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PUMPS AND WATER LIFTERS FOR RURAL DEVELOPMENT

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## Chapter 1

### 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 (SOTA) presents 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 inventories 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 adaptations of existing devices which can be used with natural prime movers, in light of recent energy shortages.

This report is condensed from the Master Thesis of the senior author. His Master of Science studies and the preparation of this report were sponsored by the U. S. Agency for International Development under contract AID/csd-2460, Institutional Development Grant on Optimum Utilization of Water Resources with Emphasis on Water Driving and Removal Systems.

### 1.2 Historical Review of Water Lifting

Archaeology gives us some clues as to the early forms of water lifting. 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 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 3.3) 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.

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 3.20); however, dates vary anywhere from 1500 to 3000 B.C. (Ewbank, 1876; Eubanks, 1971; Rouse and Ince, 1963). 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 pots such as in Figure 3.1 (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 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 3.21)--a self-powered waterwheel (Roger, 1905). Although wind and waterpower developed during the second millennium 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 and 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 3.25 (Tokaty, 1971).

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" (Ivens, 1920).

Although references do not mention the invention of the paddle or scoopwheel (Figure 3.17), sometime during the last centuries B.C., the Chinese modified this scoop-rotary water lifter into the water ladder (Figure 3.18). 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. 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. In the 15th century A.D., Leonardo da Vinci used a 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 Philehert 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. Some consider this to be the first centrifugal pump, however the action is purely positive displacement.

In the early 17th century, the first gear rotary pump was invented by Grollierde Serviere. Galiler also 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).

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, were 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 1.1). 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.

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 the design to increase steam pressure and thus, performance.

In 1730, Demour designed and built the vertical pump in Figure 1.2 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).

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. About this same time, John Smeaton is credited with developing the idea of the hydraulic ram (Tokaty, 1971). However, the first ram known to be built was constructed by

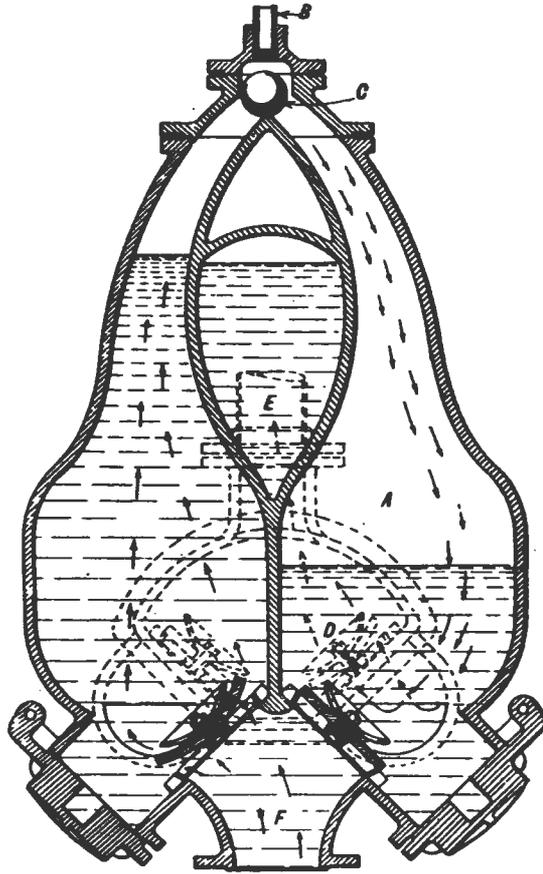


Figure 1.1 Pulsometer

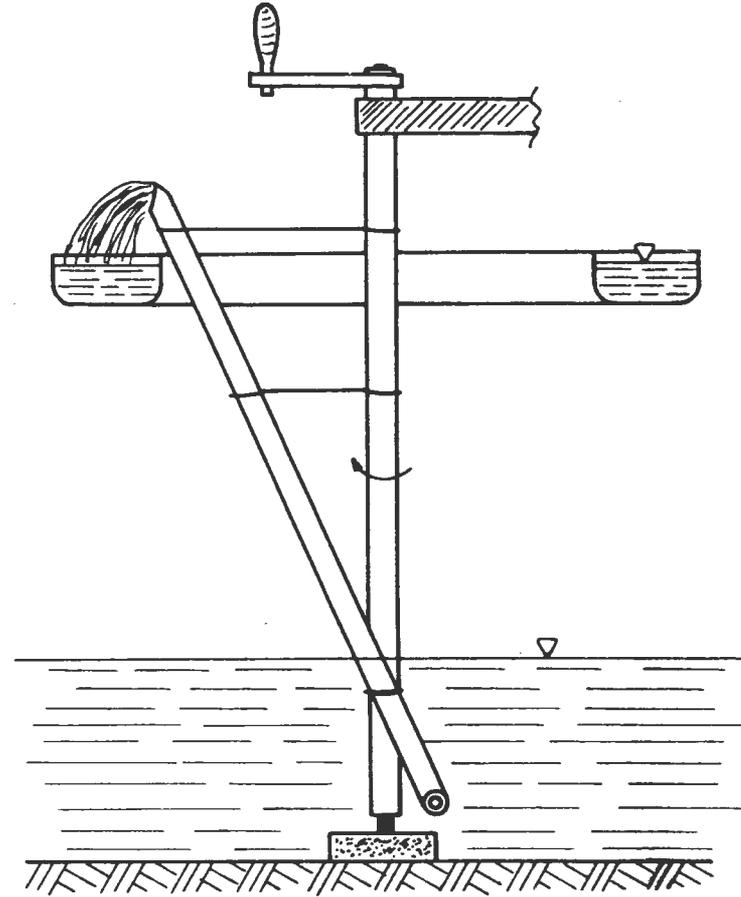


Figure 1.2 Demour's centrifugal pump

Whitehurst in 1772, although it required manual opening of a valve to operate. The first self-acting ram was built in 1796 by Montgolfier and in 1797, Matthew Boulton got the first patent on such a hydraulic ram.

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 (Lazarkiewies and Trokolanski, 1965).

With the beginning of the 19th century, rotodynamic pumps finally received notice and began to develop. In 1816, M. Jorje took the novel centrifugal of Figure 1.2 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 1939 *The Engineer* (London). Several other improvements and design alterations were also made by the Americans, Andrews, Johnston, and Bessemer, and the Englishmen, Appold, Thompson, and Guynne, which brought about rotodynamic pumps as we know them today.

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. (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 key to draining the valuable polder land. (The Engineer, 1869 and 1870; 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 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. After 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."

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 which was developed from the principle of John Barber's 1791 explosion pump.

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.

### 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 along 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.

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 Pump 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.

## 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

---

<u>Criteria</u>	<u>Examples</u>
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, broiler-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 sub-classes, utilizing several of the criteria listed in Table 2.1.

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. Therefore, this section discusses the basic water lifting parameters; head, discharge, power and efficiency as they apply to all methods.

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

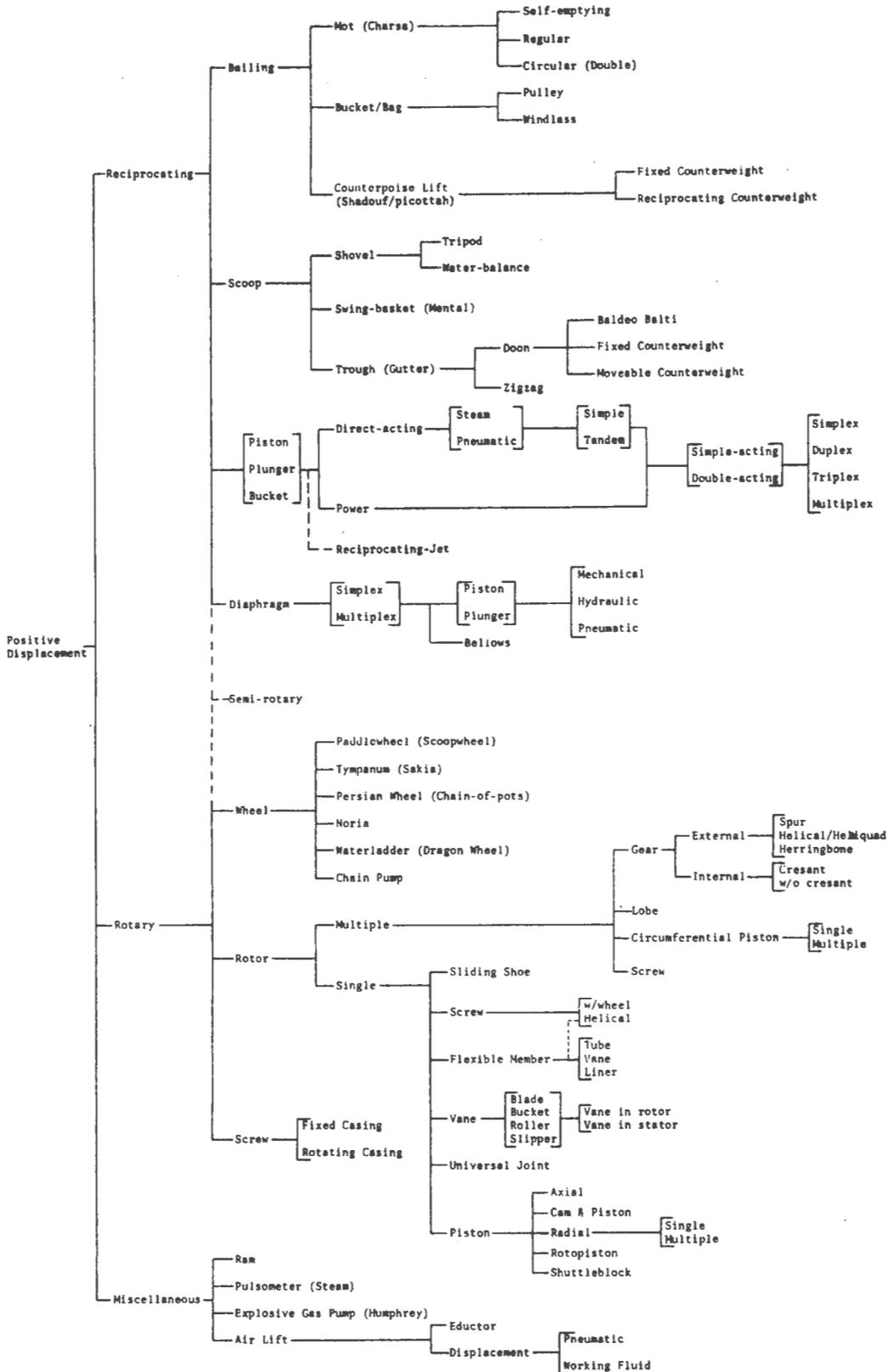
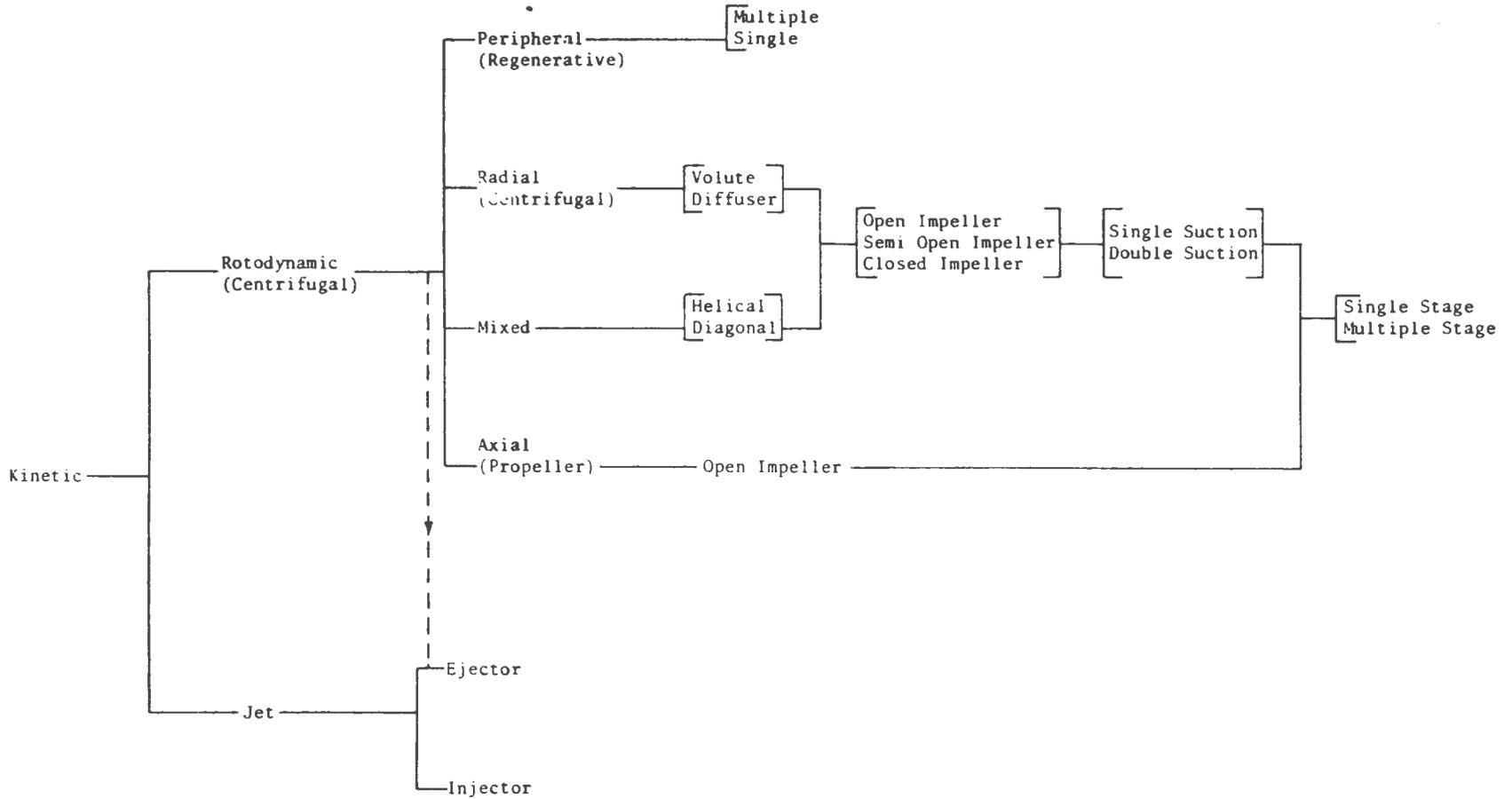


Table 2.2b Classification of water lifters and pumps--kinetic methods



### 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 the lifting device or pump delivers. 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.

### 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. 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, when the system is at rest. In devices, which have 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.
- (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.

- (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.
- (d) Total static head ( $H_{TS}$ ) is the vertical distance from the static supply surface to the free delivery elevation, i.e.,  
When a suction lift exists,

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

or, when a suction head exists,

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

- (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 great enough to be significant.
- (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.
- (g) Pressure head ( $H_p$ ) need only be considered in systems 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) 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.
- (i) 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), i.e.,

$$H_{DSL} = H_{SSL} + H_{FS} - H_{VS} \quad (2.3)$$

- (j) Dynamic suction head ( $H_{DSH}$ ) is the sum of the static suction head and suction velocity head, minus suction friction head and drawdown, i.e.,

$$H_{DSH} = H_{SSH} + H_{VS} - H_{FS}' \quad (2.4)$$

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

$$H_{DSH} = H_{SSH} - H_{FS} - D \quad (2.5)$$

- (k) Dynamic discharge head ( $H_{DD}$ ) is the static discharge head plus the discharge friction and velocity heads, plus any pressure head. When velocity head is considered,

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

or where a pressure head exists,

$$H_{DD} = H_{SD} + H_{FD} + H_P \quad (2.7)$$

- (1) 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,

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

but where a suction lift is present,

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

As shown in Figure 2.1, 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 illustrated in the example system head curve of Figure 2.1.

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.

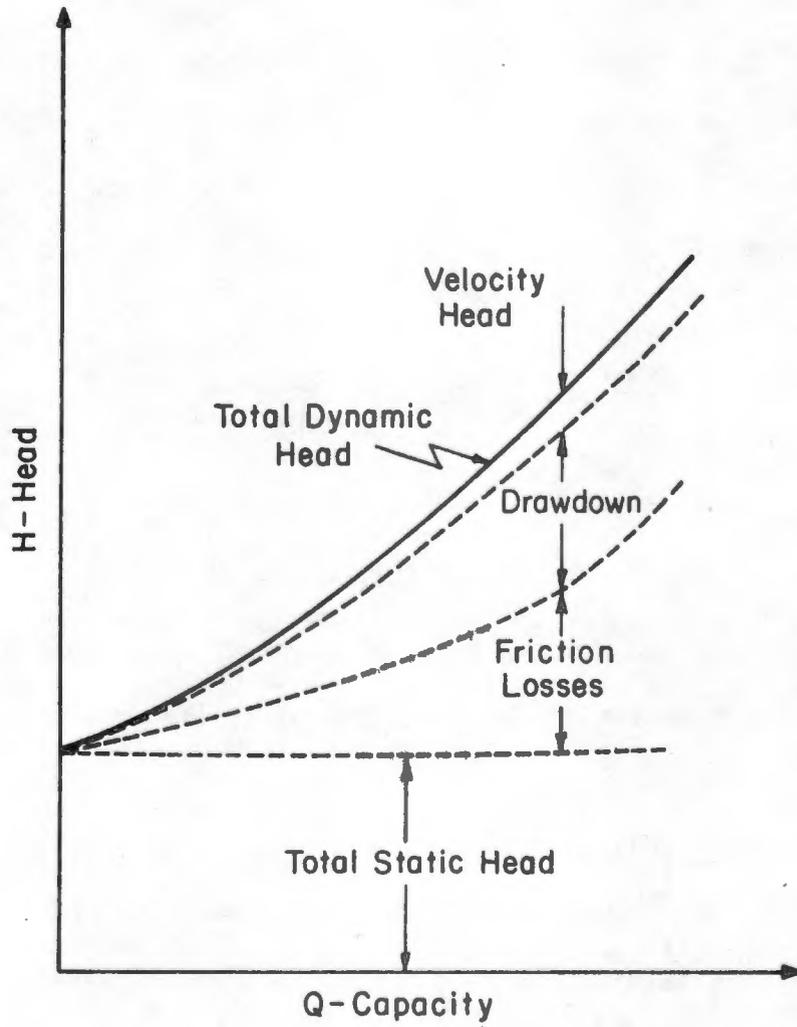


Figure 2.1 Example system head curve showing the change of TDH components with Q

NPSHR is the maximum dynamic suction lift which a pump can handle 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 New Positive Suction Head Available (NPSHA) should be determined for any pumping system planned, and should always exceed the NPSHR. From Figure 2.2

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

where  $P_{\text{atm}}$  = absolute atmospheric pressure, and

$P_V$  = vapor pressure of pumped liquid.

$P_{\text{atm}}$  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.

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

$$\text{WHP} = \frac{Q \cdot H_{\text{TD}} \cdot \gamma_w}{k}, \quad (2.11)$$

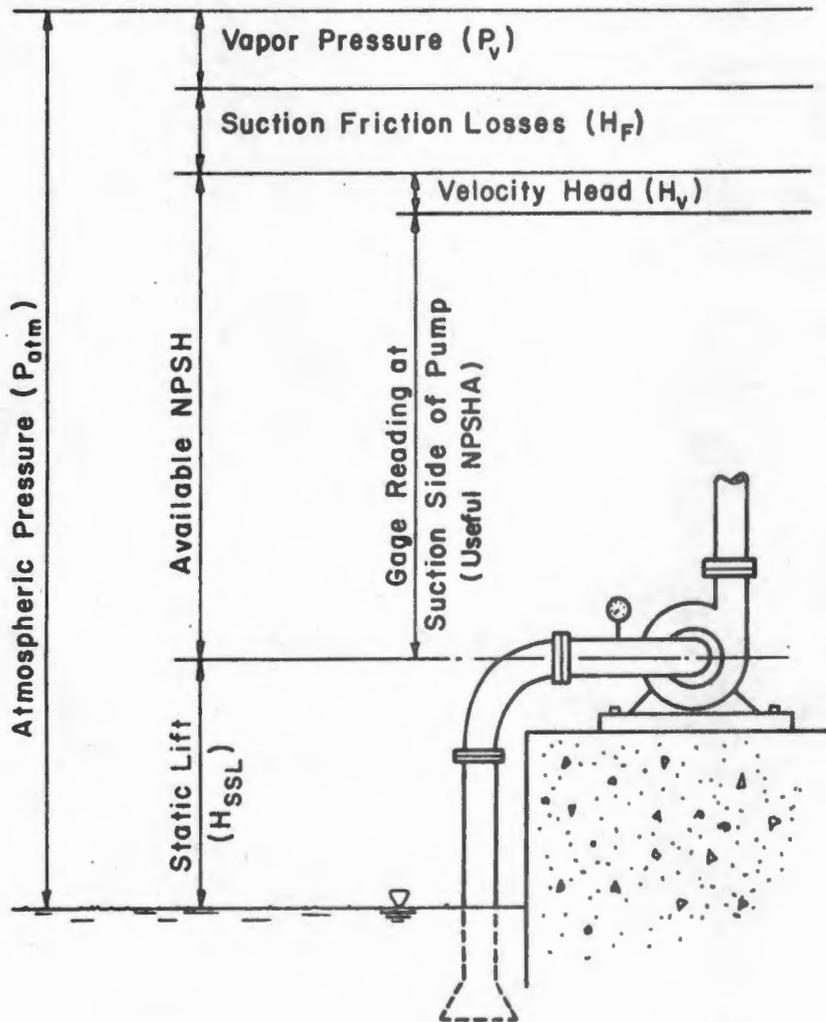


Figure 2.2 Net positive suction head (NPSH)

where

$\gamma_w$  is the specific weight of water and  $K$  is a constant which depends on the units of measurement used for the other terms.

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.

#### 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,

$$\text{Eff} = \frac{\text{WHP}}{\text{BHP}} \quad . \quad (2.15)$$

An efficiency can also be calculated for the prime mover which supplies the BHP to the water lifter. Where the method of transmitting this prime mover power (BHP) 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,

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

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 2.1 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. 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 2.3. Similarly, the variation of BHP and Eff with Q can be plotted. These performance curves are not limited to modern pumps.

These four characteristic parameters are often plotted together for a specific device using Q as the common abscissa. A fourth curve,

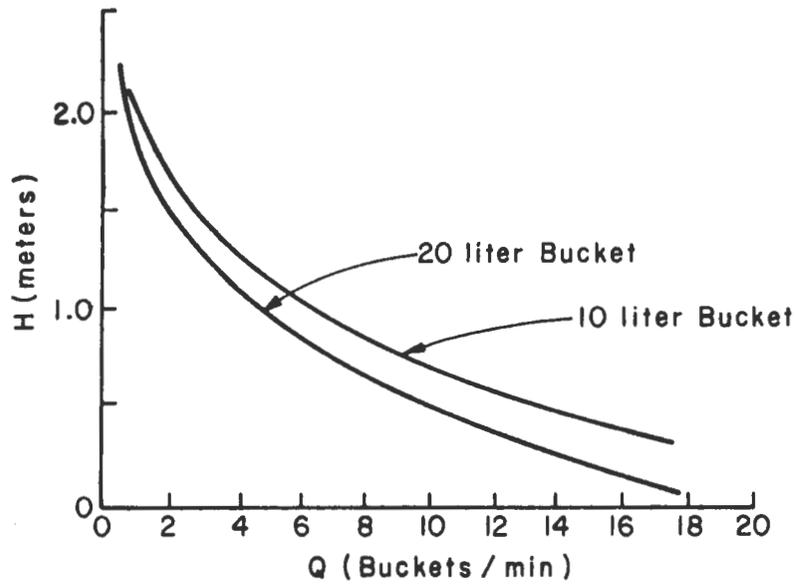


Figure 2.3 Example H-Q curve  
(not based on actual data)

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

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 lifters have one thing in common which is the basis for their classification.

#### 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 2.3, 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 (Weisback and Herrmann, 1897) reports that using a  $0.35 \text{ ft}^3$  (10 liter) 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 0.033 WHP.

When the required 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 passes, or (c) utilizing a pole or rope (chain, etc.) attached to the bucket. Alternative (a) is a continuation of Figure 2.3, 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 hand 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 of overcome friction. However, centering the bucket over the well or water source 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. 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, the amounts 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.

Of course, with the introduction of such mechanical devices as the pulley, friction losses become a reality and will be reflected as the difference between the measured pull and that predicted by theory. 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,

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

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).

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 in use in developing countries for centuries. Among the other names found for this device are:

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

Several variations of this basic device are often used to improve its efficiency and performance. Where possible, the animal(s) walk down a slight incline (usually 5 to 10 degrees), thereby utilizing its weight (i.e., gravity) to aid in the lifting (Figure 3.1). Often 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

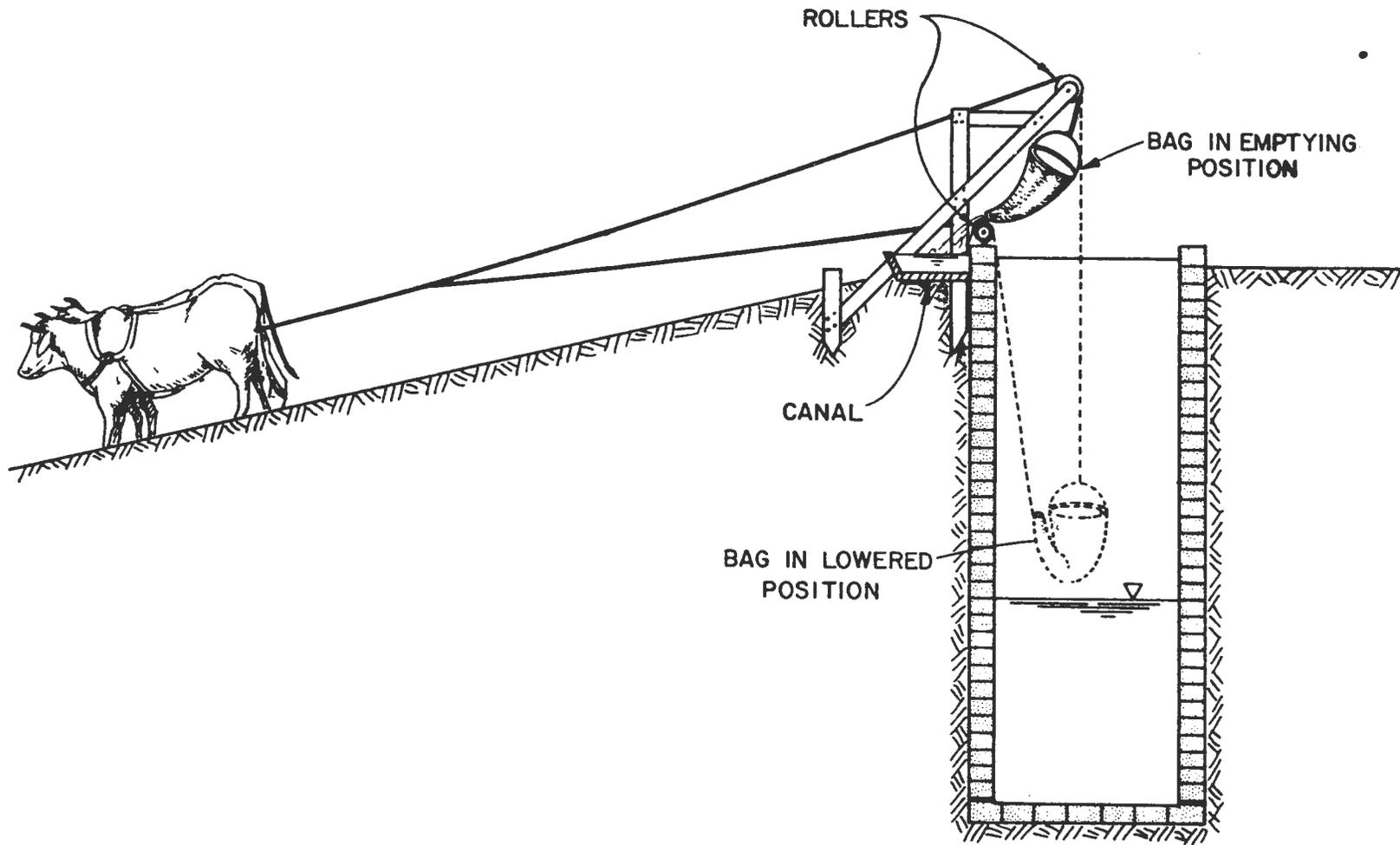


Figure 3.1 Self-emptying mot with inclined tow path

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 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). Lifts usually vary from 10 to 50 feet for not 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 3.2. 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

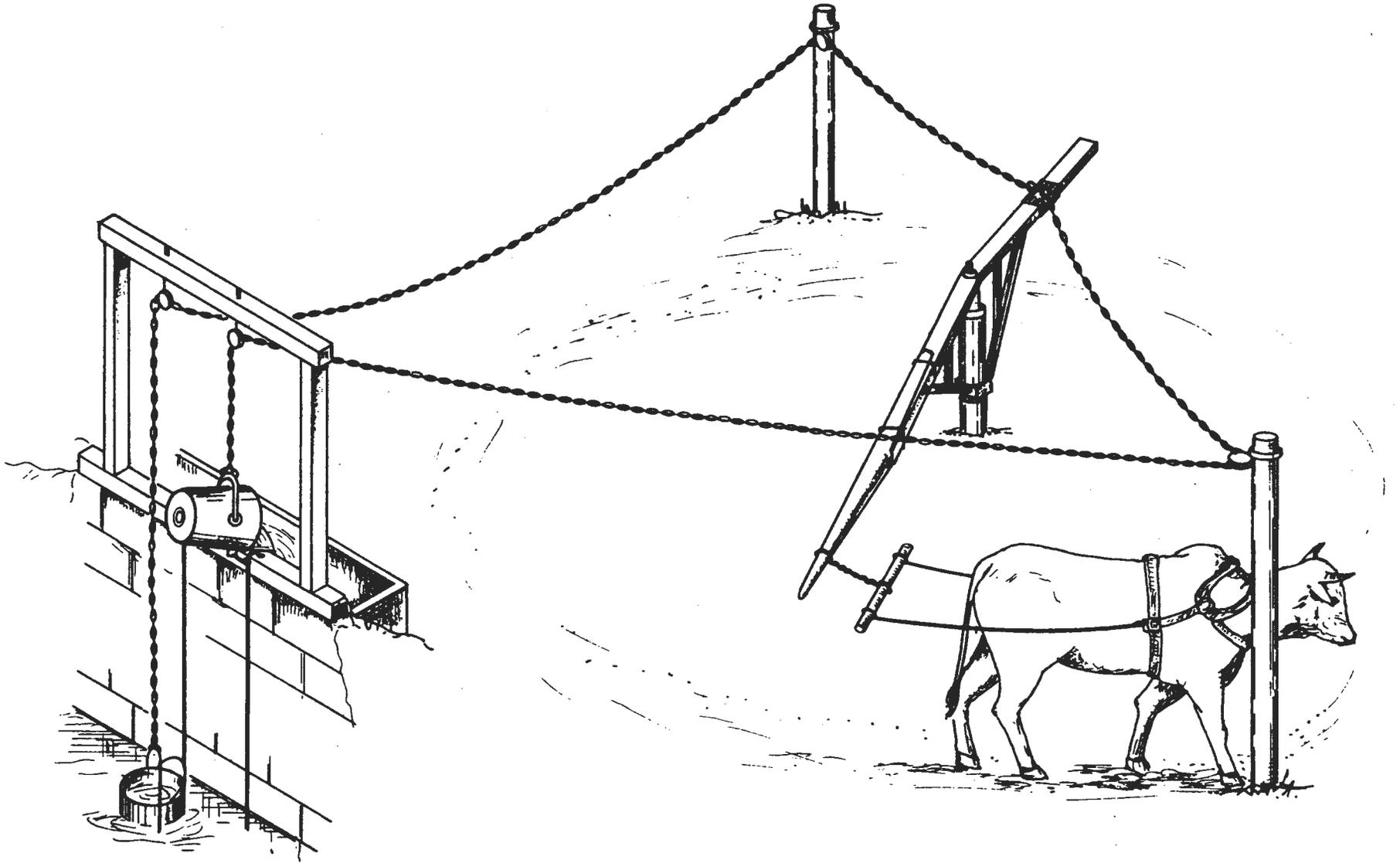


Figure 3.2 Circular mot utilizing two buckets with flap-valves in bottom

here, the circular mot is 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 and the land needed to grow feed for the animal (multiplied by the percentage of time for water lifting) must also be included in initial costs. In addition, the cost of feed or loss of production of the land must be considered in the operating cost.

#### 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 increased capacity (load) of a bucket and rope. Many variations of the windlass are possible, including combinations with pulleys, gears, treadmills, etc. 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. 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 losses. No data appears available on the performance and cost of this simple lifter.

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\* Costs throughout this paper have been adjusted to 1975 United States of America Dollars.

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

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

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 3.3, this level pivots about a horizontal cross-bar 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

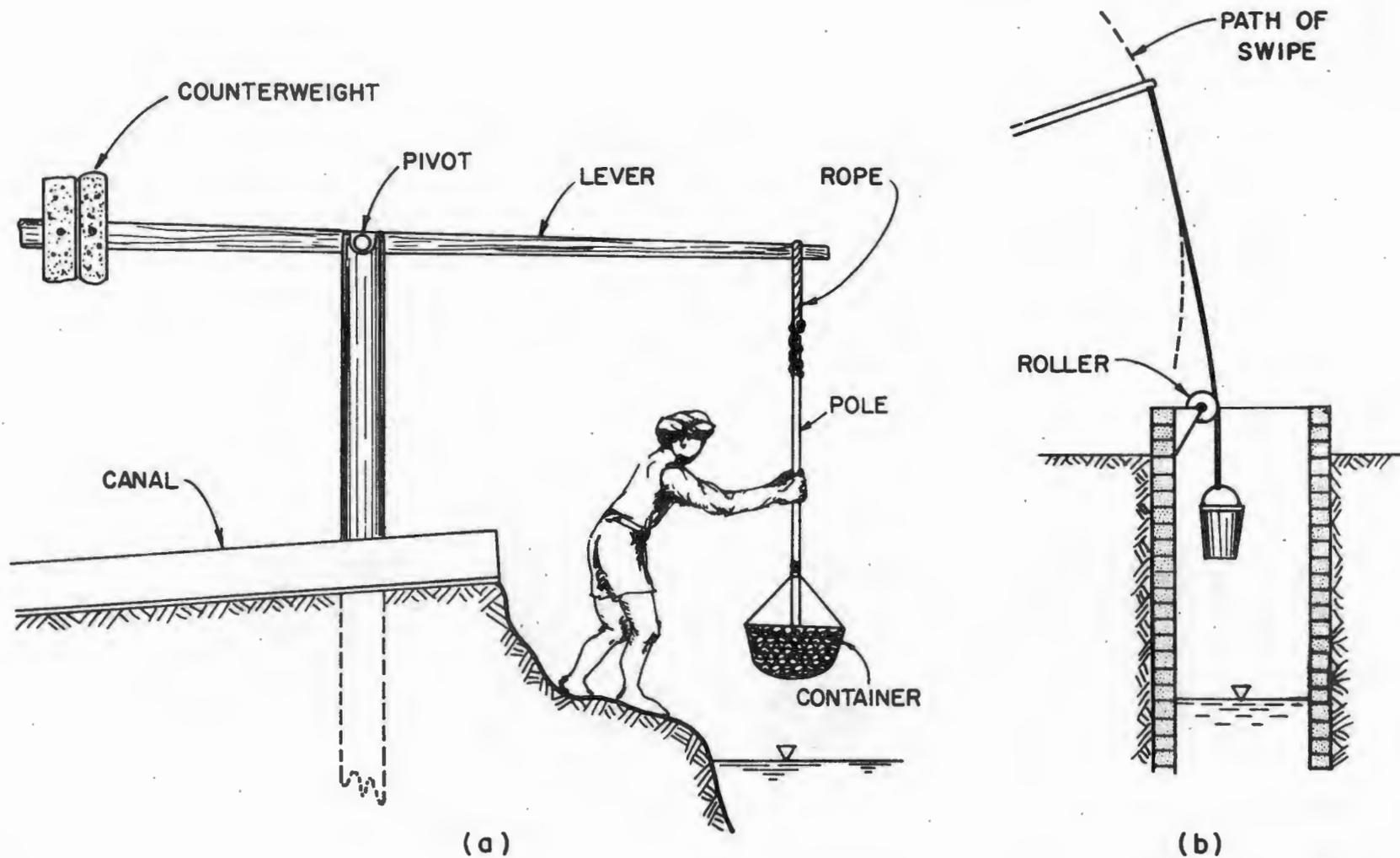


Figure 3.3 (a) Counterpoise lift, and (b) with roller for narrow well

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 3.3), a rope or chain may be used instead of a pole. When the lift of 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 be 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.

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 3.4). 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

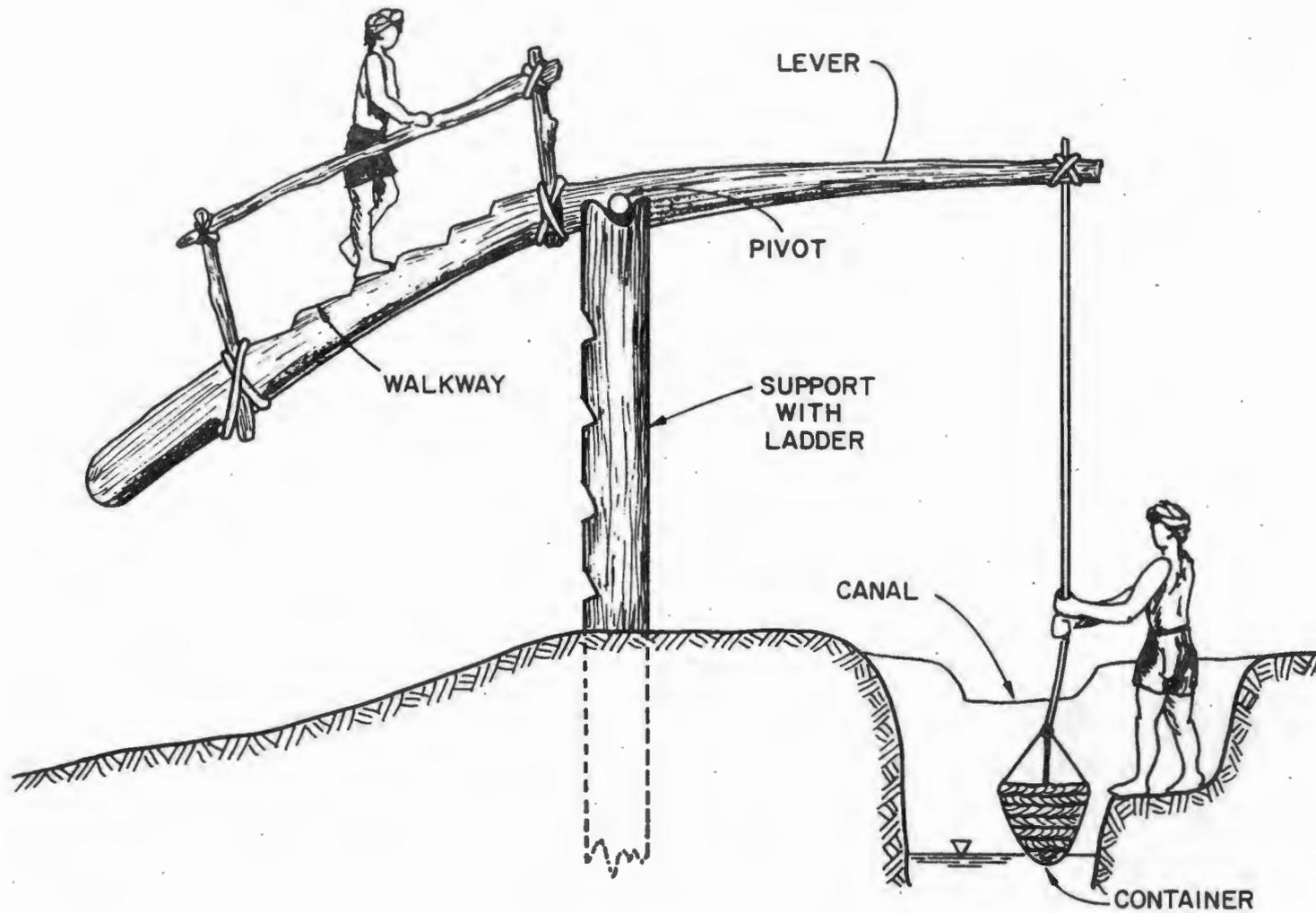


Figure 3.4 Picottah, using man as moveable counterweight

Table 3.1 Shadouf performance

<u>Lift (ft)</u>	<u>Discharge (cfh)</u>	<u>Reference</u>	<u>Remarks</u>
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

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 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 usually done to throw the water up. This simple device is also referred to as:

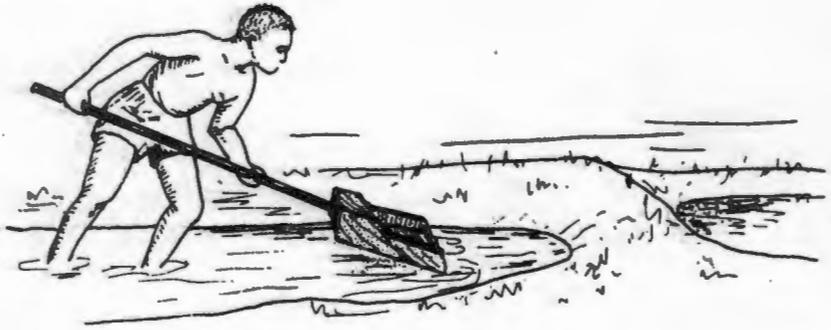
latha	katweh	jhatta (Pakistan)
mental	basket scoop (India)	

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 with 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.

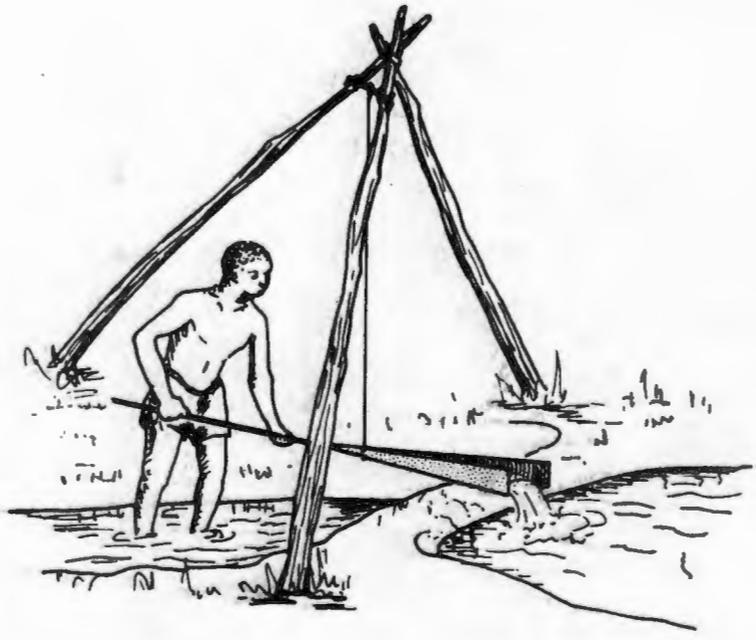
Of course, the initial cost of the basket and ropes is very little and repairs can be made almost immediately.

#### 3.2.2.2 Shovel or Scoop

By merely using a semi-enclosed shovel, such as the Dutch scoop in Figure 3.5, a single person can throw water. However, Weishack 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 3.5. 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.



(a)



(b)

Figure 3.5 Scoop (a) used as shovel, and (b) with tripod

This device can be quite simple 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.

This throwing method can be modified by another device to increase performance. The water balance shown in Figure 3.6 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. Although the oscillations per unit time will vary with size of balance and number of operators, Weisback and Herrmann (1897) report that about 4700 to 5500 cfh can be raised 4 feet.

### 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 3.7a (also note flap valve). Where this device is used extensively in Portugal, it is called cegonho (translated as swipe, from Dias, 1953). Another modification is to use the picottah principle and have the operator shift his weight back and forth on a "seesaw" gutter as seen in Figure 3.7b. 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

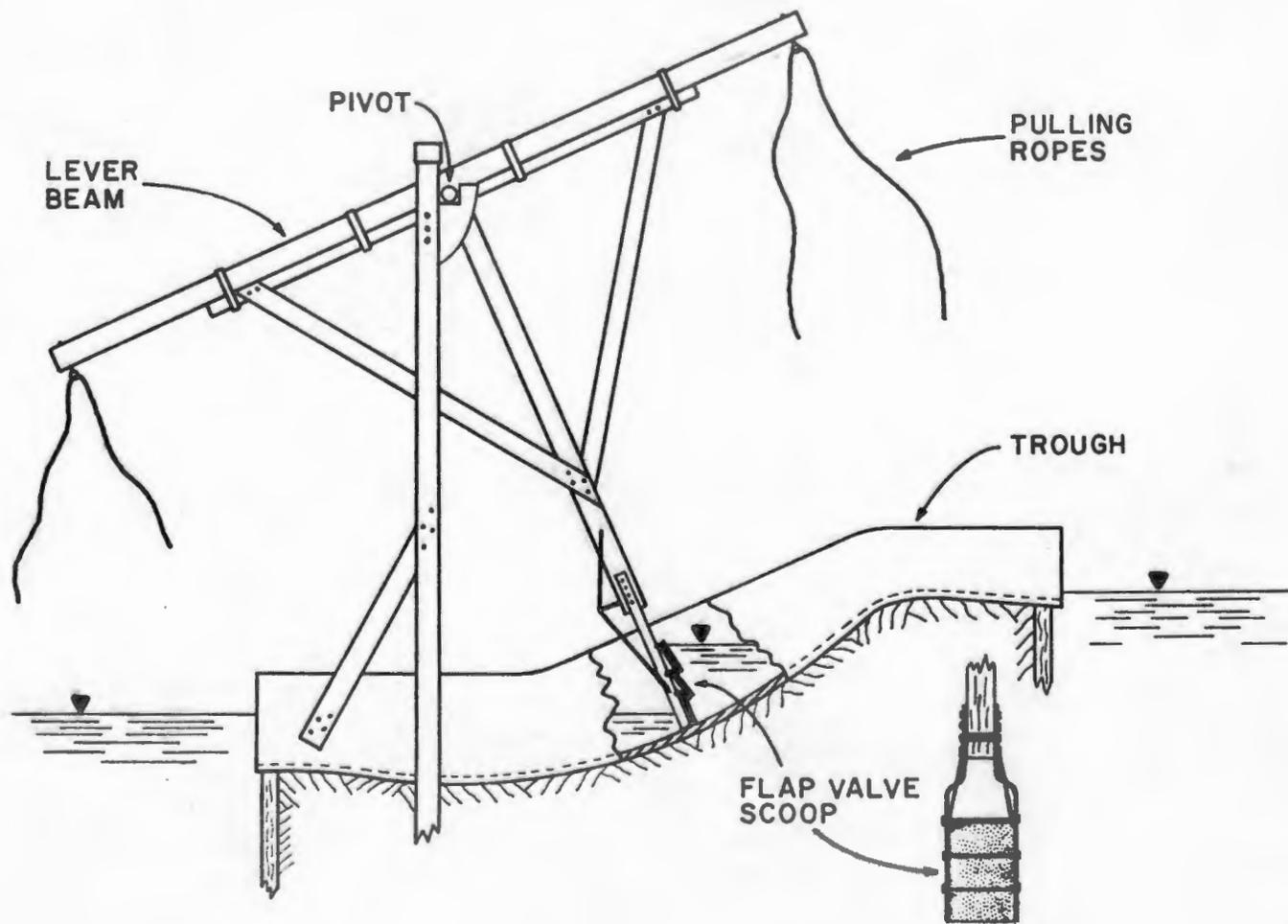


Figure 3.6 Water balance with flap-valve scoop

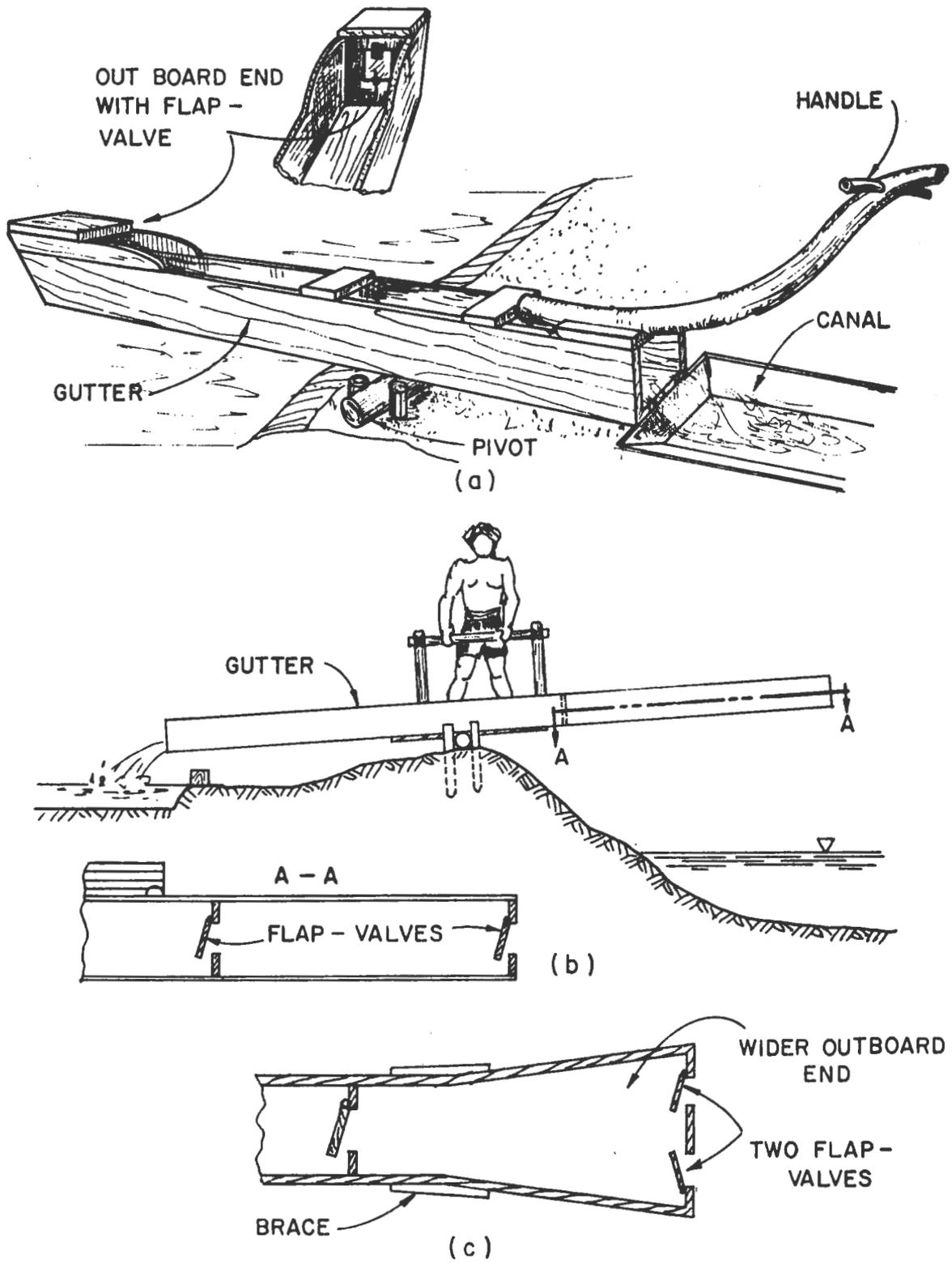


Figure 3.7 (a) Single gutter with handle, (b) "see-saw" gutter, and (c) modifications to increase gutter capacity

water. The capacity of this device could be significantly increased by extending and/or widening the outboard end as in Figure 3.7c.

By using the same circular sweep as in the circular mot, two single gutters can be operated by animal power, as indicated in Figure 3.8. 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 3.9a, 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 3.9b) which again copies the picottah 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.

Two more versions of the gutter have been recently introduced. The first, shown in Figure 3.10a, 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

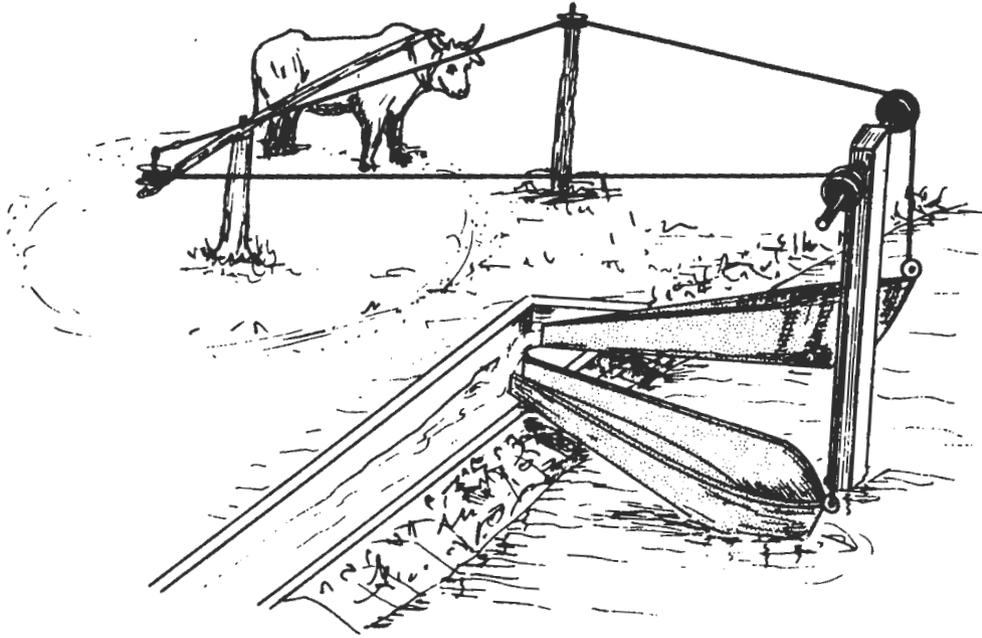


Figure 3.8 Double gutters (a) with lever, and  
(b) as baldeo balti

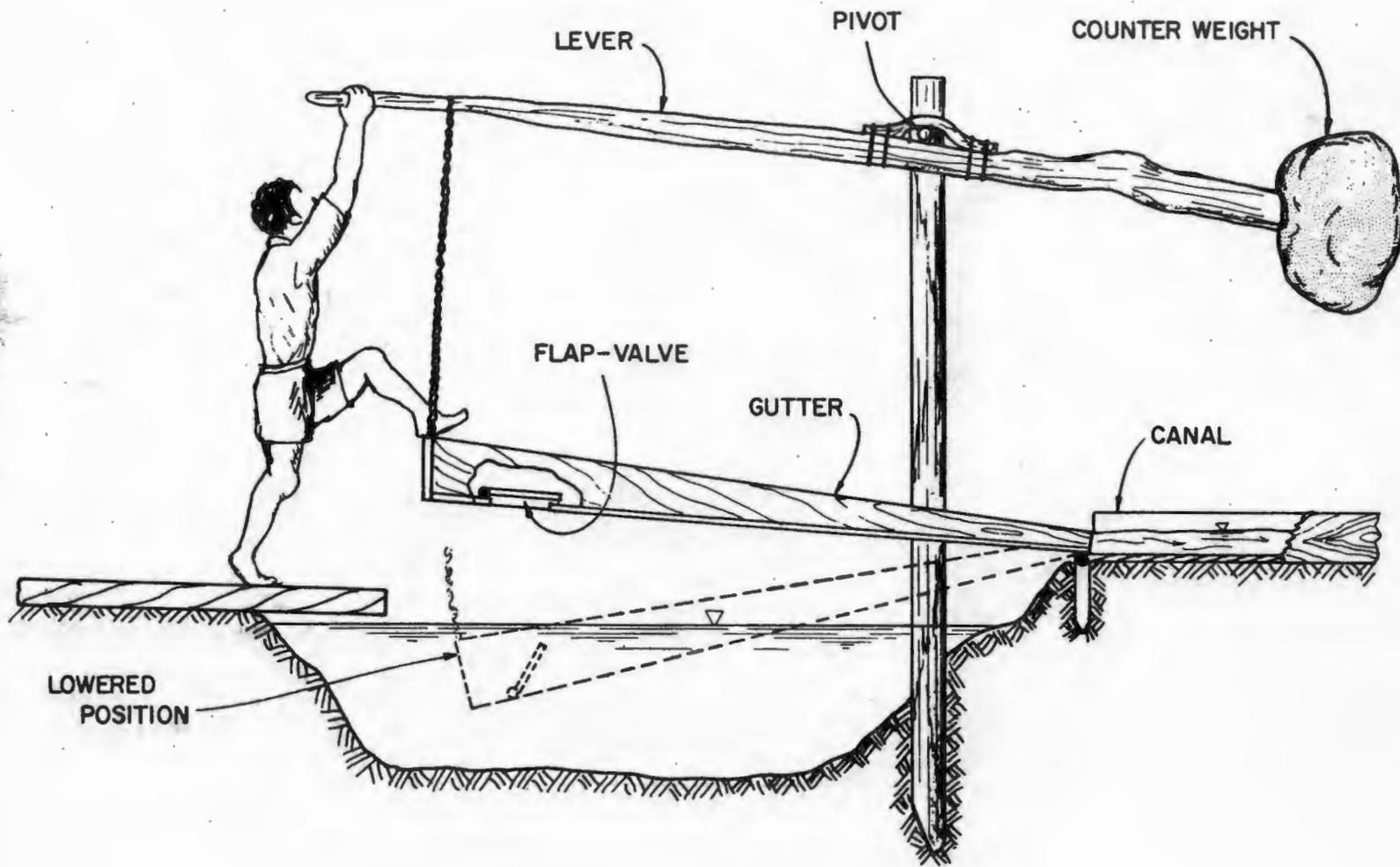


Figure 3.9(a) Doon with flap-valve for aiding submergence

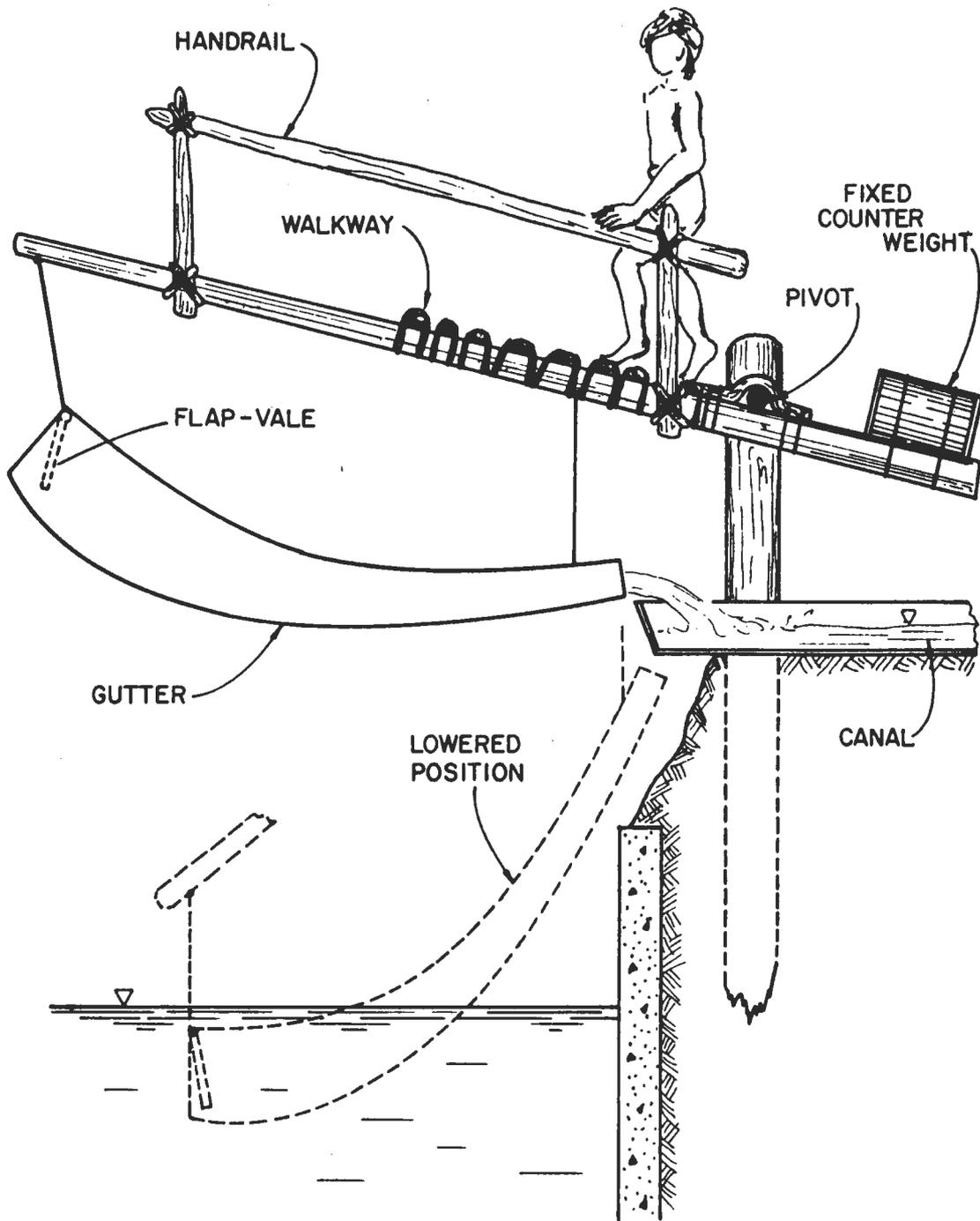
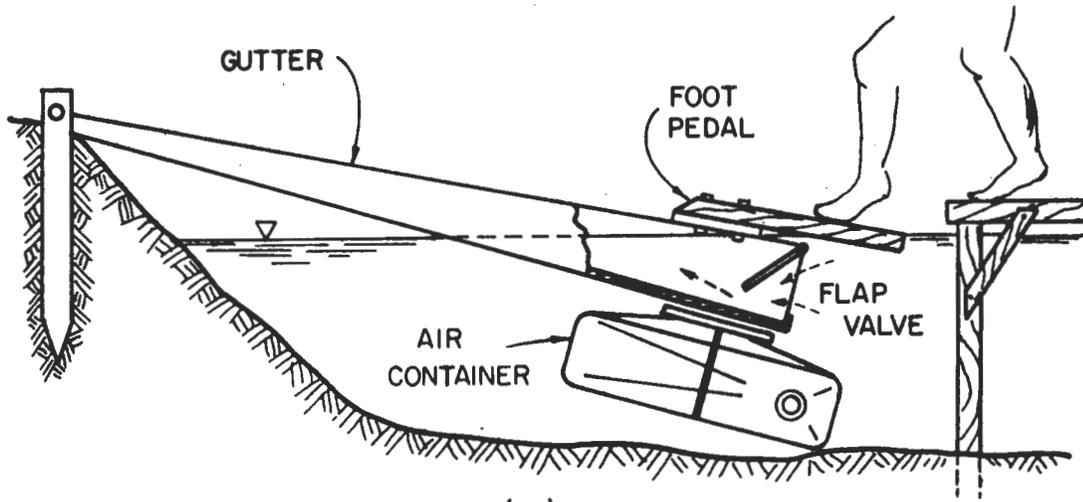
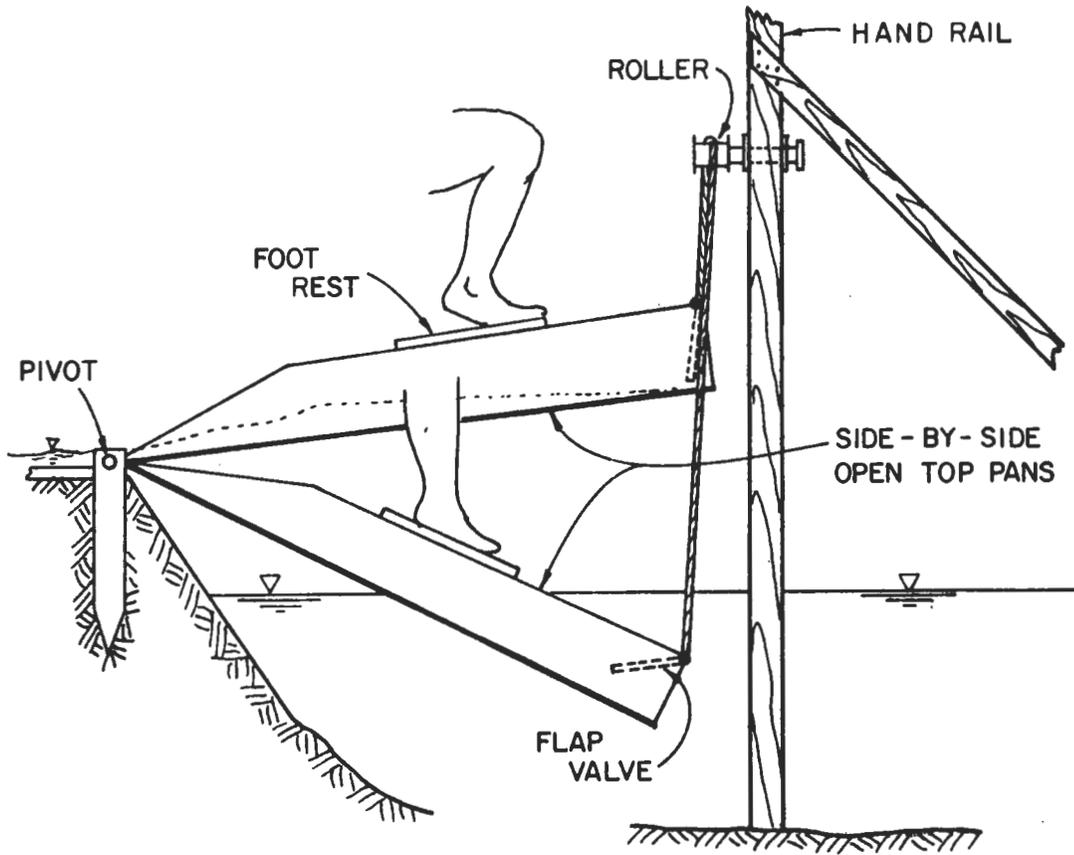


Figure 3.9(b) Picottah-style doon with flap-valve



(a)



(b)

Figure 3.10 Recent modifications of the door

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 3.10b, 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 quite efficient and easy to operate. As this device is still under study, no data on costs or efficiency is yet available.

### 3.2.3 Piston-, Plunger-, and Bucket Pumps

This third subclass of reciprocating methods ranges from the simple, hand "lift pump" (Fig. 3.12) to the sophisticated, direct-acting "steam pump" (Fig. 3.11). Unlike the reciprocating devices previously discussed, these pumps do not need to be submerged (have a static suction head) to lift water, but instead have the ability to "suck" water from a static 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. 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.). On the reverse stroke (downward), the plunger forces water out through another, but outward opening, check-valve.

- (b) The piston-pump 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 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 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 Figure 3.11, 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 inlet and

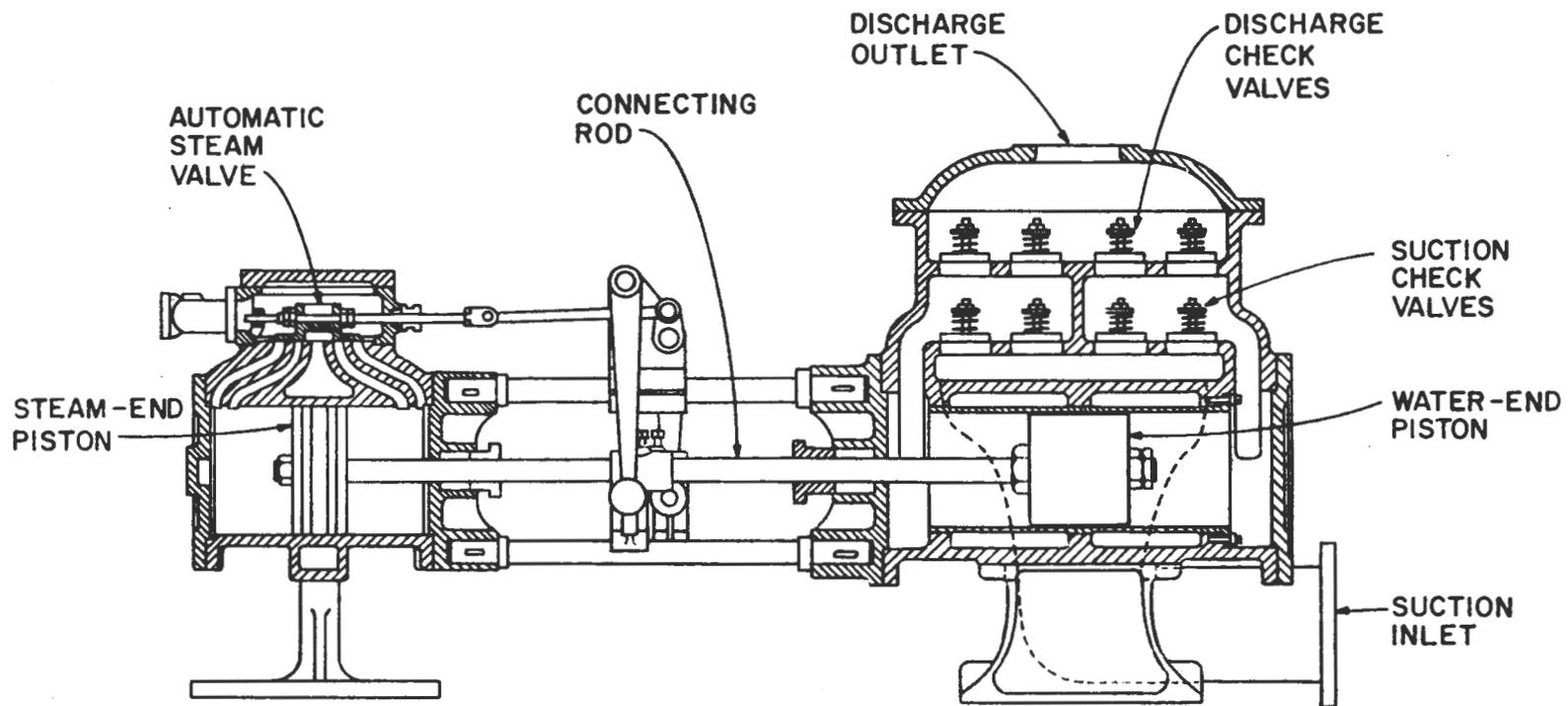


Figure 3.11 Direct-acting, double-acting, piston pump

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 the basic "hand pump", Figure 3.12, the manual power is normally transmitted by means of a reciprocating lever.

#### 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 over-heat 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 and seal along the cylinder wall as 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.

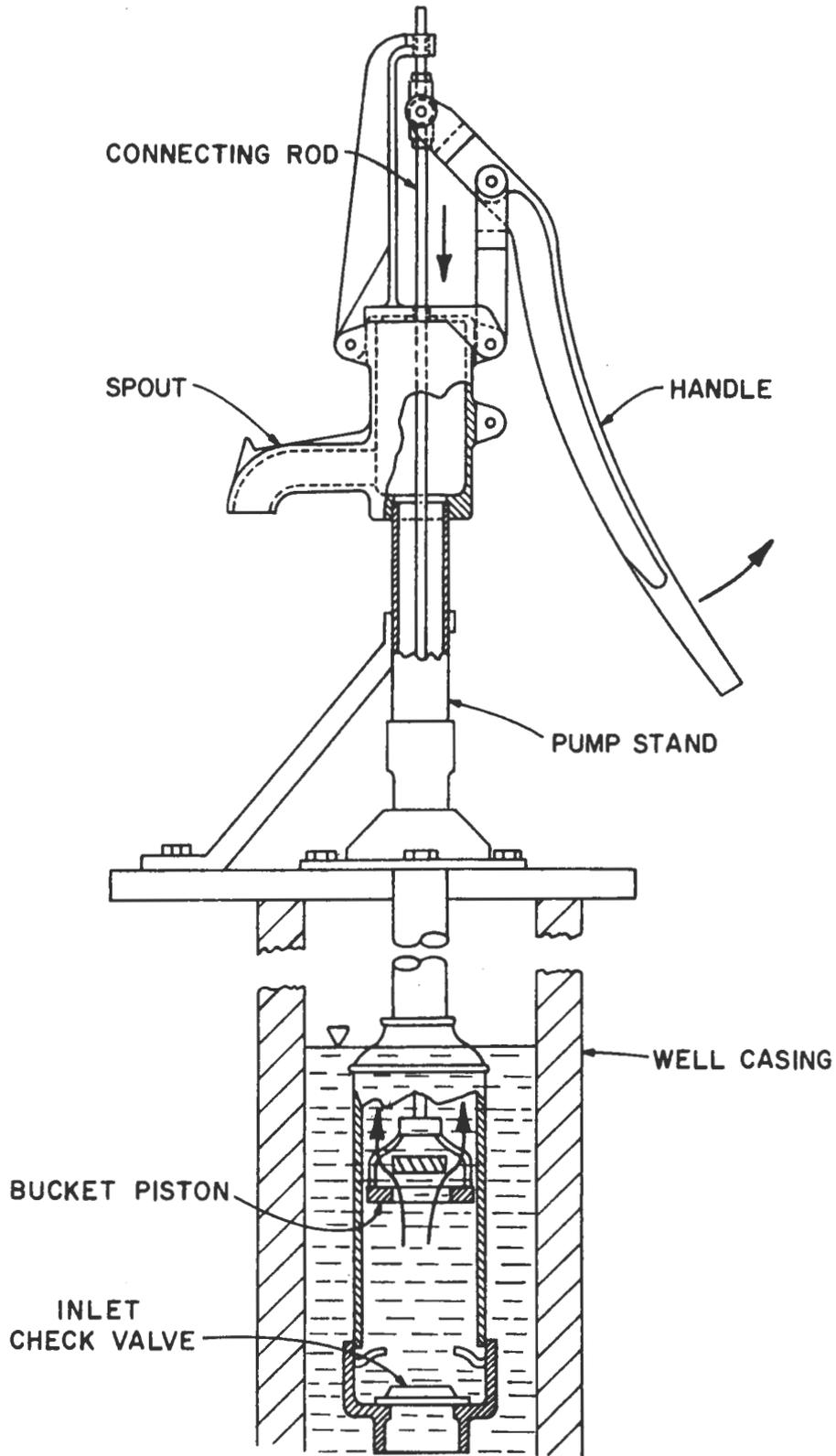


Figure 3.12 "Hand pump" with single-acting, bucket-piston

Another significant difference between direct-acting and power pumps is their discharge per time characteristics. Figure 3.13 illustrates some typical Q-T curves for various reciprocating pumps. Power and direct-acting pumps are similar in that like other positive displacement devices, they have little variation of Q with H .

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.

#### 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.

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. In this application, the dynamic suction lift must be considered so as not to exceed the NPSHR. When a conventional direct-acting or power pump cannot be installed near enough to the water surface (e.g., in a well or mine

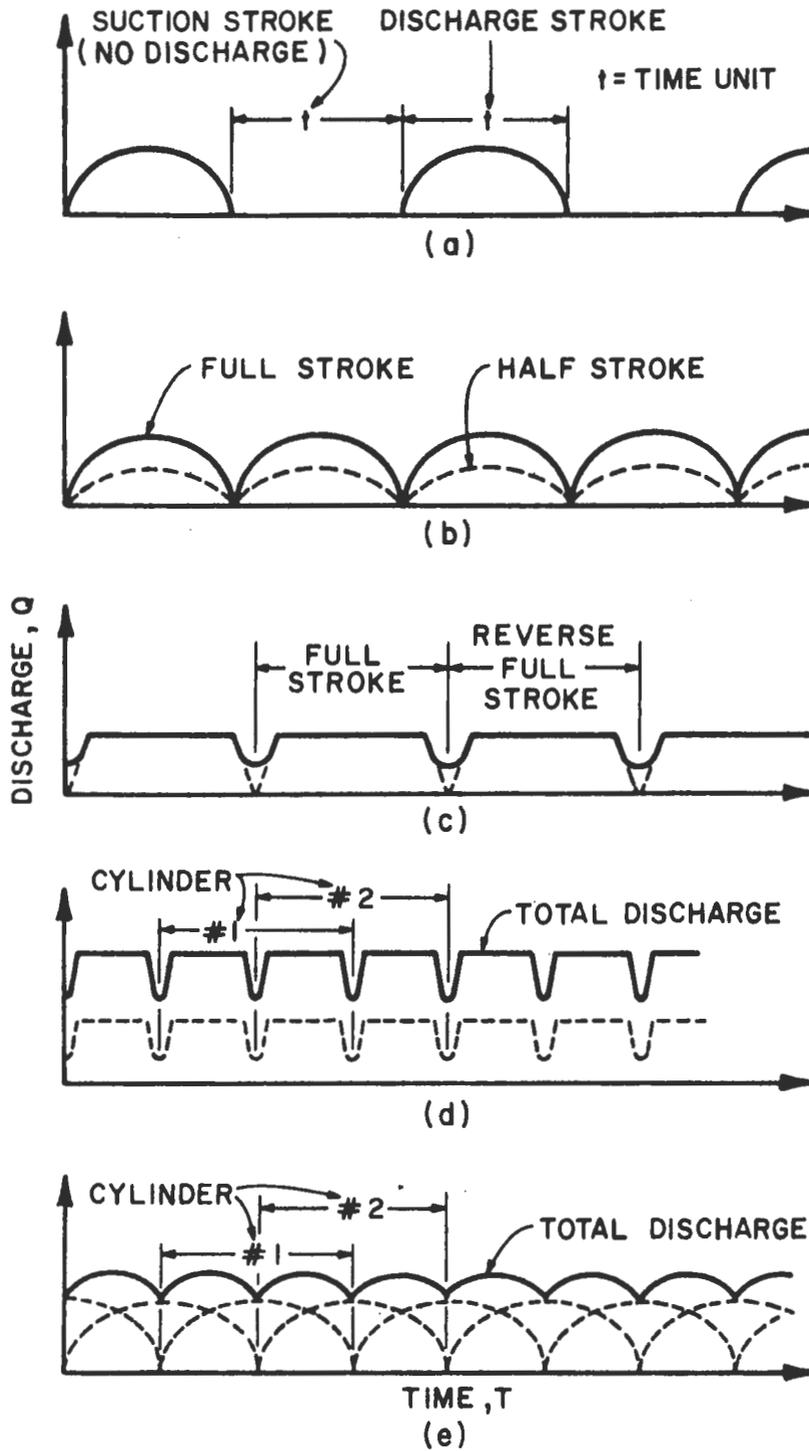


Figure 3.13 Q-T curves for (a) simplex, single-acting power, (b) simplex, double-acting power, (c) simplex, double-acting steam, (d) duplex, double-acting steam, and (e) duplex double-acting power pumps

shaft), two other forms of these pumps can be utilized. The first is commonly called a mine or sinking pump and is simply a compact, direct-acting pump which can be lowered into a narrow shaft along with steam or compressed air hoses for power. The second alternative for deep well pumping is to lower a bucket-piston with connecting rod to within NPSHR limits 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 or electric motors, however, throughout the early 1900's, steam pump heads were common (Greene, 1913). These bucket-pumps can be single-acting or can utilize double-acting cylinders as in Figure 3.14.

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 3.14, 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.

However, in addition to these commercial bucket-pump units, less sophisticated units are easily constructed by local craftsmen in many developing countries. The 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.

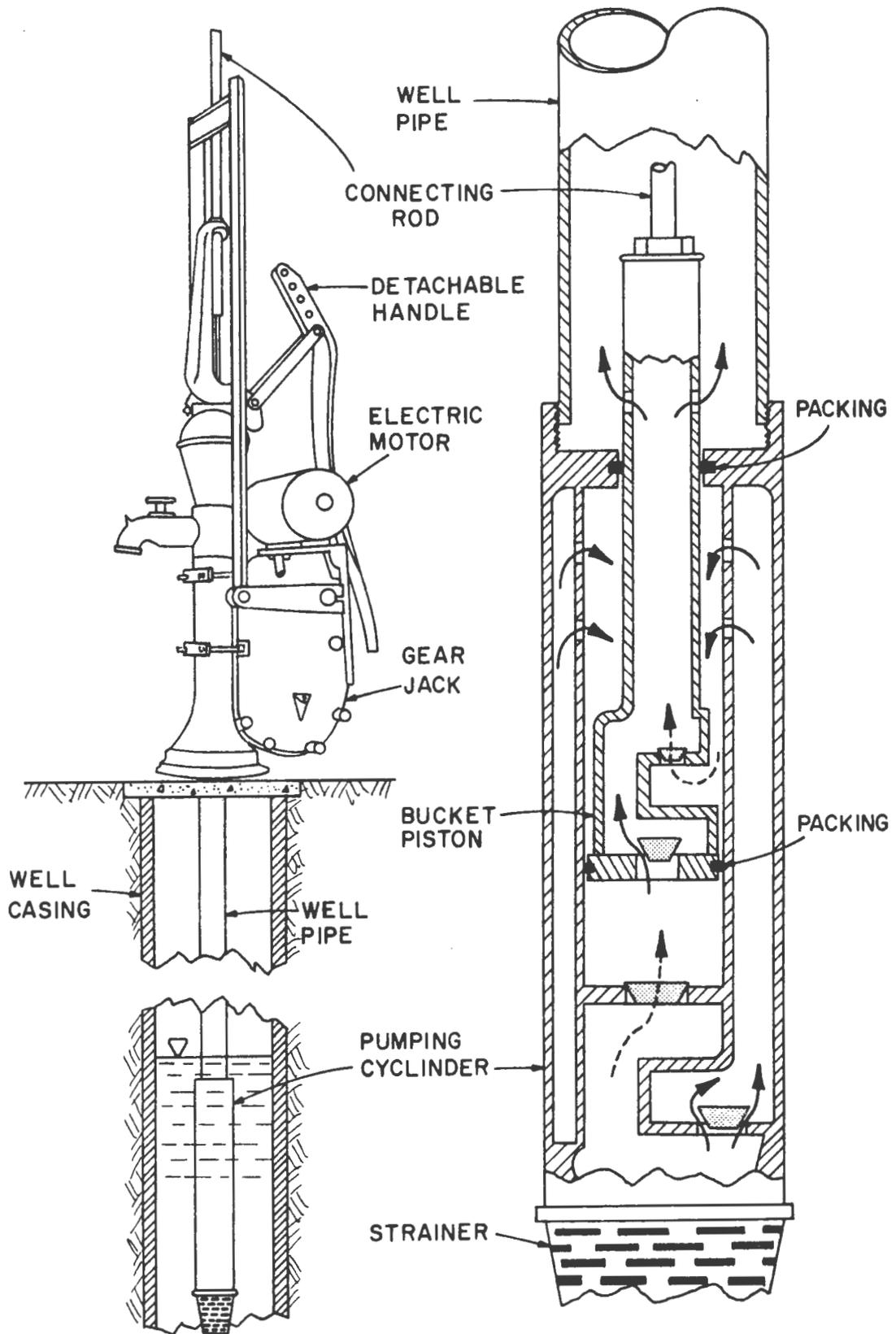


Figure 3.14 Pump head for mechanical or manual power with double-acting, bucket-pump

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 scrap 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 used scrap material, no cost estimate is given.

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) manufacture 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 3.12--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.

#### 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. The expanding bellows draws water in past an inlet check-valve just as the retracting piston or plunger does. Then, as the bellows in contracted, the water is forced through an outlet check-valve.

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 3.15, 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.

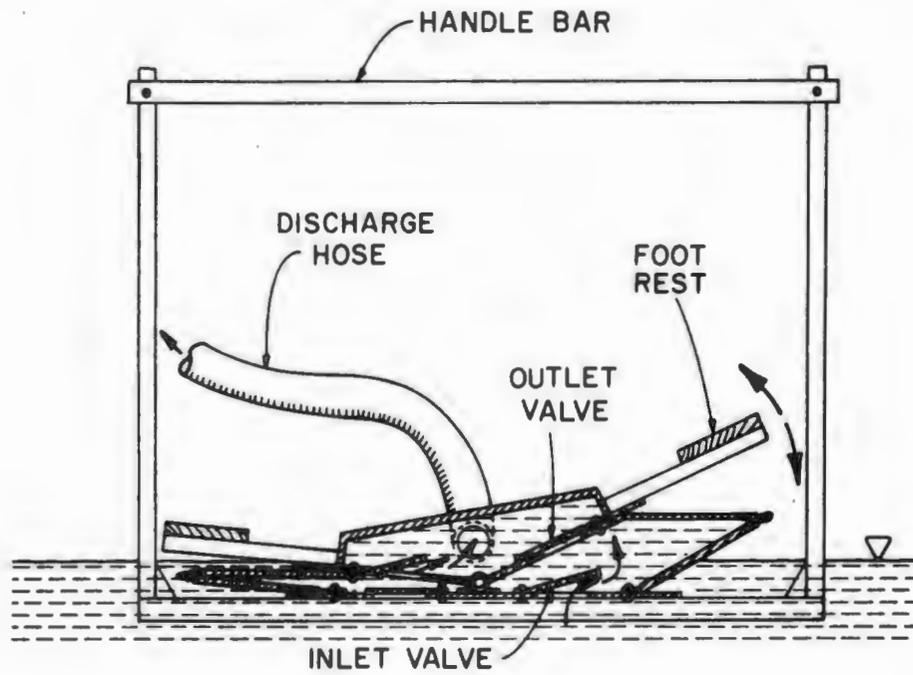


Fig. 3.15 Foot-operated bellows pump  
(Courtesy of IRRI)

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. 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). No cost estimates were available and 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 3.16, 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. The piston can be reciprocated by a mechanical driver (e.g. gas or diesel engine), or for smaller capacities by hand or foot level mechanisms (Figure 3.30). The other method, 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).

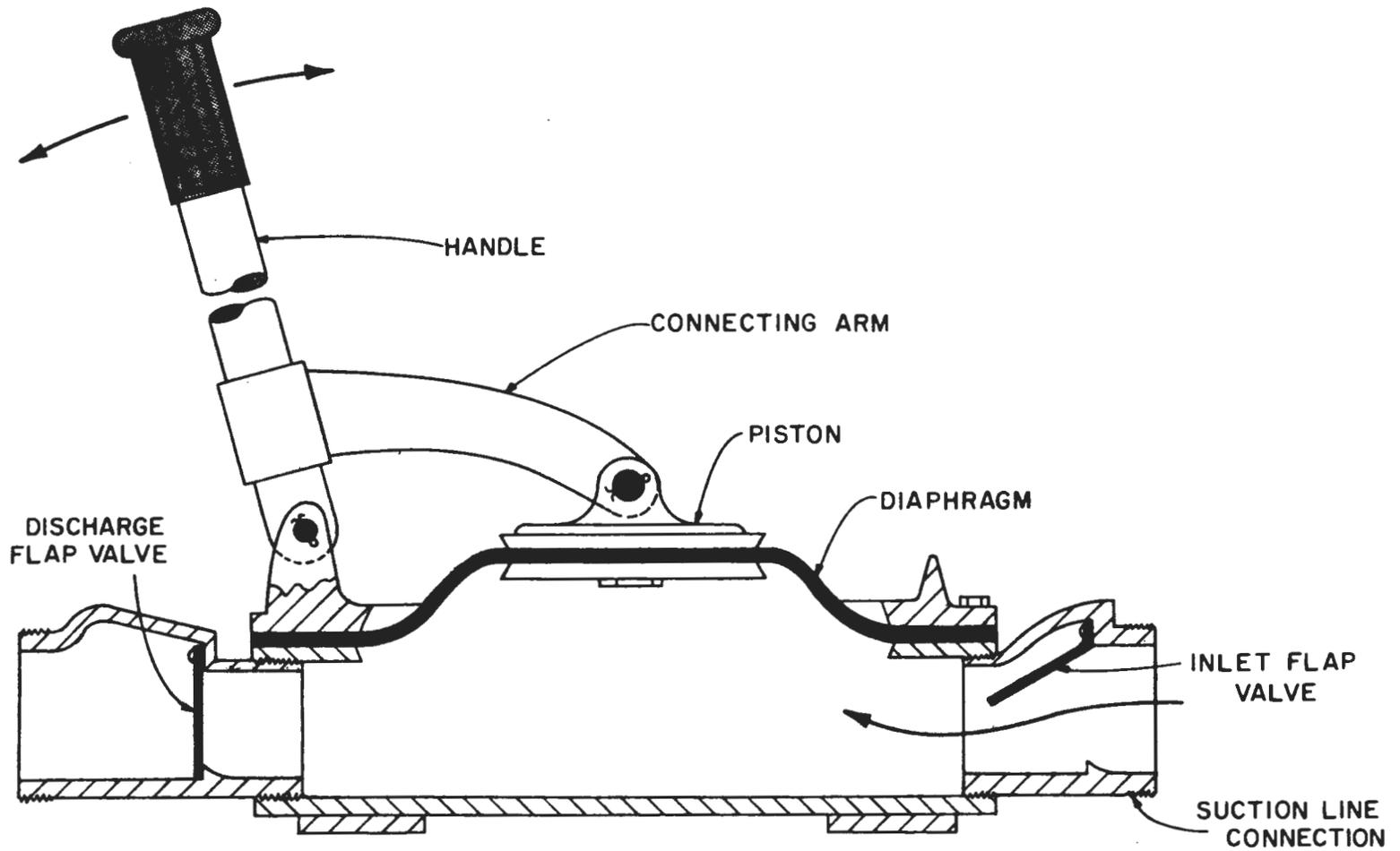


Figure 3.16 Diaphragm pump with handle-lever for manual operation

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. 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 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 on 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 3.17, 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 3.17 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. With such a channel, Molenaar (1956) reports the performance of various size paddle-wheels as given in Table 3.2.

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 were used extensively in low-lying areas, such as Holland, around the turn of the 20th century.

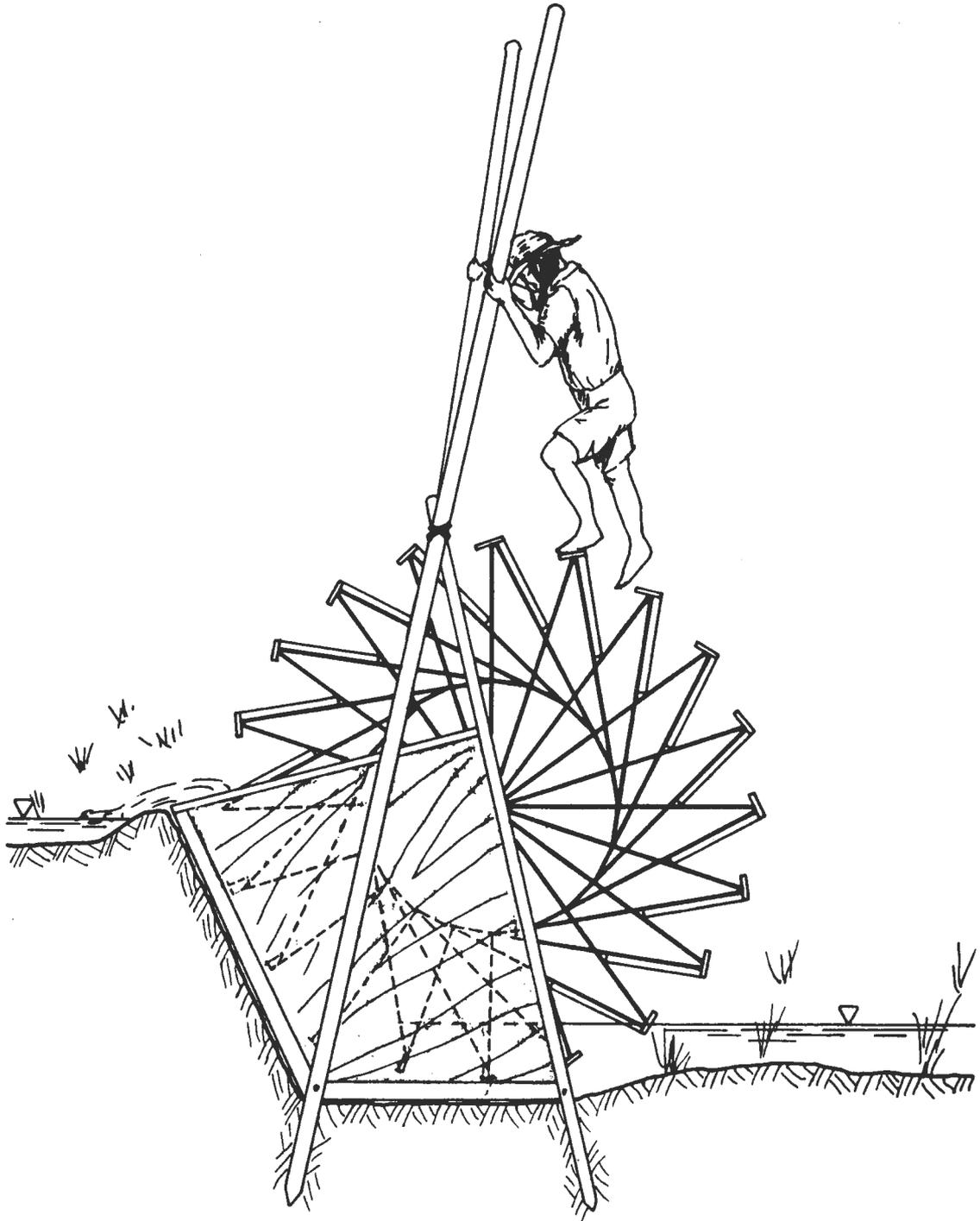


Figure 3.17 Paddle-wheel operated as treadmill

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)	(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

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).

#### 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)	link-belt box elevator
dragon wheel (China)	paddle pump
chain 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 3.18. The entire device can be made of wood, which allows for construction in developing areas and ease of maintenance. The driving sprocket is attached to a shaft which can be driven by several prime movers. Older designs used the same direct pedaling power as the paddle-wheel (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

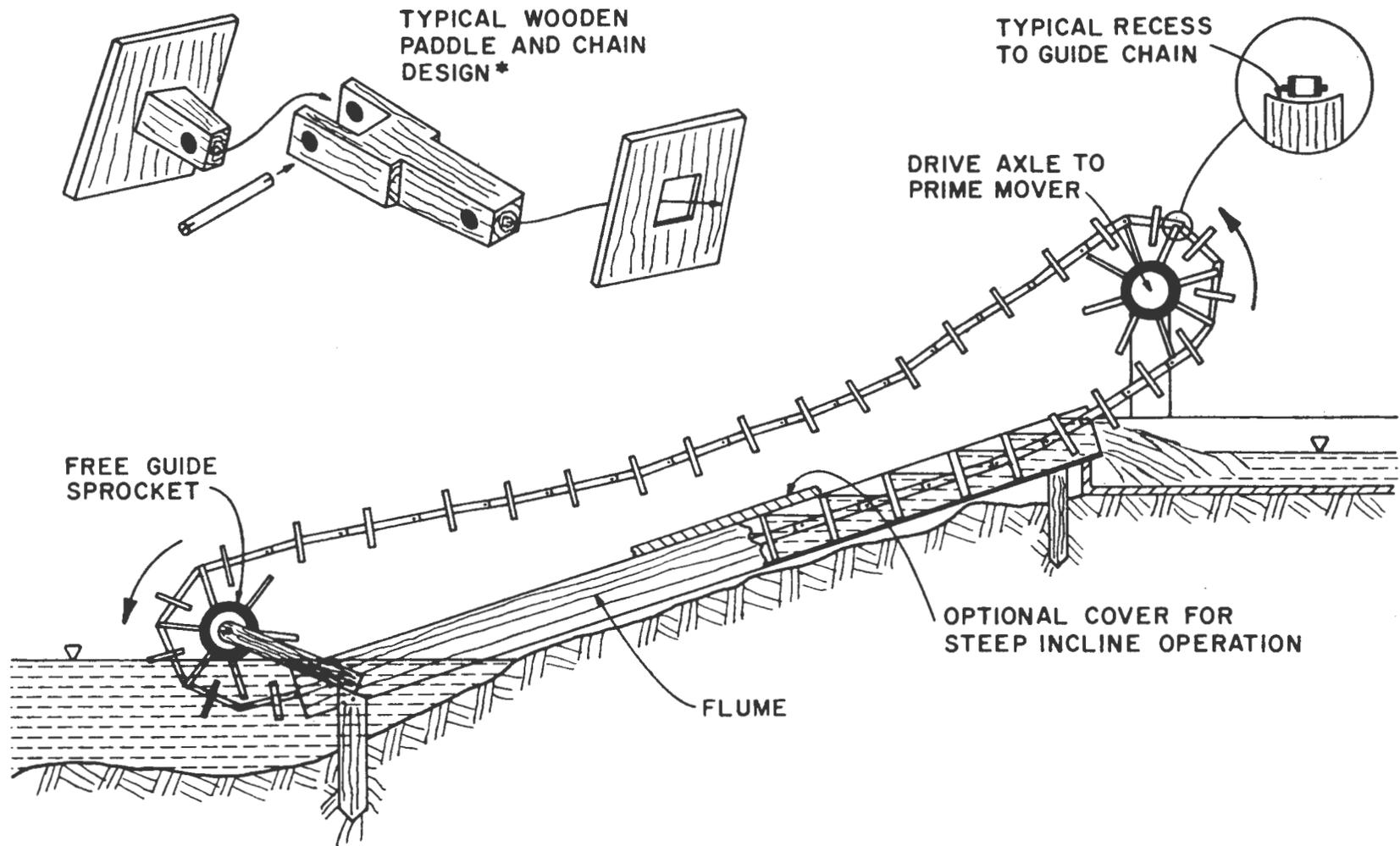


Figure 3.18 Water ladder with open flume (Note: enclosed-flume water ladder is essentially a "chain pump.") (After Schioler, 1975)

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. 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. The 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 3.19. 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 discs 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.

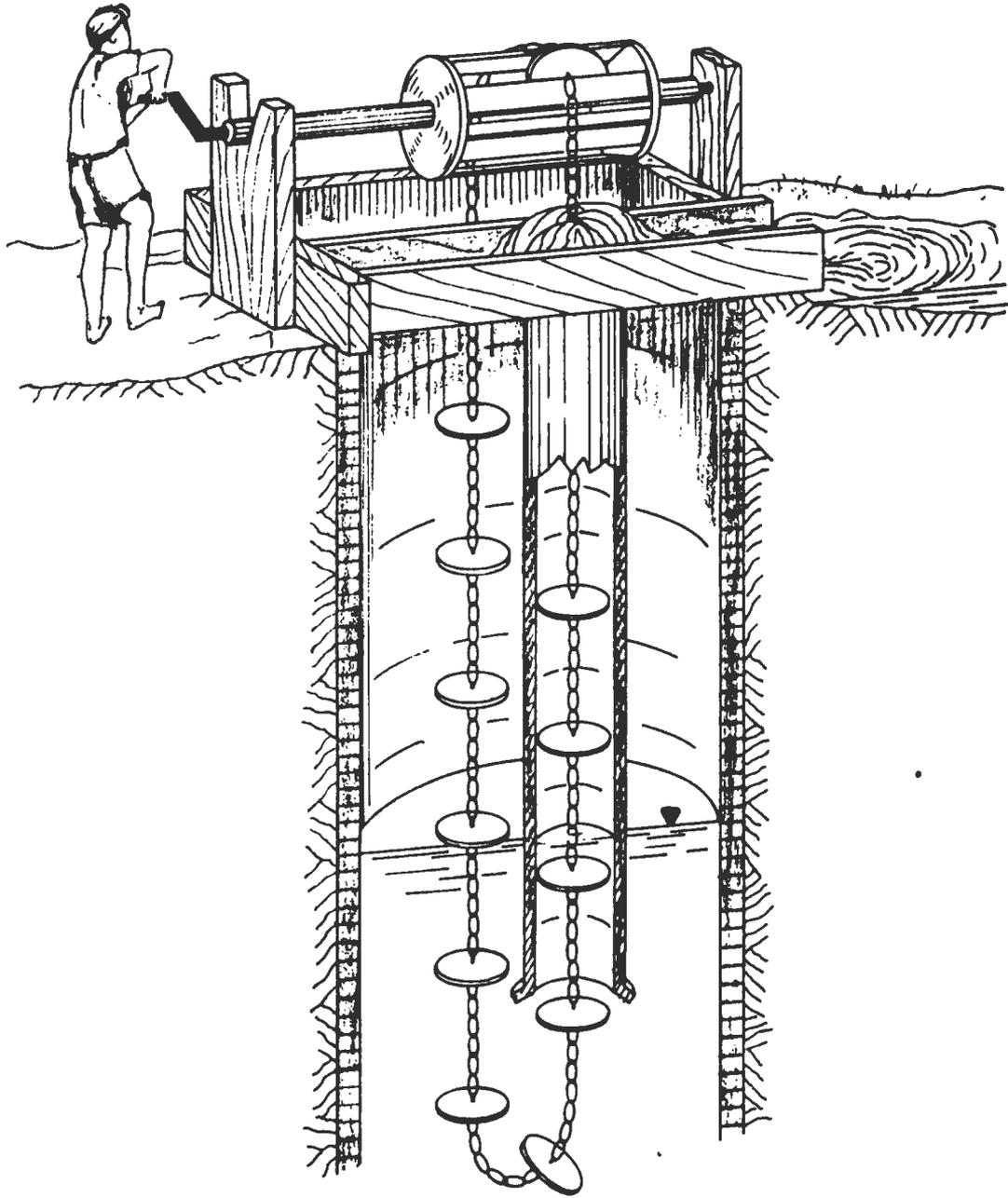


Figure 3.19 Chain pump with manual windlass

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

#### 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 3.20. 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.

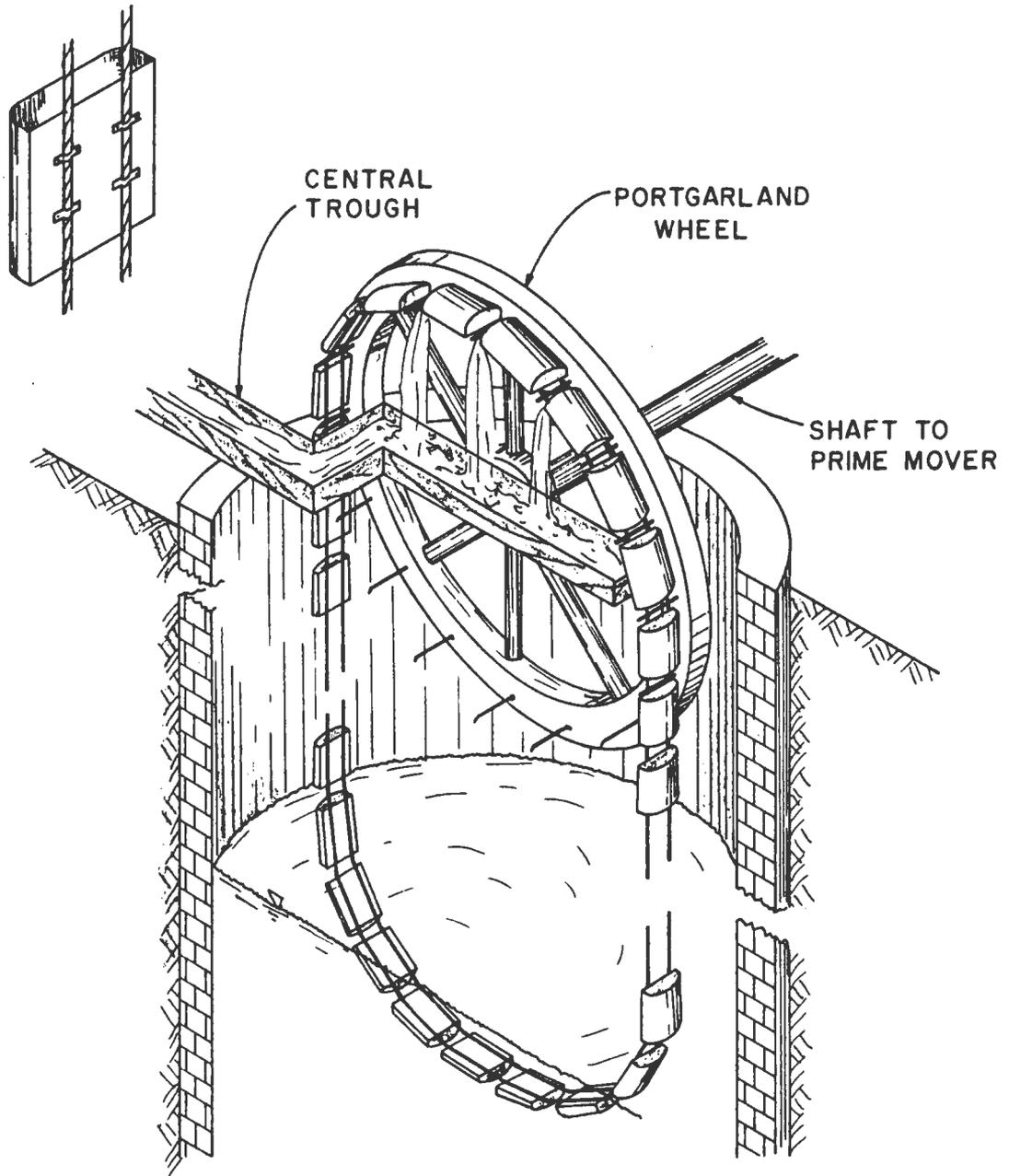


Figure 3.20 Persian wheel with portgarland drive wheel and horizontal drive shaft

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 3.20). 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 great 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. Table 3.4 lists available performance data on some typical wooden Persian wheels.

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

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

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, 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 receive the dumped water and channel it to a 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.

#### 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 force, e.g., Figure 3.21. 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

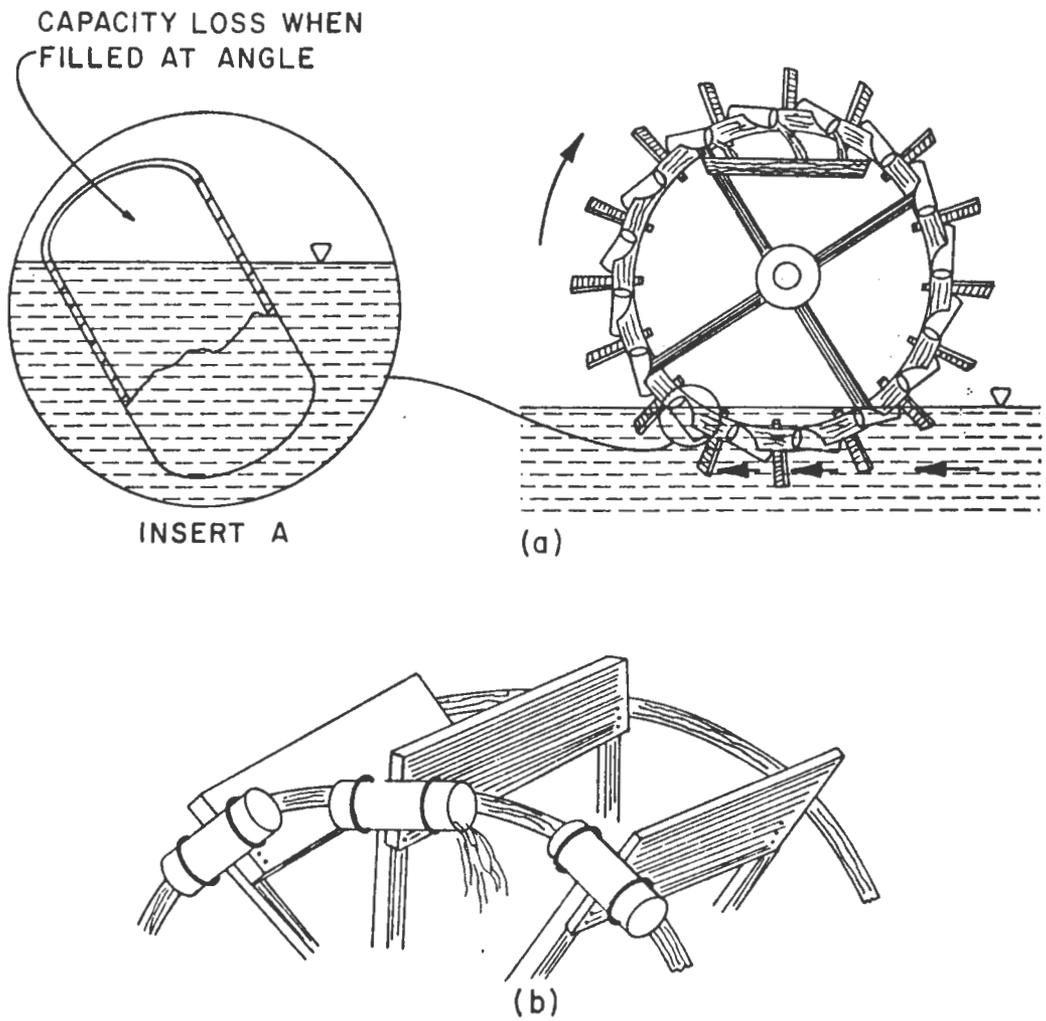


Figure 3.21 Noria; (a) with fixed buckets, driven by current, (b) with larger paddles,

noria and the discharge and head it must supply need to be matched to the available water source is velocity and the paddle surface area. If for instance, the small paddles in Figure 3.21a do not afford enough surface area to receive the necessary momentum of the water flow, then the size of the paddles may have to be increased--possibly utilizing a design more like Figure 3.21b. Two alternatives to increasing paddle size (which increases weight and therefore friction) are; (a) increase the water supply's velocity by decreasing its channels'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 noria as an undershot wheel (see Section 5.1). Of course, a separate driving wheel (i.e., water mill) 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 3.22.

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 3.2.a to decrease spillage.
- (b) Use of movable buckets, e.g., Figure 3.21c, to allow complete filling (i.e., as opposed to fixed containers which fill at an incline--see Figure 3.21a, Insert A) and prevent emptying until the bucket reaches the upper level trough.
- (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 3.22. The

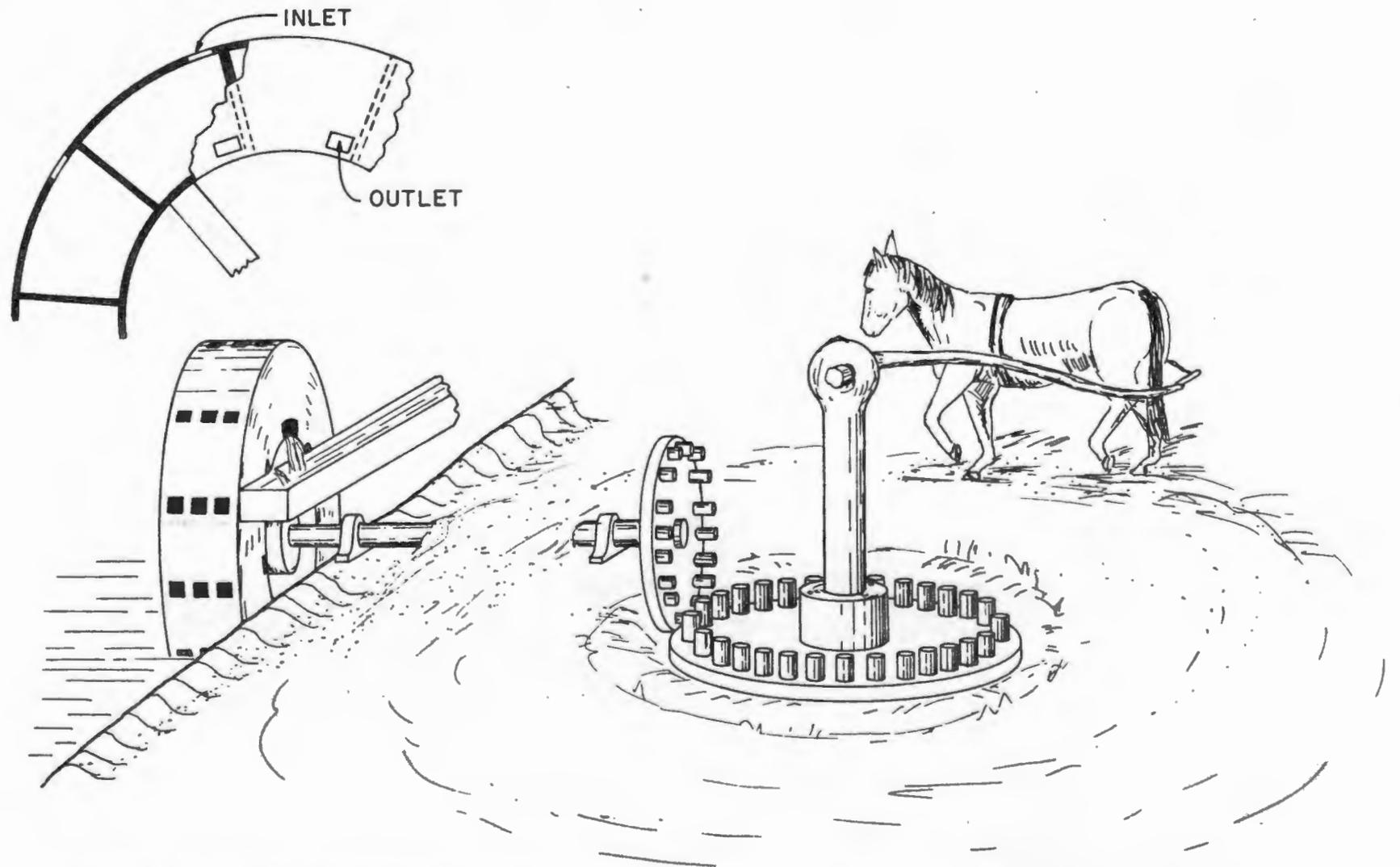


Figure 3.22 Noria with enclosed compartments driven via long shaft and pinion gears by animal

enclosed circumference can also be utilized as a treadmill so that manual power can be directly applied without the use of gears, shafts, etc.

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

scoop-wheel	waterwheel elevator (Algeria)
bucket-wheel	Persian wheel
sakia (Egypt)	tanbusa
dawlab (Persian)	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 3.23. 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.

Several other names which are applied to this device include:

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

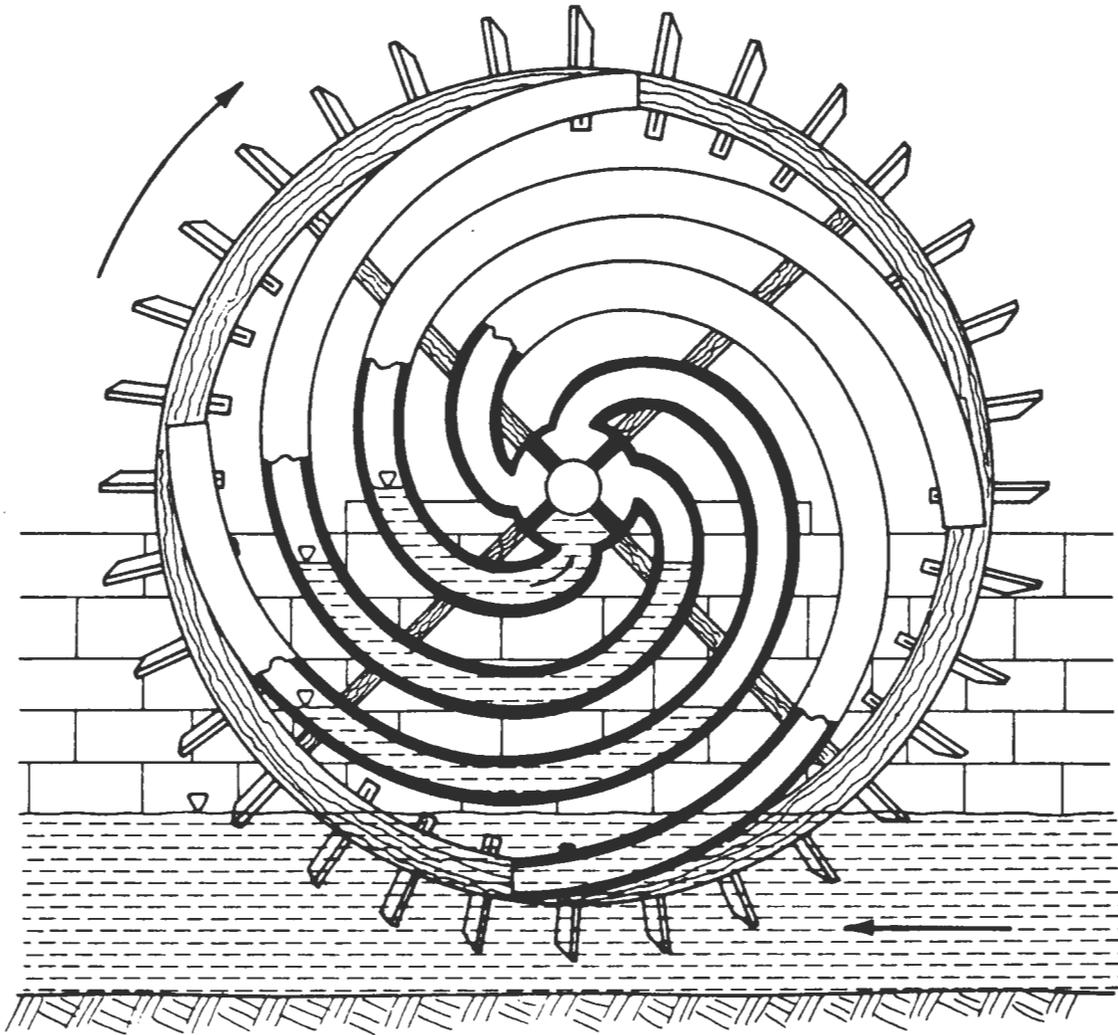


Figure 3.23 Tympanum with spiral troughs equipped with paddles to be current-driven

Most early tympanums were of the easy-to-construct design labeled HRES-D<sub>2</sub> in Figure 3.24. However, early in the 17th century, La Faye noted that this design kept the water at the periphery of the compartment. The water exerted the maximum resisting moment 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 3.33 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 3.24) are also widely used today.

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 3.24, they determined that the D<sub>2</sub> design was capable of higher discharges at a given head than the others 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<sub>1</sub>, D<sub>2</sub>, and Fathi designs in Figure 3.24, 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.

Tympanums, 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.

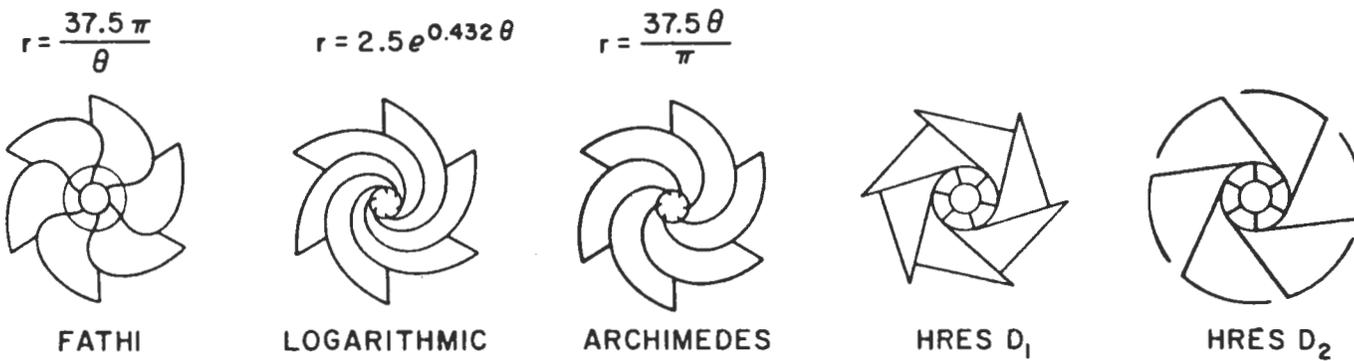
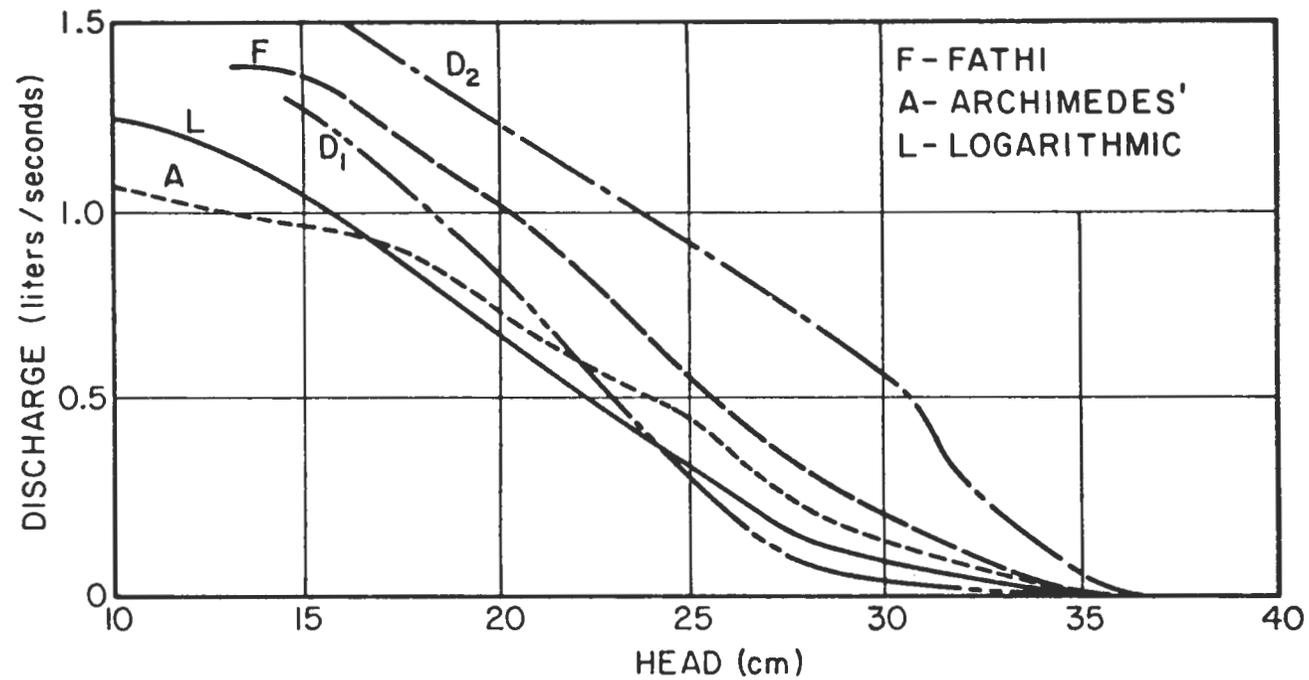


Figure 3.24 Comparison of various typanum designs (HRES, 1965)

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

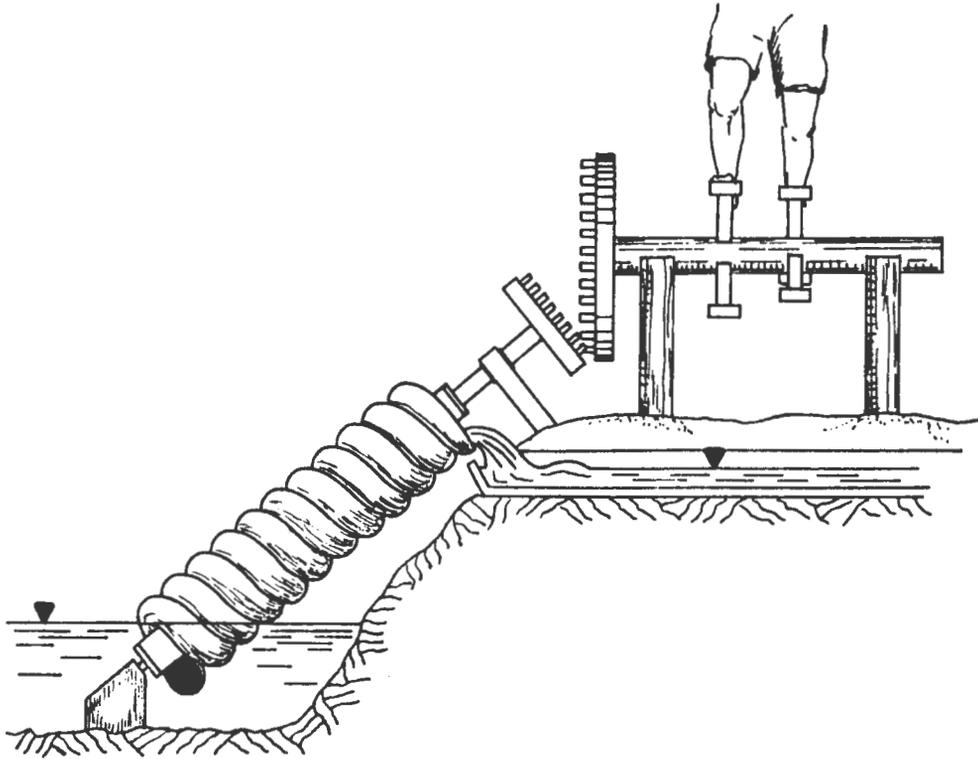
### 3.3.2 Screw

The basic screw or auger 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 Weisback and Herrmann, 1897.

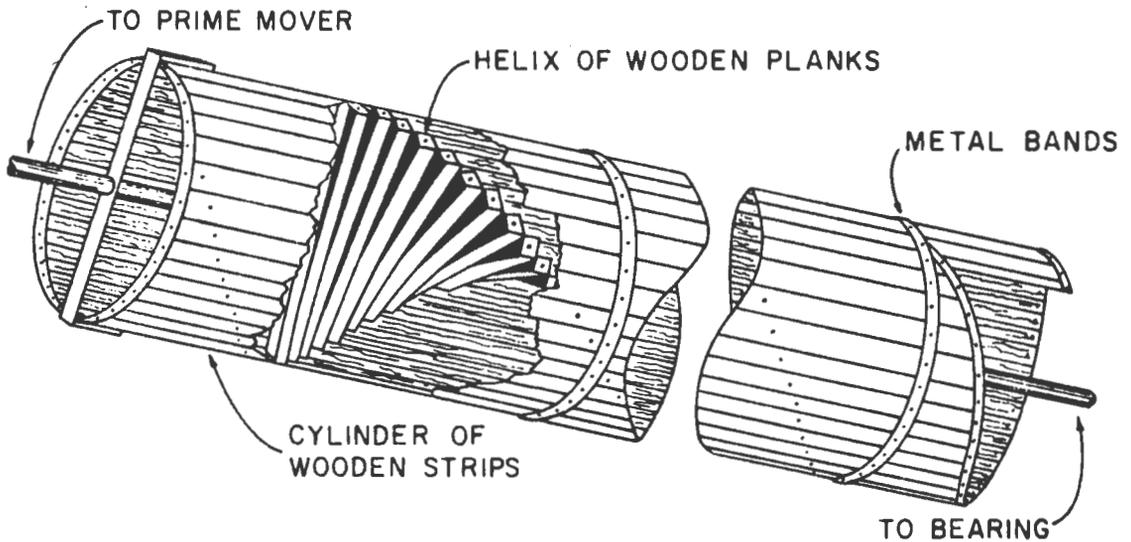
One of the earliest designs for a water-lifting screw utilized a flexible tube wrapped around and secured to an inclined axle, as in Figure 3.25a. This design is often referred to as a water snail, Egyptian screw, or cochleon, however it is rarely used today. Instead, the commonly referred to Archimedean screw, which has been in use for centuries (see Section 1.2), is the more popular screw-device presently in use. Several other names are applied to this water lifter:

screw pump	Roman-screw
water-screw	screw mill
	tambour

As illustrated in Figure 3.25b, this device can be easily constructed primarily of wood with a few basic tools. This type construction is



(a)



(b)

Figure 3.25 (a) Pedal-power water-snail, and (b) construction of simple, wooden Archimede's screw

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 crew 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 2.3. Such

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

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).

### 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. 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 almost continuous flow of water. Like reciprocating pumps, rotary pumps maintain an almost constant  $Q$  for varying  $H$ , and 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. 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 upwards

of 3000 gpm or 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 3.26, 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 to an electric motor for pumping from shallow wells, i.e., they have NPSHR limitations just like any other pump. 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 3.27. 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.

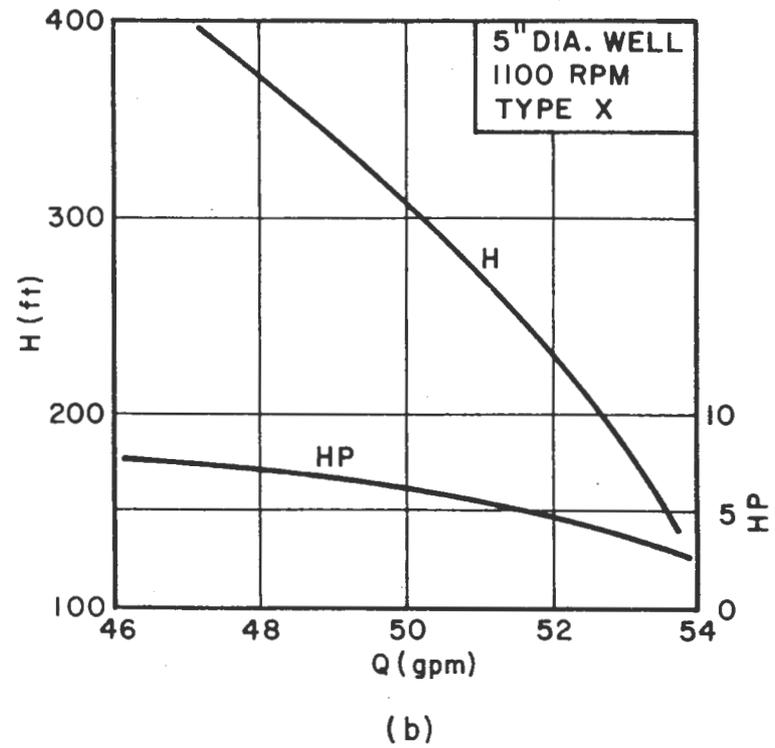
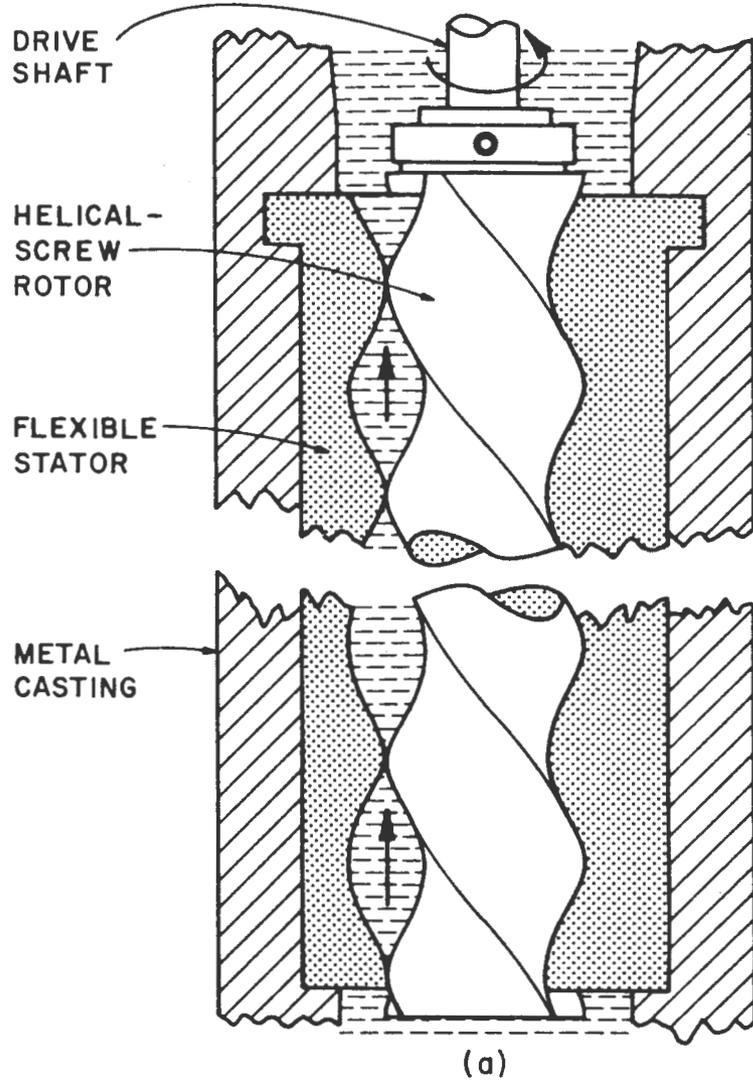


Figure 3.26 (a) Helical-screw rotary, and (b) typical performance curve of "vertical helical" pump

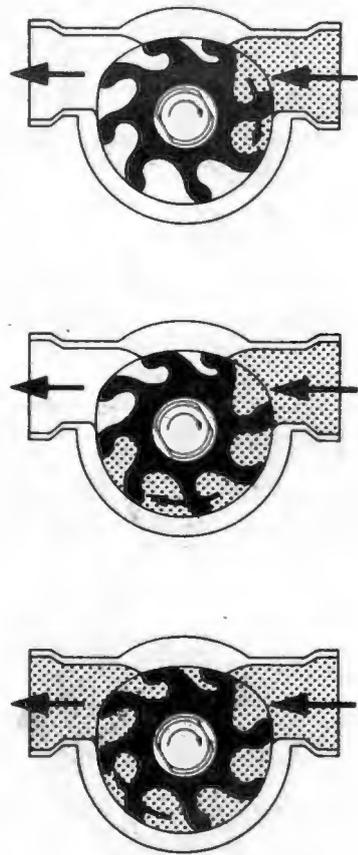


Figure 3.27 Operation of flexible-rotor pump  
(Courtesy of Jabsco Pumps)

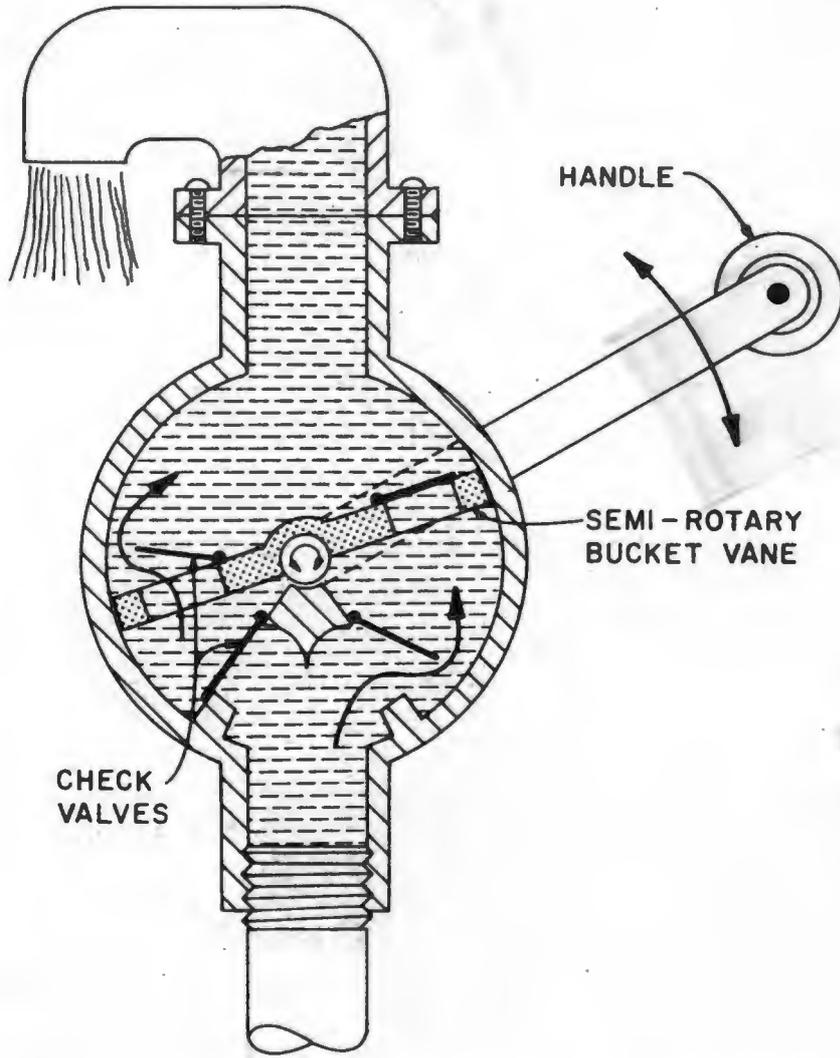


Figure 3.28 Manual, double-acting, semi-rotary pump

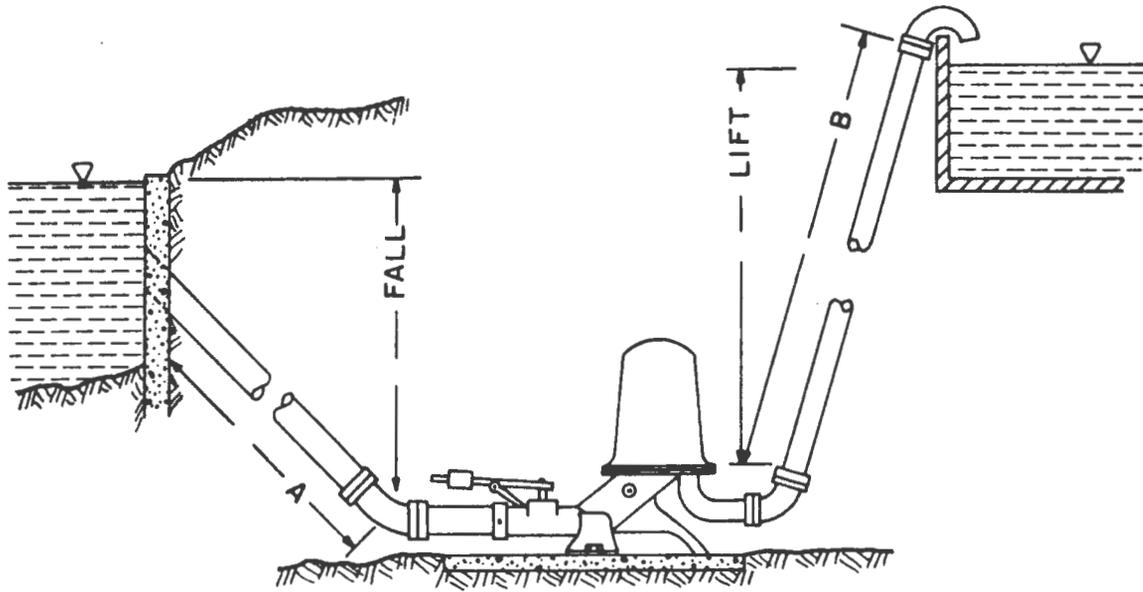
The semi-rotary pump, shown in Figure 3.28, is a half-bread device which utilizes both rotary and reciprocating motions. A vane, very similar to the bucket-piston (i.e., with flap valve(s)) is rotated through an arc in a circular casing which also contains a check valve(s) fixed to the casing. As the 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 3.28, 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

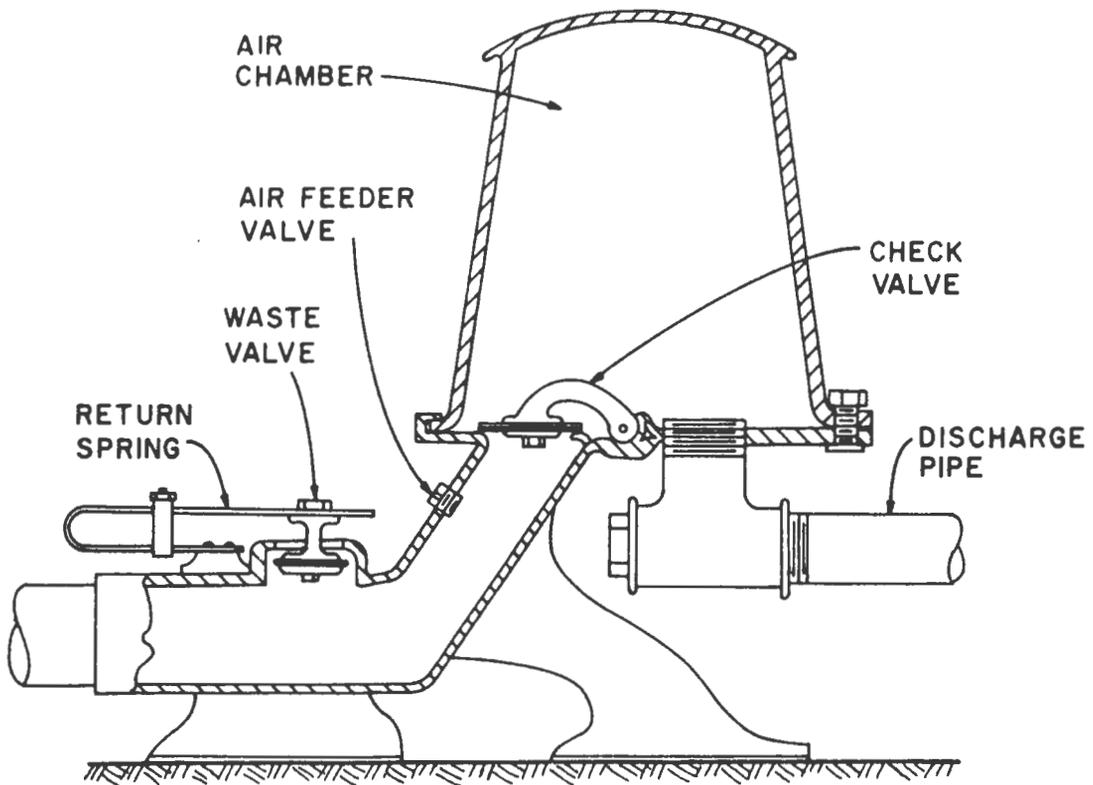
As previously mentioned, a few water lifting methods exist which do not fit, either individually or collectively, into any of the established classes. However, since they exhibit primarily positive displacement characteristics, they are appropriately considered in this chapter.

#### 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. As illustrated in Figure 3.29, 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 3.29, 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.



(a)



(b)

Figure 3.29 (a) Installation, and (b) typical design of hydraulic ram

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

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).

Table 3.8 Ram performance

## A. Typical capacities for various size rams:

Drive Pipe (in.)	Delivery Pipe (in.)	Minimum $Q_f$ (gpm)
1	$\frac{1}{2}$	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)

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

water-ram

impulse pump

hydraulic engines

### 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 3.30, 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 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. 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. 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.

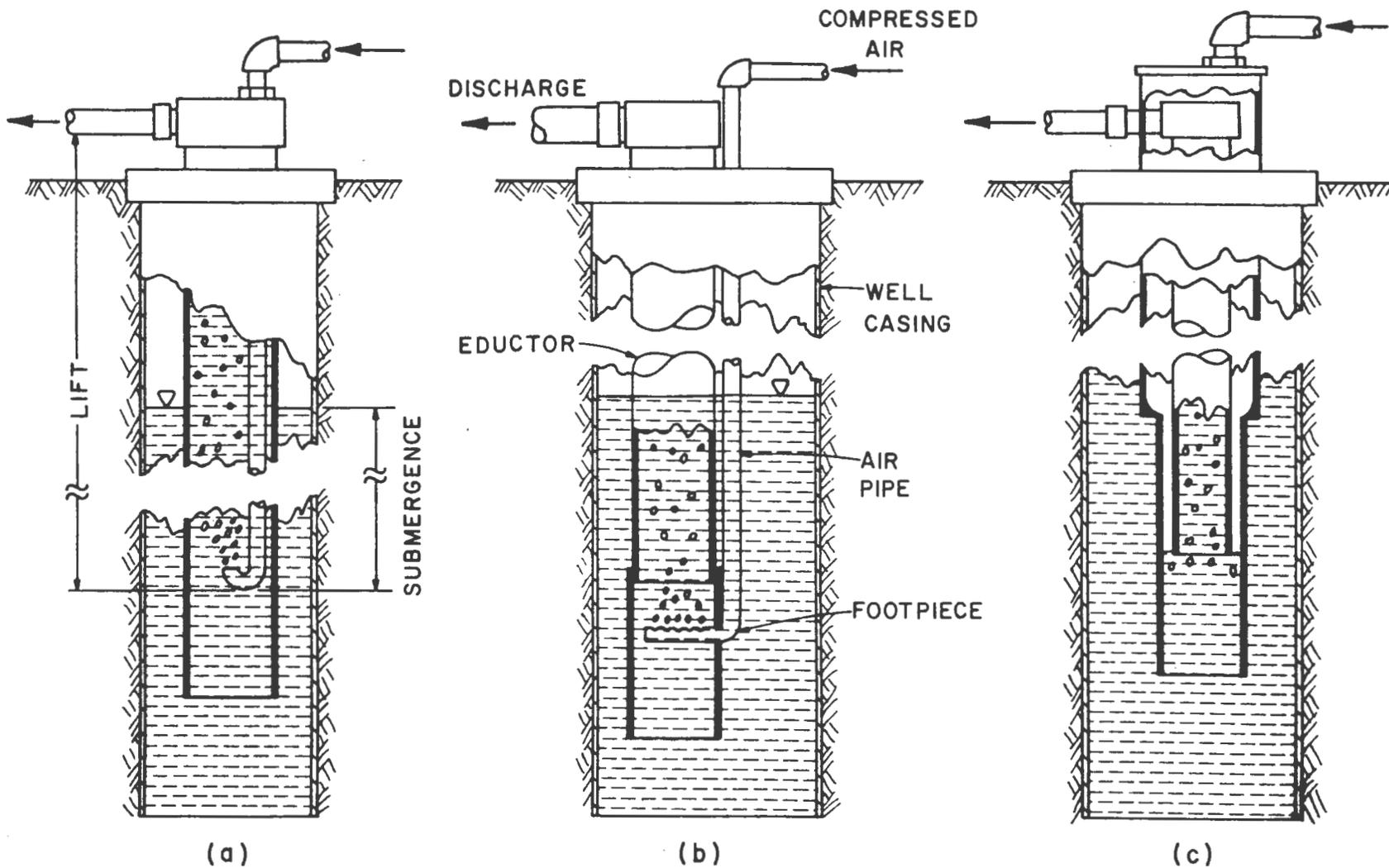


Figure 3.30 Eductor air-lift methods; (a) air pipe in eductor, (b) air pipe outside eductor, and (c) eductor inside air pipe

### 3.4.2.2 Displacement Method

As mentioned in Chapter 1, the displacement method of lifting water was discovered by Heron. Air is withdrawn from a container which allows water to flow into it. Air is then forced back into the container, displacing the water and forcing it up a discharge pipe.

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 3.31, 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.

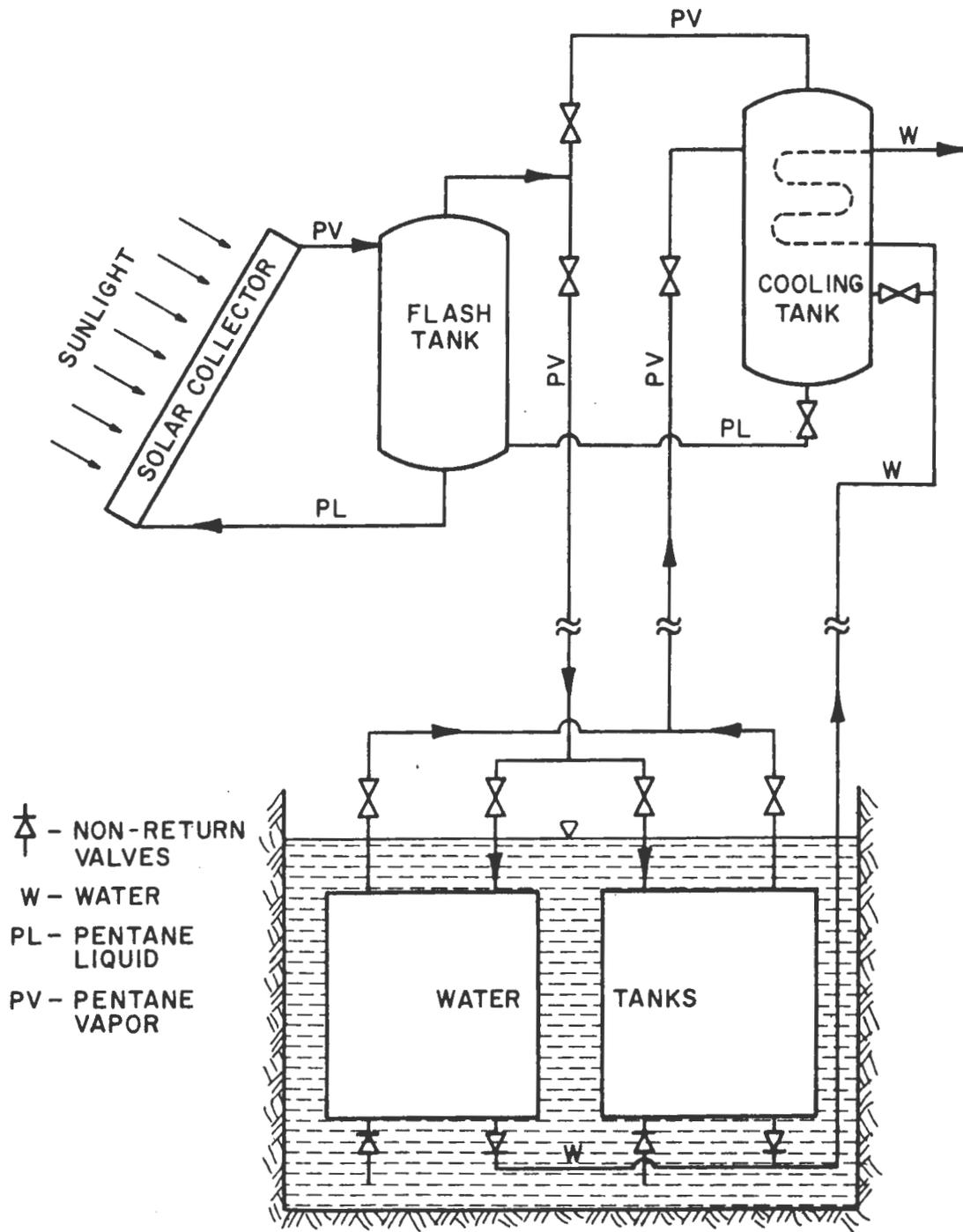


Figure 3.31 Schematic operation of water-cooled solar pump

As that vapor is condensing and returning to the flash tank, water is flowing into the second tank 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 3.9 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 3.9 Solar pump performance

Lift (ft)	Air-cooled system with 10 x 12 ft water tank		Water-cooled system with two 3 x 5 ft water tanks	
	Discharge (ft <sup>3</sup> /day)	Collector Area (ft <sup>2</sup> )	Discharge (ft <sup>3</sup> /day)	Collector Area (ft <sup>2</sup> )
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 3.9 cost about \$1,420 for the tanks, plumbing, and insulation, and \$4.50 per ft<sup>2</sup> for the collector. The water-cooled system cost about \$2,100, plus the \$4.50 per ft<sup>2</sup> 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 3.32. 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 change 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 chf 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

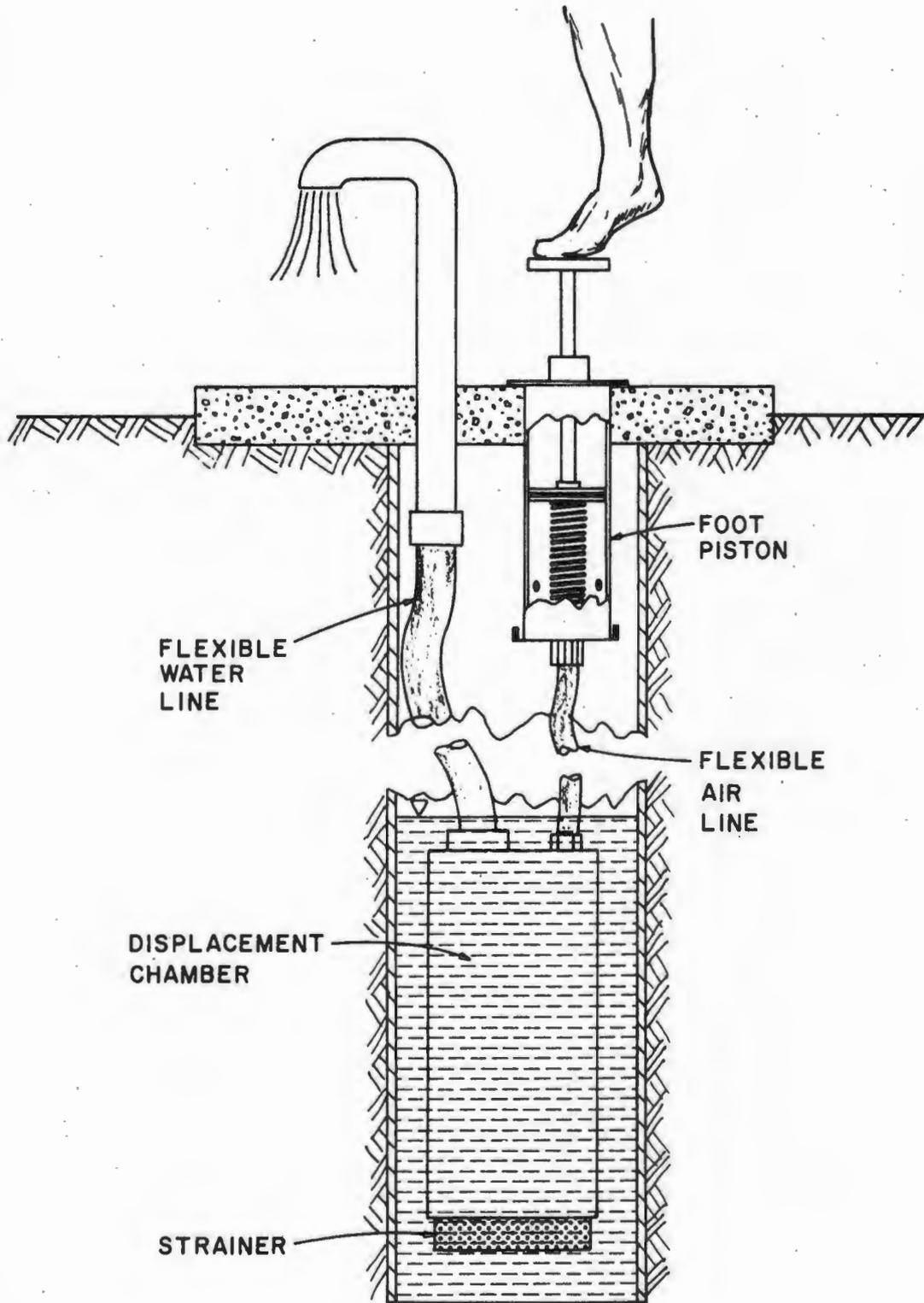


Figure 3.32 Displacement air-lift method operated by foot piston

air-lift pumps. 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. (See also Rogers, Vol. 2, 1905, pp. 269-280; Weisback and Herrman, 1897, pp. 286-291).

#### 3.4.4 Explosion Pump

Another unique, but obsolete, water lifter is the explosion pump of Humphrey. 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 exploded in a chamber which drives the water in that chamber up a discharge pipe. The spent gases are exhausted through a valve and a new unit of water is drawn in through inlet ports. The rebound of water in the discharge pipes is the method for exhausting the gases and compressing the new charge of coal gas. Ignition of the explosion is by electric spark (see Unwin, 1909).

## 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.

"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 Trokolanski, 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.

#### 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. 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, the water is discharged by the vanes into a widening spiral casing, which converts velocity head into pressure head. In a diffuser casing, a ring of guide vanes, curved backward to the impeller vanes, perform much as multiple volutes--expanding outward to make the pressure conversion. In multiple stage pumps, e.g. submersible well pumps, 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. 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.

#### 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. 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.

#### 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  $0^\circ$  and  $90^\circ$  from the axis. Mixed flow impellers are used in two basic pump designs; the helical flow which utilized a volute casing, and the diagonal flow, 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. A peripheral impeller receives the water, as its name implies, at its periphery and recirculates the water several times about its short double blade 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 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 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. The first such parameter is called (nominal) specific speed, or more properly, kientic 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. 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. Figure 4.1 shows this relationship between  $N_s$ ,  $D_2/D_1$ , and impeller type. By utilizing  $N_s$  as a selection tool, optimum installation conditions can be designed.

Another parameter, suction specific speed is defined as

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

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

Also included in Figure 4.1 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.

Although the regenerative pump is not in the radial/mixed/axial family of rotodynamic pumps, it also has distinctive curves. The performance curves resemble, in shape only, those of an axial flow pump. This 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.

Two additional aspects of rotodynamic pump operation are important to their application; capacity regulation and priming. 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 changes in pump speed or impeller diameter. Using performance curves with constant

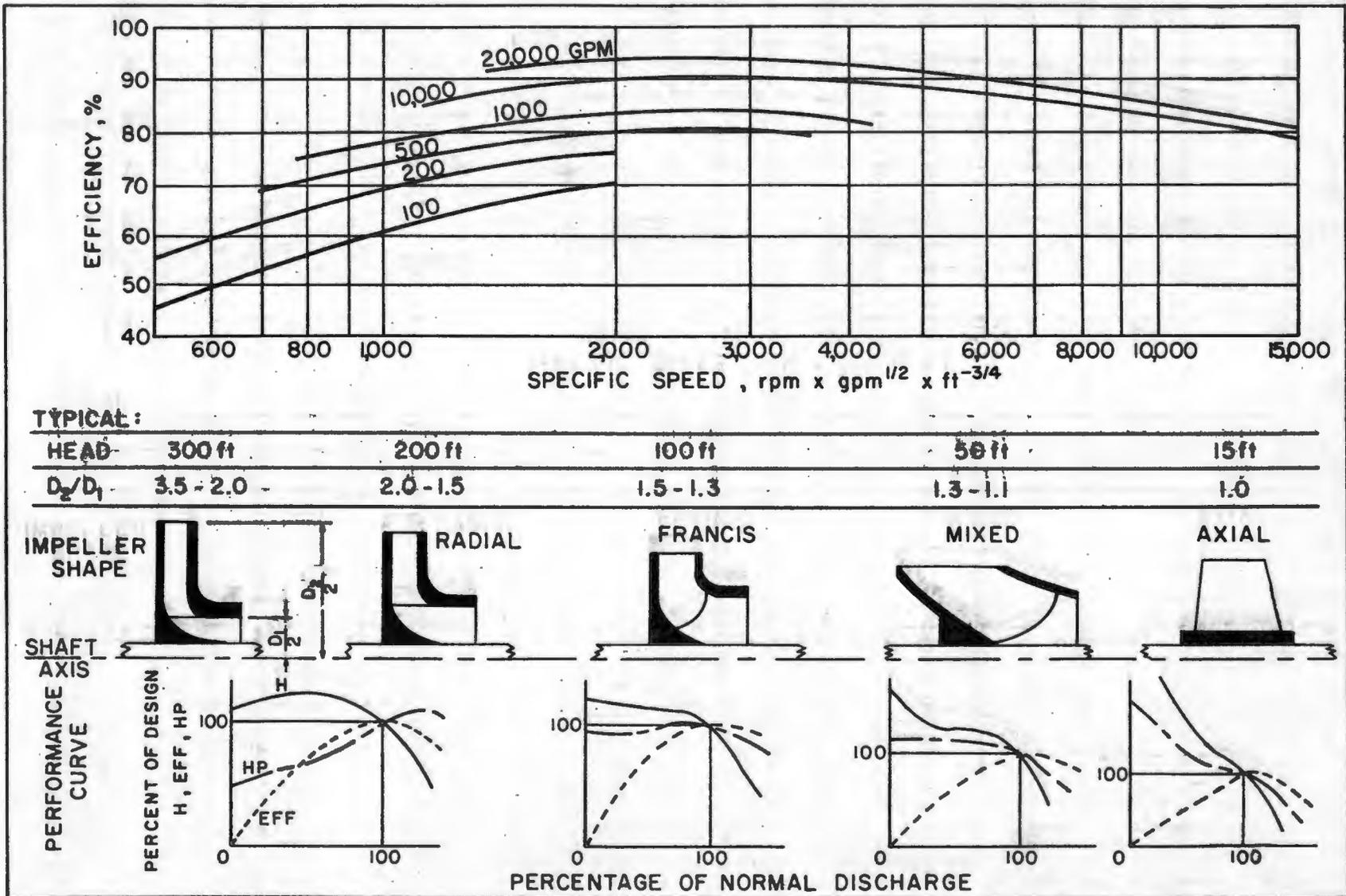


Figure 4.1 Approximate relationships of rotodynamic pump characteristics

speed lines, 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 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.

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 auxiliary 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.

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.)

Manufacturers produce a wide range of basic rotodynamic pumps covering many specific head-discharge-application requirements. By modification of

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	2.2	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	4.8	Depth to water level limited by NPSHR.
	4) In pit over shallow well		Allows increase of NPSHA.
	5) On float or boat in water supply with pipe or flexible suction		Good for greatly fluctuating water level in pond, river, drainage ditch, etc.
	6) In combination with ejector		For shallow or deep wells.
Incline	7) On trailer, submersed in water supply		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	4.2	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	4.3	Close-coupled with submersible motor.
	12) Single stage, mixed flow bowl assembly		Uses diagonal impellers; commonly called <i>vertical turbine pump</i> .
	13) Multi-stage, mixed flow bowl assembly	4.4	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	4.5	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		Used in large pumping stations-- not practical for small agricultural uses due to low efficiency and priming difficulties.
	2) At vertical wall of pit		Self priming; for high discharges.
Incline	3) Fixed on shore		Good for installation on levee or canal bank.
	4) On portable frame on shore	4.6c	Allows for use at various heads and locations.
	5) On portable frame on boat	4.6b	Utilizes boat motor and propeller.
Vertical	6) Mounted in well		Only for shallow wells.
	7) Fixed on shore		Can be used with siphon, as shown, to decrease power consumption.
	8) On portable frame		Same as inclined (4) (5).

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 motor (3-1/2-7 hp.) with a cylinder. As illustrated in Figure 4.6, 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 4.6b) or dismantled and used on shore (Figure 4.6c). 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 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).

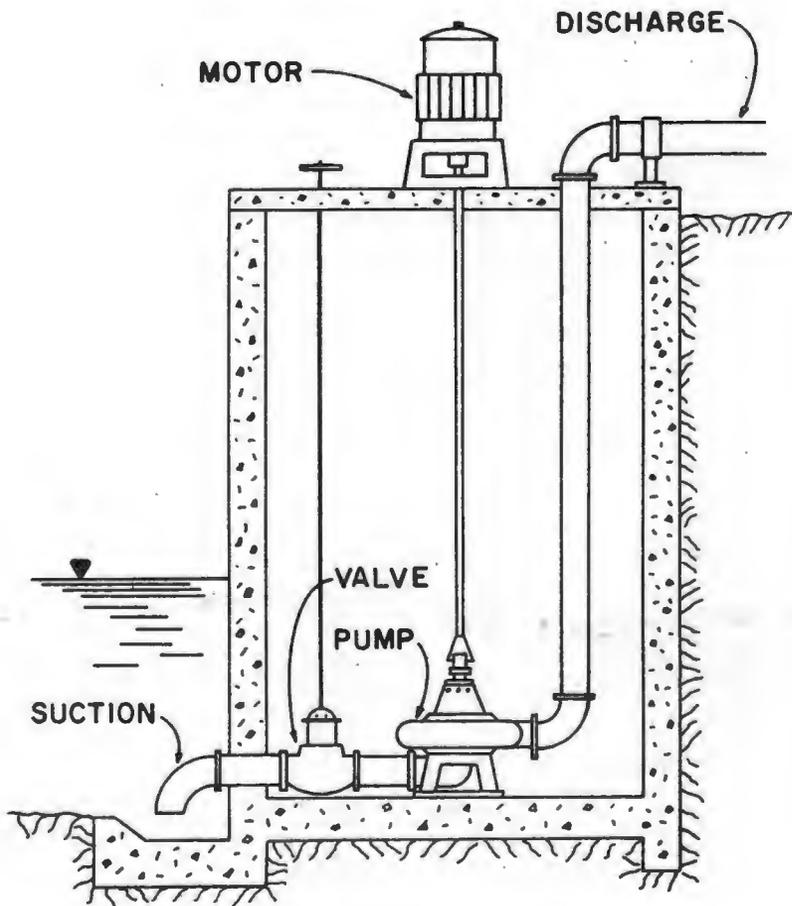


Figure 4.2 Vertical volute in dry pit

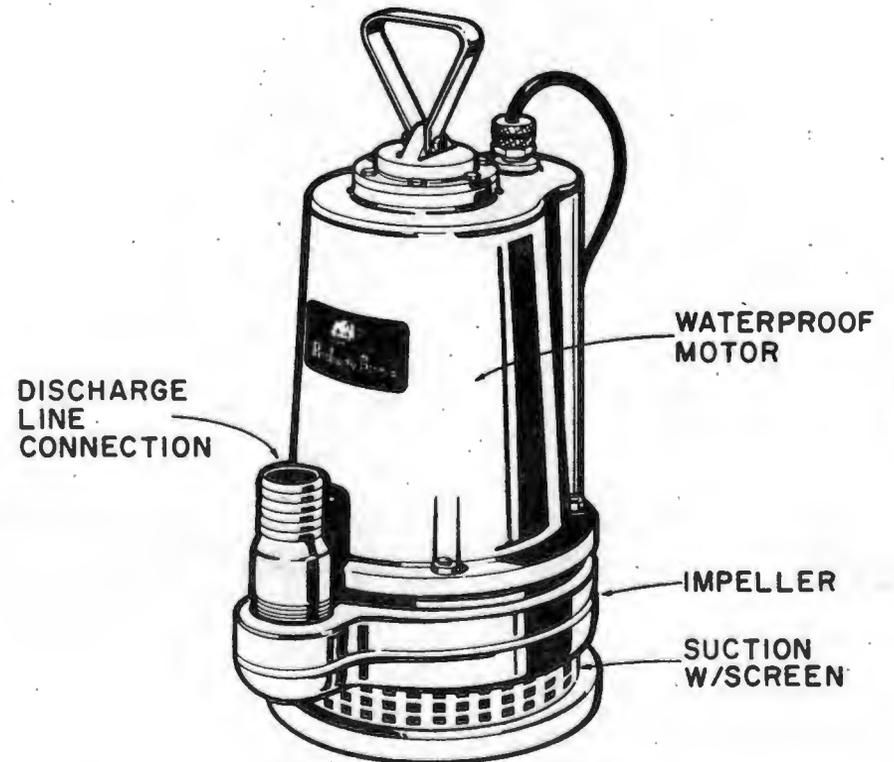


Figure 4.3 Submersible, portable volute pump (courtesy of Peabody Barnes Pump Co.)

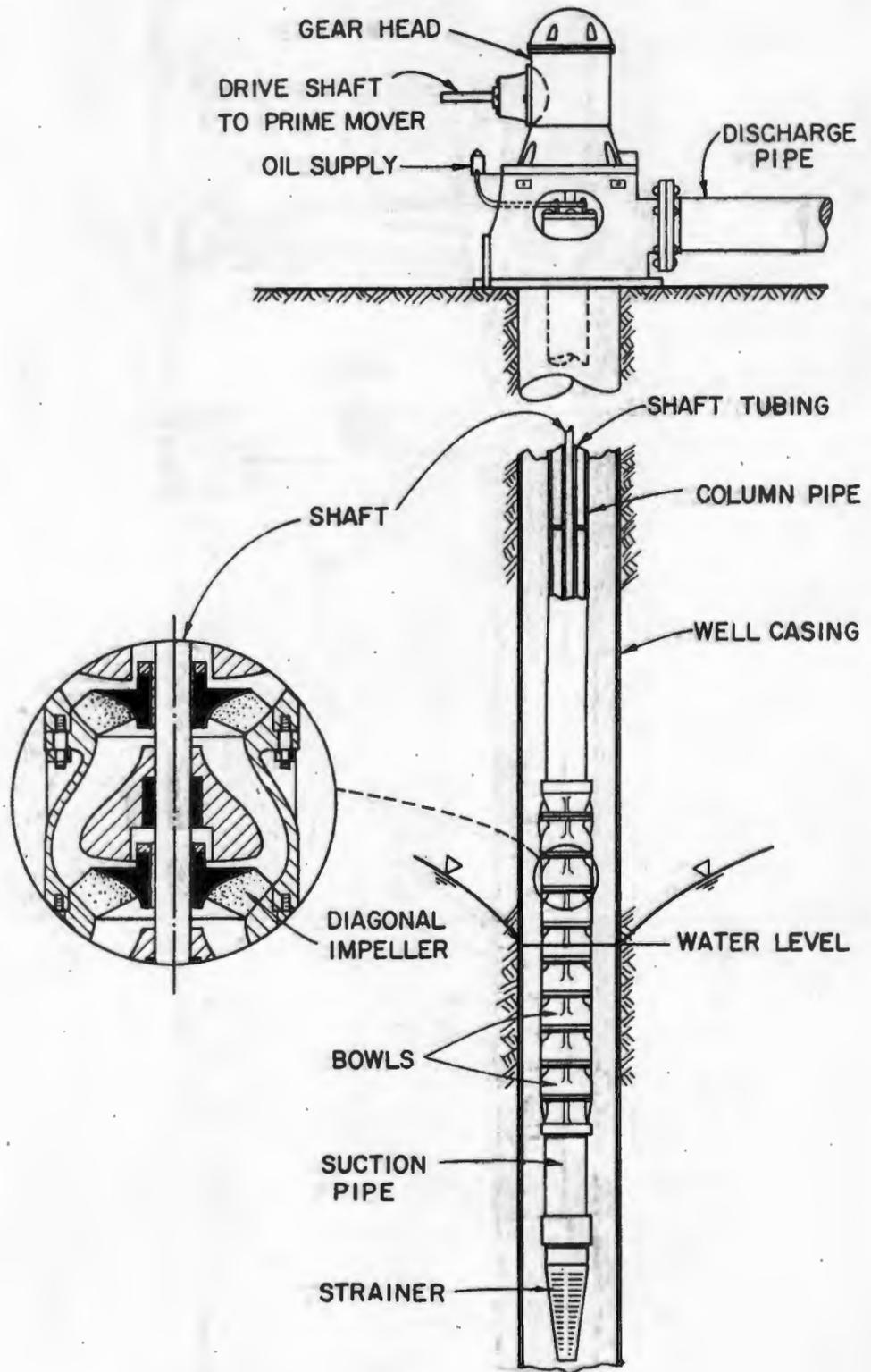


Figure 4.4 Mixed-flow, vertically-mounted, "turbine" pump

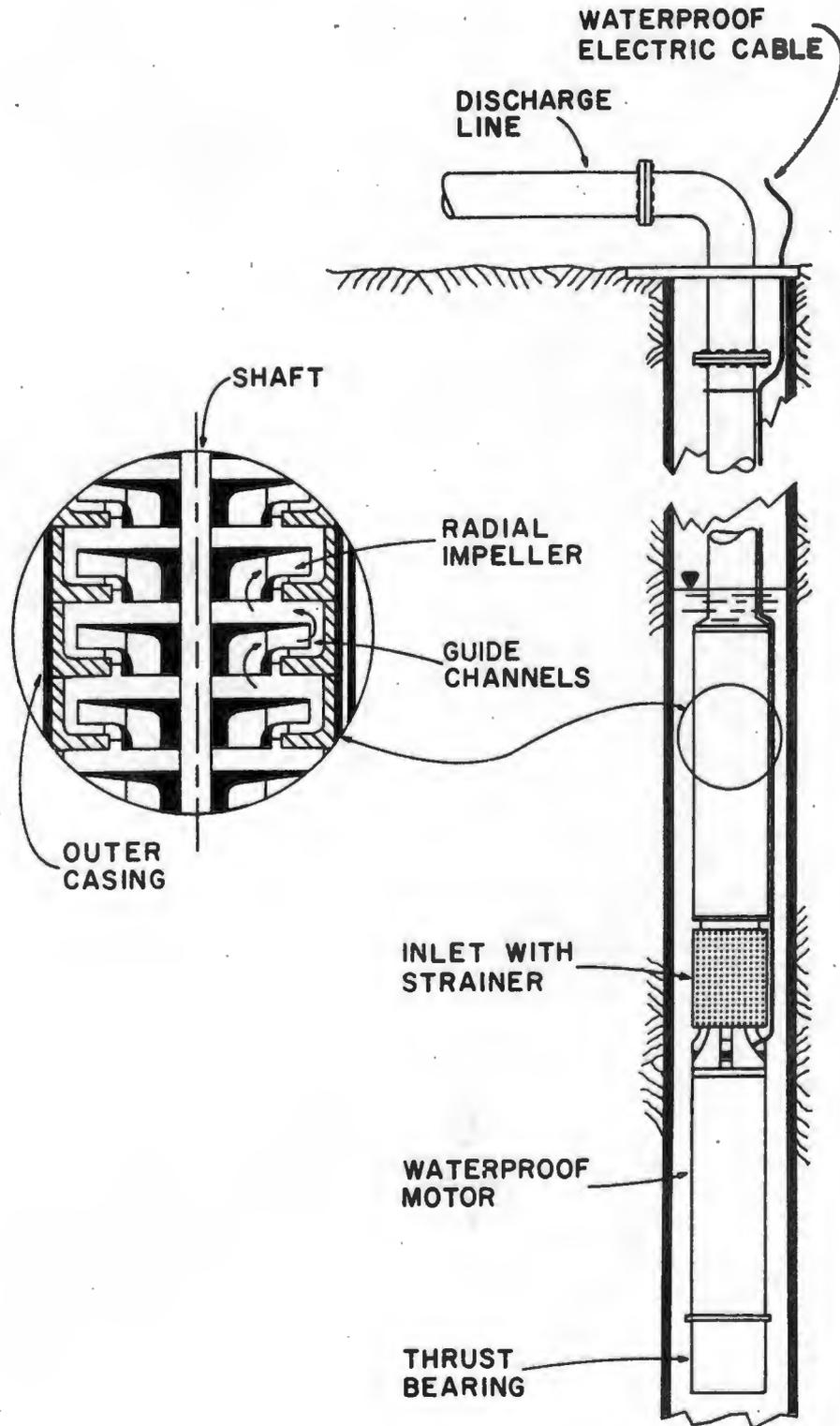


Figure 4.5 Radial-flow, vertically-mounted, "submersible" pump

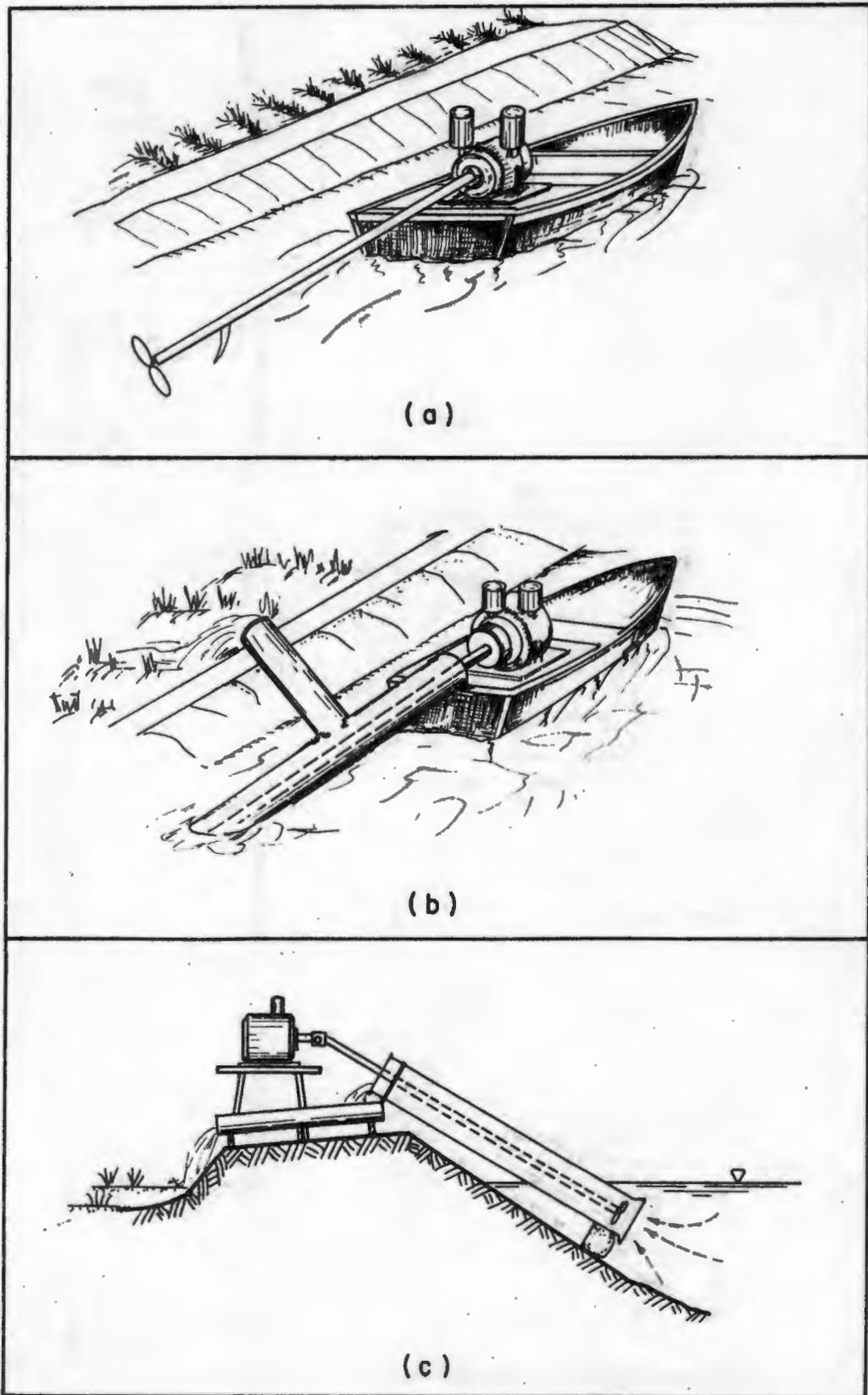


Figure 4.6 (a) Thai-style outboard engine and propeller used (b) for pumping from boat, and (c) from shore

### 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 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 4.7. For ease of operation and installation in wells, the sequence of Figure 4.7b is usually utilized in irrigation and drainage systems. However, it is the design in Figure 4.7a that is often used to add fertilizer to irrigation water. The arrangement of Figure 4.7b 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 also an effective way to increase the suction lift capability of a centrifugal

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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.

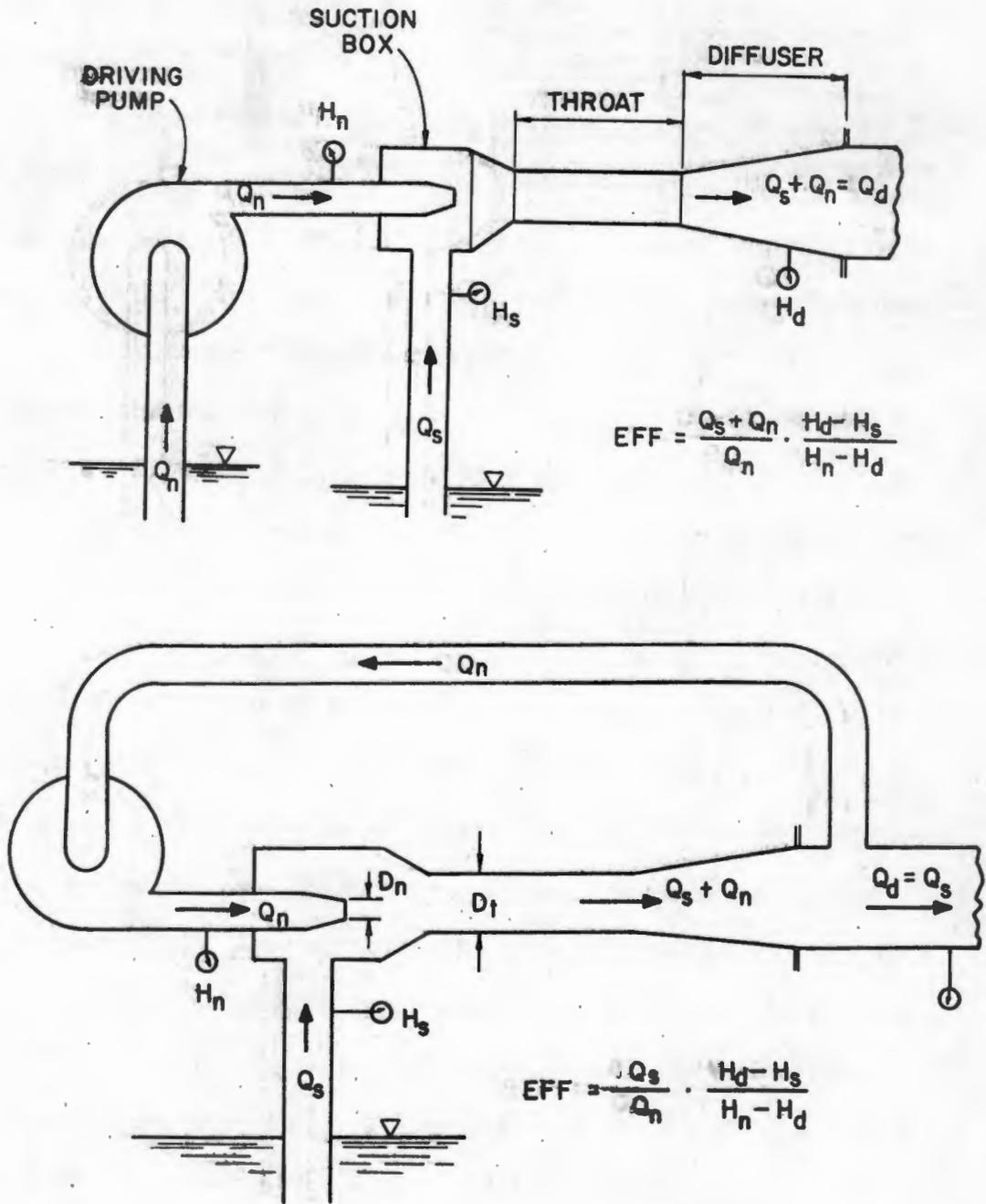
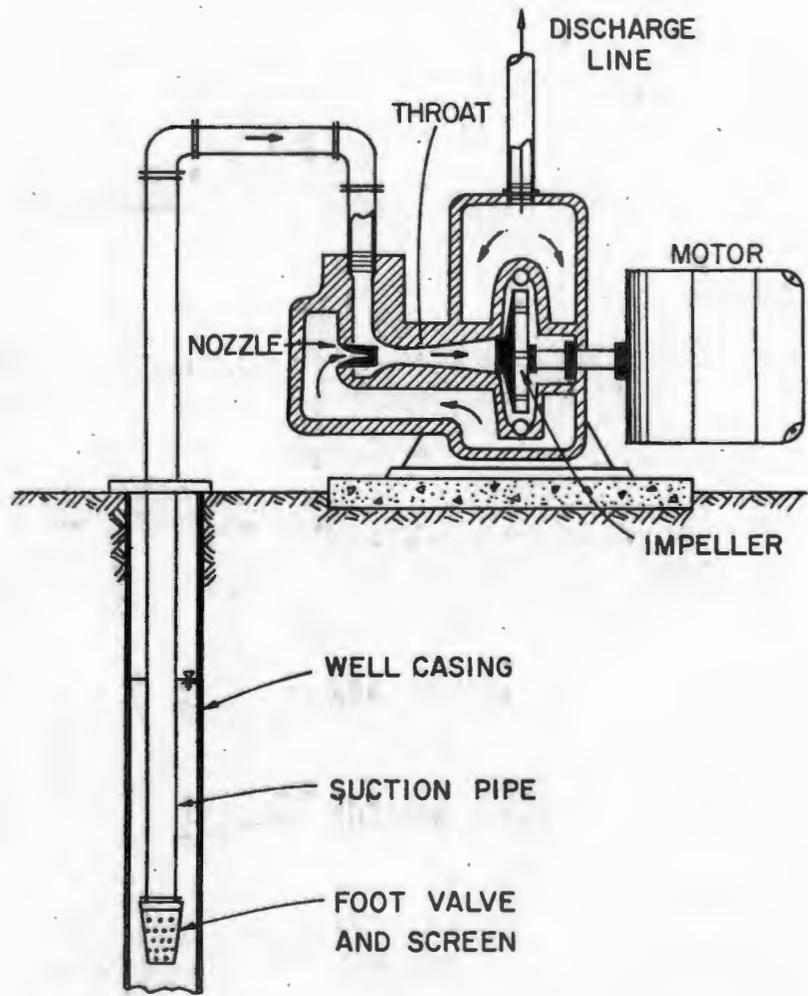


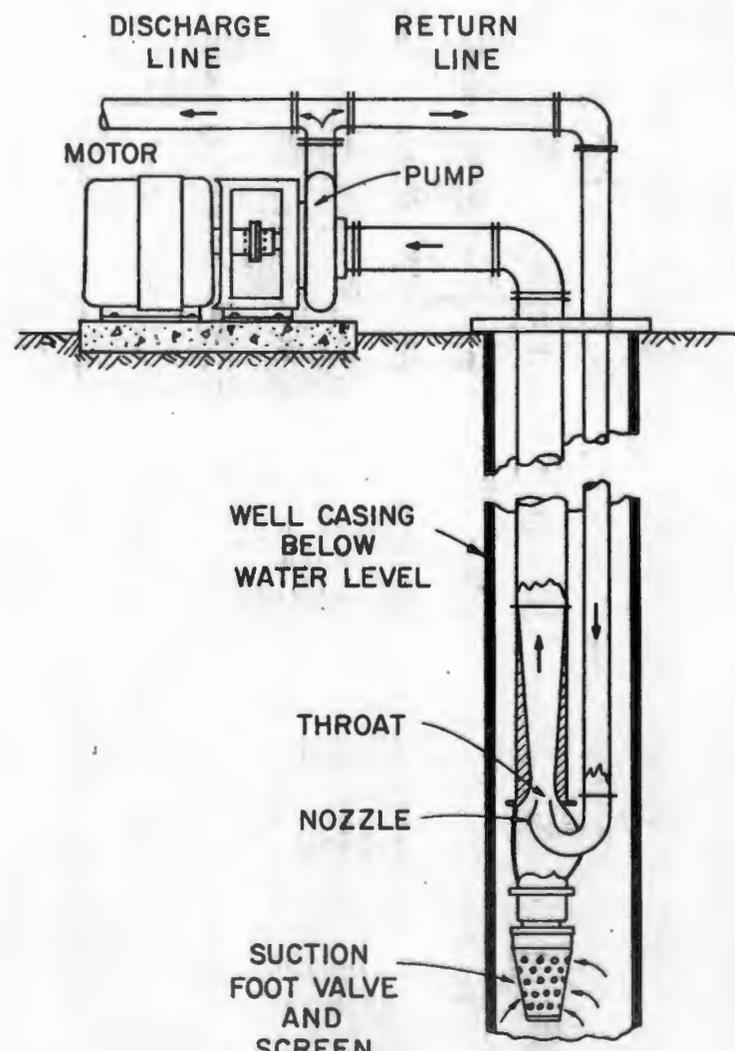
Figure 4.7 Two ejector arrangements:  
 (a)  $Q_d = Q_s + Q_n$ , (b)  $Q_d = Q_s$ ,  
 with  $Q_n$  recycled

pump--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 4.8 illustrates the common arrangement of ejectors for shallow and deep wells.

Because the centrifugal-jet arrangement of Figure 4.7a 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. The IRRI design makes this system applicable for low lift agricultural pumping situations, e.g. between canals and paddies.



(a)



(b)

Figure 4.8 Jet pumps for (a) shallow well with ejector/impeller combination unit, (b) deep well with ejector in the well

## Chapter 5

### Prime Movers

#### 5.1 Introduction

In the preceding chapters, the operations 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, shaft, etc.).

#### 5.2 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 under-employment 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) dollar 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. However, available literature relating to water lifting report 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 Staff, 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).

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

A recent development by Tim Journey (formerly with UNICEF in Bangladesh) 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 lifts 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 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 from 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.)

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.

### 5.3 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, 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.

Table 5.1 Manual power applications

<u>A. Reciprocating motions</u>			
<u>Performed with</u>	<u>Transmission</u>	<u>Water lifter</u>	<u>Remarks</u>
arms and/or upper torso	rope (may also include pulleys, etc.)	bucket	figure 3.0
	rope	swing basket	may require some leg movement; for 2 persons
	rope	water balance	figure 3.6 can also operate with one person and counterweight
	rope and pole	counterpoise lift	figure 3.3
	rope and pole	shovel	figure 3.5 may require some leg movement
	handle	gutter	figure 3.7a
	handle	diaphragm pump	figures 3.16
	handle and connecting rod	piston pump	figure 3.12 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 Behler (1975), p. 10
	pedal and spring return pedal	diaphragm pump	adaptation of figure 3.16
		air displacement pump	figure 3.31
	rocking foot rests	bellows pump	figure 3.15
	direct	doors	figures 3.9a and 3.10
	walkway	pitotlan	figure 3.4
	walkway	gutters	figure 3.7b
walkway	pitotlan-style door	figure 3.9b	
<u>B. Circular motions</u>			
arms and/or upper torso	crank	screw	
	crank	water ladder	figure 3.18 small capacities
	crank and small gear train	rotary	see Lubans (1971), and Hadeckel (1939)
	lever	semi-rotary	figure 3.28
	crank and windlass	bucket	
	crank and shaft	chain pump	figure 3.19
crank and cam	piston pump	utilizes eccentric type gearing	
legs and lower torso	horizontal axis treadmill or pedals (on lifter or separate with connecting shaft)*	paddle wheel norio 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 3.17 pedaling usually done in sitting position
	horizontal axis treadmill or pedals connected via shaft	screw water ladder chain pump	see figure 3.25 as above
	horizontal axis treadmill and windlass	rope and bucket	needs human ability to turn and reverse rotation
	horizontal axis treadmill (or pedals) and cam	piston pump	with eccentric gear
	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.

In some traditional system 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, 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. 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, 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). 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.

Schioler makes a 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 (1957), p. 22.

#### 5.4 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.

Table 5.2 Animal power applications

Motion of animal	Transmission	Water lifter	Remarks
A. Reciprocating	rope and roller	mot	figure 3.1 this requires wasting energy on a non-lifting return trip
-----			
B. Circular	sweep, rope, pulleys	two-bucket lift	figure 3.2 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 3.22 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	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	see donkey-wheel in Schioler (1975) p. 14; normally limited to smaller animals

#### 5.4.1 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 spoles 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, 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.

Another simple, but higher speed windmill consists of a set of long, narrow blades (e.g., 5ft x 10 in.) fixed to a hub. 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

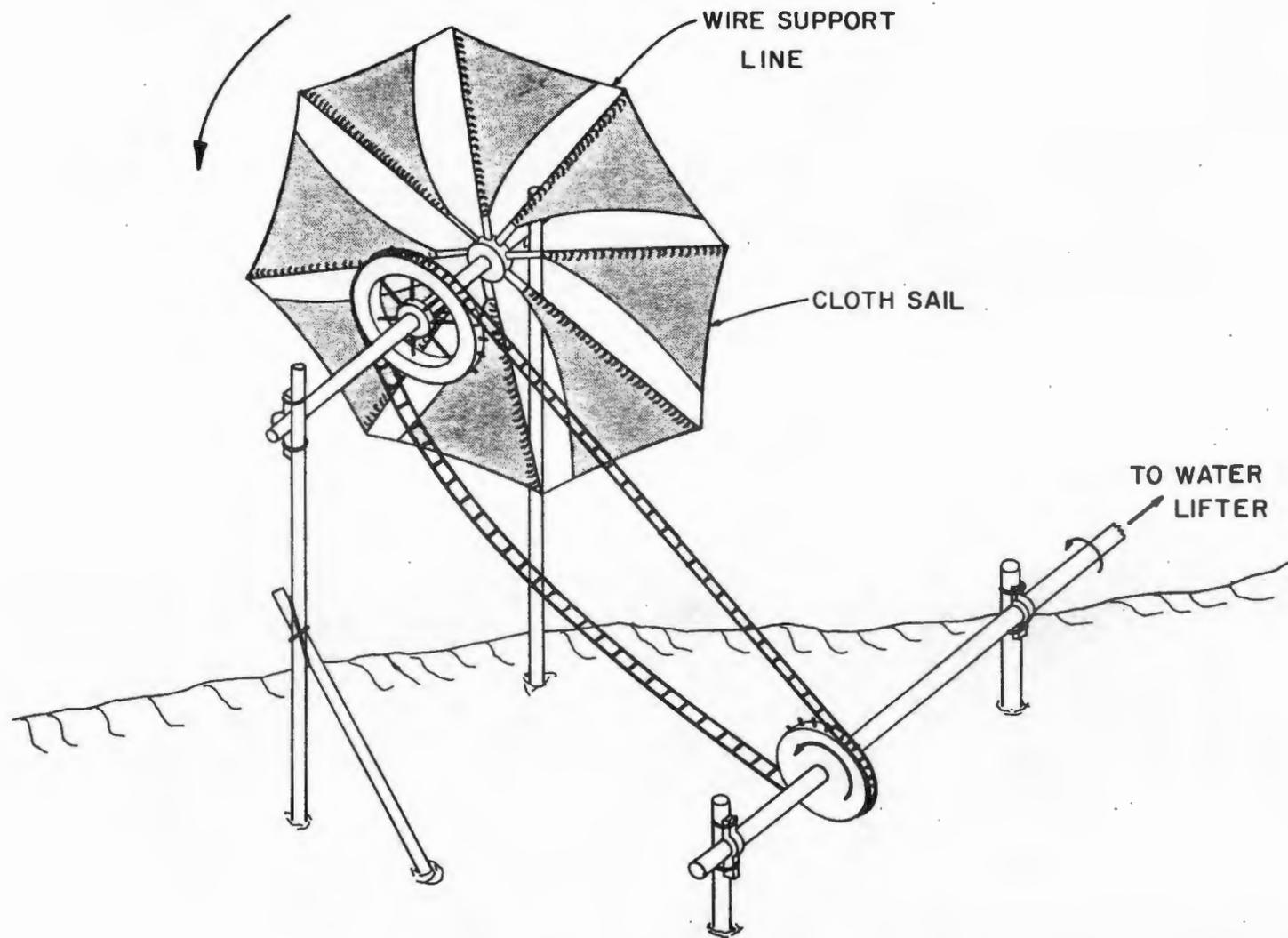


Figure 5.1 Sail type windmill with chain drive

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 5.2 have become a standard for water lifting purposes. Several commercial variations of this basic design are also available which utilizes more, but narrower blades than in the previous figure. Although most of these mills utilize a cam mechanism to provide reciprocating motion for a piston pump many are attached to gear mechanisms which retain their rotary form of power.

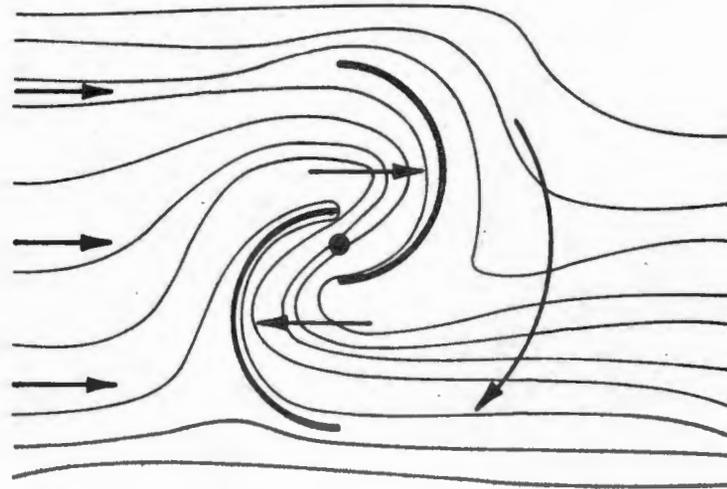
Commercial windmills of this type range in cost from about \$470 for 6 ft diameter mills (including sail wheel, guide vane, brake, turntable, and transmission) to over \$4,000 for 16 ft diameter models. Metal towers for these assemblies to be mounted on usually range from about \$44 for 3 ft heights to over \$3,000 for 47 ft designs.

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).

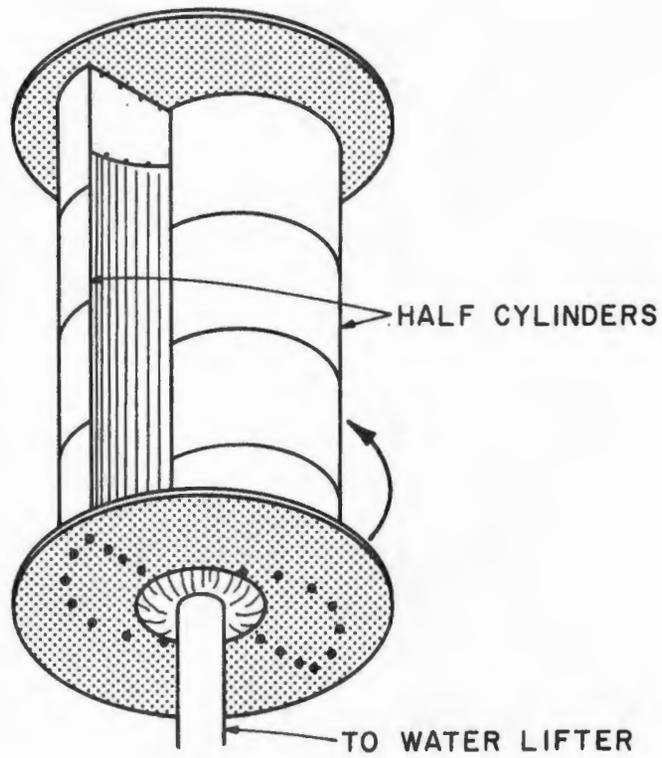
Two more recently popular designs in this class are shown in Figures 5.3 and 5.4. The savonius rotor can be quite simply constructed. A typical design consists of a 50 gallon drum, cut in half longitudinally, and the halves offset by about two-thirds of their diameter. When fixed to



Figure 5.2 American-style windmill with storage tank



(a)



(b)

Figure 5.3 Savonius rotor; (a) air flow and (b) construction

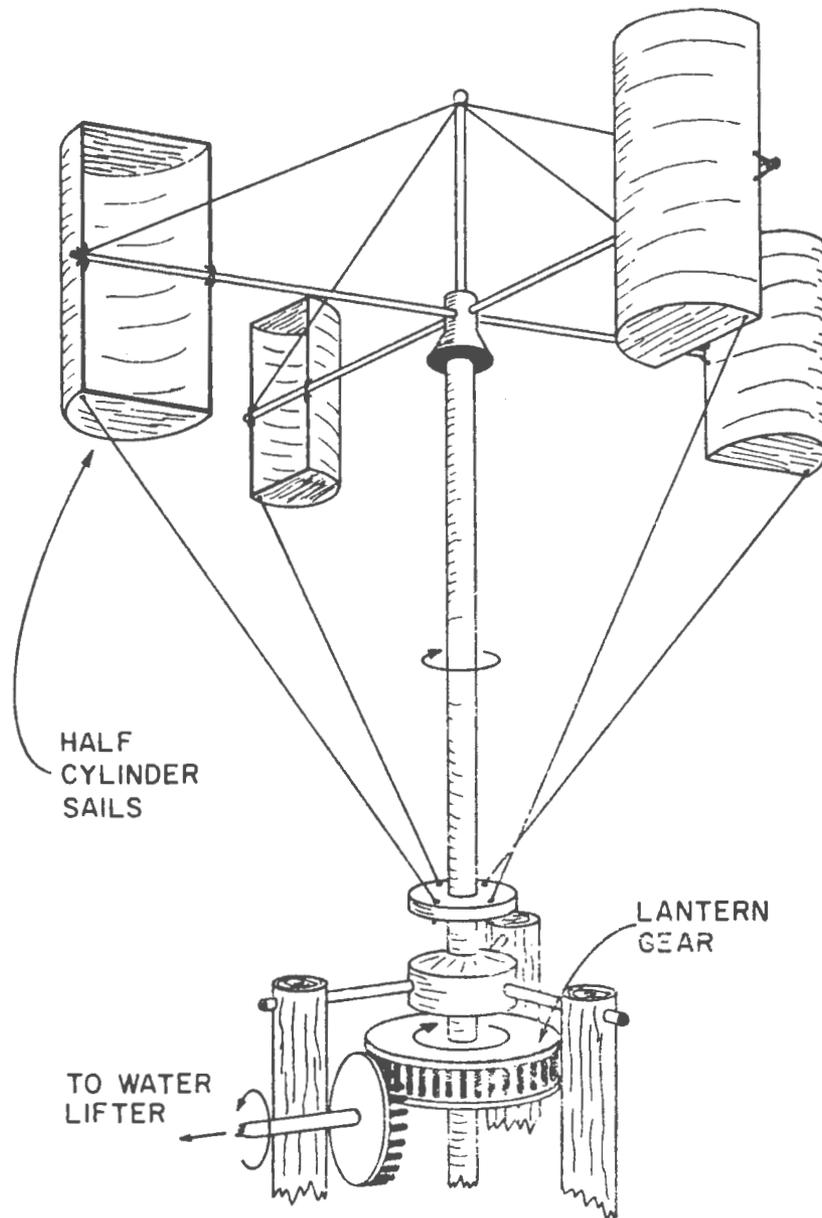


Figure 5.4 Anemometer-type windmill with lantern gear to transmit horizontal rotary motion

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. Savonius 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. 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. 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).

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). High speed/low starting torque designs, are more readily adaptable to driving rotodynamic pumps.

The Brace Institute utilized a three-blade "airscrew" windmill 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 5.3 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 auxiliary 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 tank (Figure 5.2), 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.

#### 5.4.2 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 windmills receive wind energy), and those which impart energy to water (e.g., noria, tympanum, etc.) as "waterwheels"--see Reynolds, 1070.) 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)

Table 5.3 Typical windmill applications

<u>A. Horizontal-shaft windmills</u>			
<u>Type</u>	<u>Transmission</u>	<u>Water Lifter</u>	<u>Remarks</u>
sail (figure 5.1)	on same incline shaft with on tower with chain and sprockets to horizontal shaft	screw paddle wheel noria tympanum Persian wheel water ladder chain pump	see Reynolds (1970), p. 150 for tower arrangement, see Beaumont (1974);
	as above plus angle gear on tower with eccentric mechanism and connecting rod	screw bucket pump diaphragm pump	figure 3.25 figures 3.14
propeller Figure 5.2	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 rōto- dynamic pump	as above
American	angle gear to vertical shaft with increasing ratio gear train	vertical-shaft roto- dynamic 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 angle gears or belts, and increasing ratio gear train to horizontal shaft	screw horizontal-shaft rotodynamic or rotary pump	table 4.1
	eccentric mechanism to connecting rod	bucket pump diaphragm pump	figures 3.14
<u>B. Vertical-shaft windmills</u>			
savonius (figure 5.3 or anemometer (figure 5.4	90° angle gearing to horizontal shaft	paddle wheel tympanum Persian wheel noria water ladder chain pump	see "sail"
	incline angle gearing eccentric mechanism and connecting rod	screw bucket pump diaphragm pump	figure 3.25 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

(more than one water lifter is often driven off of the same watermill shaft). Table 5.4 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 mill version (Bradley, 1912, p. 78), shown schematically in Figure 5.5a. It is installed so that its peripheral paddles (at least two at all times) are immersed in the driving flow. Figures 3.21a and b show such mills combined into a single unit with norias.

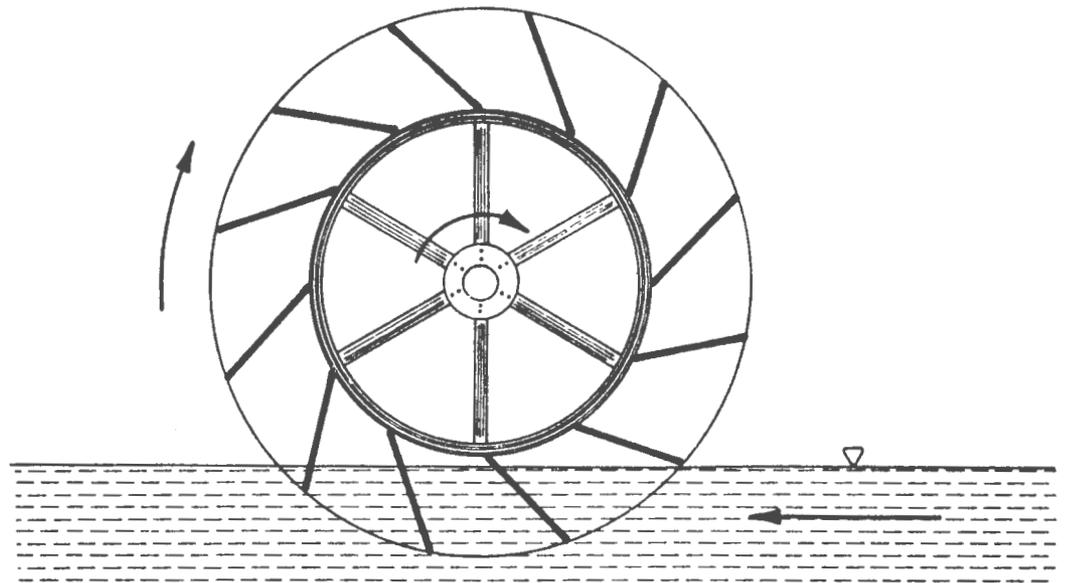
Because the efficiency of floating mills is rather low, another version of the undershot wheel, the Poncelet wheel, was developed (about 1800) which, when a suitable site is available, yields better efficiencies. As shown in Figure 5.5b, this mill requires the flow (or at least a portion of it) to be restricted to a channel, the 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. Poncelet wheels can be expected to have efficiencies between 60 percent to rotate the mill. Figure 5.6a and b illustrate medium and high breast wheels, respectively. A low breast wheel is essentially the same as a Poncelet wheel.

A major loss in efficiency of a breast wheel design is that, unlike 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 5.6b. Breast wheels

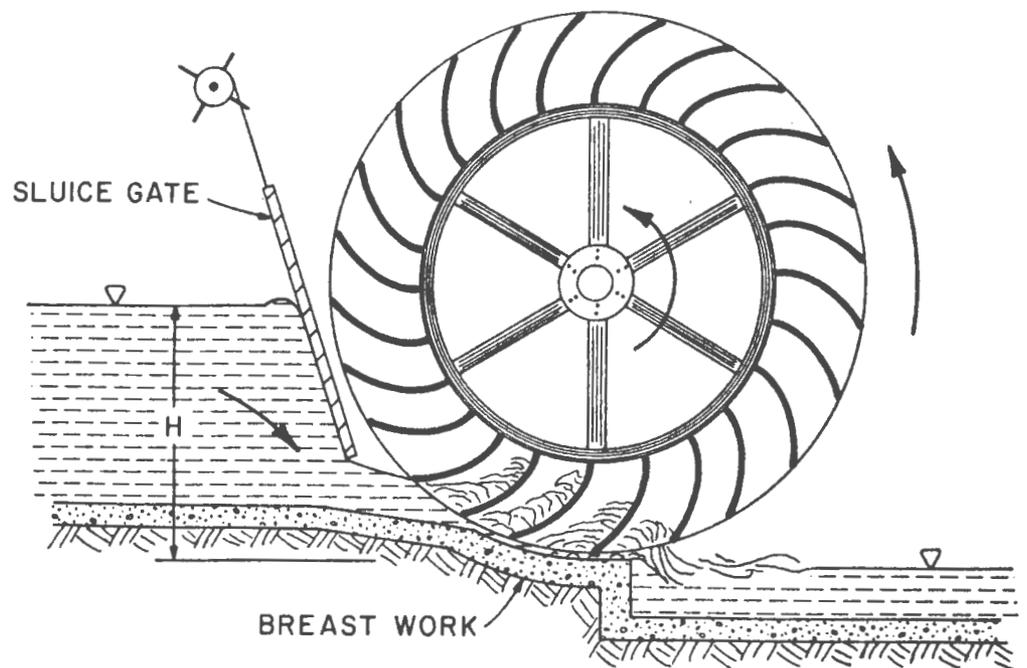
Table 5.4 Typical watermill applications

A. Horizontal-shaft watermills							
Type	Eff (%)	H (ft)	D-Diameter (ft)*	Optimum* rpm	Transmission	Water lifter	Remarks
float mill (figure 5.5a)	30-45	(current flow)	10-50	$\frac{72.8}{\sqrt{D}}$	combined into single unit	paddle wheel noria tympanum	figures 3.21a & b
Poncelet (figure 5.5b)	60-80	3-10	2H-4H (> 14)	$\frac{42.1\sqrt{H}}{D}$			
Breast (figure 5.6)	40-70	6-15	H-3H	depends on breast height	above plus increasing gear train	rotodynamic or rotary pumps	
Overshot (figure 5.7)	60-85	10-50	0.75H	$\frac{41.8}{\sqrt{D}}$	eccentric mechanism	bucket-piston pump diaphragm pump	figures 3.14 see VITA (1975), p. 117
Pelton wheel	75-90	> 50	1-20	$\frac{76.6\sqrt{H}}{D}$	increasing or equal gear train	rotodynamic or rotary pumps	
Michell turbine	60-85	> 15	1-3	$\frac{72\sqrt{H}}{D}$	above plus eccentric mechanism	high-speed piston, plunger, or diaphragm pumps	
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	80-90	> 15	1-30	50-220			

\*after Merrill, R., 1970



(a)



(b)

Figure 5.5 Undershot wheels; (a) floating mill, and (b) Poncelet wheel

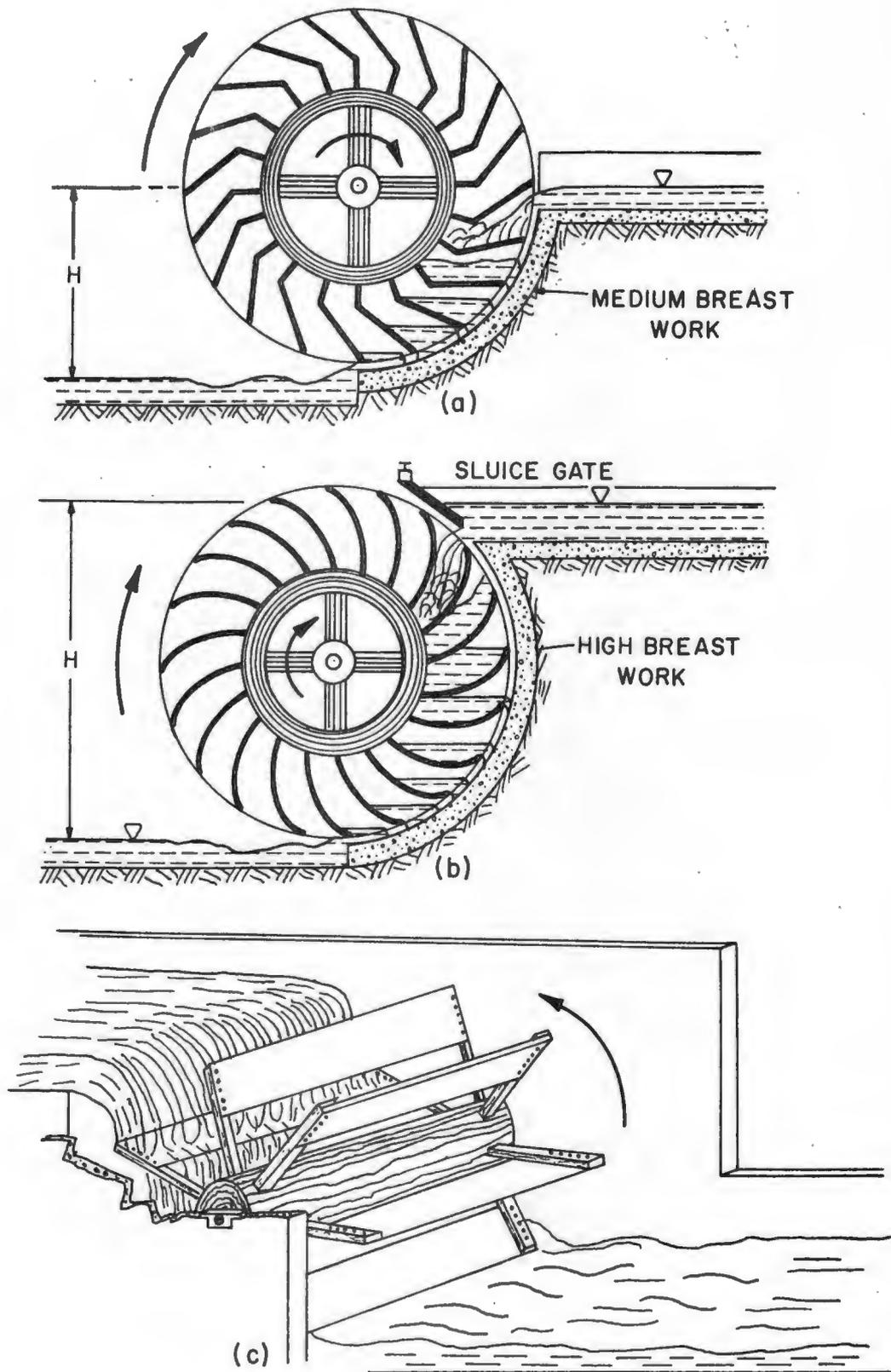


Figure 5.6 (a) Medium-breast wheel, (b) high-breast wheel with sluice gate, and (c) flutter-wheel

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 5.6c) 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 applications features as a breast wheel if the paddles extend to the hub--unlike Figure 5.6c (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 5.7, 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.

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,

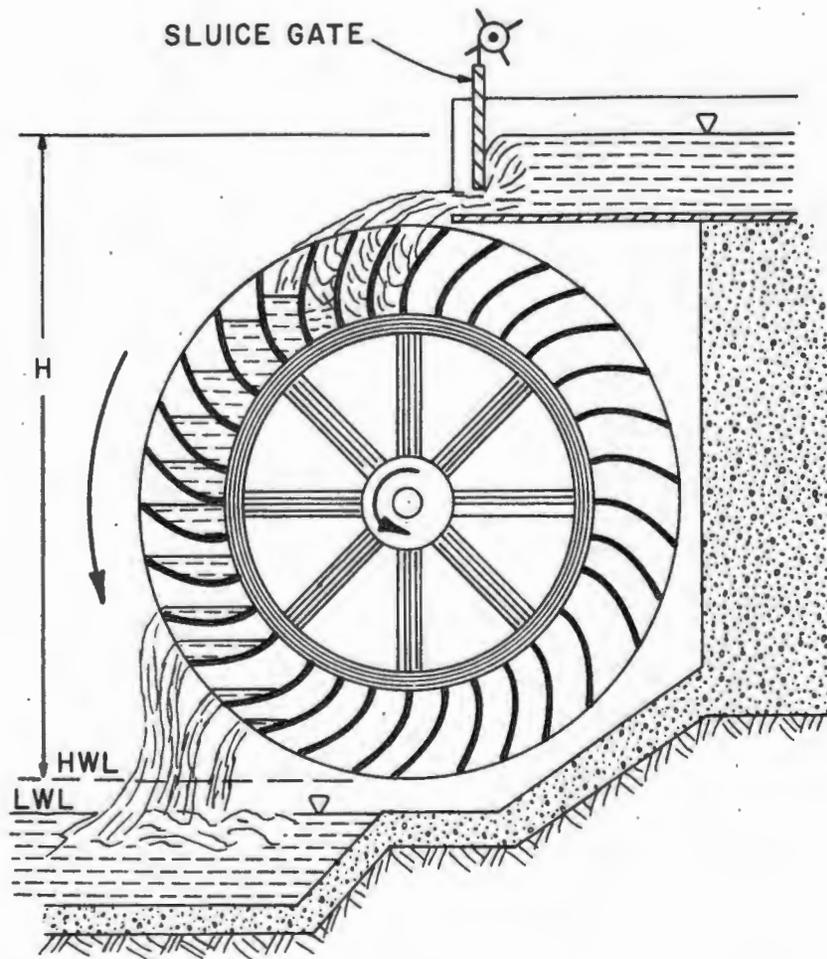
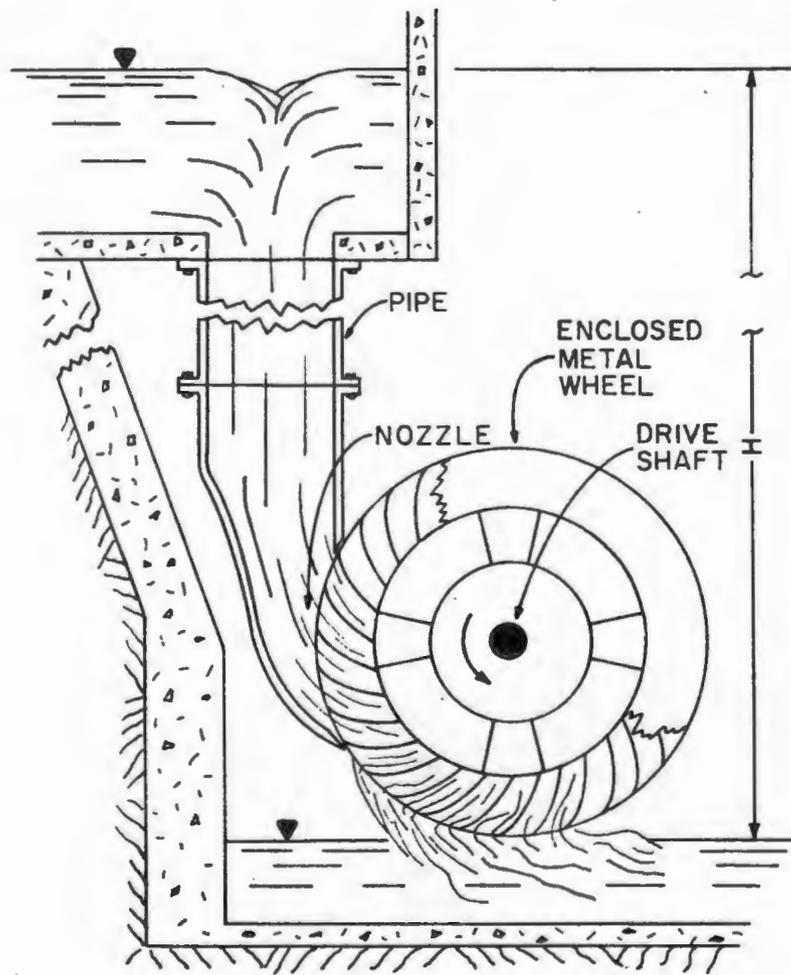


Figure 5.7 Overshot wheel with sluice gate

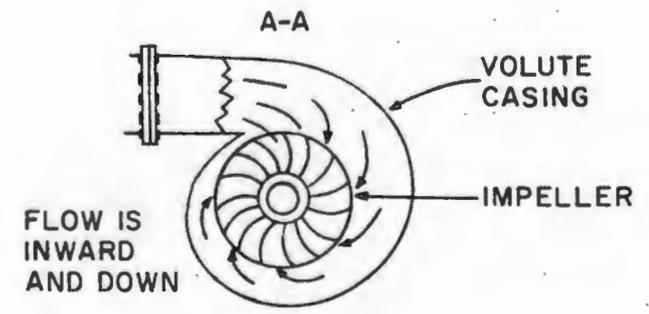
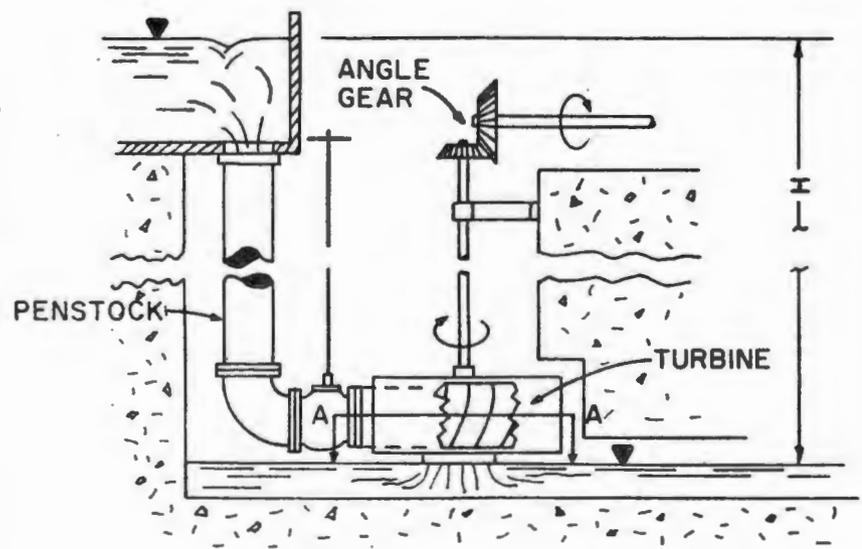
Although rarely in appropriate sites for irrigation or drainage water lifting, tidal water is another form of natural energy which, if properly harnessed, can provide an inexpensive source of power.

Wave action is a power source which has been adapted 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 described 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 5.8, this wavemill consists of two large, buoyant cylinders, set half of an average wavelength apart and each 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 (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.



(a)



(b)

Figure 5.8 (a) Horizontal-shaft tangent wheel (Michell turbine), and (b) impeller turbine (Francis type)

#### 5.4.3 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).

#### 5.4.4 Solar

Solar energy is another source of "free" power which has just recently reached a level of technology 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. Although solar energy has long been used for such purposes as heating and drying, the current world energy situations 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. Batelle 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.

### 5.5 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. 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 weatherproff models are also usually specified to protect a motor from natural elements, i.e., dust, rain, ice, insects, etc.

The efficiency of motors (i.e., in converting electrical to mechanical energy) increases with size. Table 5.5 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 5.5 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 expected to cost closer to \$700 (Molenaar, 1956).

Table 5.5 Typical electric motor efficiencies and prices

Size (rated hp)	Price (U.S. 1975 \$)*		Eff (%)
	New	Used	
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.

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 along 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. Table 5.6 list typical/values and the BHP-hr that can be expected from an engine using various fuels. In general, new gasoline engines have efficiencies 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.

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.)

Table 5 6 Typical energy values and performance of fuels

<u>fuel</u>	<u>energy value</u>		<u>performance*</u>
	<u>BTU/gal</u>	<u>hp-hr/gal</u>	<u>BHP-hr/gal</u>
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 <sup>3</sup>	0.4/ft <sup>3</sup>	5-7/100 ft <sup>3</sup>
electricity	--	1.34/kw-hr	0.5-1.2/kw-hr
coal			
bituminous	13,000/lb	--	--
lignite	7,000/lb	--	--

\*after Pair (1969)

Again, geography will influence cost, e.g., in Asia \$1,000 might buy 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

While, 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.

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 lift time and running intervals), user's preference, and power requirement. The following is a common guide to selection by power size:

less than 7-1/2 hp -- gasoline engine or electric motor  
 7-1/2 - 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

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).

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). A common arrangement for driving a vertical turbine pump is 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. 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.

6.1 Introduction

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.

6.2 Availability and Adaptability

The availability of goods and services will be the first factor to narrow the field to 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. It should also be noted that although 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, nor kept, available. Thus, in many instances, water lifters fall into disuse and eventually, when left to natural elements, become unrepairable (Fannon and Frink, 1970).

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.) to make them unusable. 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.

### 6.3 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 mind if applicable.

Throughout the preceding chapters, the  $Q$  and  $H$  ranges for various water lifters and pumps have been given. Figure 6.1 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, manufacturer's charts, should be consulted to find the optimum size and design. These charts are a performance composite of several pumps. From this selection, the performance curve can be obtained and compared to the  $H$ - $Q$  curve of the pumping system (see Figure 2.1). 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 near as possible 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.

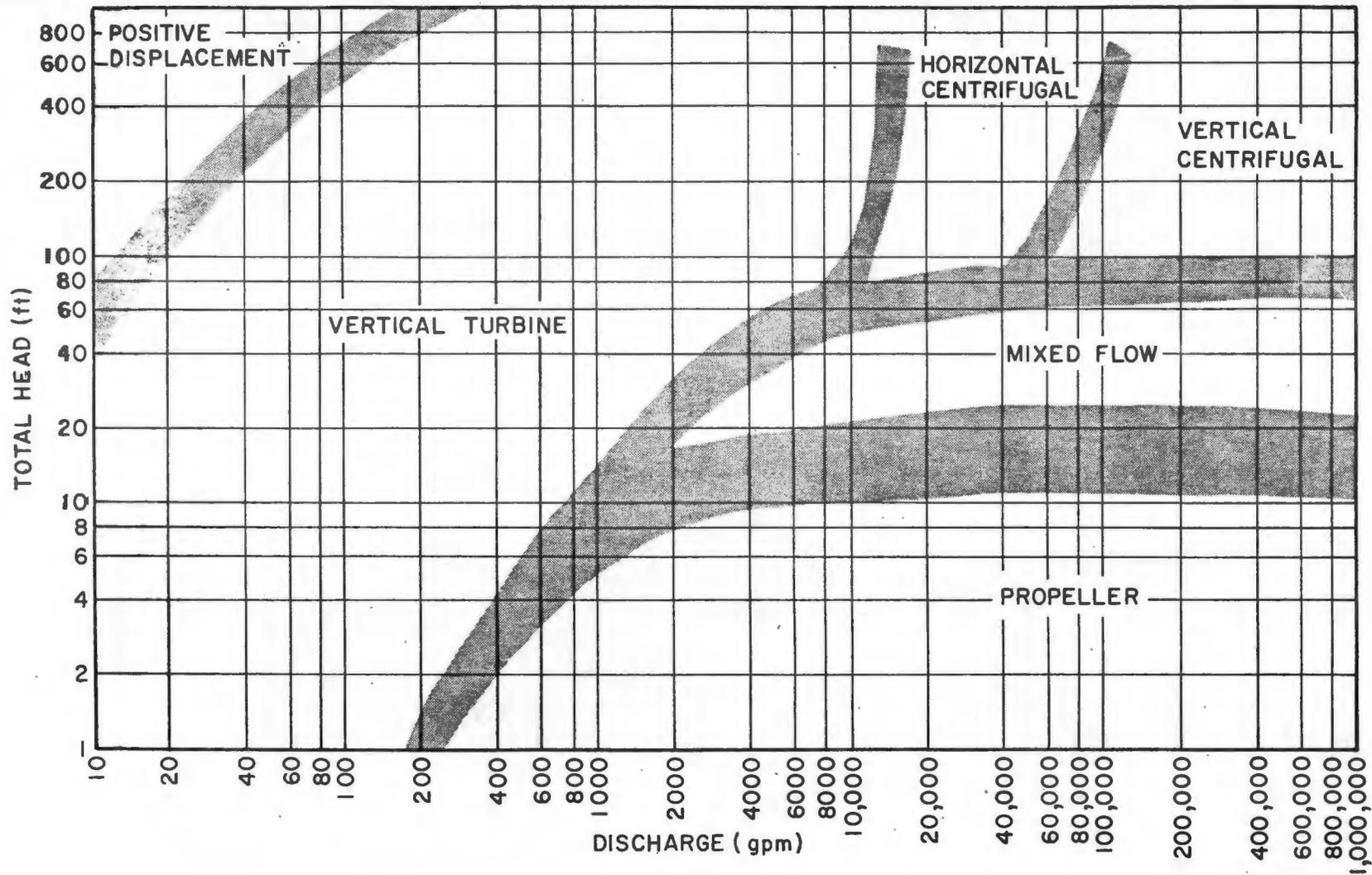


Figure 6.1 Pump selection guide based on H-Q performance (after Finch, 1948, and ECAFE, 1973)

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 2.3, H-Q curves 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.

#### 6.4 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.

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 6.1 (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)	<u>300.00</u>
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%)	<u>30.00</u>
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	<u>.05</u>
Total operating costs per acre-in.	\$ 3.29

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\* 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 6.2 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.

Because not all water lifting operations can easily be evaluated in monetary units, the following 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.

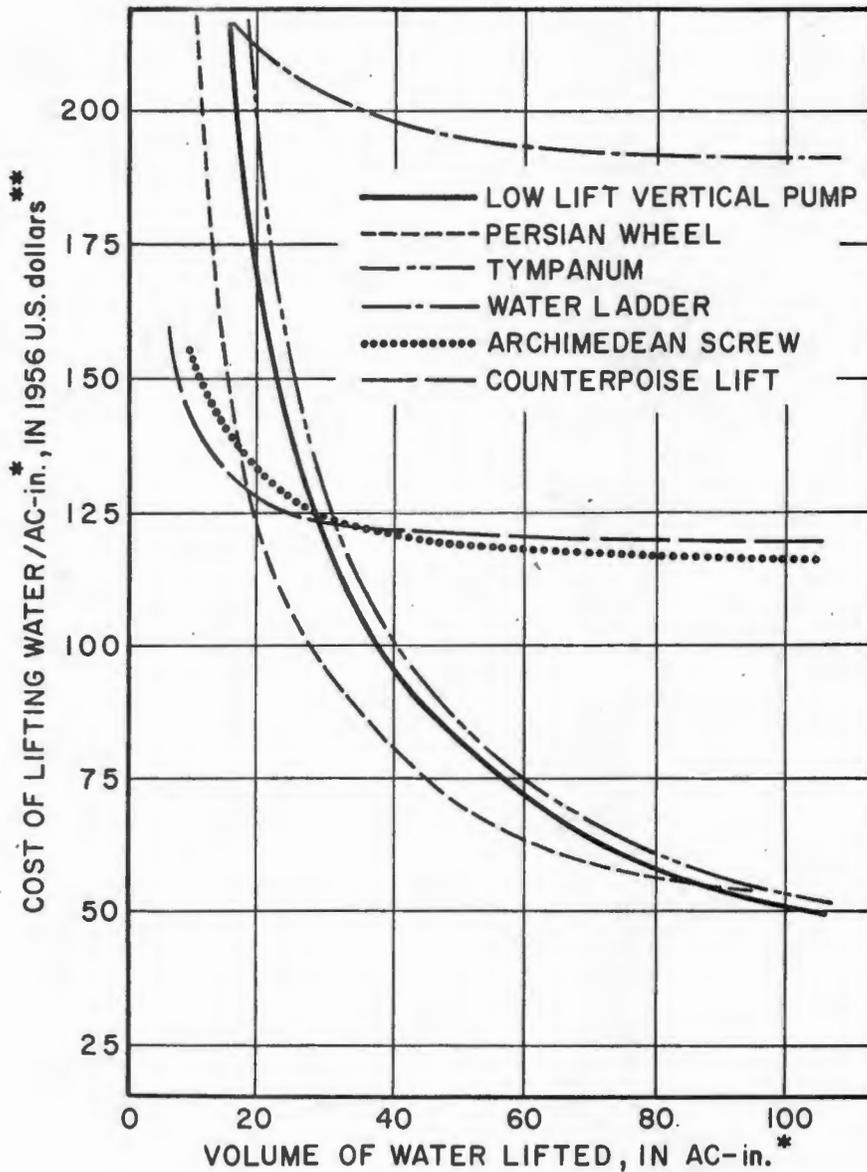
Example 6.2 (from Allison, 1975):

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<sup>3</sup> of water 10 ft = 62.4 lb/ft<sup>3</sup> x 10 ft = 624 ft-lb/ft<sup>3</sup>.



\* OR HA-cm (1 HA-cm = 0.97 AC-in.)

\*\* U.S. \$1.00 (1956) = U.S. \$1.85 (1975)

Figure 6.2 Comparative cost of lifting water to a height of 5.0 ft using various devices (from Molenaar, 1956)

Example 6.2 - Continued

- d) Approximate discharge =  $(18.33 \text{ ft-lb/sec}) \div (624 \text{ ft-lb/ft}^3) = 0.03 \text{ ft}^3/\text{sec} = 13.5 \text{ gpm}$ .
- e) Water required =  $33.3 \text{ in.} \times 0.5 \text{ ac.} = 16.7 \text{ acre-in.} = 450,000 \text{ gallons (U.S.)}$ .
- f) Time required =  $\frac{450,000 \text{ gal}}{13.5 \text{ gpm}} \times \frac{1 \text{ hr}}{60 \text{ min}} = 556 \text{ hours}$

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

## 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 7

### Improvements and Research Needs

#### 7.1 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 of 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.

#### 7.2 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 paper, 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 paper, 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 motts, 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).

### 7.3 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-existent 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 untrapped 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 work. 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

unit \ abbr.	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

unit \ abbr.	ft <sup>2</sup>	m <sup>2</sup>	ac	ha
foot <sup>2</sup>	1.0	0.093	2.30x10 <sup>-5</sup>	9.3x10 <sup>-6</sup>
meter <sup>2</sup>	10.76	1.0	24.7x10 <sup>-5</sup>	1x10 <sup>-4</sup>
acre	43,560	4,047	1.0	0.405
hectare	107,630	10,000	2.47	1.0

1 centare (ca) = 1 m<sup>2</sup>

1 in.<sup>2</sup> = 6.45 cm<sup>2</sup>

1 ft<sup>2</sup> = 144 in.<sup>2</sup>

Table A.3 Volume conversions and abbreviations

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

unit \ abbr.	ft <sup>3</sup>	m <sup>3</sup>	l	gal	ac-ft
foot <sup>3</sup>	1.0	0.0283	28.3	7.48	2.30x10 <sup>-5</sup>
meter <sup>3</sup>	35.3	1.0	1,000	264.2	8.11x10 <sup>-4</sup>
liter	0.0353	0.001	1.0	0.264	8.096x10 <sup>-7</sup>
U.S. gallon	0.134	0.00379	3.79	1.0	3.07x10 <sup>-6</sup>
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<sup>3</sup> = 1728 in.<sup>3</sup> = 0.037 yd<sup>3</sup>

Table A.4 Pressure conversions and abbreviations

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

unit \ abbr.	ft water	psi	in. Hg	mm Hg	kg/cm <sup>2</sup>
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

unit \ abbr.	fps	mps	mph	km/h
<u>foot</u> second	1.0	0.305	0.682	1.097
<u>meter</u> second	3.28	1.0	2.24	3.6
<u>mile</u> hour	1.47	0.447	1.0	1.61
<u>kilometer</u> 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	l/sec	mgd
$\frac{\text{foot}^3}{\text{second}}$	1.0	488.8	$9.81 \times 10^{-6}$	0.646
$\frac{\text{gallon}}{\text{minute}}$	$2.23 \times 10^{-3}$	1.0	0.063	$1.44 \times 10^{-3}$
$\frac{\text{liter}}{\text{second}}$	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

unit \ abbr.	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
$\frac{\text{foot-pound}}{\text{second}}$	$1.82 \times 10^{-3}$	$1.36 \times 10^{-6}$	1.0	$1.94 \times 10^{-2}$
$\frac{\text{kilogram-calorie}}{\text{minute}}$	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 <sup>3</sup> /sec m	(6) m <sup>3</sup> /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<sup>3</sup> 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 revolutions 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
$\gamma$	- specific weight
$\rho$	- specific mass