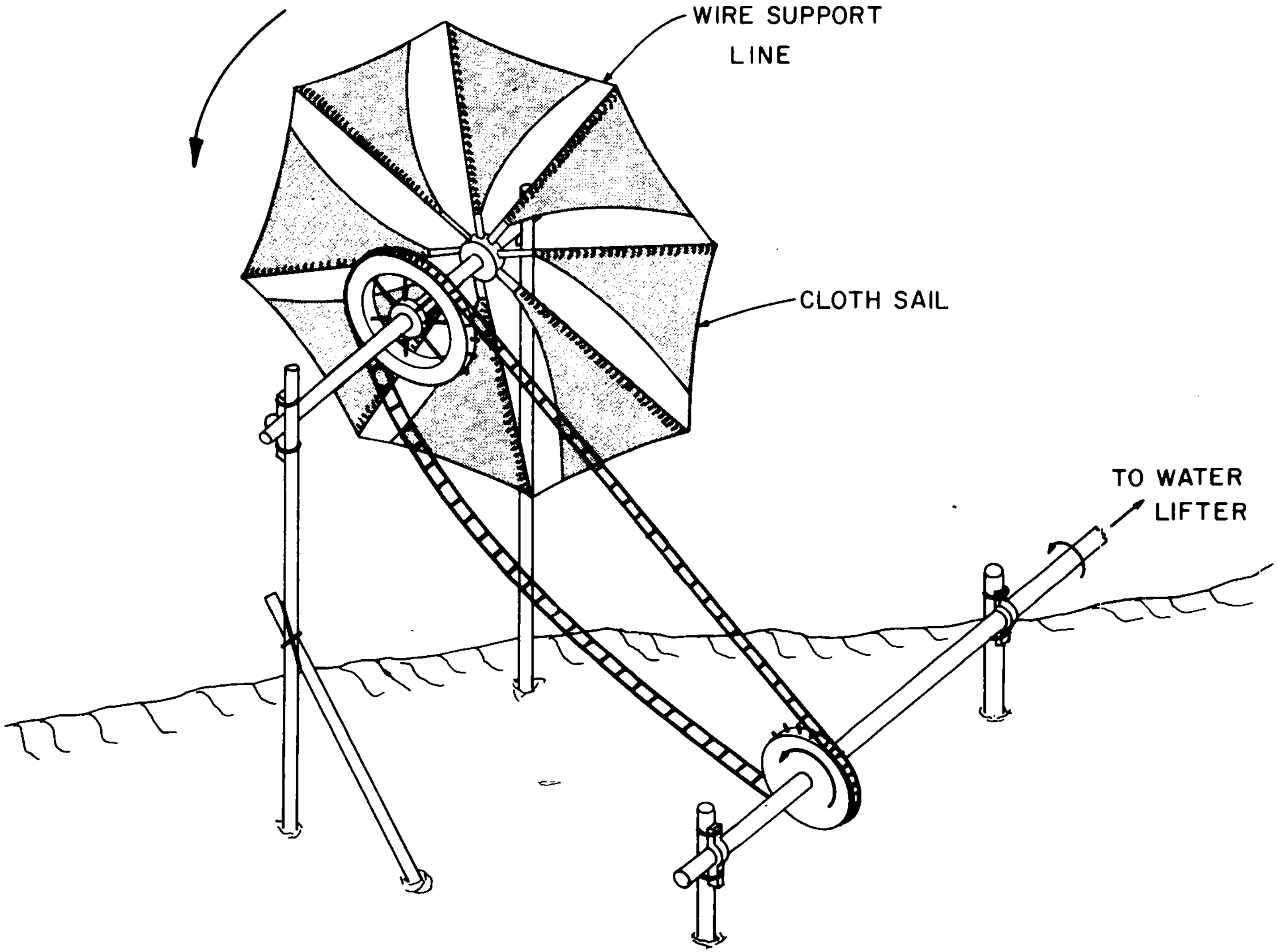


Figure 5.1 Sail type windmill with chain drive

similar to those in designs to be discussed later, can be adapted to this type windmill to make it functional in wind from any direction. Although the speed of rotation, and thus rate of pumping, depend on wind speed and mill and pump size, such sail mills on 9-15 ft towers, in a moderate breeze will typically rotate at 1 rpm and pump 50-100 cfh. In windy conditions, this may increase to 300-500 cfh (Beaumont, 1974). These sail type windmills are found in many parts of the world, however they are particularly evident in Crete's "Valley of 10,000 Windmills" (Schioler, 1975).

Another simple, but higher speed windmill consists of a set of long, narrow blades (e.g., 5 ft x 10 in.) fixed to a hub, similar to the electric generating design in figure 5.2. In developing areas, this design is constructed of 3-4 wooden blades on a wooden or iron hub, and, like the sail type, are usually used to provide a rotational motion via gears or belts for rotary water lifters. One district in Thailand had 21,000 such "propeller engines" in a 1949 survey (Molenaar, 1956).

The large, Dutch-style windmills were the design of a previous age of windmill popularity. However, their spread to the United States (some even saw use on the windy plains of Kansas--Murphy, 1901) brought about the development of the *American-style windmill* which is now used worldwide. Many crude, inefficient designs have been concocted with scrap materials over the past century (see Fetters, 1972), however, wooden and/or metal designs like that in figure 5.3 have become a standard for water lifting purposes. Several commercial variations of this basic design are also available, such as the one in figure 5.4 which utilizes more, but narrower blades than in the

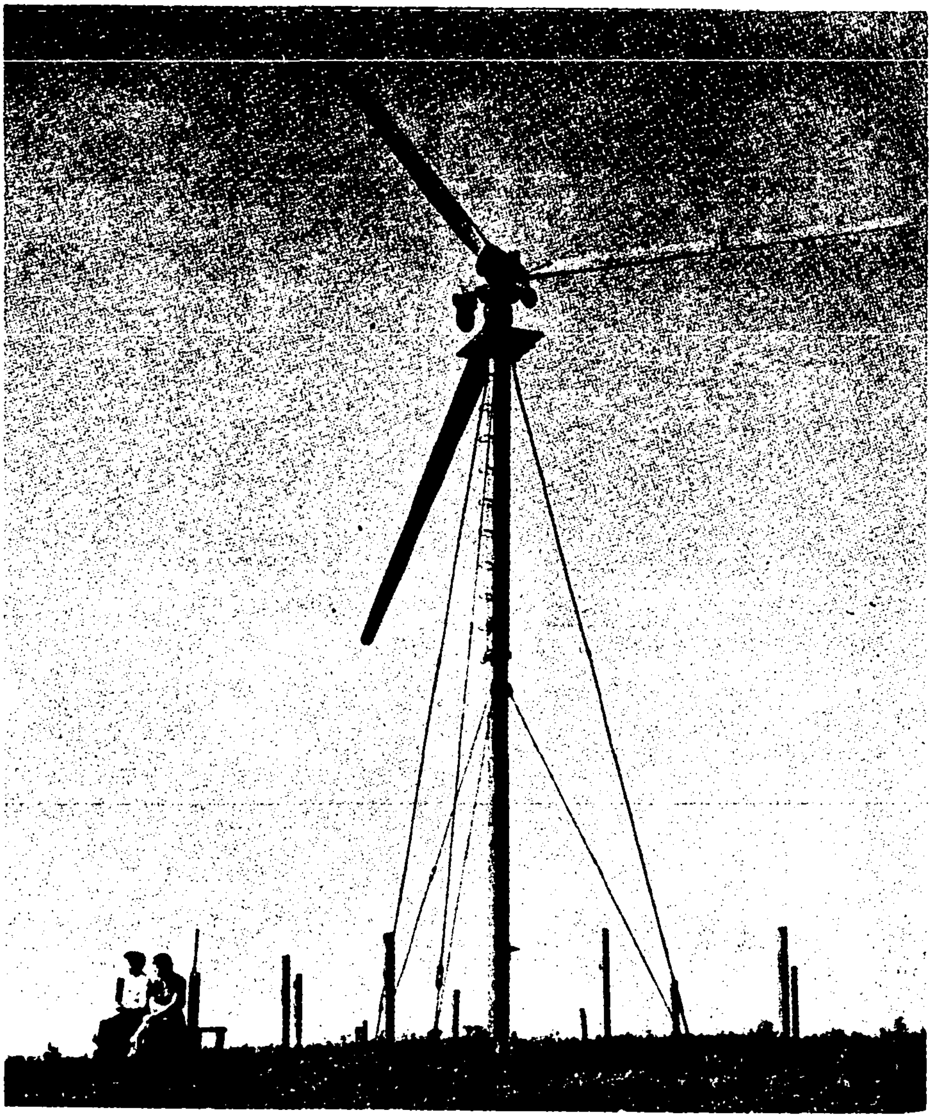


Figure 5.2 Modern, high-speed "propeller" windmill (from Golding, 1962)

Figure 5.3 American-style windmill with storage tank

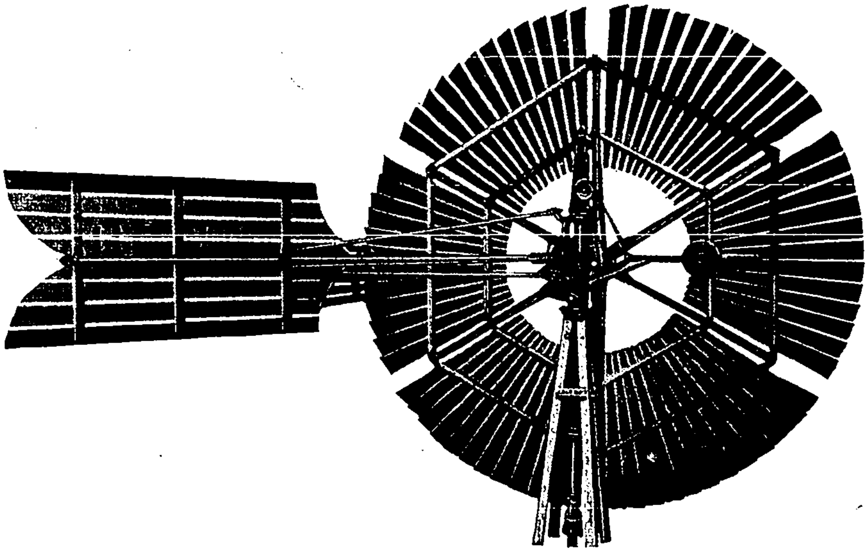


Figure 5.4 Halladay-style American windmill

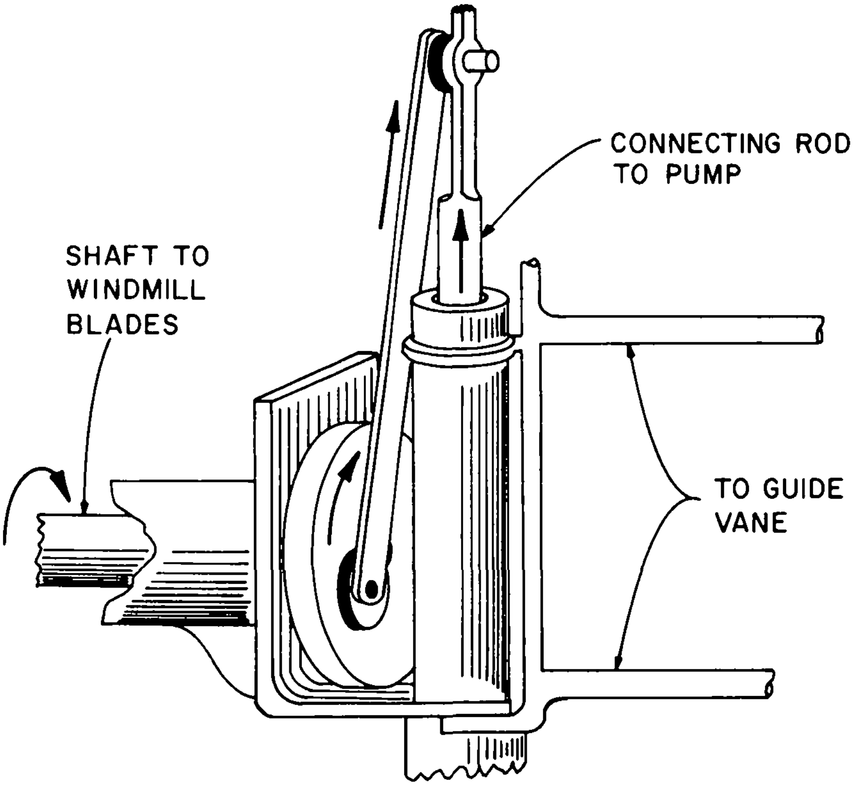


Figure 5.5 Typical cam mechanism to convert windmill rotary motion to reciprocating motion

previous figure. Although most of these mills utilize a cam mechanism (such as that shown in figure 5.5, or simply a crankshaft) to provide reciprocating motion for a piston pump (see figure 3.27), many are attached to gear mechanisms which retain their rotary form of power. Table 5.3 gives some performance data that are typical of these windmills when used with piston pumps. Commercial windmills of this type range in cost from about $470 for 6 ft diameter mills (including sail wheel, guide vane, brake, turntable, and transmission) to over $4,000 for 16 ft diameter models. Metal towers for these assemblies to be mounted on usually range from about $44 for 3 ft heights to over $3000 for 47 ft designs.

Before discussing the application of windmills in general for water lifting, another group of windmill types should be mentioned. The designs previously discussed all had horizontal shafts and rotated perpendicular to the wind direction. Another class of windmills has either vertical or horizontal shafts and rotates in the direction of the wind. One type in this class is constructed like a paddle wheel (mounted vertically or horizontally) and the wind is forced to blow on only the paddles on one-half of the wheel by a shield covering the other half--thus causing rotation. Such windmills have been tried throughout the ages (see section 1.2), but in general have very low efficiencies and are restricted to wind from one direction (Murphy, 1901).

Two more recently popular designs in this class are shown in figures 5.6 and 5.7. The *savonius rotor* can be quite simply constructed. A typical design consists of a 50 gallon drum, cut in half longitudinally, and the halves offset by about two-thirds of their diameter.

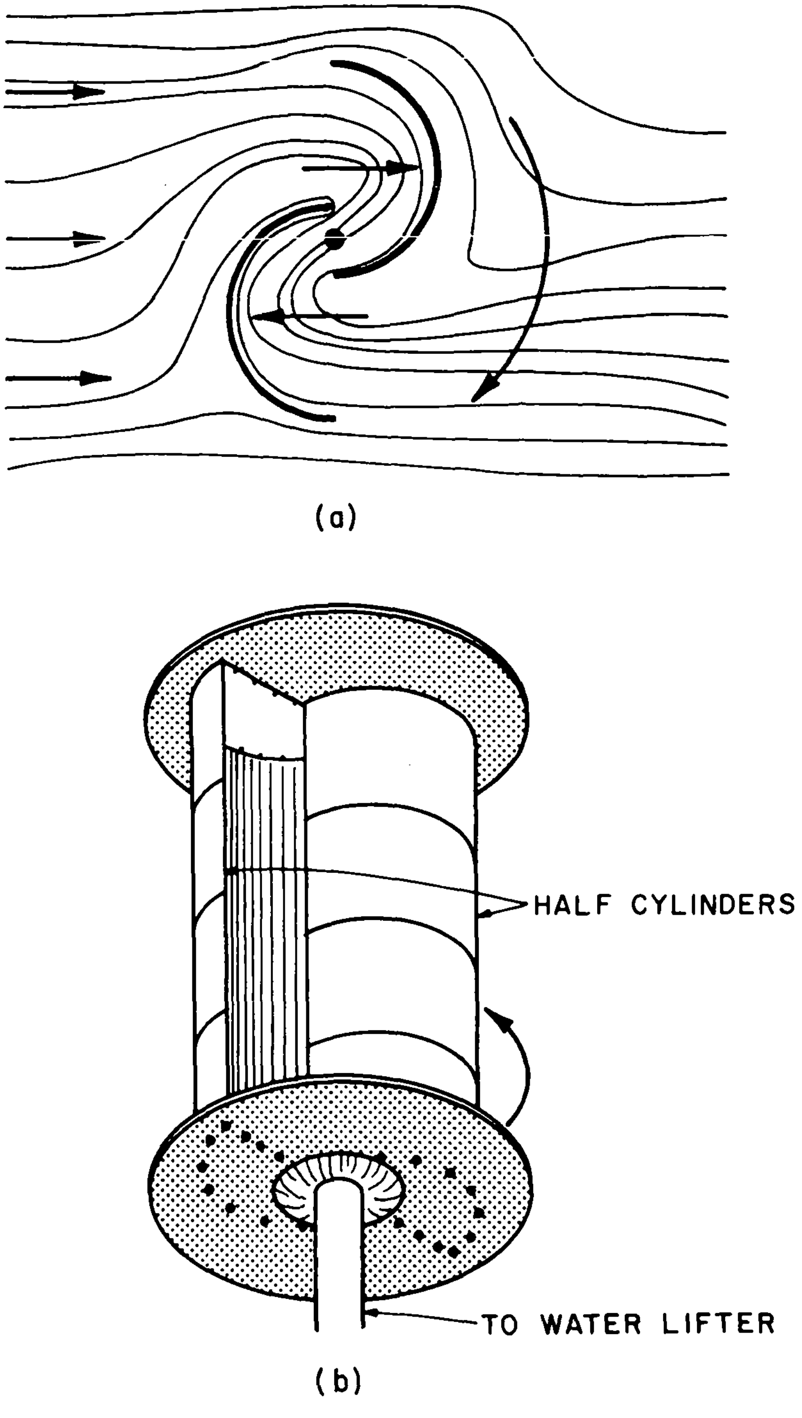


Figure 5.6 Savonius rotor; (a) air flow and (b) construction

Table 5.3 Typical performance of various windmill-driven piston pumps at 15-20 mph

Windmill Diameter (ft)	Strokes per minute		Cylinder Size (in.)							
			1-3/4	2	3	4	6	8	12	15
6	45	TDH (ft)	115	85	40	27				
		Q (gph)	110	140	350	570				
8	42	TDH	185	130	60	35	17			
		Q	150	195	490	700	1,875			
10	37	TDH	240	175	85	40	25	14		
		Q	150	200	540	900	1,875	3,300		
12	31	TDH	420	325	150	80	38	22		
		Q	150	495	475	840	2,000	3,300		
14	29	TDH	600	460	210	125	55	30		
		Q	150	190	470	870	1,900	3,400		
16	21	TDH	1,000	750	360	200	90	50	30	
		Q	150	190	470	800	1,700	3,150	6,750	
18	17	TDH						100	50	30
		Q						2,400	5,450	8,500

All performance values are approximate (after Aermotor, 1975; Pumping Manual, 1964) for long stroke settings. Short strokes increase TDH by about 1/3 and decrease Q by about 1/4.

When fixed to a vertical shaft, the wind will flow into one half, creating a rotating moment, and then "spill" into the other half cylinder, causing a similar effect. Thus, this design is insensitive to changes in wind direction. Several layers of these rotors, with each layer open to a different direction can also improve this insensitivity and increase efficiency. Savonious rotors rarely attain efficiencies above 31 percent, but due to their easy construction are often found in developing areas. (Performance testing has been done at Brace Institute on a savonius rotor--see Simonds and Bodek, 1964.) The *anemometer-type* windmill in figure 5.7 is also easy to construct using cylinder halves and is also functional in wind from any direction.

For the most part, however, the American-style windmill is the most common for water lifting purposes, with some recent applications of the higher-speed propeller designs for use with centrifugal pumps. Hamilton (1975) estimates that in the United States alone, there are some 150,000 working windmills and another 50,000 repairable ones. With the recent energy crisis, much interest has been rekindled in windmill use. New Mexico State University offers a course in repairing windmills. Much research is underway or being initiated to improve windmill designs, particularly for the generation of electricity (Putnam, 1948 and Hamilton, 1975). However, much of the new knowledge in this general area is being utilized for water lifting and other direct power uses. Utah State University (working through AID) is studying specific improvements for harnessing wind power in water lifting. Also working under AID, Herbert Preal at the Punjab Engineering College has set forth plans for an easy-to-construct, low-cost, sail-type windmill. VITA (Bossel, 1972) and Brace Research

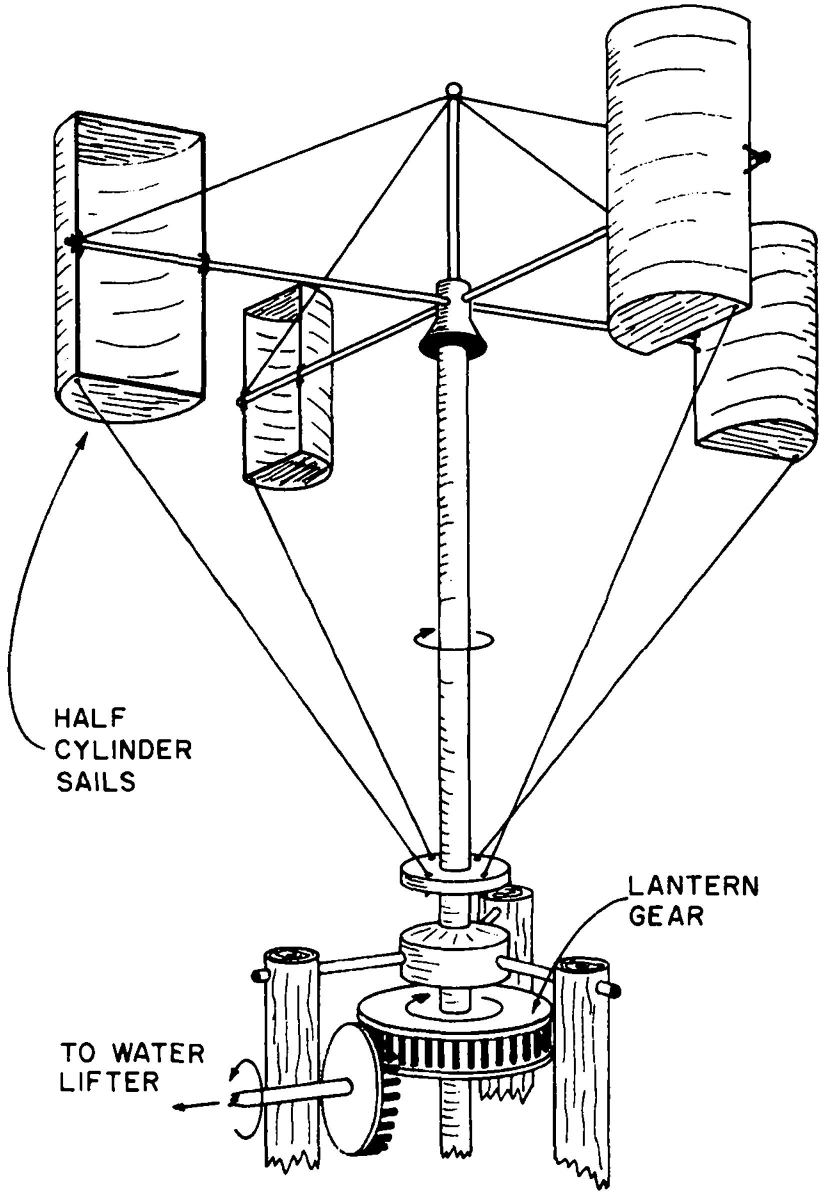


Figure 5.7 Anemometer-type windmill with lantern gear to transmit horizontal rotary motion

Institute (Bodek, 1973) are also among the organizations which have developed windmill designs which are easy to construct (often utilizing scrap material such as auto axles and transmissions) and particularly applicable in developing countries. Several commercial kits are also available for assembling ready-made mills--see Merrill, R. (1974). Much work is also being done to evaluate the potential of wind power in various areas of the world to facilitate economic analyses of utilizing windmills (e.g., Latif, 1972).

In general, the power in a windstream is proportional to the area of the stream (A_w) and the velocity of the wind (v_w), cubed; i.e.,

$$HP = K\, A_w\, v_w^3$$

where K equals 7.1 x 10^{-6} when A_w is in ft^2 and v_w is in mph. K will vary slightly depending on the air density due to weather and altitude--see Fatayev, 1948. Theoretically, windmills are capable of extracting a maximum of about 59.3 percent of this power (where A_w becomes the diameter of the mill), however, in practice, 40 percent efficiency is considered good (Golding, 1962). Since doubling the wind velocity results in an 800 percent increase in power, obtaining the maximum available wind is important. Normally, this means putting the mill as high as possible (at least 3 ft above ground) and with no obstructions in a 300 ft radius around it. At 30 ft above ground level, the wind is often 25-30% faster than at 3 ft. The top of smooth, exposed hills are usually optimum sites for fast, dense winds--see Golding (1962), p. 21.

Windmills such as the American-style are utilized for low-speed/low-power applications such as driving a piston pump, however, with a centrifugal clutch and appropriate gearing, they can be used to drive rotodynamic and rotary pumps (Golding, 1962). These low power mills normally have a "cut-in" speed of 6-7 mph, i.e., to overcome friction, and rarely increase power output above a "cut-out" wind speed of 20 mph. At very high wind velocities, most windmills are provided with a feathering or trip mechanism to prevent damaging high-speed rotation. When a windmill cannot be located directly above the pump or water lifter (e.g., poor wind available) belts, gears, and shafts may be used to transmit rotating motion (e.g., figure 5.1) or an arrangement like figure 5.8 may be used to convey reciprocating power.

High speed/low starting torque designs, e.g., figure 5.2, are more readily adaptable to driving rotodynamic pumps. Figure 5.9 shows another high speed design which is being used to pump water via a centrifugal pump in a drainage ditch. The Brace Institute utilized a three-blade "airscrew" windmill (similar to figure 5.2) to power a vertical turbine pump which supplied water to a sprinkler irrigation system. This study was conducted in Barbados, West Indies. The pump was run at 2500-3500 rpm to deliver 150-200 gpm at a pressure of 20 psig to the sprinklers. The system was supplemented by a diesel engine for windless periods (Ionson, 1969).

Table 5.4 gives some typical water lifting applications of windmills. In general, since wind is a variable power source, two precautions are usually taken to insure water is available when needed. As in the Brace study, an auxillary power source (e.g., gas engine, electric motor) is kept in reserve for times of low or no wind. The other alternative is to provide a storage facility, e.g., a pond or

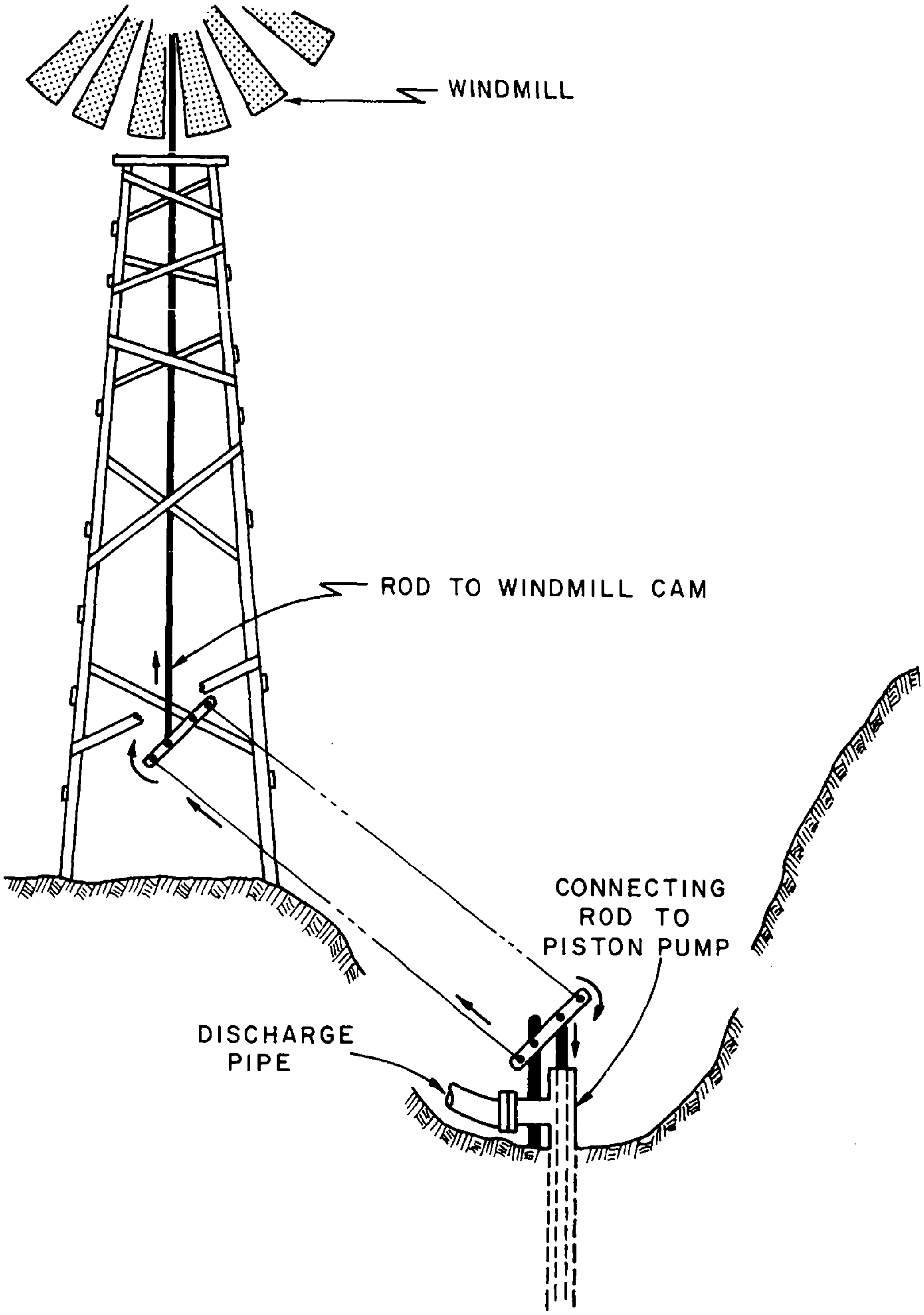


Figure 5.8 Mechanism for providing offset reciprocating motion to pump in poor windmill site

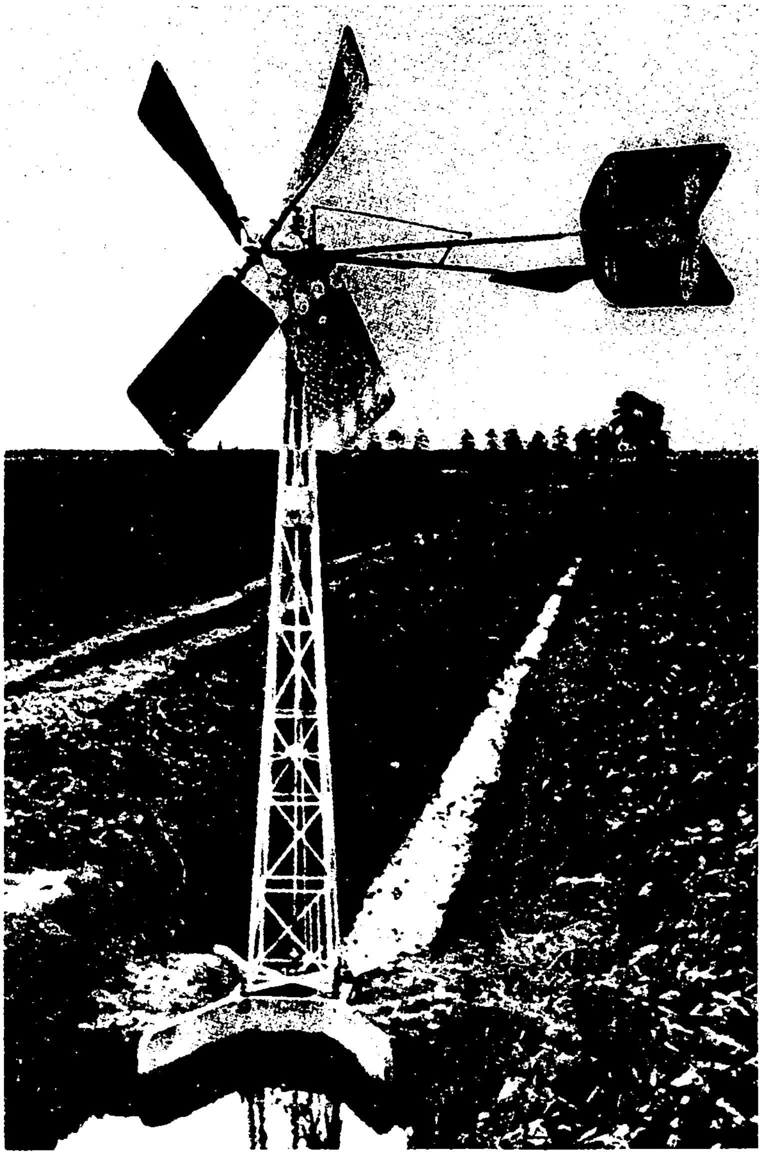


Figure 5.9 Windmill for lifting drainage water (from Golding, 1962)

Table 5.4 Typical windmill applications

Type	Transmission	Water Lifter	Remarks
A. Horizontal-shaft windmills			
sail (figure 5.1)	on same incline shaft with	screw	see Reynolds (1970), p. 150
	on tower with chain and sprockets to horizontal shaft	paddle wheel noria tympanum Persian wheel water ladder chain pump	for tower arrangement, see Beaumont (1974); see also figures 3.34, 3.36, 3.37
	as above plus angle gear	screw	figure 3.47
	on tower with eccentric mechanism and connecting rod	bucket pump diaphragm pump	figures 3.27, 3.28, 3.31
propeller (figures 5.2 and 5.9)	one angle gear and increasing ratio gear train	vertical- or incline-shaft rotary or rotodynamic pump	table 4.1; also see Fateyev (1948), p. 277
	two 90° angle gears and increasing ratio gear train and/or belts and pulleys	horizontal-shaft rotary or rotodynamic pump	as above
American (figures 5.3 and 5.4)	angle gear to vertical shaft with increasing ratio gear train	vertical-shaft rotodynamic or rotary pump	table 4.1
	angle gears or belts to horizontal shaft	paddle wheel chain pump water ladder noria tympanum Persian wheel	see "sail"
	above to incline shaft	screw	
	angle gears or belts, and increasing ratio gear train to horizontal shaft	horizontal-shaft rotodynamic or rotary pump	table 4.1
	eccentric mechanism to connecting rod	bucket pump diaphragm pump	figures 3.27 and 3.31
B. Vertical-shaft windmills			
savonius (figure 5.6) or anemometer (figure 5.7)	90° angle gearing to horizontal shaft	paddle wheel tympanum Persian wheel noria water ladder chain pump	see "sail"
	incline angle gearing	screw	figure 3.47
	eccentric mechanism and connecting rod	bucket pump diaphragm pump	see "sail"
	increasing ratio gear train and/or belts and pulleys	vertical-shaft rotodynamic or rotary pump	well suited for axial-flow or helical pumps; table 4.1

tank (figure 5.3), which is capable of holding sufficient water for the longest expected period of windless days. When a rotodynamic pump is powered by a windmill, the installation must provide the pump with a dynamic suction head or an automatically regulated supply of priming water to insure the necessary prime needed for pump operation--see Fateyev (1948), p. 277 (in translation). Except for occasional adjustments and lubrication, windmills have almost no operating costs. Also, when not needed for water lifting and provided with the proper gearing, they can be used to power other devices (e.g., saws, grinders, etc.) or to generate electricity (Merrill, R., 1974; Golding, 1962; Fateyev, 1948).

5.2.3.2 Water

Where a sufficient flow or head of water exists, the energy of this water can be used to rotate a *watermill*, which can then be used to drive several types of water lifters. (To avoid confusion, it is convenient to refer to wheel devices which receive energy from water as "watermills" (just as wind<u>mills</u> receive wind energy), and those which impart energy to water (e.g., noria, tympanum, etc.) as "waterwheels"--see Reynolds, 1970.) Depending on the amount of available flow or head, one or more types of watermills may fit the given installation and intended water lifter(s) (more than one water lifter is often driven off of the same watermill shaft). Table 5.5 summarizes some typical watermill specifications and applications discussed below.

When essentially no head is available, except for that which produces a flow (e.g. stream, river, canal), it is practical only to use an *undershot wheel*. The simplest to construct is the *floating*

Table 5.5 Typical watermill applications

Type	Eff (%)	H (ft)	D-Diameter (ft)*	Optimum* rpm	Transmission	Water lifter	Remarks
A. Horizontal-shaft watermills							
float mill (figure 5.10a)	30-45	(current flow)	10-50	$\frac{72.8}{\sqrt{D}}$	combined into single unit	paddle wheel noria tympanum	figures 3.40a & b, 3.41;
Poncelet (figure 5.10b)	60-80	3-10	2H-4H (> 14)	$\frac{42.1\sqrt{H}}{D}$	direct shaft, belts, or gears	above plus; Persian wheel water ladder chain pump screw	see table 5.4
Breast (figure 5.11)	40-70	6-15	H-3H	depends on breast height	above plus increasing gear train	rotodynamic or rotary pumps	figure 4.11
Overshot (figure 5.12)	60-85	10-50	0.75H	$\frac{41.8}{\sqrt{D}}$	eccentric mechanism	bucket-piston pump diaphragm pump	figures 3.27, 3.31; see VITA (1975), p. 117
Pelton wheel (figure 5.13)	75-90	> 50	1-20	$\frac{76.6\sqrt{H}}{D}$	increasing or equal gear train	rotodynamic or rotary pumps	figure 4.11
Michell turbine (figure 5.14a)	60-85	> 15	1-3	$\frac{72\sqrt{H}}{D}$	above plus eccentric mechanism	high-speed piston, plunger, or diaphragm pumps	figures 3.21, 3.25
B. Vertical-shaft watermills							
tangent wheel	--	> 15	--	--	Same as Pelton and Michell; angle gears can allow use with horizontal-shaft rotodynamic or rotary pumps.		
turbine (Francis--figure 5.14b)	80-90	> 15	1-30	50-220			

*after Merrill, R., 1970

mill version (Bradley, 1912, p. 78), shown schematically in figure 5.10a. It is installed so that its peripheral paddles (at least two at all times) are immersed in the driving flow. Figures 3.40a and b show such mills combined into a single unit with norias. As mentioned in the discussion on paddle wheels (section 3.3.1.1), paddles which are slightly inclined (figure 5.10a) or curved (figure 3.35) enter the water with less effort and thus improve efficiency. Since faster velocities are often found in width increments of a river's cross section other than near the shoreline, it is sometimes advantageous to place a mill in that increment (this is often called a *midstream wheel*) and transmit the power to shore via a chain and sprocket system--see Wilson (1896), Plate V. As mentioned in the noria discussion (section 3.3.1.5), the power applied to the mill by the flow is proportional to the submerged paddles area and the water velocity cubed, i.e.,

$$HP = \frac{\rho_w A_p v_w^3}{K} , \qquad (5.1)$$

where, if ρ_w, A_p, and v_w are in foot-pound-second units and HP is in horsepower, then K is 550 (see table A.7). However, the drag of the paddles through the water and any mechanical friction usually prevents floating mills from providing more than 45 percent of this power to the transmission system.

Because the efficiency of floating mills is rather low, another version of the undershot wheel, the *Poncelet wheel*, was developed (about 1800) which, when a suitable site is available, yields better efficiencies. As shown in figure 5.10b, this mill requires the flow (or at least a portion of it) to be restricted to a channel, the

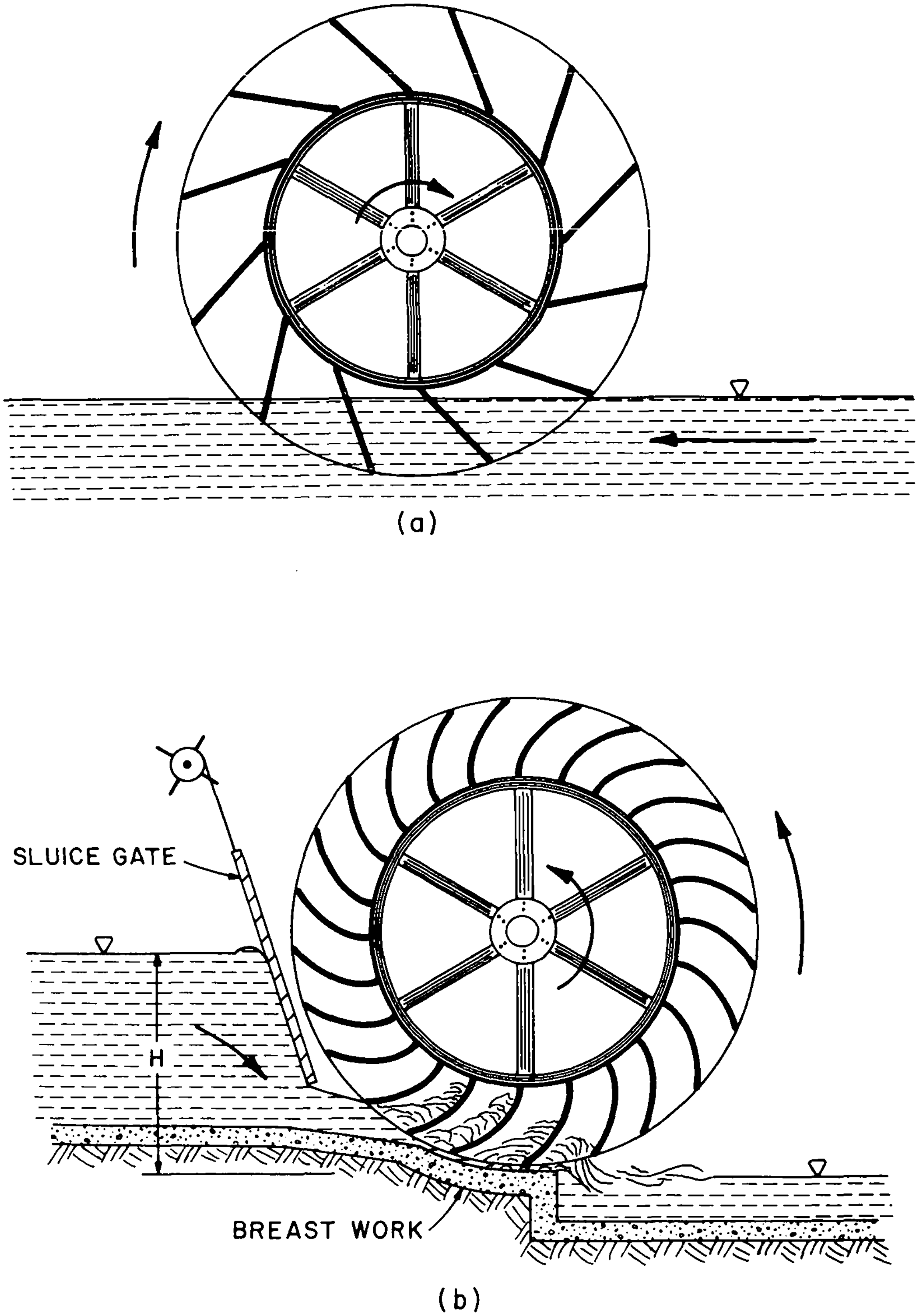


Figure 5.10 Undershot wheels; (a) floating mill, and (b) Poncelet wheel

width of the Poncelet wheel, and that a sluice gate be provided just upstream. In this way, a portion of the available flow depth is converted to a velocity head which can increase the power applied to the mill--i.e., in equation 5.1, A_p, which is directly proportional to HP, is reduced in order to increase v_w, which is proportional to HP by a factor of three (3). Furthermore, since the tailwater is below the mill, no drag occurs through the water to increase friction losses. Thus, Poncelet wheels can be expected to have efficiencies between 60 percent and 80 percent.

Where more head is available (6-15 ft), but possibly less Q, *breast wheels* can be used which employ the falling mass (i.e., weight) of water to rotate the mill. Just as the energy added to "pumped" water is a function of the mass flow rate (i.e., $\gamma_w Q$) and the head added (i.e., H_{TD}), so also is the power applied to a breast wheel by falling water, i.e.,

$$\text{Power}_{in} = \gamma_w Q H,$$

where H is the vertical distance the water falls within the wheel.

Figures 5.11a and b illustrate medium and high breast wheels, respectively. A low breast wheel is essentially the same as a Poncelet wheel (figure 5.10b). With the available H, it must be decided whether a small wheel with high breast or a large wheel with low breast better fits a given installation. For equal Q and H, smaller wheels provide less torque but turn at higher rpm's (Merrill, R., 1974). Cost must also be considered since a smaller wheel may cost less, but the higher breast form work may cost more. A major loss in efficiency of a breast wheel design is that, unlike

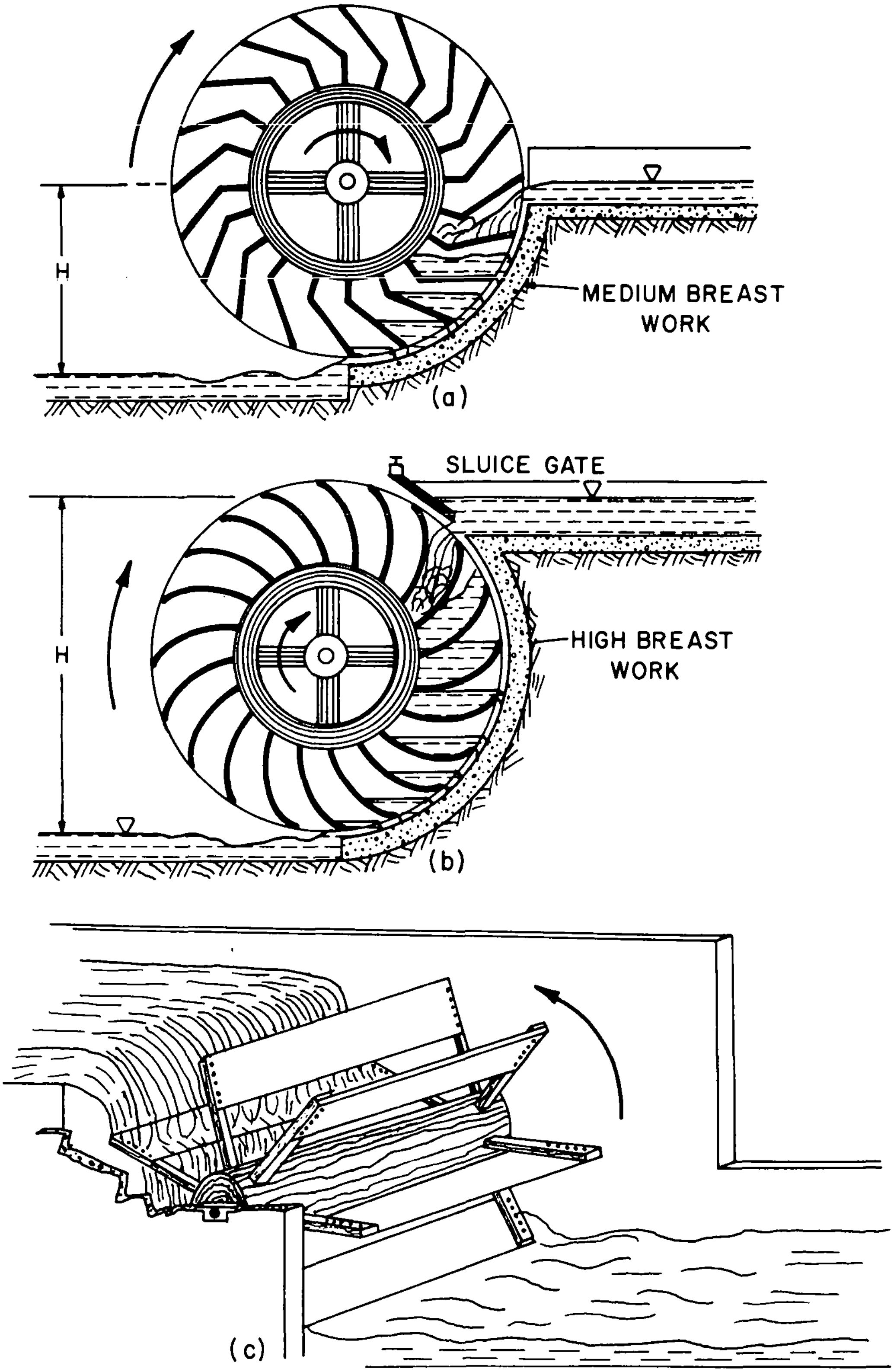


Figure 5.11 (a) Medium-breast wheel, (b) high-breast wheel with sluice gate, and (c) flutter-wheel

under- and overshot wheels, the wheel is moving toward the incoming water rather than in the same direction, thus creating energy losses (e.g. for any breast higher than the wheel axle, a moment, counter to the falling-water moment, is produced). This counter moment can be reduced to some degree by the use of a sluice gate, as in figure 5.11b. Breast wheel efficiencies usually range from 35-40 percent with lower breast works to 60-65 percent for higher breast works.

A rather simple, easy-to-construct version of the breast wheel is the *flutter-wheel* (figure 5.11c) which is powered partially as an undershot wheel, i.e., impulse of flowing water, and partially as a breast wheel, i.e., weight of falling water. Although little information is available on this simple mill, it would appear to have much the same performance and application features as a breast wheel if the paddles extend to the hub--unlike figure 5.11c (see Rogers, 1905, Vol. 2, p. 121). This design could be well suited to many developing areas with very light industry.

Overshot wheels can obtain some of the best efficiencies (60-85%) of the watermills which can be constructed of wood and/or metal with only low to medium technology. They are normally used when heads (H) of 10 to 30 ft are available. When used with a sluice gate, as in figure 5.12, the power applied to the wheel is a result of both the impulse of the high velocity water from under the gate and the weight of the water falling within the wheel. The driving flow must enter the wheel at or beyond the vertical centerline to avoid the reverse moments encountered with breast wheels.

Construction of overshot wheels is usually with a wooden rim and spokes (to decrease weight) and steel bucket partitions and hub. (Merrill, R. (1970) gives some guidelines to the design and construction of these and other type watermills.) In order to save on rising fuel costs, several Colorado ranchers have built and installed such steel-and-wood overshot wheels to replace gas or electric motors for driving their modern pumps. These wheels are typically 17 ft in diameter and 4 ft wide, with 20-30 buckets. When driven by 5-8 cfs of water, they rotate at about 9-10 rpm and provide about 12 hp of output power. To obtain the necessary rpm's for a centrifugal pump, one rancher utilized an old tractor transmission with a 32.5:1 gear ratio between the wheel and a belt drive (24 in. to 5 in. pulleys), which then turned the pump shaft. Such a wheel cost one rancher about $1,200 to build himself, while another had his commercially built for about $6,000 (Roach, 1975). In Pakistan, construction of a small mill (about 2 ft diameter, 1.5 ft wide) costs about $80 (Ahmed, F., 1976).

Possibly the largest overshot wheel ever built was at the Isle of Man. It was 72.5 ft in diameter, 6 ft wide, and provided about 200 hp to a series of mine pumps (Reynolds, 1970; Roger, 1905).

When heads higher than about 15 ft and some medium industry are available, higher efficiencies (80-90%) can be obtained by utilizing watermills which are commonly called *turbines*. Due to the high pressures and velocities involved in a turbine's operation, they are made almost entirely of metal. Turbines are normally utilized to drive electric generators, however, with the proper transmission, turbines can be used to drive rotodynamic and rotary pumps.

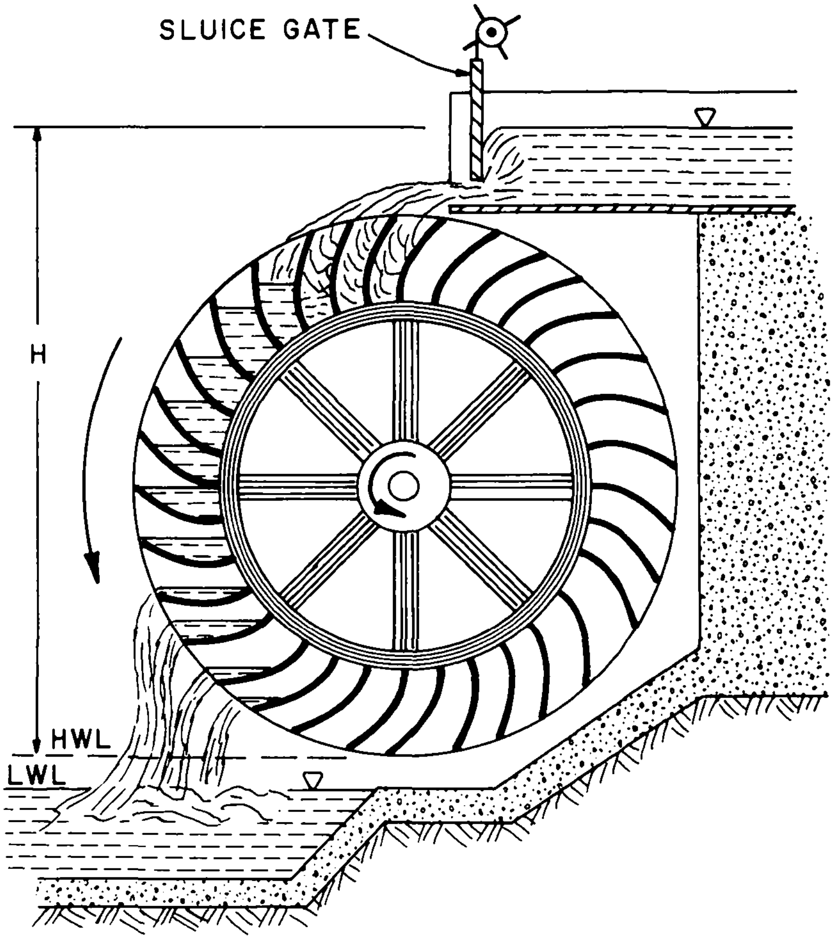


Figure 5.12 Overshot wheel with sluice gate

Among the simplest turbines are *tangent wheels*, which like the under- and overshot wheels, receive a moment causing impulse from a tangential flow of water. However, by employing penstocks and nozzles, high velocities can be brought to impinge on a tangent wheel's buckets. The *Pelton wheel* is such a device. As shown in figure 5.13, it utilizes double-cup buckets to split and direct the impinging jet out to the side and away from the following bucket. A small (2 ft diameter by 6 in. wide) Pelton wheel constructed in Pakistan, costing about $300 is used primarily to generate electricity, but can also be utilized for driving a small pump (Ahmed, F., 1976).

Another tangent wheel is the *Michell turbine*, which utilizes a breast-type nozzle, as shown in figure 5.14a. It is not normally capable of efficiencies as high as Pelton wheels, but is easier to construct. Another device, commonly referred to as just a "tangent wheel" (Bradley, 1912), operates with a vertical axis. It combines the nozzle of a Pelton wheel and the single-curved buckets of a Michell turbine and can probably be expected to operate within the performance range of both.

Turbines such as the Francis-type shown in figure 5.14b are the most sophisticated watermills--large turbines in hydro-electric plants can yield upwards of 100,000 hp to drive electric generators (Starr, 1971). They are, in essence, a rotodynamic pump working in reverse. As in figure 5.14b, water, under a relatively large head, flows into a volute casing which directs it into an impeller, causing it to rotate. The water then flows down and out through the impeller eye into the tailwater. (For further discussion and other turbine designs, see Rouse, 1950.)

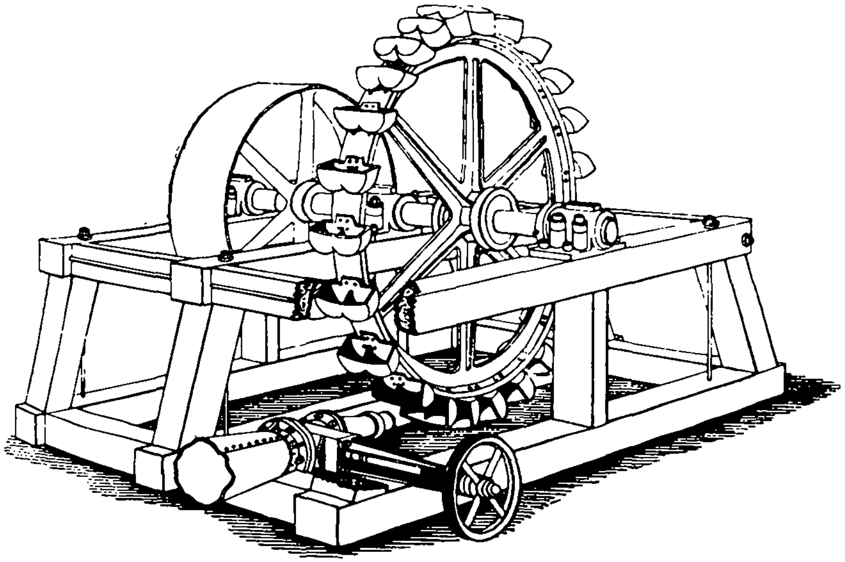


Figure 5.13 Pelton wheel with flat belt drive wheel

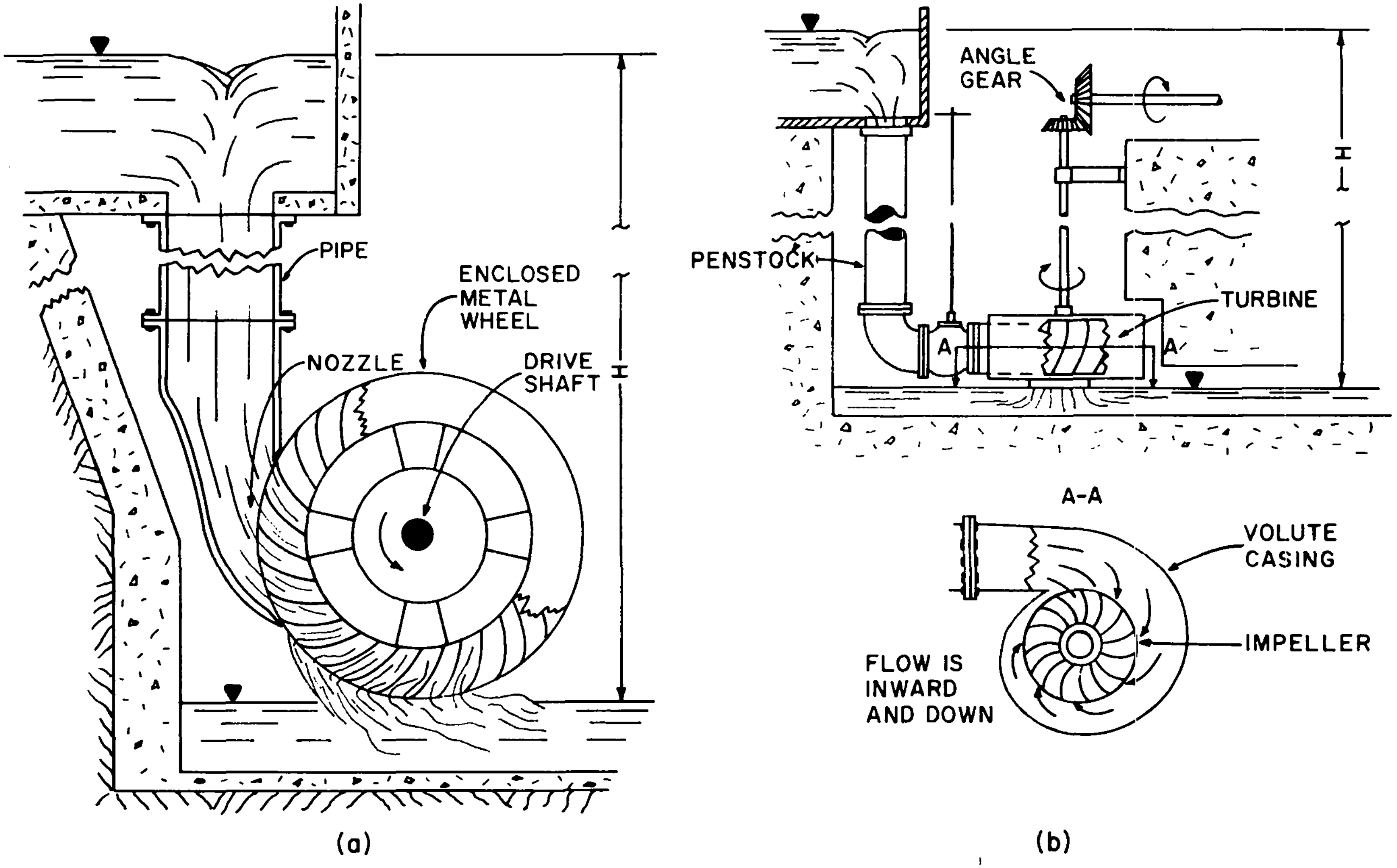


Figure 5.14 (a) Horizontal-shaft tangent wheel (Michell turbine), and (b) impeller turbine (Francis type)

Although rarely found in appropriate locations for irrigation or drainage water lifting, tidal water is another form of natural energy which, if properly harnessed, can provide an inexpensive source of power. Where tides are sufficient (e.g., Hudson River, Bristol Channel, Bay of Fundy, Severn Barrage) electric generation plants have been seen as feasible projects since 1925, ranging in size from 3,000 to 1,000,000 kw (Parker, 1949). Several plants, such as the one in Brittany, France (Eccli, 1974), are currently in operation, supplementing electric power from conventional generating plants (i.e., coal, water). However, tide fluctuation is generally not a feasible alternative power source for directly driving water lifters.

Wave action is a power source which has been converted through various schemes directly to mechanical energy which can and has been used to pump water. In Monaco, three horizontal, side-by-side rotors drive cam mechanisms, which in turn reciprocate two double-acting piston pumps. The rotors are partially submerged about three feet from a cliff so as to be rotated by both incoming waves from above, and out-going undertow from below. Bob Morgan describes another device called a "Sea Horse" which he uses to drive a small electric generator, but could also be used to drive small water lifters directly (Eccli, 1974, pp. 102-104). As shown in figure 5.15, this wavemill consists of two large, buoyant cylinders, set half of an average wavelength apart. Each is attached to a wire which passes under a pulley directly below the cylinder. As the cylinders bob up and down in the waves, they alternately pull (i.e., one rising while the other falling) on their respective wires. In Morgan's design, these wires drive a ratchet wheel which provides a continuous rotating motion to a flywheel

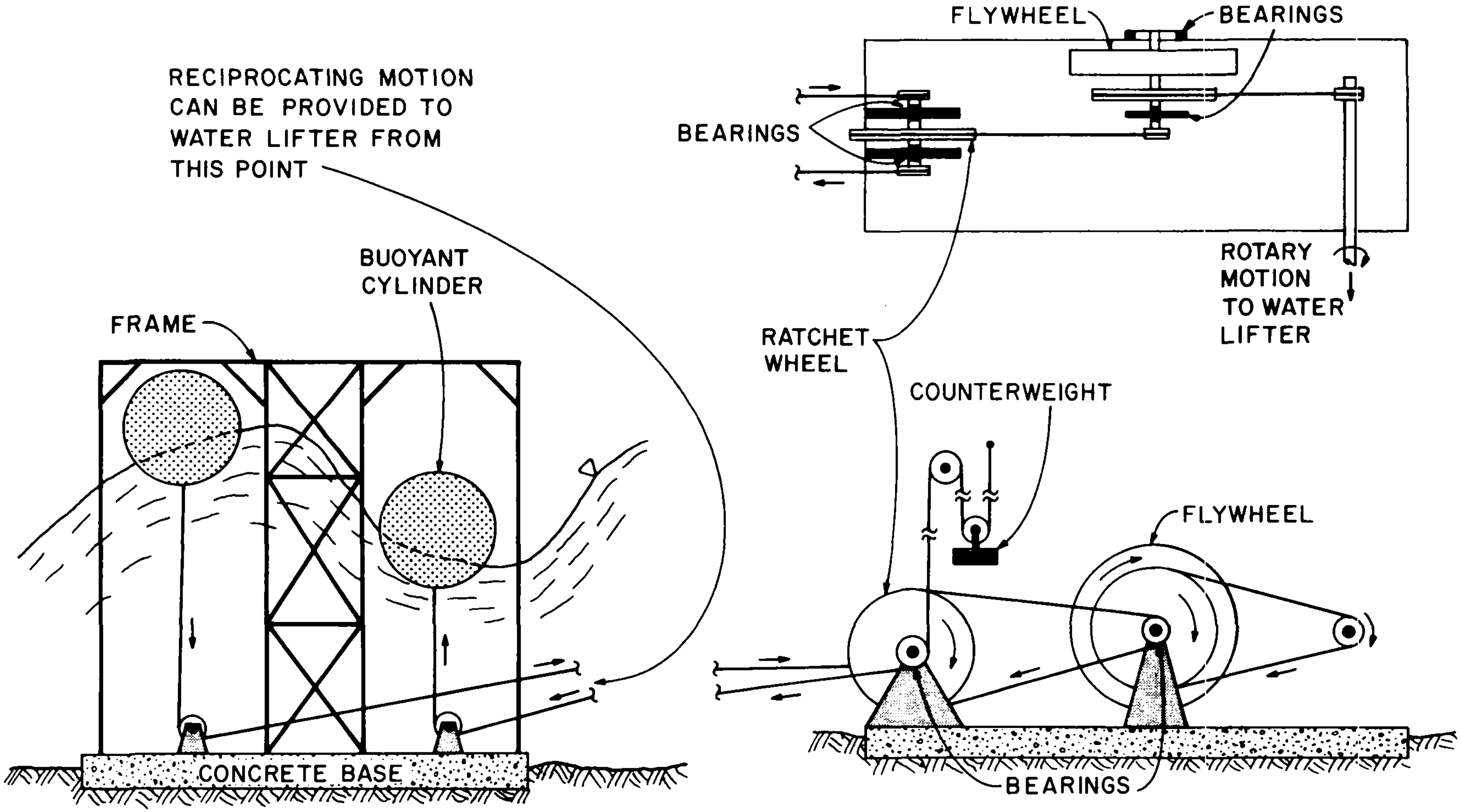


Figure 5.15 Schematic of device for obtaining reciprocating or rotary power from wave action (after Morgan in Eccli, 1974)

(conserves energy during non-power periods) which in turn drives an electric generator. However, this same scheme could possibly be used to drive reciprocating water lifters, utilizing just the cylinders and wires, or to provide rotary power with the added ratchet wheel and flywheel.

Except for a few schemes, such as those mentioned, tidal power is still an undeveloped source of natural energy.

5.2.3.3 Geothermal

Like tidal energy, geothermal (or terrestrial heat) energy is a "free" natural source of power which is being developed for several uses, but as of yet, not directly for water lifting. In some areas it exists at the ground surface naturally as geysers (e.g., Wairakei, New Zealand; Geysers, California), while in other places it can be reached by borehole. Currently, geothermal heat is used to drive steam turbines for electric generation or for industrial processes (e.g., paper pulp). Its conversion directly to mechanical energy which could be used to drive water pumps is currently unfeasible (i.e., low torque).

5.2.3.3 Solar

Solar energy is another source of "free" power which has just recently reached a level of technological development which provides for its conversion to mechanical energy. Unlike other natural resources, it exists in all areas of the world, although its degree of intensity varies with latitude, season, weather, and time of day. In the temperate zone, approximately 2,000 BTU per ft^2 reach the earth surface every day (Parker, 1949). In general, solar energy, in sufficient amounts for efficient conversion to other forms, is available between 45° North and South latitudes (Mother Earth News, 1974).

Although solar energy has long been used for such purposes as heating and drying, the current world energy situation has spurred interest in making its use for these purposes more efficient (i.e., for building heating, cooking, etc.) and in developing new uses. Section 3.4.2.2 included a discussion of the use of solar heating to expand a working fluid which directly pumped water by the displacement method. Many other projects are underway by various research organizations to convert solar energy to mechanical energy which can then be used to do work such as pumping water.

Near Mexico City, four prototype pumping plants are being used which will eventually (according to plans) be developed into a pumping system with a 330,250 gpd capacity. Each of the prototype plants currently lifts 1600 gph, more than 163 ft from a well into storage tanks. Flat-plate solar collectors heat a working fluid (butane) which expands to drive a turbine. This turbine or "expansion motor" powers a small pump to recirculate the butane and a hydraulic press, which in turn drives a piston pump in the well. Each of these 33 hp prototype plants costs about $400,000, which when amortized over 50 years results in a cost per ft^3 of water of about $0.01-0.03 (Engineering News Record, 1975).

Battelle Memorial Institute is also working to develop a 50 hp pumping plant. Beale et al. (1971) report on work done at Ohio University to develop a free piston Stirling engine, which (as they suggest) would be of a size capable of such jobs as lifting water. Beason (1975) reports on a project by Farber, Ingley, and Prescott at the University of Florida to develop another piston-type engine.

This engine utilizes a series of pistons, driven by a solar expanded refrigerant, to turn a crankshaft which provides rotary motion.

Many such projects are underway to harness solar energy, but for irrigation and drainage water lifting applications, there is still much to be done.

5.2.4 Mechanical

Mechanical prime movers are devices which convert electric current or the combustion of a fuel, e.g., wood, oil, gas, into mechanical energy which can then be used to drive a water lifter. A common terminology, which will also be used here, is to call fuel consuming devices *engines*, and electric prime movers *motors*. Although the number of engine and motor types constitutes a subject equally or more complex and lengthy than the one of water lifters themselves, this section briefly describes the basic operation and water lifting applications of mechanical prime movers.

Where sufficient electric energy is available, the electric motor can be the ideal prime mover for water lifters, particularly modern pumps. In most installations, it is only necessary to turn the electric current on and the water lifter can operate at a constant, uninterrupted rate for long periods until the electricity is switched off. Protective devices should be installed with the motor to prevent damage to it by fluctuating voltage or overload by the pump. Regulation devices (e.g., rectifiers) can also be installed (or included) with the motor to allow variation of speed which will in turn vary the water lifter's performance. Either alternating current (AC) or direct current (DC) motors can be applied to water lifting requirements, however, due to performance characteristics (e.g., speed-load curve--see

Pumping Manual, 1964, pp. 221-228) and the usually more common availability of alternating current (Anderson, 1973), AC motors are more often utilized. Both types of motors have single or three phase varieties of construction, with single phase units used primarily for power requirements of less than 10 hp. Particularly when used outdoors, *waterproof* or *weatherproof* models are usually specified to protect a motor from natural elements, i.e., dust, raing, ice, insects, etc.

The efficiency of motors (i.e., in converting electrical to mechanical energy) increases with size. Table 5.6 gives some typical efficiencies of various hp sizes. Although the price of motors varies with factors such as manufacturer, size, construction, (and for used motors, condition), table 5.6 also lists some typical 1975 prices in the United States. Geographic area will, of course, also vary price, e.g., in Southeast Asia, a locally manufactured 25 hp motor could be

Table 5.6 Typical electric motor efficiencies and prices

	Price (U.S. 1975 $)*		
Size (rated hp)	New	Used	Eff (%)
1/12	30	20	70
1/4	65	40	
1/2	85	50	
1	123	55	
5	200	--	75
10	320	175	86
25	580	--	
50	1,030	290	90
100	2,800	1,300	

*Without accessories (e.g., starter); typical prices @ 1800 rpm, higher prices for higher or lower rpm models.

expected to cost closer to $700 (Molenaar, 1956). In addition to the price of the motor itself, accessories (e.g., starter, circuit break, etc.) and wiring must also be obtained and installed. This could require the services of a skilled electrician. An initial installation charge is also usually required by the electric power company--if new lines must be installed, this could be rather expensive.

Electric motors are usually expected to have a life of 25-30 years (or 75,000 hrs of actual running time). Many factors can add to or reduce this life, e.g., running the motor at 10°C above or below the rated operating temperature can decrease or increase, respectively, the life by 50% (Colorado Power Council, 1975). Over the life of the motor, repairs can be expected to be about 45% of the first cost. The cost of electricity will, of course, vary greatly with geographic availability, however, power companies often give a lower irrigation rate to farmers. A minimum annual charge is usually made (e.g., in Northern Colorado this is about $75 for single-phase and $125 for three-phase) in addition to a graduated consumption charge (e.g., $.05 for the first 100 kw/hp and $.015 for every 100 kw/hp thereafter).

Where electric power is not economically available, large power requirements are needed, or mobility is desired, engines can be utilized. As with motors, there are a large variety of sizes and designs; e.g., air-cooled, water-cooled, two-stroke, four-cylinder, etc. However, the only major difference to be considered here will be among fuels. Engines using gasoline create a mixture of air and gas, ignite them under compression with an electric spark which causes combustion and thus power to a driving piston. By modification of such components as the manifold, carburetor, timing, and compression ratio, gasoline engines can be adapted to burn butane, propane, or natural gas (methane). Engines for diesel fuel obtain combustion and power by compression of the fuel and air mixture, which causes ignition. Diesel engines can also be altered to burn a mixture of diesel and methane (called duel-fuel). Kerosene engines are also commonly used (particularly in developing countries--Molenaar, 1956).

The choice of which type engine to use will depend on availability and cost (of both engine and fuel) and power requirements. With the current fluctuating energy prices, it is senseless to give examples of fuel costs, however, figure 5.16 gives the cost per hp-hr that can be expected from various fuels based on their energy value as a function of cost per unit of fuel. These values will also vary depending on the quality of fuel, however, table 5.7 lists typical energy values and the performance that can be expected from an engine using this fuel. In general, new gasoline engines have efficiencies

Table 5.7 Typical energy values and performance of fuels

	energy value		performance*
fuel	BTU/gal	hp-hr/gal	BHP-hr/gal
gasoline	126,000	50	6-10
diesel	145,000	55	6-15
kerosene	118,000	47	5-10
butane	102,000	40	4-8
propane	92,000	36	4-8
natural gas	1,100/ft^3	0.4/ft^3	5-7/100 ft^3
electricity	--	1.34/kw-hr	0.5-1.2/kw-hr
coal			
bituminous	13,000/lb	--	--
lignite	7,000/lb	--	--

*after Pair (1969)

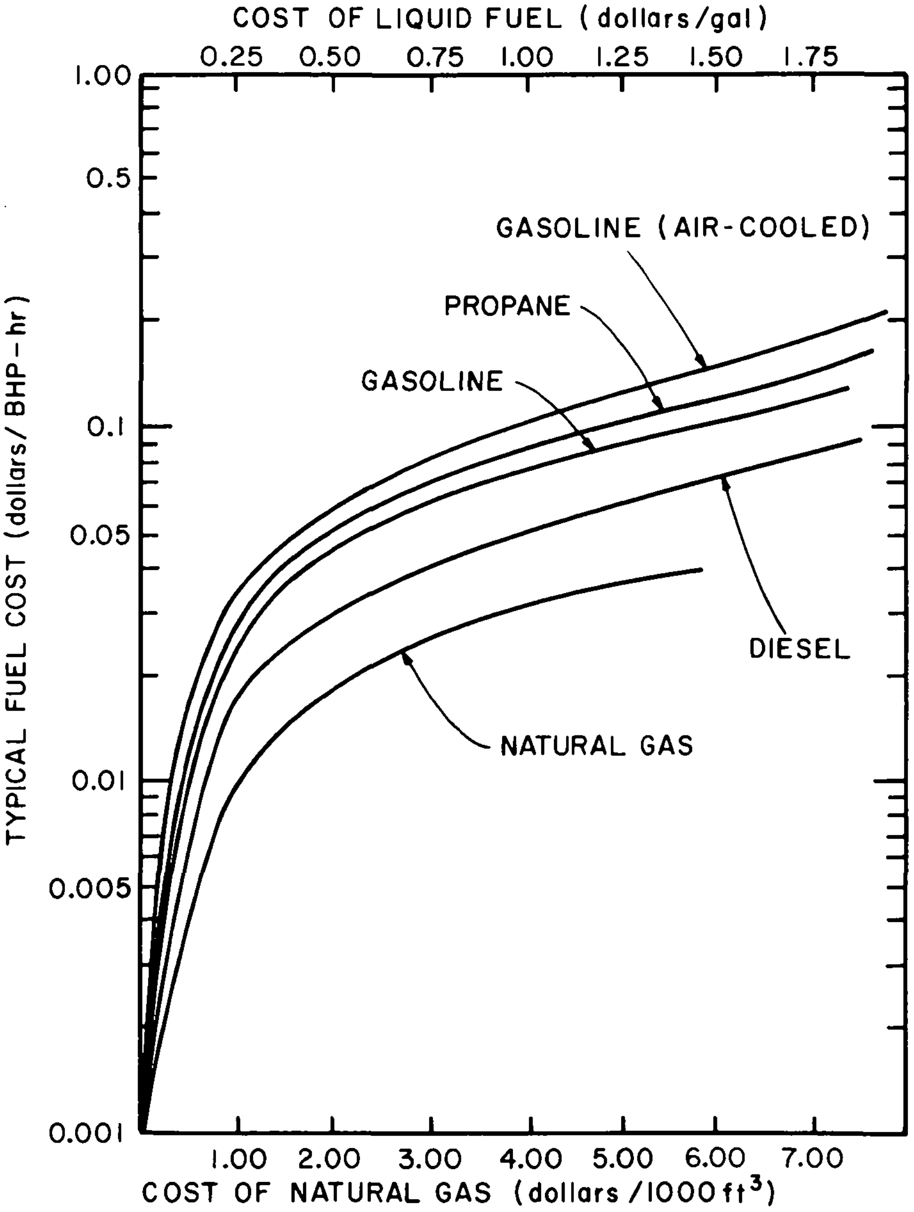


Figure 5.16 Typical fuel costs for various engines (after Pair, 1969)

of about 20 percent, diesel engines slightly higher, and natural gas engines about 15-17 percent. Of course, these efficiencies will vary with engine maintenance and condition, but figure 5.16 gives an idea of the relative energy costs for various fuels.

However, fuel cost is usually inversely proportional to the price and life of the engine with which it can be used. For example, while a typical 10 hp gasoline engine might cost about $440 and have a 9 year life, the same size diesel engine should last about 15 years, but cost about $1,000. (Air-cooled gasoline engines are usually allotted only about a 4 year life.) Again, geography will influence cost, e.g., in Asia $1,000 might buy only about a 3-5 hp engine. A few other typical U.S. prices for gasoline engines are:

3 hp (1 cyl.) -- $ 100
6 hp (1 cyl.) -- 320
20 hp (2 cyl.) -- 720
30 hp (4 cyl.) -- 950
65 hp (4 cyl.) -- 1700 ,

For comparison, a 3 hp diesel sells for about $700, and a 30 hp is about $2,300. Regular maintenance replacement parts (e.g., lube, plugs, filters) are usually about 15 percent of fuel costs. In addition, repairs on an engine can usually be expected to be about 200 percent of original cost, over the engine's life time.

Although engines are normally rated for various conditions by the BHP which they will provide, unless already included in the rating, the following reductions of BHP should be made for these factors:

3% for every 1000 ft above sea level
1% for every 10°F above 60°F (or rated temperature)

5% for accessories (e.g., generator, heat exchanger)
5% for fan and radiator
20% continuous load.

The BHP remaining after these reductions is that which can be applied to the transmission (if any).

Methane is becoming a more popular fuel since the recent increase in other fuel prices. Because methane can be produced by the fermentation of plant and animal waste matter, recycling of such matter to produce methane is becoming a growing practice--see Merrill, R., 1974.

Steam engines and turbines are also possible drivers for water lifters, however, the need for a boiler usually prohibits their use for agricultural irrigation or drainage.

The choice then between which type of engine or motor depends on their prices and availability, the price and availability of fuel (or electricity), the amount of use (i.e., both life time and running intervals), user's preference, and power requirement. The following is a common guide to selection by power size:

less than 7½ hp -- gasoline engine or electric motor
7½ - 40 hp -- gasoline or 3-phase electric
40 - 150 hp -- gasoline or diesel (diesel if more than 1000 hr/yr)
more than 150 hp -- diesel (Wilson, T. V., 1954).

One aspect of user's preference is the ability to obtain skilled attendants to operate and maintain these mechanical drivers. This is a particularly common problem in developing countries (Molenaar, 1956).

As with other prime movers, it is usually beneficial if the driver can be time-shared among several duties. A tractor is often an ideal multi-use driver. A pump can be driven from its PTO directly, as in figure 4.13, or via belts or chains as in figure 5.17. An irrigation scheme in Indonesia uses several pumping units, with each unit consisting of 10 pumps powered simultaneously by the same tractor that transports the unit from field to field (ECAFE, 1959). For mobile, small-power requirements, small engines can be installed on dollies for easy moving. An almost infinite number of transmission arrangements can be devised to fit many types of water lifting installations. Among the basic transmission components are: V-belts, flat-belts, gears (parallel and angle), silent chains, hydraulic-fluid couples, friction clutches, flexible-shafts (e.g., universal joint). Figure 5.18 shows a common arrangement for driving a vertical turbine pump with an engine through a standard, right-angle, pump head transmission. Of course, where the engine or motor, and pump speeds are matched, they can be operated without a transmission, i.e., close-coupled, as is the motor in figure 5.19. Another form of transmission, but usable with only a few specialized water lifters (e.g., submersible centrifugal, air-lift, and diaphragm), is compressed air. It, in effect, transmits power from a compressor engine to the lifter. Hydraulic fluid can be similarly used in some applications (see Mexican solar pump in section 5.2.3.3).

For driving modern pumps, mechanical prime movers have been the primary source of power. However, the changing world energy situation is causing many consumers to improve mechanical operations and/or consider natural energy sources to drive their water lifters, particularly in developing countries.

Figure 5.17 Tractor PTO driving centrifugal pump through V-belt and pulley transmission

Figure 5.18 Stationary engine driving vertical turbine pump through angle gear head

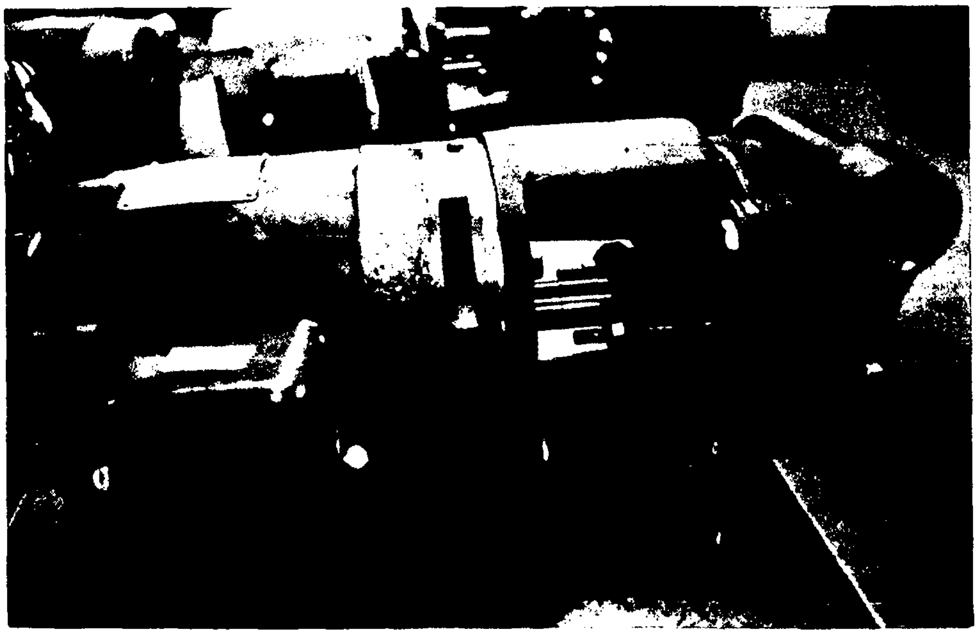


Figure 5.19 Electric motor close-coupled to centrifugal pump

5.3 Selection

As should be evident from the great number of water lifters and prime movers reviewed in the preceding chapters, selection of the best lifter/mover combination for a specific application must involve quite a narrowing-down procedure. This procedure can be quite complex for modern pumps and engines (or motors), however the selection process in general comprises three basic areas of consideration; (a) availability and adaptability, (b) water requirements, and (c) cost.

5.3.1 Availability and Adaptability

The availability of goods and services will be the first factor to narrow the field of types of water lifters and drivers which can be utilized for a given application. Of course, with enough capital, any water lifter can be provided or built anywhere in the world, however, normal economic feasibilities will render some pumps unavailable in many areas, particularly in the agricultural regions of developing countries. This availability goes beyond just the initial acquisition of a water lifter and driver. Also included are the availability of spare parts, fuel (or electricity) of the proper quality and in sufficient amounts, and labor, trained to operate and/or maintain the devices.

If a pump and driver are to be bought commercially, the ability to order them in a geographic area and at a given time must be considered. If the water lifter is to be built (e.g., noria, water ladder), the necessary construction materials must be available. In either case, personnel capable of building and installing the devices must also be available. For water lifters which require the constant attention of an operator, the dependability of this person(s) need also be assessed. In one recent study of water lifting in a developing rural area, it was found that pump attendants would often leave the pump to attend other matters--see Alam, 1974, p. 31. It should also be noted that while the use of natural or mechanical drivers does not directly employ individuals as does a manually-operated water lifter, the employment needs for the light or medium industry to locally produce natural and mechanical drivers can often provide more occupational opportunities than would the need for individual water-lifter operators.

Although assistance programs often provide developing regions with new water lifting equipment, sufficient training and/or spare parts are sometimes not made, and kept, available. Thus, in many instances, water lifters fall into disuse and eventually, when left to natural elements, become unreparable (Fannon and Frink, 1970). Even in developed areas where channels are available to order parts, shipment may take several weeks. During an irrigation season, any such delays can mean crop losses, so the dependability of pump dealers also becomes a selection factor.

Not only must the availability of a fuel or electricity be considered, but also their quality. Fuels, particularly in developing countries, are often of such low octane or contain too many impurities (e.g. dirt, water, etc.) for them to be usable. If natural prime movers are to be used, their energy potential must be evaluated at the water lifting site--e.g., mean wind or water velocity, daily solar radiation.

In addition to various water lifters and drivers being available for a given installation, they must also be physically adaptable. For example, as mentioned in Chapter 3, some pumps are not well suited for pumping abrasive water. Also, certain prime movers may not be environmentally acceptable to a site (e.g. noise, air pollution).

Likewise, the environment may not be conducive to optimum prime mover operation. As previously mentioned, engines and motor perform poorly when they are too hot, become clogged with dust, rust from exposure, etc. Similar consideration must also be given to manual and animal prime movers. Poor environmental conditions, such as heat, humidity, dust, and insects, can quickly tire man and animal, causing loss of water lifting performance. In such conditions it may be advantageous to provide supplemental power sources. For example, when dust is a problem, the wind may be strong enough to drive the water lifter via a windmill. As drivers using solar energy become more available, they would seem the ideal power when the heat is too great for man or animal.

5.3.2 Water Requirements

After the number of water lifters usable for a given application has been reduced by availability and adaptability, possible water lifters must then meet the water requirements for the situation. As discussed in section 2.2, these are basically the discharge and total head, however the NPSHR and power needs should also be kept in minds if applicable.

Throughout the preceding chapters, the Q and H ranges for various water lifters and pumps have been given. Figure 5.20 presents a guide to the selection of positive displacement and rotodynamic pumps based on typical H-Q ranges. The gray areas serve only as rough boundaries and do not represent absolute limits. Once such an examination of ranges (see also figure 4.8) has narrowed the field to a few types of pumps, manufacturers' charts, such as figure 5.21, should be consulted to find the optimum size and design. These

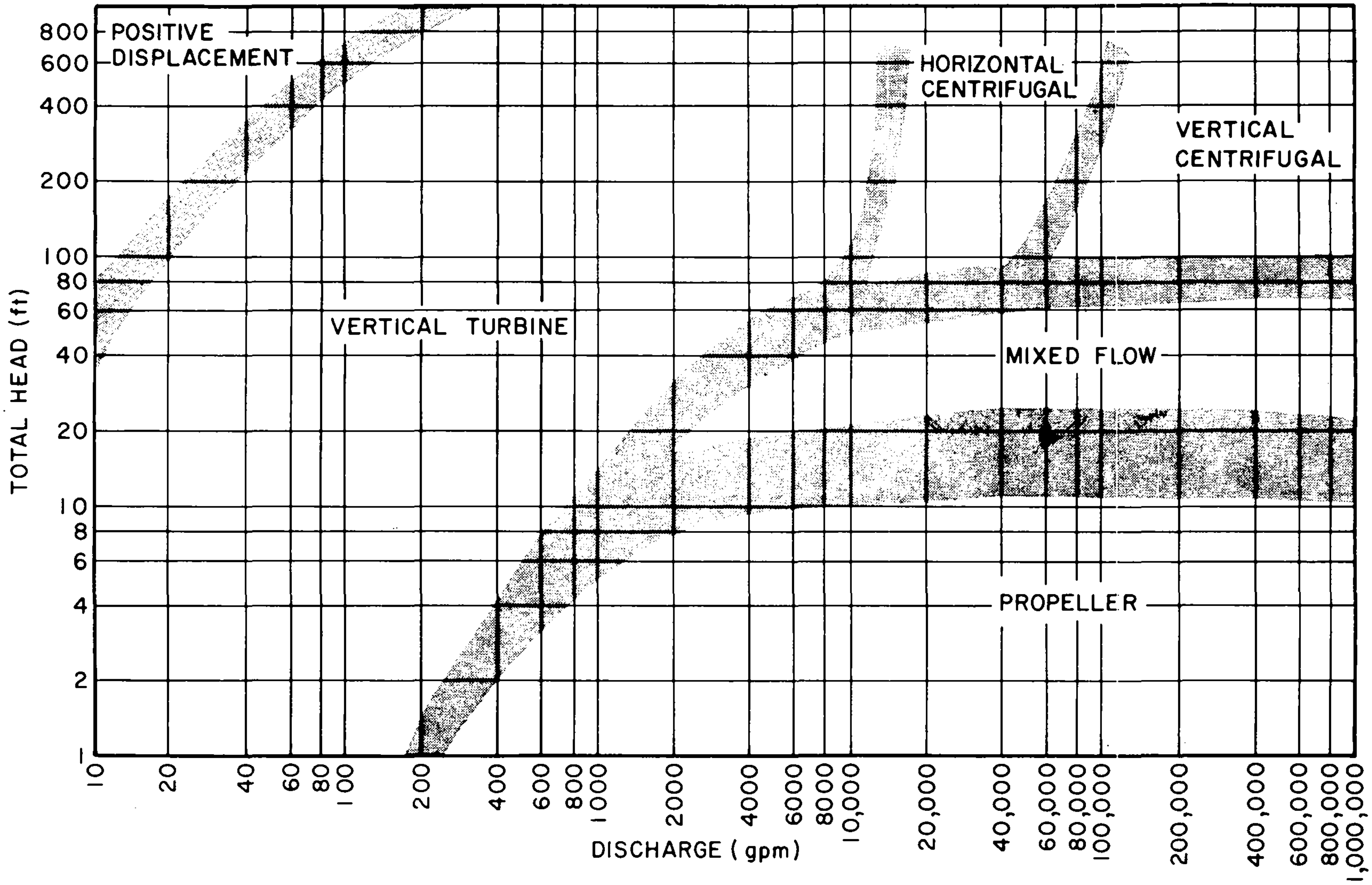


Figure 5.20 Pump selection guide based on H-Q performance (after Finch, 1948, and ECAFE, 1973)

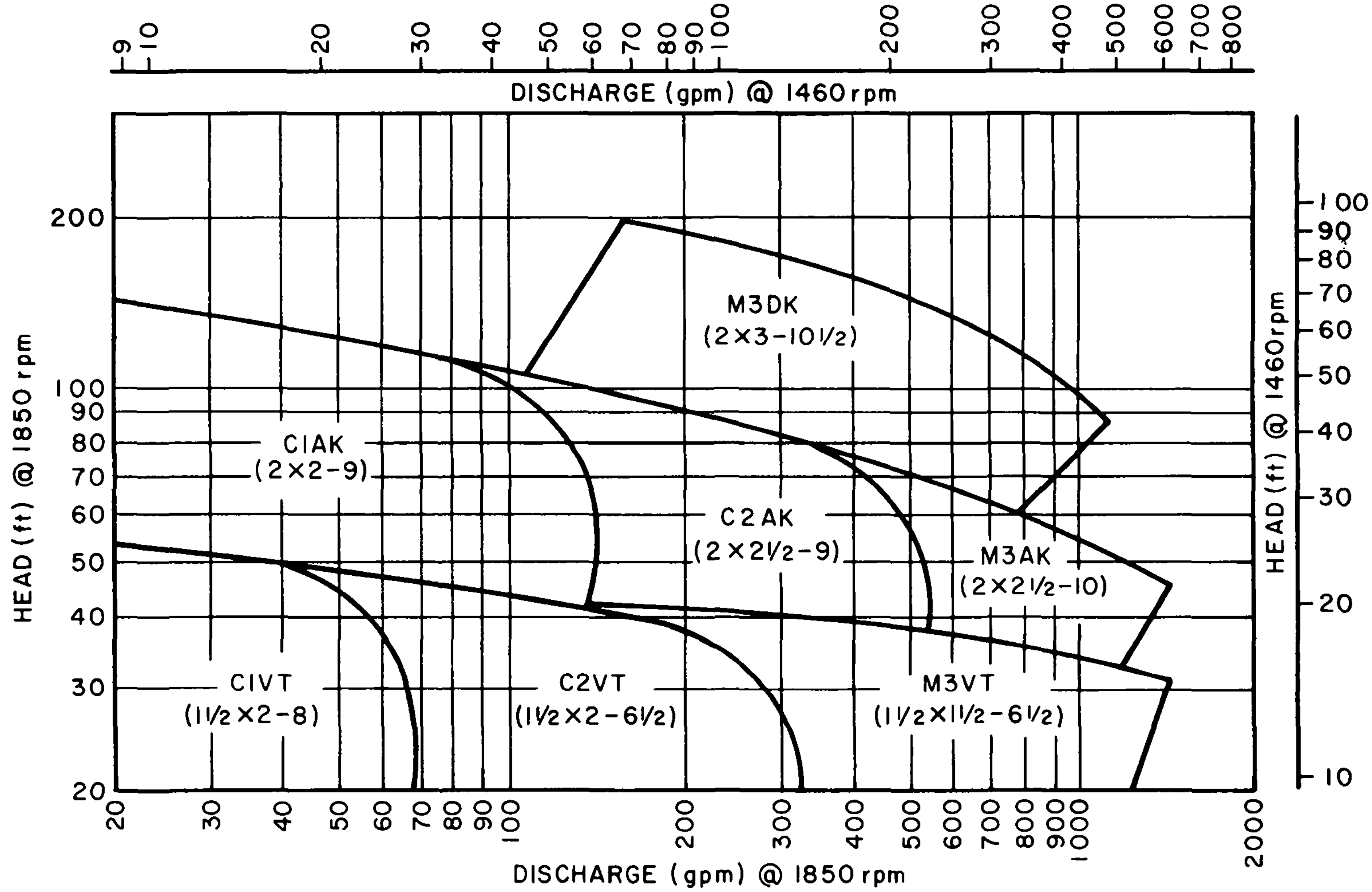
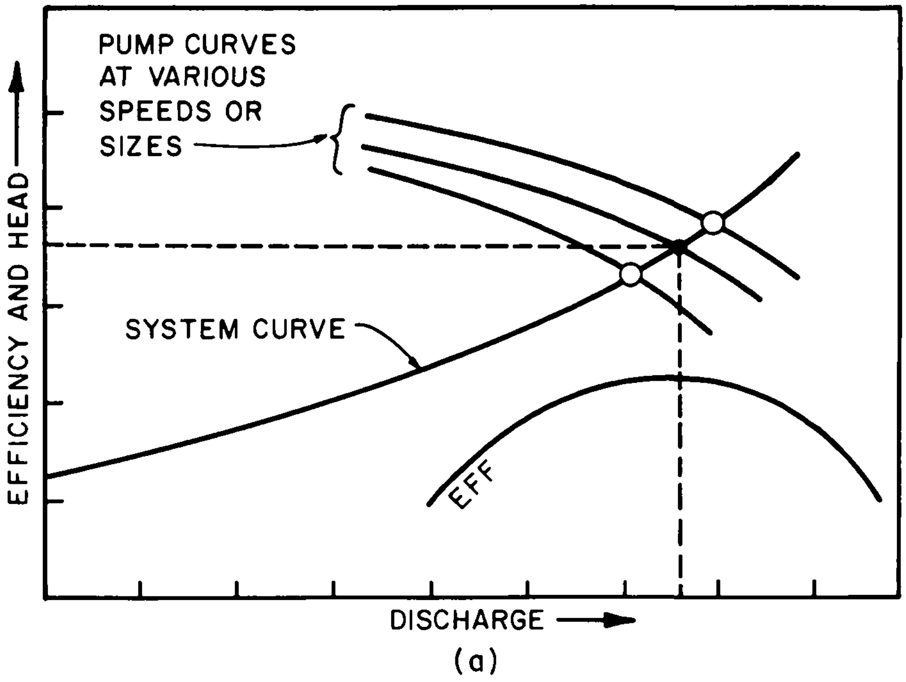


Figure 5.21 Example of manufacturer's selection chart showing pump performance ranges at two operating speeds. Pumps are usually identified by a number/letter name and size. (Note: above is not based on actual data)

charts are a performance composite of several pumps. From this selection, the performance curve (e.g., figure 2.9) can be obtained and compared to the H-Q curve of the pumping system (see figure 2.5). As shown in figure 5.22a, the intersection of the system and pump curves indicates the H and Q at which they will operate. This point should also correspond to as nearly as possible to the maximum efficiency of the pump. If the pump is to operate over a range of discharges or heads, the efficiency curve should be as flat as possible throughout that range. Figure 5.22b illustrates the resulting performance after a pump and system (i.e., pipe, valves, etc.) have been in operation for some time. In addition to the observed loss of head and discharge (i.e., from A to B in the figure), the operating point will be below the maximum efficiency, thus requiring more input power (i.e., BHP). For this reason, pumps are sometimes selected to operate slightly to the right of the optimum point (i.e., point C). In this way, as the pump and system are "broken in", the performance will move left and into the optimum point. However, the use of such techniques, as well as the evaluation of complex systems, e.g., parallel and series pumps, requires further consideration--see Hicks and Edwards (1971), Addison (1966), Holland and Chapman (1966), and Pillai (1969).

Such systematic selection is not usually possible when dealing with the less sophisticated water lifters, such as shadoofs, mots, norias, etc. Although these devices are often built by trial and error (Schioler, 1975) to fit the given installation, a careful analysis of the head and discharge needs, as well as available power (e.g., animal, slow stream, fast wind, etc.) can allow selection of a good water lifter. Furthermore, as was shown by figure 2.7, H-Q curves



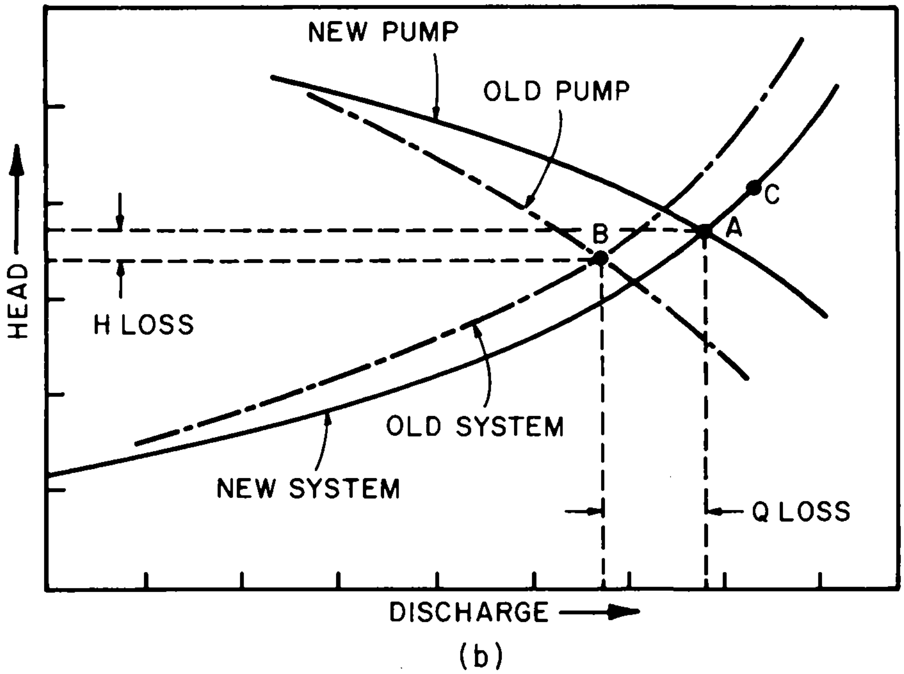


Figure 5.22 Comparing system and pump H-Q curves, (a) to find optimum pump and (b) to observe wear effects

can be developed for any water lifter--even one as simple as the bucket. Such performance curves can be a great asset in improving the application of many of the less sophisticated water lifting devices.

5.3.3 Cost

After the above factors have been considered in the selection process, those water lifters which appear applicable should then be evaluated for economic feasibility. The initial cost alone of some water lifters and pumps may be too great to be economically competitive with others. However, in some instances, a slightly higher initial cost for higher quality may be offset by lower operating and maintenance costs. Likewise, an economic analysis of the pumping system, i.e., pipe, valves, etc. (if one exists) should be considered in relation to the required pump. For example, while smaller diameter pipe may cost less than larger pipe, for a given discharge, the velocity will be greater, and consequently also the friction head in a smaller pipe. Thus, it will require more power and probably a more costly pump to deal with the higher head. The alternative of larger pipe, less power, and a smaller pump should also be considered.

In addition to first costs of the water lifter and system (which may include sinking a well), which should be evaluated as depreciation and interest over the projected life of the equipment, other fixed costs (i.e., taxes and insurance) and operating costs (i.e., power, maintenance, and labor) must be evaluated. The following example illustrates how such an economic analysis may be considered for a mote.

Example 5.1 (after Molenaar, 1956):[*]

Two pair of bullocks and three men are employed to operate a mote which requires 6 hours of operation to provide 1 acre-inch of water with a 30 ft lift.

1. Initial investment:

a) Well digging and lining	$300.00
b) Mote and installation	50.00
c) 4 bullocks (50% of value charged to water lifting)	300.00
Total investment	$650.00

2. Overhead charges:

a) Interest on investment[**] (@ 10%)	$ 65.00
b) Depreciation of equipment[**]	
well (40-year life equals 2½%)	7.50
mote (5-year life equals 20%)	10.00
bullocks (10-year life equals 10%)	30.00
Total annual overhead	$112.50

3. Operating costs per acre-in. (i.e., 6 hours)

a) Bullock feed (@ $0.12/hr per pair)	$ 1.44
b) Labor wages (@ $0.10/hr per man)	1.80
c) Repairs	.05
Total operating costs per acre-in.	$ 3.29

---

[*] Costs adjusted to U.S. dollars (1975).

[**] Interest and depreciation calculated on by the straight-line method.

This type analysis can be developed for any water lifter to observe the annual and operating costs. Figure 5.23 presents the results of such economic analyses for several water lifters used in developing countries in such a manner as to compare them for selection purposes. Note that this figure is for a constant head and varying discharge, however other variable combinations can be utilized.

Such analyses can also be utilized to compare alternative methods of driving a water lifter. The following example compares a Persian wheel driven by bullock and by an electric motor. Note however, that to be adaptable to an electric motor, a better quality, and thus more expensive, Persian wheel was needed.

Example 5.2 (after Roberts and Singh, 1951):*

	Bullock-Driven		Electric-Driven	
1. Overhead charges:				
a) Well (cost $800)				
interest (@ 4%)	$32.00		$32.00	
depreciation (@ 3%)	24.00		24.00	
b) Persian wheel and driver	(cost $120.00)		(cost $500.00)	
interest (@ 4%)	4.80		20.00	
depreciation on wheel (@ 25%)	10.00	(on 40.00)	15.00	(on 60.00)
depreciation on driver (@ 10%)	8.00	(on 80.00)	44.00	(on 440.00)
	$78.80		$135.00	

---

* For example purposes, original data in 1938 rupees was converted directly to 1975 U.S. dollars since 3 rs (1938) ≈ $1.00 (1938) and $1.00 (1938) ≈ $3.00 (1975).

Example 5.2 - Continued

	Bullock-Driven	Electric-Driven
2. Annual operating charges:		
a) Repairs and maintenance	$4.00	$43.00
b) Lubrication	2.00	8.30
Total annual charges	$84.80	$186.30
Above costs/acre-irrigation:*		
by bullock (125)	$ 0.68	---
by electric (172)	---	1.08
3. Motive power (per acre-irrigation) bullock (requires 2.31 days @ $1.00/day)	2.31	---
electric (requires 14.6 Kw-hr @ $0.097/Kw-hr)	---	1.41
4. Manual labor (per acre-irrigation)		
bullock (man @ $2.00 and boy @ $1.00 per day for 2.31 days)	6.93	---
electric (man @ $2.00/day for 1.97 days)	---	3.94
Total cost per acre-irrigation	$ 9.92	$ 6.43
Total cost per acre-inch*	$ 3.76	$ 2.71

---

* Bullock device provided 64 gpm and applied 2.64 in. of water per acre, while the electric version discharged 55 gpm and applied 2.29 in. of water.

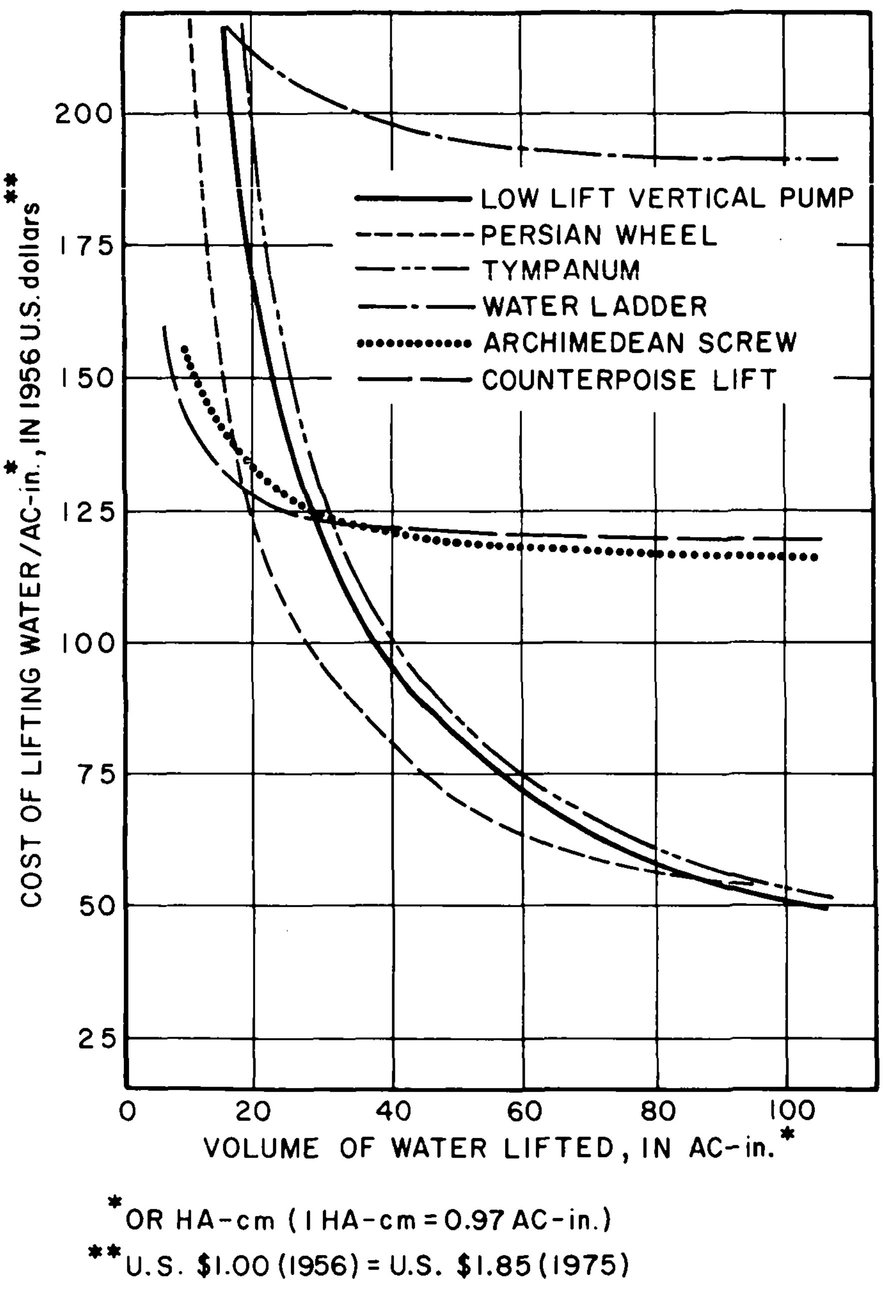


Figure 5.23 Comparative cost of lifting water to a height of 5.0 ft using various devices (from Molenaar, 1956)

Example 5.3 illustrates the same type of comparison between natural gas and electric drivers.

Example 5.3 (after Miles and Longenbaugh, 1968)

The following presents the estimated annual pumping costs for a typical vertical turbine pump lifting 1000 gpm at 260 ft of head. This pump operates 2000 hr per year. The costs are for 1968.

	Natural Gas		Electric	
a) Well (300 ft @ $15/ft = $4500)				
Depreciation and interest (CRF for 25 yrs @ 6%)	$326		$326	
Property tax (1%)	45		45	
		$371		$371
b) Pump ($3854)				
Depreciation and interest (CRF for 15 yrs @ 6%)	397		397	
Taxes, Insurance, and fees	114		114	
		511		511
Pump oil	20		20	
Pump repairs	50		50	
		70		70
Total Annual Well and Pump Costs		$952		$952

Example 5.3 - Continued

	Natural Gas	Electric
c) Power Unit		
Depreciation and interest		
(engine - $3690 over 15 yrs @ 6%)	$380	---
(motor - $2097 over 25 yrs @ 6%)	---	$164
Property tax	32	23
Insurance	16	40
Transmission (motor is close coupled)	110	---
Gas line and accessories	35	---
	$573	$227
d) Operating Costs		
Engine oil and filters	86	---
Plugs and points	56	---
Tune-ups	20	---
Other maintenance	111	20
Oper. & Maint. Labor	115	30
	$388	$ 50
Total Annual Costs other than fuel or electric	$1913	$1229
e) Fuel	901	---
Electricity	---	2040
Total Annual Costs	$2814	$3269

Because not all water lifting operations can easily be evaluated in monetary units, this last example is used to illustrate cost in terms of food consumed. It also analyzes the power and efficiency of the manual operation for a bucket-piston pump.

Example 5.4 (from Allison, 1975):

1. Basic parameters:
   a) One small man under tropical conditions can provide about 2200 ft-lb/min (0.067 hp).
   b) Human efficiency in converting food to mechanical work (beyond basal metabolism) is about 20%.
   c) Work capacity of one man at 2200 ft-lb/min is about 5 hrs/day (excluding rest periods).
   d) A boro crop requires about 33.3 inches of water for a season of 120 days.
   e) Pump efficiency is about 50%.
   f) Crop yields 2,600 lbs of rice per acre.
   g) Area irrigated by single family unit is about 0.5 ac.
2. Calculations:
   a) Energy input = 2200 ft-lb/min = 36.6 ft-lb/sec.
   b) Energy delivered to water (50% eff) = 18.3 ft-lb/sec.
   c) Energy required to lift 1 ft^3 of water 10 ft = 62.4 $\text{lb/ft}^3 \times 10$ ft = 624 ft-lb/ft^3.
   d) Approximate discharge = (18.33 ft-lb/sec) $\div$ (624 ft-lb/ft^3) = 0.03 ft^3/sec = 13.5 gpm.
   e) Water required = 33.3 in. x 0.5 ac. = 16.7 acre-in. = 450,000 gallons (U.S.).
   f) Time required $= \dfrac{450{,}000 \text{ gal}}{13.5 \text{ gpm}} \times \dfrac{1 \text{ hr}}{60 \text{ min}} = 556$ hours

   i.e., this is less than the 5 hr/day working limit over the 120 day season.

Example 5.4 - Continued

3. Food required to generate energy:

   a) To work at 2200 ft-lb/min with a 20% efficiency, requires man to have an energy input =

   $$\frac{2200 \times 60}{0.20} = 660{,}000 \text{ ft-lb/hr.}$$

   which at 3087 ft-lb/calorie = 214 cal/hr.

   b) In 556 hours of pumping, the worker will use

   $$556 \times 214 = 118{,}000 \text{ cal.}$$

   c) At 1814 calories per lb of rice, this is equivalent to

   $$\frac{118{,}000}{1814} = 66 \text{ lbs of rice.}$$

   d) This energy input of rice required for the lifting of water is thus about 2.5% of the expected 2,600 lb yield.

These examples of cost analyses have been presented to illustrate their use in the selection of water lifters and prime movers. When coordinated with water requirement, availability, and adaptability considerations, such analyses become part of a systematic approach for efficiently matching water lifter and driver to a given application.

Chapter 6

Improvements and Research Needs

6.1 Introduction

The current state of water lifting methods in the world, as seen through the preceding chapters, varies from ancient to futuristic. With this vast difference in technological levels, emphasis in the past has all too often been on refining recent advances or developing new variations for sophisticated applications. However, the present world energy situation and international assistance organizations have called attention to the need for improving the often grossly inadequate methods used in developing countries. These improvements must be done without making the improved methods dependent on imported parts or fuel for maintenance and operation.

6.2 Modifications to Existing Methods

Additional studies are needed to determine designs and applications of existing methods which maximize efficiency. Too often traditional devices have been passed along for generations without any thought toward efficiency. Even in developed nations using modern pumps, emphasis is on maximum discharge for most irrigation and drainage purposes. However, the need to conserve energy has focused attention on efficiency.

The tympanum study, mentioned in section 3.3.1.6, which compared the discharge performance of various designs was a step in this direction. However, additional research was suggested there to include power and efficiency analyses. Similarly, the SEATO thesis in section 3.3.1.2 developed performance characteristics of just one size and design of a water ladder, which was powered by one type of prime mover. The performance of other water ladder designs, with a variety of prime movers and transmissions needs to be studied also to better evaluate its application and provide criteria for selection.

With such studies as the two above serving as basic examples, similar research into the performance of other water lifters needs to be conducted. As mentioned throughout this thesis, data on many devices is either non-existent or available in only a limited quantity and quality for a scattered or narrow range of capacities, heads, and designs. A survey study is initially needed to determine the present levels of usage and possible benefits of modification for each type of water lifter. In this manner, a priority for detailed performance studies can be made to organize a thorough research program. Through the review of references for this thesis, some specific lifters which have a lack of data, but would appear to benefit from such studies include: (a) the mot, particularly the circular mot driven by other than animal power; (b) the counterpoise lift and doon, with emphasis on counterweight placement and weight to minimize manual effort without the present trial-and-error construction techniques; (c) the picottah; (d) the bellows (as partially undertaken by IRRI); and (e) all screw and wheel devices with particular attention to presenting performance as a function of size, power, and speed of operation (i.e., rpm). Among the missing data on most of these devices is cost. Some basic cost parameters such as cost of construction or initial purchase, and of operation, need to be established to provide a practical component for the selection process (section 5.3).

These studies must include a thorough program encompassing a survey of user's needs, design, testing and evaluation. Such a program was undertaken by Battelle Institute on its AID hand pump and serves as a good example for further projects (Fannon and Frink, 1970). The feasibility of manufacturing these improved designs with local industry must be kept in mind during these studies. Not only does this minimize foreign dependence, but also increases local employment.

A few specific improvements which might be considered are; (a) the use of flexible tubing in the construction of tympanums and screws (see figure 3.47a), (b) use of multiple pulley systems to reduce load and therefore animal size or number in mots, and (c) the increased use of flap valves in devices which require submergence of a container (e.g., gutters, shadoof, etc.). An idea, similar to that of the Ag Bank's to build Persian wheels from truck differentials (Svendsen, 1975), is to use automotive rear axles, set vertically on one end, for a circular sweep which can be used with animal power to drive wheel-type water lifters. Specifically, a horizontal arm can be welded (or otherwise attached) to the wheel at the upper end of the axle from which to harness the animal, while the drive-shaft from the water lifter can be attached to the differential--where the automotive drive-shaft was originally connected. Additionally, combinations of prime movers should be studied, e.g., the use of bicycle and manual power in rotary devices, using wind- or watermills with several rotary lifters, and making prime movers more economical by time-sharing among other duties. The improvement of existing prime movers and transmissions is equally as important toward increasing overall water lifting efficiencies. Prime mover studies should not be limited to mechanical methods. Programs to optimize wind- and watermill efficiencies could follow a format of planning, testing, and evaluation similar to that advocated above for water lifters. Coordination of physiological information on manual and animal power with the designing of water lifters is another area which could substantially improve and encourage the use of often under- or unemployed labor resources. The linkage and gear system developed to allow manual power with a centrifugal pump is a good example of such designing (see section 5.2.1).

Although such projects can undoubtedly improve water lifting methods, without an equal amount of effort to distribute information of new developments, they are of little use. In addition, education in operating and maintenance techniques must accompany any device into the field to avoid inefficient performance and/or breakdown with later abandonment. The introduction of modern pumps into a developing region should eventually lead to the development of the light or medium industry in that region which can supply and service water lifting operations. This can also create employment for individuals replaced by mechanical drivers (Wade, 1975). A shift in attitudes (by education) is also needed to reduce the emphasis often placed on using larger or more modern devices. The use of animal power should be particularly encouraged in the many developing areas where working livestock is in abundance but often stands idle. In these areas, animal power is usually found to be cheaper to utilize than mechanical power when evaluated on an annual cost basis (Svendsen, 1975).

6.3 Technological Gaps

Although many improvements to water lifters are possible within the limitations of current technology, there are also several advancements which will require the discovery of new technologies and refinement of areas which are just now at the threshold stage. These are primarily in the generation of usable energy, e.g., solar, geothermal, nuclear, tidal. Reynolds (1970) writes, "...man must pay more attention to the development of natural power, conserving where he can the world's depleted stocks of fuel."

The National Academy of Sciences (1972) specifically advocates research to develop semi-conductor solar generators and working fluid solar engines (see section 5.2) to lift water. The automotive world has recently reminded us that the internal combustion engine is relatively inefficient, but still capable of major improvements. Nuclear power originally appeared as an answer to natural energy resource shortages, however, environmental and safety problems (or potential problems) are delaying development of this resource.

Inventories of the world's energy potentials are also needed to plan application of various prime movers in different geographic areas. Long, accurate records of such resources as wind and solar energy are usually available in developed countries, but often non-existant in developing areas.

Policies regarding the economics of our resources must also be changed in many areas to both promote conservation and encourage more, but smaller users. The economics of obtaining energy from recycled material (e.g., methane from plant and animal wastes) must be made advantageous so as to both conserve untapped resources and to utilize to the fullest those resources already in use. As mentioned in previous sections, our technology is too often aimed at the large industries and/or at refining already sophisticated devices. However, as E. F. Schumacher advocates (Wade, 1975), improvements and advancements in technological methods and equipment need to be made "suitable for small scale application." The solar pump, described in section 3.4.2.2, is an example of such a need to "scale down." At the present prototype size and cost, this water lifting method is too large and costly for the low-acreage farmer in developing countries--although he could probably benefit the most from such a "free" natural-energy pumping method.

This is not to say that water lifting advancements should be retarded, but only that they should include small-user applications. Just as engineers at the turn of this century thought that no pump could outperform the steam pump (see section 1.2), the current level of pumping technology must not be considered the last word. Advances such as the KROV pump (Keller, 1975) and the osmotic pump (Levenspiel and de Nevers, 1974) may eventually turn out to be among the commonplace water lifters of the future.

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APPENDIX

Table A.1 Length conversions and abbreviations

For example, read: 1 inch = 2.54 centimeters

abbr. unit	in.	cm	ft	m
inch	1.0	2.54	0.0833	0.0254
centimeter	0.394	1.0	0.0328	0.01
foot	12.0	30.5	1.0	0.305
meter	39.4	100	3.28	1.0

1 mile (mi) = 1.61 kilometer (km) = 5280 ft

1 yard (yd) = 3 ft

Table A.2 Area conversions and abbreviations

For example, read: 1 square foot = 0.093 square meters

abbr. unit	ft^2	m^2	ac	ha
$foot^2$	1.0	0.093	2.30×10^{-5}	9.3×10^{-6}
$meter^2$	10.76	1.0	24.7×10^{-5}	1×10^{-4}
acre	43,560	4,047	1.0	0.405
hectare	107,630	10,000	2.47	1.0

1 centare (ca) = 1 m^2
1 $in.^2$ = 6.45 cm^2
1 ft^2 = 144 $in.^2$

Table A.3 Volume conversions and abbreviations

For example, read: 1 cubic foot = 0.0283 cubic meters

abbr. unit	ft^3	m^3	l	gal	ac-ft
foot^3	1.0	0.0283	28.3	7.48	$2.30\mathrm{x}10^{-5}$
meter^3	35.3	1.0	1,000	264.2	$8.11\mathrm{x}10^{-4}$
liter	0.0353	0.001	1.0	0.264	$8.096\mathrm{x}10^{-7}$
U.S. gallon	0.134	0.00379	3.79	1.0	$3.07\mathrm{x}10^{-6}$
acre-foot	43,560	1,233.5	1,235,131	325,892	1.0

1 U.S. gallon = 0.833 Imp. gallon = 8.33 pounds water @ 60°F

1 ft^3 = 1728 $\mathrm{in.}^3$ = 0.037 yd^3

Table A.4 Pressure conversions and abbreviations

For example, read: 1 foot water = 0.433 pounds/square inch

abbr. unit	ft water	psi	in. Hg	mm Hg	kg/cm^2
foot of water	1.0	0.433	0.833	22.43	0.0304
$\frac{\text{pounds}}{\text{inch}^2}$	2.31	1.0	2.04	51.82	0.0703
inch of mercury	1.133	0.491	1.0	25.4	0.0345
millimeters of mercury	0.0446	0.0193	0.0394	1.0	0.0014
$\frac{\text{kilograms}}{\text{centimeter}^2}$	32.8	14.22	28.97	736.03	1.0

Table A.5 Velocity conversions and abbreviations

For example, read: 1 foot/second = 0.305 meters/second

abbr. unit	fps	mps	mph	km/h
$\frac{\text{foot}}{\text{second}}$	1.0	0.305	0.682	1.097
$\frac{\text{meter}}{\text{second}}$	3.28	1.0	2.24	3.6
$\frac{\text{mile}}{\text{hour}}$	1.47	0.447	1.0	1.61
$\frac{\text{kilometer}}{\text{hour}}$	0.911	0.278	0.621	1.0

1 knot = 1.151 mph

Table A.6 Discharge conversions and abbreviations

For example, read: 1 cubic foot/second = 488.8 gallons/minute

abbr. unit	cfs	gpm	1/sec	mgd
$\frac{\text{foot}^3}{\text{second}}$	1.0	448.8	$9.81x10^{-6}$	0.646
$\frac{\text{gallon}}{\text{minute}}$	$2.23x10^{-3}$	1.0	0.063	$1.44x10^{-3}$
$\frac{\text{liter}}{\text{second}}$	101,937	15.87	1.0	0.0229
$\frac{\text{million gallon}}{\text{day}}$	1.55	694.4	43.7	1.0

1 cubic foot per hour (cfh) = 3600 cfs

Table A.7 Power conversions and abbreviations

For example, read: 1 horsepower = 0.746 kilowatts

abbr. unit	hp	kw	$\frac{\text{ft-lb}}{\text{sec}}$	$\frac{\text{kg-cal}}{\text{min}}$
horsepower	1.0	0.746	550	10.55
kilowatt	1.34	1.0	737.6	14.34
$\frac{\text{foot-pound}}{\text{second}}$	$1.82x10^{-3}$	$1.36x10^{-6}$	1.0	$1.94x10^{-2}$
$\frac{\text{kilogram-calorie}}{\text{minute}}$	0.0935	0.0697	51.43	1.0

1 hp = 1.014 metric hp

Table A.8 Specific speed (N_s) conversions

For example, read: N_s = 1 (cfs, ft, rpm) equals N_s = 21.19 (U.S. gpm, ft, rpm)

Units of Quantity and Head*	(1) cfs ft	(2) U.S. gpm ft	(3) Imp. gpm ft	(4) l/sec m	(5) m^3/sec m	(6) m^3/n m
(1)	1.0	21.19	19.34	12.98	0.41	24.63
(2)	0.047	1.0	0.91	0.61	0.019	1.16
(3)	0.052	1.096	1.0	0.67	0.021	1.27
(4)	0.077	1.63	1.49	1.0	0.032	1.90
(5)	2.44	51.64	47.13	31.62	1.0	60.0
(6)	0.041	0.86	0.79	0.53	0.017	1.0

*Rotational speed in revolutions per minute (rpm)

Table A.9 Miscellaneous conversions

Weight

1 ft^3 water = 62.4 lbs
1 liter water = 1 kg
1 gal water = 8.35 lbs
1 lb (avoir) = 1.215 lb (troy) = 0.0005 ton (short)
= 0.000446 ton (long) = 0.454 kg

Temperature

Temp °C = [Temp °F - 32] x 5/9

Work

1 BTU = 777.6 ft-lbs

Table A.10 Symbols

A - area
BHP - brake horsepower
D - diameter
D - drawdown
E - energy (expressed as head)
Eff - efficiency
g - acceleration due to gravity
H - head
HP - horse power
HWL - high water level
K - constant used for unit conversion in equations
LWL - low water level
ms - minimum submergence
N - operating speed in evolutions or strokes per unit time
N_s - specific speed
NPSHA - net positive suction head available
NPSHR - net positive suction head required
OAE - overall efficiency
P - pressure
Q - discharge
T - time
V - volume
v - velocity
WHP - water horsepower
Z - elevation
γ - specific weight
ρ - specific mass