Pump Selection: a Field Guide for Developing Countries
WASH Technical Report No. 61

By: Richard McGowan and Jonathan Hodgkin

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WASH

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PUMP SELECTION: A FIELD GUIDE FOR DEVELOPING COUNTRIES

WASH TECHNICAL REPORT NO. 61

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under WASH Activity No. 316

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ABBREVIATIONS AND ACRONYMS

AC	alternating current
ADP	animal-drawn pump
AID	U.S. Agency for International Development
ALCC	annualized life-cycle cost
ARD	Associates in Rural Development, Inc.
CIF	cost/insurance/freight (delivered price)
DC	direct current
FLFC	full-load fuel consumption
FOB	freight on board (ex-factory price)
g/kWh	grams of fuel consumed per rated kilowatt-hour
Hp	horsepower
I/V	current/voltage
J	joule
Jm^2-sec	joules per sequare meter per second
kW	kilowatt
kWh	kilowatt-hour
kWh/m^2d	kilowatt-hours per square meter per day (irradiation)
LPD	liters per person per day
l/s	liters per second
mg/l	milligrams per liter
MJ	megajoules
MJ/m^2d	megajoules per square meter per day
m^3/d	cubic meters per day
m^3/h	cubic meters per hour
mph	miles per hour
MPPT	maximum power point tracker
m/s	meters per second
MW	megawatt
NGO	nongovernmental organization
O&M	operation and maintenance
PCU	power-conditioning unit
PCV	Peace Corps volunteer
psi	pounds per square inch
PV	photovoltaic
PVO	private voluntary organization
rpm	revolutions per minute
TDS	total dissolved solids
VLOM	village-level operation and management of maintenance
W	watts
w/m^2-sec	watts per square meter per second
WASH	Water and Sanitation for Health Project
WHO	World Health Organization
Wp	peak watts

PREFACE

This manual was written to help professionals and technicians in developing countries select water pumping equipment that closely matches their requirements in terms of performance, cost, and long-term system support. Funding for the manual was provided by the Water and Sanitation for Health (WASH) II Project under the auspices of the U.S. Agency for International Development's (AID) Bureau for Science and Technology, Office of Health. It was prepared by the engineering staff of Associates in Rural Development, Inc. (ARD).

Much of the information in this manual is based on the authors' experiences with pump testing and evaluation in a variety of developing countries, including Botswana, Malaysia, Sudan, Yemen, Somalia, and Djibouti. We would like to thank the many people who helped us on these projects, including host-country and expatriate engineers, economists, and technicians as well as a number of people from private voluntary organizations (PVOs) and the Peace Corps. We would also like to thank the persons who have reviewed drafts of this report for their useful comments: Peter Bujis of CARE, Joseph Christmas of UNICEF, Mike Godfrey of CARE/Rwanda, Peter Lehman of Humboldt State University, Rita Kirkpatrick of ARD, Ron White--consultant with ARD, and Alan Wyatt of Research Triangle Institute. We would also like to thank John Ashworth (formerly with ARD) for his help in conceptualizing the early phases of this work. In the final stages of preparation, the manual was edited by Diane Bendahmane whose careful reading and detailed comments are greatly appreciated. Finally, we would particularly like to thank Phil Roark (WASH) for his active support throughout the development of this field guide. He has not only kept the writing, shaping, and review of this guide moving forward, he has also made many useful suggestions during the development of the technical approach and presentation of the material.

The cost and performance data given herein represent the best available estimates as of the date of this report for the types of equipment discussed. These values can and do vary considerably, depending on the country where the equipment is used, the expertise of the operator, and the extent to which proper system sizing, operation, and maintenance procedures are followed.

WASH hopes this manual provides a helpful method for pump selection that will be useful to a wide variety of readers. Comments on the method and any additional local data on experiences with equipment, costs, performance, and availability would be welcomed by the authors for inclusion in subsequent revisions.

Chapter 1

INTRODUCTION

1.1 Why This Manual?

The improvement of rural water supplies has been a major focal point of rural development efforts in developing countries. These efforts have not always met with success, often because inadequate attention has been given to proper equipment selection and use. The importance of strengthening local institutions that are capable of handling necessary equipment-support functions, including system design, installation, operation, maintenance, and repair, has frequently not been recognized. Even well designed pumping systems often fail prematurely due to a lack of planning and insufficient funding for the long-term recurrent costs of maintenance and repair.

Over the past few years, system designers have begun to consider recurrent costs in the pump selection process, primarily in response to the rising cost and increasing scarcity of conventional energy supplies in developing countries. Attention is also shifting to alternative energy sources for pumping, particularly in rural areas where users often do not have access to the national power grid. In such areas, users have typically had only two options--diesel systems or handpumps. Dramatic increases in petroleum fuel prices over the last two decades have heightened interest in other types of low- to medium-capacity pumps, such as those powered by wind and solar radiation.

This manual was written to aid a wide variety of people who are involved in making decisions about water pumping equipment and its use:

- managers of water resources development projects;
- development professionals (with some degree of experience with pumps);
- host-country and expatriate engineers and technicians working in both public and private sectors, including nongovernmental organizations (NGOs);
- Peace Corps (PCVs) or other volunteers with a technical background; and
- technically inclined pump users.

It is intended to enable readers to understand better and evaluate more carefully the advantages and disadvantages of different types of pumping systems and their components (e.g., pumps, engines, and controls), associated costs, and long-term operation and maintenance (O&M) requirements. With this information, readers can make knowledgeable, cost-effective choices of water pumping equipment, which will result in water development projects that are more effective and that offer increased water availability and decreased costs to users.

Many handbooks have been written on the subject of rural water supply, irrigation, and pump selection (see the annotated bibliography in Appendix A). Until recently, most of these focused primarily on the technical aspects of choosing a pump. Issues such as recurrent O&M costs, availability of technical skills and spare parts, system reliability, ease of installation and/or operation, and related considerations that are or may be of paramount importance to users were discussed only briefly.

Pump users in developing countries face a wide range of constraints in ensuring the reliability of water supplies, including

- lack of trained, experienced mechanics and engineers to handle system design, installation, operation, maintenance, and repair;

- lack of fuel and spare parts;

- very limited selection of locally available system types and sizes to meet specific water needs;

- a sometimes wide variety of locally unsupported pumping equipment, chosen not because it meets local needs but rather because the donor prefers it; and

- inadequate information on how properly to match available equipment to water pumping needs.

Pump selection must take all of these constraints into account. The alternative—selecting a system without being adequately informed—will undoubtedly increase water costs and maintenance and repair requirements. Inappropriate equipment selection can have major adverse implications for a project, including

- inadequate or grossly over-sized system capacity;

- over- or under-used water sources;

- increased capital equipment costs;

- higher recurrent costs;

- overly frequent maintenance and repair; and

- unnecessary system downtime due to fuel shortages, inadequate renewable energy resource base, or lack of on-demand water pumping capability.

This manual provides information on the operating characteristics, design procedures, O&M requirements, and advantages and disadvantages of various equipment alternatives to help readers make a better pump selection for both groundwater and surface-water use.

1.2 Goal and Purposes

This manual is designed to enable field technicians and managers who do not necessarily have extensive experience in water engineering to make appropriate choices of water pumping systems and components. It presents the decision-making process as a logical progression, first discussing what information is needed before examining pumping system alternatives, and then showing readers how to gather and analyze the needed information so it can be used in applying a set of selection criteria. The criteria are given in flowchart fashion, so users can apply the data they have acquired to make useful, accurate decisions about pumping equipment alternatives.

To achieve this purpose, the manual attempts to

- describe the process of properly selecting pumping equipment for small-scale potable water supplies, based on site and resource characteristics, as well as the engineering, economic, and institutional characteristics of each type of system;

- assist with the initial screening of water pumping technologies by describing what information is necessary to determine equipment needs and how to gather it;

- provide detailed guidelines for analyzing the data required for a technical comparison of diesel, wind, hand, and solar pumping systems (other types of systems may be included in later revisions of this manual);

- inform readers on recent and past operating experience with diesel, solar photovoltaic (PV), wind, and handpump systems, including problems and attempted solutions as well as new approaches to making different designs more appropriate for operating conditions in developing countries; and

- give estimates of typical capital and recurrent O&M costs for the systems considered here, along with guidelines for adapting these costs to reflect specific conditions in the user's country or region.

This manual is written for a wide audience—it is not intended to be a comprehensive reference manual on the engineering and economic design and analysis of all small-scale water pumping equipment. Where appropriate, readers are referred to other references (see Appendix A) that contain in-depth treatments of particular topics, so those who are interested in the intricacies of a certain subject can examine other resources for additional information. Here, detail has been sacrificed to provide broad coverage of all relevant areas.

1.3 Overview of the Pump Selection Process

This manual uses a straightforward pump selection method that takes into account technical, social and institutional, and cost factors in choosing the most appropriate pumping system(s) for a given level of water demand and specific set of site constraints. It shows readers how to collect and analyze the basic engineering and cost data needed to select any of the four system types considered here—diesel, solar PV, wind, and handpump systems. There are a variety of other types of pumping systems used in developing countries, including hydraulic rams, biogas-powered pumps, and animal traction pumps. These are not covered in this manual, but information on these systems is given in the bibliography (especially Fraenkel 1986).

The selection process involves several stages of information gathering and analyses:

- determining water demand at the site, based on the number of water users (e.g., human, animal, and agricultural);
- measuring and calculating the energy requirement to meet that water demand, based on the physical characteristics of the water source and system design;
- reviewing what equipment is locally available or can be imported to define the range of available pumping options;
- estimating the output of the four types of pumping systems covered in this manual--diesel, solar, wind, and hand;
- determining site-specific cost factors for an economic analysis that compares the life-cycle costs of competing systems; and
- reviewing other supporting issues (e.g., social and institutional) that are important to the successful long-term operation and maintenance of pumping systems.

Flowcharts and illustrations are used to describe the pump selection process. After estimating water demand and applying the technical selection criteria, several viable alternatives often remain. A brief survey of locally available equipment and an informal evaluation of an area's support infrastructure (e.g., equipment dealers, mechanics, sources of credit, pump user groups, and local O&M costs) emphasizes the importance of pump selection criteria that focus on more than just technical issues. Capital and recurrent cost data that reflect typical system costs in developing countries are used further to reduce the number of acceptable options. Finally, social and institutional criteria are applied to make the final selection.

While the technical constraints associated with various types of pumping systems are fairly obvious and well known, pumping costs (especially for O&M) are not. This manual stresses the typical performance of pumping equipment in developing countries (based on field-test measurements) and the importance of local infrastructural support for long-term reliability. Until recently, very little recurrent cost and performance data have been available that accurately reflect the unique constraints faced by users in developing countries. The cost estimates used in this manual are based on information gathered in a variety of developing countries; they can be adjusted to permit the inclusion of local site-specific data. The cost data presented here draw heavily on a four-year study of diesel, solar, wind, and handpump costs in Botswana conducted by Associates in Rural Development, Inc. (ARD).

The flowchart for the overall technology selection process is presented in Figure 1. While it may appear somewhat complex at first glance, it codifies a complex decision-making process that includes consideration of a large amount of information. The following narrative description of the pump selection process refers to particular steps shown in the flowchart.

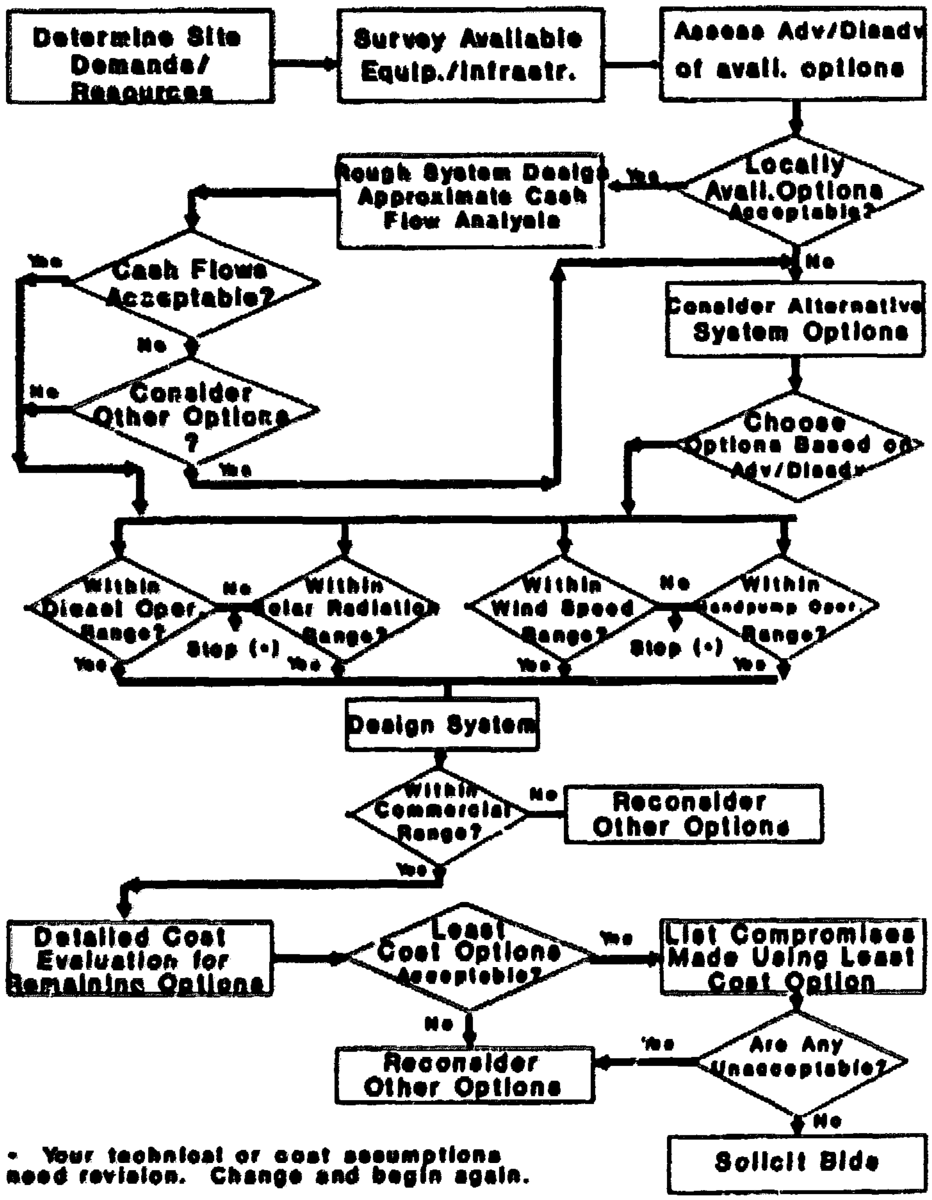
1.3.1 Determining Water Requirements and Energy Resources

The first step in the process is to determine site water demands and available energy resources, including constraints on the water source in terms of head, yield, and quality as well as locally available energy resources—diesel fuel supplies, solar irradiation levels, average wind speeds, and availability of human labor for pumping. This step should include a careful review of existing water collection techniques used at your site, if any. After deciding whether or not a pump is appropriate, and determining exactly what you have to work with at the site, you should begin to survey locally available pumping equipment and infrastructure that can support it. Check local suppliers to determine the types of pumping systems that are available, brand names of manufacturers, ranges of output for engine power and pumped water from a variety of heads, and capital equipment costs.

1.3.2 Assessing Locally Available Systems

Next, assess the advantages and disadvantages of system options that are already locally available. Determine which locally available options are acceptable for your application by answering the following questions about each option.

Figure 1. The Pump Selection Process



- Do the power ranges fit the site requirements for flow rate and head?

- Is system design assistance available?

- Is skilled labor available for equipment installation, operation, maintenance, and repair?

- Are inventories of spare parts adequate so that the system can be repaired without undue delays?

If the equipment is already being used locally, the answer to all these questions should be yes. If the answer to any of the above is no, you should begin to consider other system options.

1.3.3 Rough System Design and Cash-Flow Analysis

Assuming the answer to all the questions is yes, do a rough system design and cash-flow analysis. Chapters 5 through 8 provide information on system design analysis and Chapter 9 provides sample inputs for cash-flow analysis for the type of system(s) that are locally available. Use information from local dealers on your approximate system needs to complement the design procedures described in this manual.

Next, determine whether the cash flows are acceptable by answering the following questions.

- Can pump users or purchasers raise sufficient capital to buy the system outright? If not, do they have access to credit?

- Will pump users, or whoever is ultimately responsible for the system, realistically be able to cover expected recurrent costs? (Funds may have to be collected from user fees, returns on crops grown, or fees collected from those watering animals. Provisions for meeting recurrent O&M costs should be specified before the system is purchased.)

- Can pump users (or other groups responsible for maintenance and repair) cover the costs of unexpected, but inevitable, breakdowns?

If the answer to any of these questions is no, for whatever reason, you should consider other system options, which may result in a different cash-flow analysis that is more acceptable given the particular circumstances.

1.3.4 Additional Considerations

If the cash flow is acceptable, decide whether there are other reasons (besides financial considerations) why you might want to consider other options. These might include, but would certainly not be limited to,

- user participation and perceptions (Have users been closely involved in the decision-making process, and do they have any objections regarding the current choice of equipment?);
- system reliability (Are there other systems that may increase the probable availability of water supplies?);
- automatic operation (Would individuals or groups involved prefer that a pump operator or attendant [pumper] be hired to oversee the operation of the system or should the system operate unattended?);
- employment generation (Is increasing employment locally a concern, perhaps at additional cost in terms of money and convenience?); and
- training (If the technical support skills available locally are only marginal, is anyone willing to provide support [financial and/or administrative] for setting up training programs to change this situation?).

If you are satisfied that the system you have designed (using equipment that is already locally available) fits your needs and it is not necessary to consider other options, go ahead and <u>solicit bids</u> for procurement. If you are not satisfied, <u>consider alternative system options</u>.

1.3.5 Assessing Systems Not Available Locally

Begin by first listing probable system options, based on the information about available equipment for various system types given in Chapter 4. Which seem to fit your situation best? Review the lists of advantages and disadvantages for different types of systems, based on the comparative information given in that chapter. Decide which advantages and disadvantages are most important in your particular set of circumstances. Discuss them with prospective system users and those who may have to provide various support services--system design, repair of breakdowns, and provision of spare parts.

Depending on the system options chosen for further consideration, the easiest way to decide which of the four types of systems are most appropriate for your requirements is to determine those that can meet the basic operating and site constraints. For example, for wind pumps, is the wind speed at the site during the "design month" (i.e., the worst-case condition when available wind energy is lowest in relation to water demand) above the minimum recommended level in meters per second (3.5 to 4 m/s), and the total head less than about 60 meters?

If not, wind pumps should probably not be considered any further for this application. Similarly, for a solar pump, is the average solar radiation in the design month greater than 5 kilowatt-hours per square meter per day (kWh/m^2d)? (See Chapter 3 for an explanation of solar radiation measurements.) If not, focus your attention on other system alternatives. Similar minimum selection criteria can be used for each type of system and are discussed in subsequent chapters on system design.

1.3.6 Preparing Tentative System Designs

At this point presumably at least one system alternative will have passed the minimum selection criteria. The next step is to design the system for the selected options. Preparing a tentative system design will

- allow you to become more familiar with exactly what parameters must be considered when designing and, more important, when using each type of system and

- force you to rethink your assumptions about which system will be best for your situation, in terms of technical inputs (e.g., fuel, mechanics, and spare parts) and output (required quantities of water to be delivered according to a schedule you specify).

During system design, you should examine manufacturers' literature obtained from pumping equipment distributors in the area. In doing so, you will find out whether or not the system you are designing uses components (e.g. engines, pumps, and controllers) whose capacity is actually within acceptable ranges for commercially available equipment. For example, you may determine that given the relatively favorable wind speeds at your site and the water demand profile, a wind pump with a rotor 10 meters in diameter would be appropriate. However, the largest wind pumps have rotors that are typically only 7.6 meters across, which would not deliver as much water as you require. In that case, you should consider using two or more smaller windmills or reconsider other options.

1.3.7 Comparing the Costs of the Selected Options

If any of the options examined can meet the physical constraints of your application, the next step is to do a detailed cost evaluation of these options. This is basically a refinement of the approximate cash-flow analysis conducted earlier. The point is to get as exact an estimate as possible (given the available data) of the progression of cash flows that will occur during the system's expected lifetime. This will allow you to make reasonable decisions about whether or not those cash flows are acceptable for your system and which of the remaining alternatives is the least-cost option.

1.3.8 Making Necessary Compromises

The next step is to decide whether the <u>cash flows associated with the least-cost option are acceptable</u>. If not, go back and reconsider the other system options more carefully. If so, list the compromises you will have to make if you decide to use the least-cost system, rather than another technically acceptable, but more costly, system. For instance, less expensive equipment may have lower reliability, there may be less chance of getting repairs completed quickly, or users may be less familiar with the system. Then, decide whether any of the compromises are unacceptable to you or system users. If so, reconsider other options. If all the compromises are acceptable, go ahead and solicit bids for the system from dealers you contacted previously.

This process is intentionally somewhat repetitive, so decisions will not be made lightly or solely on the basis of first impressions or unstated motives. Systems that are already available locally are favored over those which will have to be imported. Experience has shown that systems which are newly introduced without adequate attention to developing an associated support infrastructure have typically fallen into disrepair. This is not to say that new types of systems should be avoided. Rather, it is intended to emphasize that there are additional obstacles associated with introducing new technologies which can be insurmountable unless attention is given to developing the required support infrastructure.

The flowchart shows the overall approach to making a selection among several different technologies. The process of determining the actual design of individual systems and exactly what site-specific operating constraints are in effect is covered in later sections of this manual. In the design chapters, process flowcharts are presented that lead readers through the design process for the four types of systems considered in this manual. Preformatted sheets are also provided to help simplify data collection and analysis, the results of which are used in analyzing technical performance and costs for each system type.

1.4 <u>Structure of This Manual</u>

This manual is divided into 10 sections. To compare any pumping technology options, you must first determine water demand at the site. Chapter 2 shows how to calculate this. It discusses water-resource characteristics that are important for system design, such as well yield (if the source is groundwater), pumping head, and water quality. After discussing demand profiles (i.e., how much water is needed and when), this chapter concludes with a subsection on important factors affecting water availability.

Chapter 3 describes how to calculate the energy requirements for meeting the demand profile determined in Chapter 2. It discusses the characteristics of the four types of energy considered in this manual—diesel fuel, wind and solar energy, and human power for handpumping—and recommends sources for gathering needed information on energy resources in your area.

The types of pumping equipment and their operating characteristics are covered in Chapter 4. In the pump selection process, after water demand and head requirements are determined, the next step is choosing a particular pump to match those parameters. Then, an energy source (e.g., windmill or diesel engine) is selected to provide the input energy required by the pump chosen. This chapter includes summaries of the important advantages, disadvantages, and typical applications of different types of pumps and energy sources.

The next four chapters (5 through 8) focus on technical system design for the four types of energy sources considered in this manual—diesel, solar, wind, and human power. Each chapter begins with an initial description of typical equipment, followed by a discussion of system characteristics; operation, maintenance and repair requirements; and typical capital equipment costs. Except for the section on handpumps, which is a much simpler technology, each concludes with a detailed example of the design of a pumping system using that technology. These examples indicate where each type of energy source can and cannot be used, based solely on technical criteria.

The final two chapters on economics and other nontechnical considerations are the final stages in the screening of remaining equipment options. Up to this point, only representative costs are given. Recurrent costs have not been analyzed, and no economic analysis has been undertaken. Chapter 9 briefly discusses analytical methods and then shows how to apply them by taking the reader through two detailed examples that compare two pumping options. These examples are extensions of the technical system design cases presented in Chapters 5 through 8.

It is not necessary to read the entire manual to get help with decisions about pumping systems. Skip around to locate information of specific interest to you. However, all chapters should be read before equipment is finally selected to assure that all pertinent selection criteria are carefully considered.

Chapter 2

WATER DEMAND AND RESOURCES

2.1 Demand

To select an appropriate pumping system, you must first know the water requirement at the site. The water requirement is usually measured in cubic meters per day (m^3/day) and depends mainly on the size of human and animal populations, although it may also include small-scale irrigation or other demands. The amount of water used per capita depends heavily on convenience—when water is more readily available, per capita consumption will increase. Remember this when estimating future increases in demand.

The World Health Organization (WHO) has established the minimum water requirement for human consumption at 30 liters per person per day (LPD). In practice, while 30 LPD is often used as a design value, this is often more than the actual consumption typical of many rural areas. Local water demand varies with location, customs and cultures, climate, distance to and capacity of the water source, and amount of effort or cost associated with meeting the demand. This section describes how to estimate current water requirements and evaluate environmental conditions that limit the quantity and quality of water which can be obtained from a given source. These data are used in the pump selection process primarily to determine pumping rate and, hence, the system's power requirements. Information on local water demand for people, animals, and crops is often available in already existing development reports for your area. You should check these reports and integrate that information into the demand estimation procedures given below.

2.1.1 Site-Specific Conditions

Water demand is dependent on site-specific conditions. Although general guidelines have been established by many development agencies specifying the minimum daily consumption for people, animals, and crops, actual consumption can (and does) vary considerably. This manual is intended to deal only with drinking water for people but, in fact, many village water supplies will be also used to water small livestock. Typical usage figures are given below for the most common consumers.

	People	Cattle	Goats/Sheep	Poultry	Hogs
Demand in liters/day	20-40	20-40	5-15	0.2	10-15

The water requirement for people assumes that people get their water from centrally located standposts. If house taps are used, expected consumption will be considerably greater. The total water requirement for a pump is obtained by multiplying the number of people and animals to be served by the per capita consumption, and they by adding other demands (watering gardens, selling water to nearby consumers, etc.) in the area the pump will serve (the service area). When calculating the total water requirement for a service area, consider that people may keep more animals when water is more readily available. Also, people from surrounding villages outside the service area may want to use the system if their water sources fail or if it is easier for them to get water from the new system.

2.1.2 Variations in Consumption

Water consumption varies over the course of a day, both seasonally and annually. Since pumping systems are normally sized to provide enough water to meet the largest (or peak) daily demand, it is important to determine what peak demand will be. Peak demand can be a function of social (everyone coming home for the holidays), agricultural (garden cropping patterns and watering schedules), or livestock considerations (animals returning from grazing lands during the dry season, or visits from nomadic tribes with their herds). For pumps driven by renewable energy sources (such as wind or solar power), you must also determine what daily demand is for the worst-case situation, called the "design month." The design month is the calendar month when average daily water demand is greatest in relation to the availability of the renewable energy resource. (The sections on wind and solar pump design give more information on determining the design month.) For diesel systems, which often have a very high on-demand pumping rate and so do not require as much storage, you may also have to consider hourly peak demand.

2.1.2 Growth in Demand

Estimates of system capacity require assuming a design period or horizon, which is typically 8 to 10 years. This can be different from the amortization period for economic comparison of different systems (see Chapter 10), as long as there is the potential for expanding the system's capacity at the end of the design period. All system design decisions should take into account the fact that the demand for water will probably increase over time. Demand is affected not only by population growth (people and animals) but also often by ease of access. Per capita consumption (measured in LPD) usually only increases significantly if service increases--that is, if many more water points are installed nearer to users, particularly yard taps. While it is difficult to generalize without information on local population growth, rates of 2 to 4 percent per year are typical for rural villages in developing countries. This may sound small, but a 4 percent annual growth rate means that the demand for water will increase by over 40 percent in 10 years (not assuming any increase in per capita consumption). Increased demand due to growth in population and per capita consumption can be calculated using this formula:

$$D_F = D_P \times (1 + F_{PG})^{(N-1)} \times (1 + F_{CG})^{(N-1)}$$

where D_F = future demand
D_P = present demand
F_{PG} = population growth factor
N = design period in years
F_{CG} = consumption growth factor

Steadily increasing water requirements place different demands on the various types of systems. These demands are handled in different ways. For diesel or gasoline (petrol) pumps, increased demand can be met simply by increasing the flow rate (engine speed) or operating the system for more hours each day. The latter is also true for handpumps. Solar PV and wind pumps are usually slightly oversized relative to current demand in order to account for future increases in demand. However, this can be a costly approach, particularly for PV systems. PV pump output can be increased by adding modules to the system, up to the power limit of the motor. Once installed, wind pumps have little flexibility in meeting increased demand, so it is important to estimate growth in demand as closely as possible before sizing a wind system. An example of how to estimate demand follows.

Example 1: Determining Demand

A village has 300 residents, but during the summer, 50 students return from a nearby boarding school, increasing the population to 350. The animal population is 50 chickens and 75 goats. The population growth of people and animals is estimated to be 4 percent per year. The design period is 10 years. It is assumed that per capita consumption will not increase, so the third term in the formula above equals 1. How is demand determined?

The greatest demand will occur in summer, when the population is 350. Per capita consumption is assumed to be 20 LPD for people, 5 for goats, and 0.2 for chickens. Thus, present demand is

$$(350 \times 20) + (75 \times 5) + (50 \times 0.2) = 7{,}385 \text{ LPD}$$

From the formula, the demand in 10 years will be:

$$7{,}385 \times (1 + .04)^{(10-1)} = 10{,}511 \text{ LPD (or 42 percent more than } D_P)$$

2.2 Resource Characteristics

While the number of water users and their individual consumption needs are used to calculate demand, actual demand can be constrained by the available water supply. In most cases, if you are choosing a pumping system for a given site, the water source is already known. The source may be surface water (e.g., rivers, lakes, and man-made or natural reservoirs) or groundwater (boreholes, dug wells, and springs). To determine what type of pump(s) can be used and the maximum demand that can be met, you must know certain specific characteristics of the water source:

- the yield of the source in cubic meters per hour or day (m^3/h or m^3/d),
- the static water level in meters,
- the drawdown in meters (the drop in water level during pumping), and
- the quality of the water.

For pump selection, the most important characteristics are yield, static water level, and drawdown. The energy needed to pump water is directly proportional to the total pumping head (explained below) and flow rate. The pumping head depends partly upon the static water level and drawdown. The pumping rate can be no greater than the maximum sustainable yield of the water source, which is the maximum amount of water that can be pumped without significantly depleting the source (see especially Driscoll et al. 1986 for more information). Finally, the choice of equipment may also depend on whether or not the source has significant water quality problems. For wells, information about yield, level, and drawdown should be available from well-completion certificates or test-pumping logs. Yield can limit the flow rate for pumping water and, in turn, the number of hours of pumping that are required to meet demand. This may affect equipment selection since some types of equipment are better matched to higher (diesel) or lower (solar) pumping rates.

2.2.1 Flow Rate

Daily water demand can be met in different ways. For example, if the daily water requirement is 100 m^3/day, the entire amount can be pumped in one hour or it can be pumped over the course of 10 hours at the rate of 10 m^3/hour. Pumping the water as quickly as possible saves time, but it is not always possible or advisable. Pumping at too high a rate from a source with limited yield may cause excessive drawdown. This would increase the total pumping head and would require more energy; it could even cause the pump to run dry. If the water source is a year-around river, it is unlikely there would be any problem meeting small to moderate water requirements, except in the case of a drought. However, most wells and springs are incapable of delivering 100 m^3/hour. Thus, a careful assessment of well yield and pumping rates is necessary before specifying the equipment.

For drilled and dug wells, it is important to know the maximum sustainable well yield or maximum rate at which water can be continually pumped. This provides an upper limit for the pumping rate selected during the design process. The well's maximum sustainable yield and drawdown under these conditions are usually determined as part of the test-pumping procedure. Drawdown and, hence, total pumping head will be less when the pumping rate is less, and the likely drawdown for lower pumping rates can be estimated.

For a given water demand and constant flow rate (such as a diesel pump would deliver), the design pumping rate is determined by taking the daily water requirement in m^3/day and dividing by the number of hours of pump operation per day to get m^3/hour. Your choice of technology is dependent in part upon the required pumping rate. This pumping rate must meet the demand for water, but it must not exceed the source's sustainable pumping rate. If it does, you must either increase the number of hours per day of pump operation, decrease water demand, or develop a new water source.

In addition to the maximum sustainable yield for a single well, you should also consider the sustainable yield of the aquifer catchment area in which your system(s) is to be located. For example, in some developing countries (Bangladesh and Yemen are good examples), the exceedingly large number of tubewells drilled in some areas has resulted in a drastic lowering of the regional groundwater table. This happens when the total extraction of water from all of the tubewells is greater than the maximum sustainable yield of the aquifer. If historical data on groundwater replenishment rates are available, estimate what effect the pumping rate you propose (and the number of pumps you are planning to install) will have on your water table.

2.2.2 Total Pumping Head

"Head" is a term used for several related quantities that together comprise the effective pressure against which a pump lifts water. Head, usually given in meters or feet of water, is a combination of the following components:

- elevation (static water level plus static discharge head plus drawdown),
- pipe friction,
- velocity, and
- pressure head.

These components are illustrated in Figure 2 and explained in greater detail below. Values for each component must be measured or calculated to determine total pumping head.

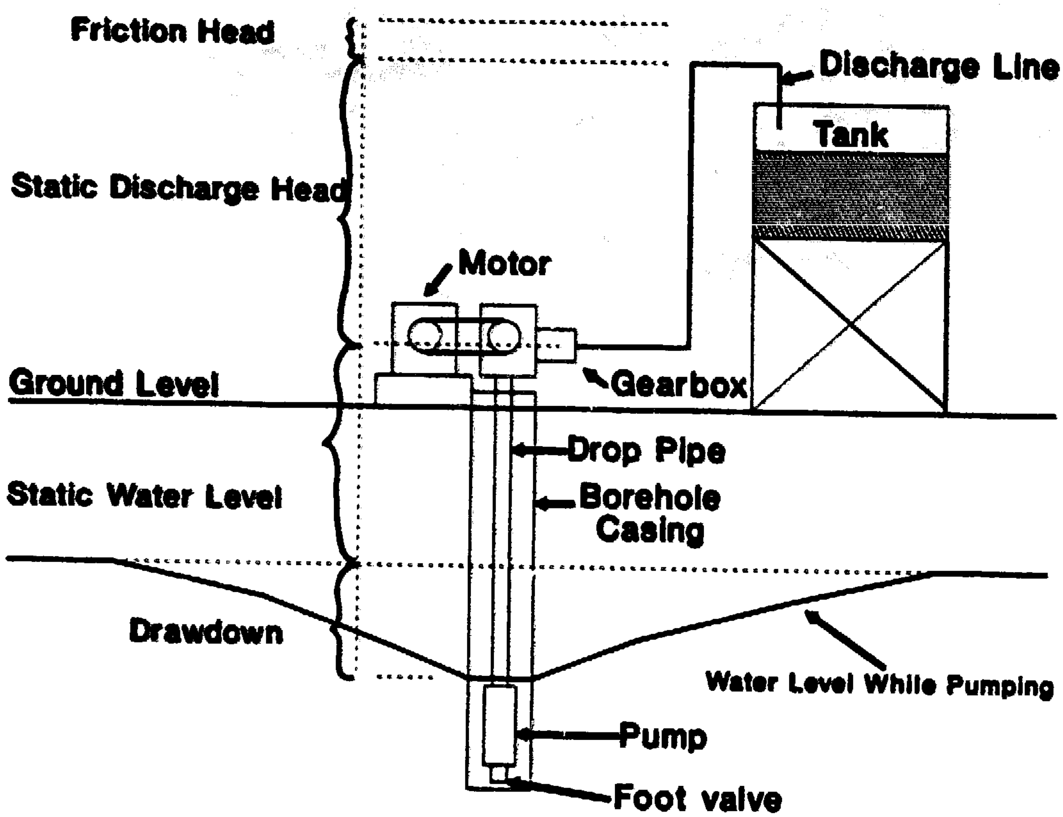
Elevation head is usually divided into three parts:

- static water level--the vertical distance from the water level to the surface of the ground;
- drawdown--the distance from the static water level to the lowered level when the pump is operating; and
- static discharge head--the vertical distance from the pump outlet to the highest point in the system, usually the storage tank if there is one.

Elevation

Static water level can easily be measured during site visits or obtained from accurate well-completion records.

Figure 2. Components of Total Pumping Head



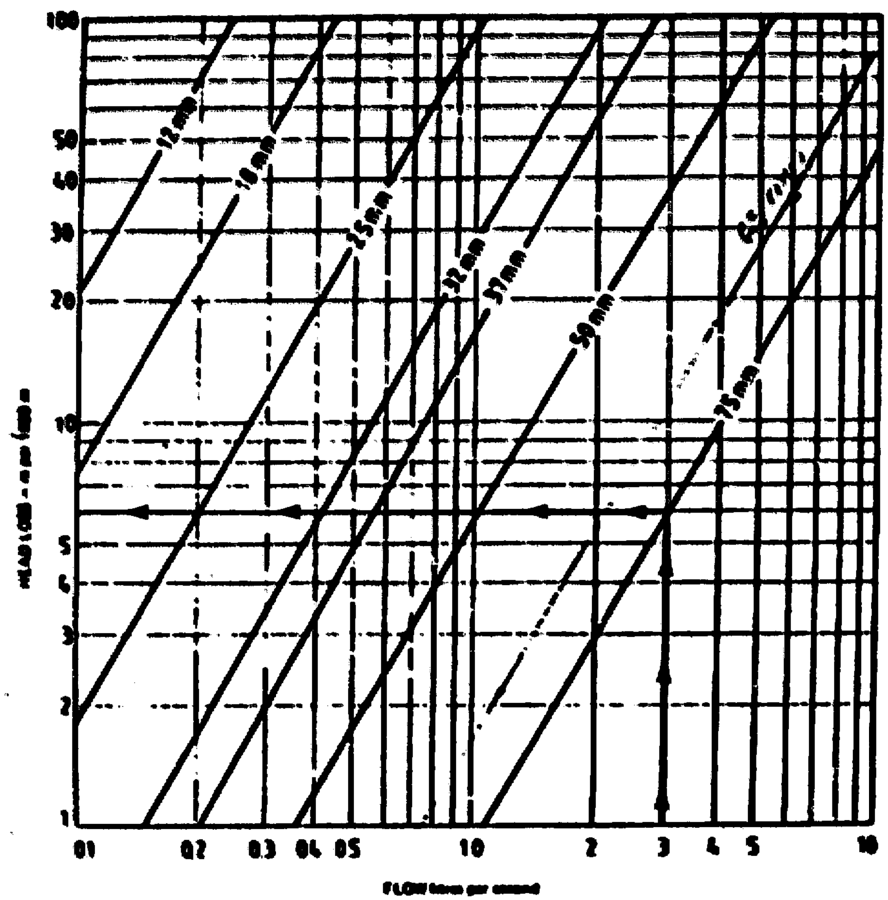
For the size of pumps commonly used for village water supplies, the drawdown is essentially zero for most rivers and streams. With boreholes (wells), the drawdown depends on aquifer performance, well design and development, and the pumping rate. Drawdown information is available from proper test-pumping records and is often given in terms of the specific capacity of the well (measured in m^3/d/meter of drawdown). Drawdown usually increases as the pumping rate increases.

Unfortunately, well drawdown figures are often not readily available. In such cases, test-pumping should be done on the water source before designing the system. If possible, do this during or shortly after the driest part of the year, when yield will likely be at its lowest. This will minimize the possibility of overestimating the yield of your water source. If this is not possible, the drawdown will have to be estimated, preferably with assistance from hydro-geologists familiar with your area. The subsequent selection of pumping equipment should reflect these uncertain conditions (see Chapter 4 on available equipment).

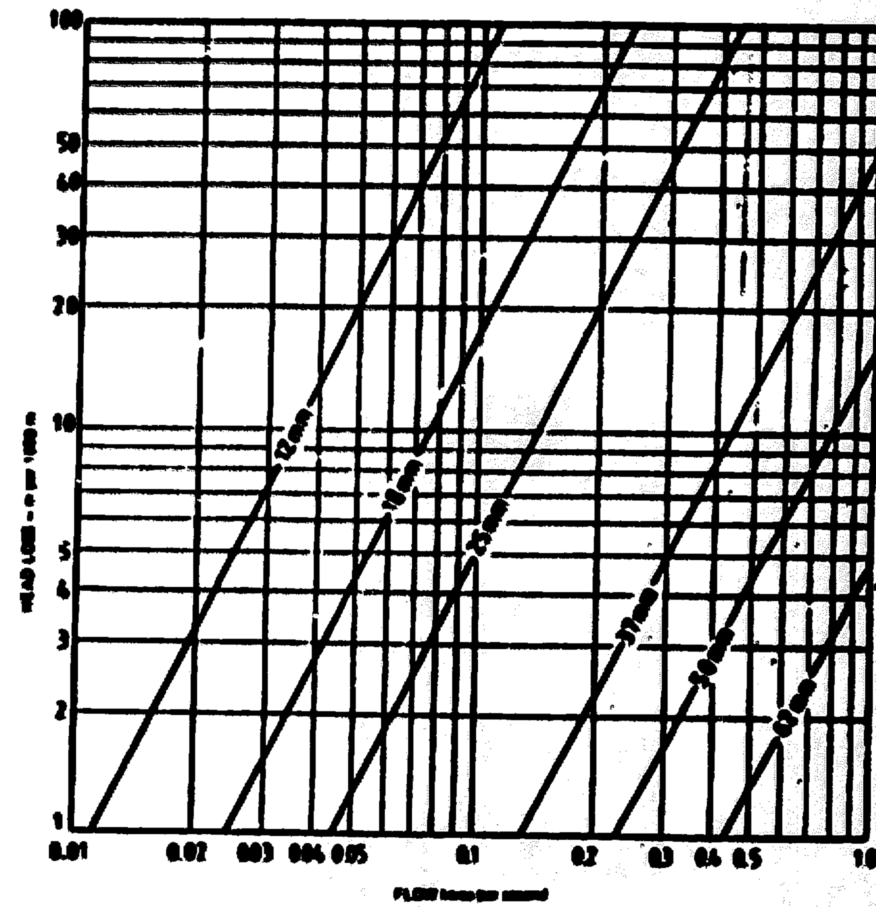
Static discharge head is a function of the system design and local topography. This component of elevation head can be measured during site visits or computed from site surveys and plans.

Pipe Friction

Pipe friction loss depends on the flow rate and the length, diameter, and condition of the pipe used. Friction losses can be calculated using formulas, but they can be determined more easily using graphs or tables. To use such a graph, you must know the type of pipe being used (galvanized iron, smooth plastic, etc.), since friction losses vary with type of pipe. For example, the graphs in Figure 3 can be used to estimate the head loss for galvanized iron or plastic pipes, according to the following example. Additional friction loss tables and figures for a wider range of pipe types, diameters, and minor losses for pipe bends and fittings are given in Appendix B.



HEAD LOSS IN PIPELINES
(High density polythene pipe)



HEAD LOSS IN PIPELINES
(Galvanised Steel)

Figure 3. Pipe Friction Loss Charts

Example 2: Pipe Friction Loss

Find the friction loss in meters of head for a smooth plastic pipe that is 250 meters long and 75 millimeters in diameter. Water is being pumped at a rate of 3 liters per second. The pipe has two bends of 90 degrees and two open gate valves.

The left side of Figure 3 for plastic pipe shows about 6 meters of head loss due to friction per 1,000 meters of pipe length (following the arrows on the graph). Since the pipe is 250 meters long, this value must be divided by 4, giving a friction head loss of 1.5 meters. The equivalent length of the bends is 2.3 x 2 = 4.6 meters and that for the gate valves is 1.2 x 2 = 2.4 meters. Since this total additional length (7 meters) is only a small fraction of the total 250 meter pipe length, the bends and valves produce negligible head loss. So, the total friction loss is still 1.5 meters.

As a second example using the same procedure, friction losses for the same pipe length and flow rate, but 50 millimeters in diameter, would be 37 divided by 4 or 9.25 meters. Again, the bends and valves add a negligible amount of head loss. Friction losses for this pipe are six times as great as for the larger diameter pipe.

The preceding example shows the importance of using pipe that is the right size to save on energy costs by minimizing head losses. One common rule of thumb is that pipes should be sized so that friction losses are less than 10 percent of the total head. Another common rule of thumb is that pipes should be sized so that water velocity in the pipes never exceeds 1 m/s. For the example above, for the 75-millimeter pipe, the water velocity (calculated by dividing the flow rate by the cross-sectional area) is 0.97 m/s, which fits the criterion. For the 50-millimeter pipe, it is 2.3 m/s, which does not fit the criterion.

Velocity

Velocity head is a measure of the energy lost when a moving liquid slows down, such as when it flows from a pipe into a storage tank. For purposes of system design, it is measured as pressure loss in meters of water, calculated using the formula:

$$\text{velocity head (in meters)} = \frac{v^2 \ (m/s)}{2 \times 9.81 \ (m/s^2)}$$

where v is the average velocity of water in the pipe and 9.81 is a constant. For most small-scale pumping applications, the velocity head is small and can be safely ignored.

Example 3: Velocity Head

Determine the velocity head if water is being pumped at a rate of 10 m^3/h through a 100-millimeter pipe at sea level under normal atmospheric conditions.

First, find the velocity v. The cross-sectional area of a 100-millimeter pipe is .031 m^2. This figure can be obtained from standard pipe size tables, such as those given in Driscoll et al. 1986, or by calculating the area from the formula:

$$A = pi \times (diameter)^2 / 4 = 3.14 \times (90.1 \times 10^{-3} m)^2 / 4 = .0064\ m^2$$

The velocity equals the flow rate divided by the cross-sectional area, so the velocity in the pipe is 10/.0064, which equals 1568 m/h or about 0.44 m/s. Using this result in the formula above gives:

$$\text{velocity head (in meters)} = \frac{(0.44\ m/s)^2}{2 \times 9.81\ (m/s^2)} = 0.01\ m$$

a velocity head which is negligible in most circumstances.

Pressure Head

Pressure head is the additional pressure required to pump water into a pressurized tank. This pressure can be given as additional meters or feet of head using the following conversion:

1 psi = 6.89 kPA = 2.306 feet of water = .703 meters of water.

(psi = pounds per square inch)

It will not often be a factor in water supply systems in developing countries, since pressurized systems are seldom used in rural areas.

Using the approach described here, total pumping head (needed later to determine pumping energy requirements) can be calculated by adding together the values for each of its components.

2.3 Water Quality

Water quality may be an important parameter in pump selection and determining whether the source is suitable for human or animal consumption. Physical parameters included in water-quality testing that are important for equipment selection are

- hardness,
- electrical conductance (or specific conductivity),
- hydrogen-ion concentration or pH, and
- salinity or total dissolved solids (TDS).

Hardness is a measure of the mineral content of water, primarily magnesium and calcium. Hardness in the range of 100 milligrams per liter (mg/l) is considered acceptable, although up to 500 mg/l may be acceptable depending on the availability of better sources. As hardness increases, encrustation and scaling on pipes and pump components is more likely. Over time, this increases pipe friction and decreases the diameter of the pipe, thus affecting the pumping rate and increasing the power requirements. Scale deposition can also decrease well efficiency and may even lead to the loss of a well in extreme cases.

High conductance (above 750 micromhos), low pH (acidic water below 6.5), and/or high TDS levels (above 500 mg/l) indicate aggressively corrosive water. Acidic water, even with low conductance or low TDS, is also corrosive. Otherwise acceptable water with high TDS levels can degrade equipment simply by an excessive wear, as particles moving over the pump's moving parts wear them down.

Corrosion can be chemical or electrochemical. The former occurs when a contaminant exists in sufficient concentration to cause corrosion over a broad area (e.g., a pump casing). The use of bronze and/or stainless-steel components will likely reduce chemical corrosion. Electrochemical or galvanic corrosion is caused by an electrical current flowing between two different metals in contact. To reduce the risk of galvanic corrosion, dissimilar metals should not be directly joined together. Instead, a nonconductive gasket should be used.

2.4 Demand and Supply Profiles

A demand profile refers to water demand over time, usually a year, although the concept can be applied over the course of a day. Water demand varies depending on need as well as supply. Humans and animals tend to drink more water in hot dry seasons. If water is available, consumption will increase at such times. (If surface water is available, the demand for pumped water for animals will decrease.) Sometimes during dry seasons, local water supplies simply dry up, so consumption decreases at some water points and greatly increases at those where water is still available. During dry seasons, borehole yields typically drop in regions where aquifers have low recharge rates. Nomadic people can also have significant effects on water demand, creating large "spikes" or short periods of very high demand in the profile. Water demand is not necessarily constant from year to year, due to population growth, human and animal migration, changes in size of livestock herds, droughts, and a variety of other factors.

The supply profile depends on the type of pump. For example, a diesel pump normally operates at a constant rate and can deliver water at a moment's notice. The same is true of handpumps, although on a much smaller scale. Solar or wind pumps can deliver water only when the energy resource is available—when the sun is shining or wind is blowing above the windmill's start-up wind speed. This has obvious impacts on system design. For instance, suppose you want to install a solar pump, but system users want water early in the morning. To meet that portion of the daily demand profile, a storage tank is needed to reserve part of the previous day's output.

As a general rule of thumb, wind and solar pumps should be designed with three to four days of storage to account for the fact that they cannot deliver water on demand. While variations in demand can be managed by designing storage into a pumping system, usually this helps meet only short-term water needs (several days at most), not seasonal variations in demand. Storage tanks or basins typically hold an amount equal to a normal village's daily water demand, say 20 cubic meters. It is not usually economical to store enough water for five days given the cost of storage, particularly when using elevated storage tanks. However, if a site is so remote that it takes five or more days to fix breakdowns, the cost of additional storage must be compared to the cost of trucking in water, higher cost preventive maintenance to increase system reliability, backup systems, or other measures to insure water availability during system outages.

Energy resources, which are discussed in detail in Chapter 3, can also vary seasonally. For example, diesel fuel is often unavailable in remote areas during rainy seasons, when roads become impassable. Renewable energy pumping systems, such as wind and solar pumps, can deliver water only when adequate energy resources are available, not during calm or cloudy periods. Other seasonally dependent factors can affect system performance—for instance, upstream flooding could raise sediment levels in a river high enough that pumps become clogged. The possibility of annual and seasonal variations in water demand and supply should be taken into account when designing pumps. With adequate safety measures, demand can usually be met. Remember that for sites where demand variability is high, no reasonably designed system can always be expected to meet demand.

2.5 Water Availability

Water availability is the percentage of time water is available to users during a specified period. This figure is never 100 percent, since every system eventually breaks down. Availability can almost always be increased, but it can be increasingly expensive to do so above a certain level. Pumped water supplies may be unavailable for three reasons—the mechanical system fails (e.g., the motor stops), the source becomes inaccessible (the water table drops below the pump intake), or the energy resource fails (the wind stops, the diesel fuel runs out, or the sun is covered with clouds). A good design practice for water pumping systems is to focus on ensuring water availability, which depends on

- equipment reliability,
- variations in water and energy resources, and
- the availability of backup equipment and water sources in the event of a system or source failure.

The reliability of different kinds of pumping equipment and system designs can vary considerably, but reliability usually depends on cost and maintenance. Often, better equipment costs more, and there are trade-offs between buying a system that has a high capital cost and low O&M requirements versus low-cost equipment that needs a high level of O&M. Users may have to make compromises if they lack adequate funds for high-quality equipment. However, the most important strategy for preventing problems and minimizing costs is to know the limitations of the water source before you choose a system.

2.5.1 Equipment Reliability

Reliability is usually measured as the mean time between system failures, given in hours of operation. This means that on the average, a component (e.g., pump, engine, or belt), *if properly maintained*, can be expected to fail after the mean time between failures has elapsed. Better (and often more expensive) components or systems have longer mean times between failures. Usually, it is very difficult to find this information for different component options, so system designers must rely on recommendations when choosing different types or brands of equipment. However, system failure does not depend simply on the quality of the parts used. Reliability is also very dependent upon other factors such as the ready availability of spare parts and people with technical skills to maintain and repair equipment.

System designers usually try to pick components with the highest efficiency that they can afford (see Section 4.1 for an explanation of efficiency). Sometimes new equipment with purportedly high efficiency is used in a system. Only later do users discover that the new part functions well for a short time but does not have the expected reliability and fails prematurely. In general, use proven components that you and local technicians are familiar with or that have proven themselves through long and steady use elsewhere, rather than buying the latest innovation. Let someone else experiment with new or unfamiliar units. In the long run, proven reliability is much more important in reducing the cost of water delivery than a small percentage difference in operating efficiency.

2.5.2 Designing for Reliability

Careful design can greatly increase water availability. For example, the level and the quality of the water in rivers, springs, and wells fluctuate seasonally and annually. System design should take expected and unexpected changes in the water source into consideration. Strategies for dealing with such changes include

- mounting borehole pumps well below the lowest expected water level and river pumps on anchored floats with flexible discharge hoses and using screens to prevent clogging and subsequent damage to pumps and motors;
- using safety devices--circuit breakers on motors to prevent overloading, overheating cutoffs to prevent seizing in pumps or motors when water levels drop below the intake, and pressure-relief valves in discharge lines; and
- designing adequate storage to meet demand during short-term system outages, expected or unexpected--remember, eventually every system breaks down.

There are other types of approaches which can increase water availability. In most common design procedures, components such as engines and pumps are typically oversized to a certain extent. Since pumps require more power to start them turning than to keep them going, motors have to supply higher starting than running torque (see Chapter 5 on diesel engines). For electric motors, this means more amps must be delivered to the motor. Thus, motors and power supplies (e.g., PV arrays or wind-pump rotors) must be sized large enough so they can provide as much as four times the normal running torque to start the system.

Components must also be oversized to account for gradual degradation of performance and growth in demand over the system's expected lifetime. For example, pipes get clogged due to scaling over time, thereby reducing the diameter through which water can flow. This increases the total pumping head and, for a given power input, reduces the flow rate through the pipe. Similarly, as electrical components wear, voltage losses occur that reduce the output of electric motors. As diesel engines become carbonized with use, they produce less shaft power to drive pump transmissions. These and other types of system performance losses mean you must begin with a slightly larger power source if you expect a certain amount of water delivery five years after the system is installed. Guidelines for component sizing that address these problems are given in Chapters 5 through 8.

The need for preventive maintenance cannot be overemphasized. Pumps run better--i.e., more efficiently and at a lower cost per unit of water--when they are regularly maintained. Yet, some user groups may not have adequate incentives to take care of their equipment. While it may seem reasonable to assume that users will take care of pumping equipment, regular maintenance will not necessarily be carried out. These issues are discussed further in Chapter 9.

2.5.3 Backup Systems

Every pumping system will eventually fail. System designers must consider how users will deal with such failures. You must determine how long an outage will be acceptable to users, remembering that no system gives water 100 percent of the time. Unless the situation is very unusual, the right spare parts or people with appropriate technical skills will not be on hand at the site to fix a system immediately after a breakdown occurs. Thus, an outage is likely to last several days at least.

System design should take into account ways of dealing with maintenance problems. First, you need to have some idea of what problems will be caused even by brief outages. Do people typically store the drinking water needed for several days at their houses, or do they draw water several times a day because they have no off-site storage? If there is little or no off-site storage, a community storage tank should be big enough to store water for at least one day.

Second, backup systems can be used whenever the primary system fails or is shut down for maintenance. While this almost guarantees that you will always have water (so long as your energy source is sufficient), it also means that the system will be more expensive. Further, people often do not place a high priority on maintaining backup systems, and a backup system will not do much good if it does not work when you need it to. Some pumping systems can easily be designed to incorporate backup engines or energy sources. For example, suppose a PV system with a vertical-turbine pump is driven by a pulley on top of the pump shaft. Normally, the pulley is driven by a belt connected to the electric motor. A backup diesel engine could be installed by mounting it so that if the solar system fails, due to equipment failure or simply to a lack of sun, the diesel engine could be used to meet demand until the PV system is working again. Similarly, handpumps could serve as backups for diesel, wind, or solar pumping systems, and diesels could back up wind pumps.

A third solution is to have more than one water supply system (pump and water source). If one system fails or needs to be taken out of service for any reason, the second will still be able to supply some minimum level of service. Of course, this requires the additional expense of digging a second borehole and installing and maintaining a second pumping system.

Any suggested solution for handling system failure must be weighed against the cost of an unexpected outage--if water is unavailable for a certain amount of time, what are the consequences:

- Can enough water be lifted by hand to supply at least drinking water until the pump is fixed?

- Can enough water be trucked in or transported by other means (e.g., donkey carts)? Are the roads passable, what would this cost, and who would pay for it?

- Would people have to travel to or temporarily move nearer another water source until the system is repaired?

- When water is being used for agricultural purposes, what happens if the crop fails?

The costs of the options discussed above or similar emergency-relief measures must be weighed against the cost of a backup system, additional storage, or developing other water sources.

Chapter 3

ENERGY DEMAND AND RESOURCES

An important aspect of choosing pumping equipment is determining the energy required to pump water and assessing what energy sources could be utilized. This chapter offers a method for calculating energy demand and discusses the characteristics and limitations of a variety of energy resources.

3.1 Hydraulic Energy Demand

Energy is the capacity to perform work. In the case of moving or lifting water, hydraulic energy is the capacity to move a specified amount of water a certain distance. Energy is expressed in joules, watt-hours, or horsepower-hours. Power is the rate at which work is performed, measured in horsepower (Hp) or watts (W). Both terms are important in determining the appropriate size for pumping equipment.

The hydraulic energy required to lift a certain volume of water is given by the following equation:

$$E_h = (p_w \times g \times Q \times H)/(3.6 \times 10^6)$$

where E_h = hydraulic energy in kilowatt-hours (kWh)

p_w = density of water (1,000 kg/m^3)

g = gravitational constant (9.81 m/s^2)

Q = volume of water pumped in m^3/day

H = total pumping head in meters

Substituting the given constants (9.81, 1,000, and 3.6), the equation simplifies to

$$E_h = .00273 \times Q \times H$$

E_h is directly proportional to the head and the daily water demand. Thus, strictly in terms of hydraulic energy requirements, pumping 20 m^3/day from a head of 50 meters is the same as pumping 50 m^3/day through 20 meters of head. Taken together, the head and daily water requirement determine the energy demand. However, this convenient simplification does not take into account differences in friction losses when water is pumped through various lengths of pipe.

The hydraulic energy requirement calculated using the above formula is significantly less than the actual energy needed to move water because of inefficiencies in delivery systems (pumps and engines). For example, the energy efficiency of converting

- diesel fuel to pumped water ranges from 5 to 20 percent,
- solar radiation to pumped water is 2 to 4 percent,
- wind energy to pumped water is on the order of 4 to 8 percent, and
- foodstuffs to water pumped by humans is anywhere from 5 to 10 percent.

When comparing different types of pumping systems, these efficiencies alone do not determine the best choice. Other system characteristics--such as cost, ease of maintenance, and capacity--are also important. However, for a specific type of system (e.g., wind pumps), efficiency is an important consideration in choosing between competing wind systems. The <u>most</u> important energy consideration is whether the available resource is sufficient to meet the pumping requirement.

Each component of a mechanical system (e.g., motor, pump, transmission, etc.) has its own efficiency, which is the ratio of the power out to the power in. Electric motor efficiencies are usually about 65-90 percent (higher for larger sizes), and pump efficiencies range between 40-75 percent, depending on how well the pump is matched to its load (i.e., the head and flow). For convenience, we will refer to the combined pump, motor, and transmission (the entire subsystem) efficiency as the "pump efficiency" or "subsystem efficiency". If pumps are normally purchased in an integral unit with the motor (such as a submersible pump), people commonly refer to the combined pump and motor efficiency as the pump or subsystem efficiency. For example, if the motor efficiency is 80 percent, the pump efficiency 70 percent, and the transmission efficiency 75 percent, the subsystem efficiency is

$$0.80 \times 0.70 \times 0.75 = 42 \text{ percent}$$

Example 4: Hydraulic Energy Requirement

A. What is the hydraulic energy required to pump 20 m^3/d through 75 meters of head? From the formula given above

$$E_h \text{ (in kWh)} = .00273 \times 20 \text{ m}^3\text{/day} \times 75 \text{ m}$$

$$E_h = 4.1 \text{ kWh}$$

B. If the pump (only) efficiency is 60 percent, how much energy must be provided by an engine?

$$E = 4.1 \text{ kWh}/.60 = 6.8 \text{ kWh}$$

C. If water is pumped over a six-hour period, what is the required mechanical power output from the engine?

$$\text{power} = \text{energy/time}$$

$$6.8 \text{ kWh/6 hours} = 1.1 \text{ kW}$$

Note that the choice of flow rate (20 m^3 in a six-hour period or 3.3 m^3/hour) does not change the energy requirement, but does determine the power output requirement for the pumping device. Diesel engines and PV modules, in particular, are denominated in power units, the rate at which a device is capable of performing work. This fact is important in later sections on engine selection.

3.2 Energy Resources

Traditional energy resources for delivering water include gravity, hand lifting, and wind energy, in some cases. More recently, petrochemical fuels and electricity have been utilized and, finally, the use of solar energy has become possible. One basic aspect of the pump selection process is evaluating the availability and potential for using different energy resources. Clearly, if water can be delivered by gravity, it is likely to be the most reliable and cost-effective system. However, if the capital cost of a long pipe or channels is high, or water quality is not suitable for the intended use, other systems should be considered. The following sections provide guidelines for determining the resource information needed to make a preliminary evaluation of pumping equipment options.

3.2.1 Hand Lifting and Carrying

Other than gravity flow, lifting and carrying water by hand is the oldest method of moving it from a source to a destination. Many hand-operated delivery systems have been used around the world (see particularly Fraenkel 1986). The major limitations of hand lifting are the sustainable energy output of humans and the relatively small water delivery rate. Hand lifting can include every option from a rope and bucket to modern, high efficiency handpumps. Remember that under certain circumstances, the bucket and rope method of drawing water may be perfectly appropriate for some sites. Do not dismiss the no-pump option before considering it thoroughly.

A human's maximum continuous power output for short periods is about 100 watts (0.1 kW). This cannot be sustained over the course of a day. For an average adult male, the energy output over a day is about 0.2 to 0.25 kWh. Assuming a pump that is 70 percent efficient, this would amount to pumping only 3.2 m^3/day for a head of 20 meters. With multiple pumpers, which would usually be the case, 0.75 to 1.0 kWh could be produced over a day.

These limits severely constrain the amount of water that can be delivered using hand-operated pumps. However, if the energy requirement is small because the water requirement and/or head are very low, and a willing labor force is available, human-powered systems should seriously be considered as a low-cost, low-maintenance option. The main question would be whether or not daily water demand could be met with handpumps.

3.2.2 Petrochemical Fuel and Electrical Energy

Petrochemical energy sources--diesel fuel, gasoline, and kerosene--are widely available in nearly every country in the world (there are, of course, periodic shortages and fuel delivery problems). Nevertheless, it is important to consider their impact on system operating costs, as well as whether or not they are and will continue to be reliably available in the quantities needed to meet daily energy requirements. Since gasoline and kerosene engines are not nearly so common as diesel motors for pumping water and are generally more expensive for most small-scale water pumping needs, they will not be discussed further here.

Fuel availability and costs depend on many factors, including

- supply at the national level;
- reliability of national and regional distribution systems--public and private, formal and nonformal;
- the existence of priority allocation schemes; and
- local variations in demand--an unexpectedly high periodic demand sometimes depletes fuel supplies.

The suitability of electrically operated pumps depends on their proximity to the electricity grid and the reliability of service. Since grid power is uncommon in most rural areas of developing countries, grid-electric pumps will not be considered further here. However, in most cases where reliable grid power is available at a site, electric pumps are the preferred system for technical and cost reasons.

The appropriateness of a diesel, electrical, or any other pumping system must be at least partially determined on the basis of past energy availability, its likely availability in the future, and the degree of system reliability that is required. When considering diesel or electric pumping systems, you should determine whether past problems with availability and fluctuations in fuel costs are great enough to warrant considering other types of systems.

Diesel engines are available in any rated power output range between 2.0 kW and 20 megawatts (MW), so finding equipment with the right capacity is generally not a problem, except for very small outputs--less than 2.0 kW. A full discussion of factors affecting diesel fuel consumption rates and methods for calculating consumption and power output are given in Chapter 5.

3.2.3 Solar Radiation

The performance of a solar pumping system will be proportional to the solar energy falling on the PV array (the set of solar modules that produce electricity). Solar energy or irradiation is measured with a pyranometer, which gives readings in power per unit of horizontal area, watts or joules per square meter per second (W/m^2 or J/m2-sec). These power measurements are integrated over time (usually a day) to give energy in kilowatt-hours or megajoules per square meter per day (kWh/m^2d or MJ/m^2d).

As an example, a good solar radiation day in a semi-arid climate at less than 25 degrees latitude produces about 6 kWh/m^2d or 21.6 MJ/m^2d, since 1 kWh/m^2d equals 3.6 MJ/m^2d. One peak sunlight hour is defined as 1 kWh/m^2h. The literature of some PV pump manufacturers refers to the number of peak sunlight hours as a way of quickly estimating local solar radiation levels. Remember that irradiation can vary considerably over a day, month, or year, depending on local weather conditions and latitude. In addition, annual averages can vary significantly from one year to the next.

Solar and wind pump sizing is based on the concept of design month, which was mentioned in Chapter 2. During that month, the ratio of available energy (monthly average solar irradiation or wind speed) to the hydraulic energy requirement is at its lowest (see example in Section 7.3.2). In general, solar pumping systems should not be considered unless irradiation during the design month is greater than about 5 kWh/m^2d. Again, this guideline is somewhat flexible, depending on site-specific costs and operating constraints. World-wide maps of solar radiation data do exist (see Kenna and Gillett 1985), but the data are not precise enough to be used as the basis for a site-specific system design.

To assess PV pump suitability and performance the following information is needed, at a minimum:

- the average daily solar energy available at the site during each month of the year and
- the average daily temperature for each month (because PV array output decreases as the operating temperature increases).

As is true of wind speed data, solar irradiation data are somewhat dependent on the terrain and microclimate. However, solar irradiation is generally not so variable as wind speeds, nor is the amount of available solar energy so sensitive to the amount of irradiation as wind energy is to wind speed. Hence the effects of differences at the site from recorded data are not as pronounced for solar as for wind-energy systems. Thus, solar irradiation data from pyranometer sites that are as far away as several hundred kilometers may be acceptable. This is fortunate as the worldwide network of stations measuring solar irradiation is much more limited than that for wind measurements. Variations in the amount of irradiation depend on how different the microclimate at the proposed pumping location is from the recording site.

The electrical energy produced by a PV array depends not only on the operating temperature and incident solar irradiation, but also on the size of the array and the angle at which it is tilted up from the ground. The more nearly perpendicular the array is relative to the sun's rays, the more electrical energy will be produced. Details on solar pump sizing, based on the energy-resource information discussed here, are provided in Chapter 6.

3.2.4 Wind Regimes

The power available in wind is given by the following formula:

$$P_w = 0.5 \times p_A \times A \times v_A^3$$

where P_w = power available in the wind in watts

p_A = air density in kg/m^3

A = cross-sectional area of wind being intercepted (i.e., area covered by windmill rotor in m^2)

v_A = air velocity in meters per second (m/s)

Note that the power in the wind is proportional to the <u>cube</u> of the wind speed. This means that <u>doubling</u> the wind speed increases the power available by a factor of <u>eight</u>. It also means that small errors in estimating windspeed can result in large errors in estimating available power in the wind. To evaluate the potential use of wind as an energy source, measurements or estimates must be made of local wind speeds over the course of a year. The energy output of a wind pump is directly proportional to power available in the wind over time. The water output for a particular windmill is proportional to the energy available, which depends on wind speed and rotor diameter, and inversely proportional to the total head.

The wind pattern or regime can be approximately characterized by an average speed (measured in m/s or miles per hour [mph] at a given height) over a given period, usually a month. Generally, windmills should not be considered if a site's average wind speed during the month with lowest speeds is less than 2.5 m/s or the total pumping head is over 60 meters. However, a combination of many site and economic factors finally determines the lowest average wind speed at which windmills are a practical alternative.

Since most people will not want to measure the wind at the proposed site for a year before deciding whether to purchase a system, windspeed data are occasionally available for nearby sites as hourly averages, but more often as daily or monthly averages. To assess the location's suitability for windmills and to estimate performance, monthly average wind speeds near the site are required for a period of at least a year. If available, recorded data for longer periods are very useful in assessing whether that year of data is an accurate representation of wind speeds at the site. The more detailed the windspeed data used in system design, the more accurately you can predict the performance of particular windmills.

At a minimum the following information is needed about the wind regime to assess windmill performance:

- monthly average wind speeds over the course of one year (used to determine the months with low wind speeds);
- the location and height of the recording instruments used, since wind speed varies with height; and
- a description of the terrain where the wind speeds were recorded, and the topography between that location and the proposed pump site (trees, hills, and other features can dramatically affect wind speeds).

In addition to wind data, other important information that must be collected about the proposed pump site includes

- the site's elevation above sea level (this affects air density and, hence, the amount of power in the wind) and
- a description of the terrain around the pump site.

Depending on the reliability of the data sources, the completeness and accuracy of the windspeed information, and the conditions under which it is collected, corrections may need to be applied properly to estimate the wind at the proposed site. These include

- a height correction if the windmill will be located at a different height than where the data were recorded;
- a correction if the data-collection period is short; and
- a correction for local terrain conditions.

Taken together, such corrections can affect local windspeed estimates by as much as 30 to 40 percent. A discussion of corrections and the calculations required to choose a windmill and predict its performance is provided in Chapter 7.

3.3 Information on Energy Resources

It is important that information on energy resources be as complete as possible. In most cases, this means gathering data locally. Site visits are highly recommended for recording important resource parameters and assessing exposure and terrain conditions relevant to possible wind or solar energy use. In addition to data collection at the site, other sources of information on energy resources include

- the national department of meteorological services;
- airports and departments of civil aviation;
- university or polytechnic science departments;
- the country's department of agriculture; and
- agencies responsible for energy, mines, and/or dams.

Additional sources of information concerning the energy resources discussed in this section are briefly described in the annotated bibliography (Appendix A). Local estimates of variability in wind or solar resources may also be helpful, especially if little or no other data are available. Talk with local people about their perceptions of area weather conditions. Their perceptions may be particularly useful in assessing daily variations in resource levels, such as periods of calm or cloud cover. While such information may not always be accurate, remember that most villagers have been living in the same place for a long time and, thus, may be able to verify data from distant weather stations.

Chapter 4

AVAILABLE EQUIPMENT—PUMPS AND DRIVERS

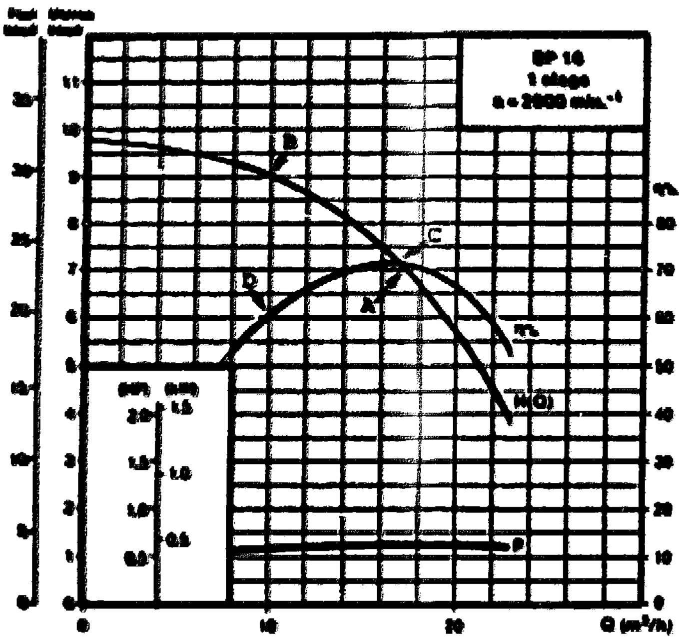
The pump is only one piece of equipment to be chosen as part of a complete pumping system. Pumps are selected based on the required flow rate and head. The engine is then chosen to match the pump's power requirements. This chapter discusses the basic operating characteristics of pumps (i.e., pump curves), the different kinds of water pumps available, and selecting the pump with suitable operating characteristics to meet a particular need. As you might expect, certain types of pumps are appropriate for certain applications—specific head, flow rate, and water quality conditions. The advantages and disadvantages of various kinds of pumps and their suitability for use with different types of engines (referred to more generally as drivers or prime movers) are also covered in this chapter. The final section of this chapter describes the advantages, disadvantages, and most appropriate applications for the four types of pump drivers covered in this manual—diesel, solar, wind, and human power.

4.1 Pump Characteristics

The most important technical characteristic for predicting pump performance is the pump curve. Pump curves (two examples of which are shown in Figure 4) depict a pump's operating range in terms of total head, flow rate, and efficiency. While each pump model has a unique pump curve, different types of pumps have characteristic curves. Figure 4a shows typical pump curves for a vertical turbine pump and Figure 4b for a positive displacement pump operating at a variety of different speeds (note that the axes are reversed in the two figures). These pump performance curves also include power consumption and efficiency curves. Efficiency curves can be used to refine system design by indicating the pump that operates most efficiently for your system's total head. If efficiency curves are not available, you can calculate them given the pumping head, flow rate, and power requirement, using the energy requirement calculation presented in the previous section.

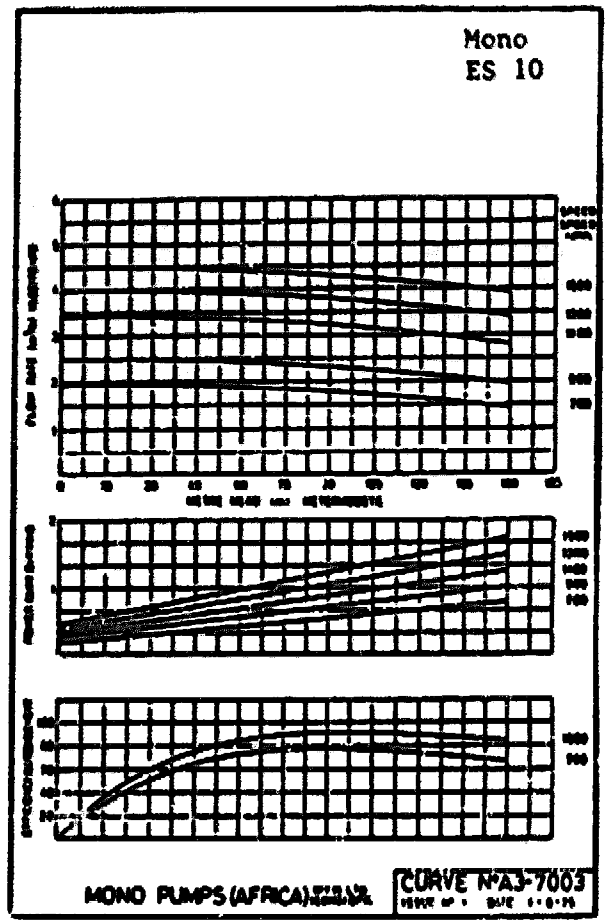
The efficiency of the pumping system and its components can have a considerable effect on recurrent costs. A system with lower efficiency consumes more energy pumping a given amount of water than a similar system with higher efficiency. However, there are often trade-offs between higher efficiency and lower capital costs. Efficiency is a function of each system component (e.g., pump, engine, and transmission) and how well the system was designed to match the physical constraints of the water source. This manual (particularly Chapters 5 through 8) includes detailed discussions of the concept of efficiency, its role in system design, and how to reduce costs by carefully integrating all components of a pumping system.

Figure 4. Pump Performance Curves



ηt = hydraulic efficiency
H(Q) = flowrate
P = power

4a Centrifugal (Grundfos) Vertical Turbine Pump



4b Positive Displacement Rotary (Mono Pumps)

To determine the required flow rate and head, you must know the characteristics of your water source, as discussed in Chapter 2. Generally, it is recommended that the average flow rate, in cubic meters per hour (m^3/h) or liters per second (l/s), should be no more than about 70 percent of the maximum sustainable yield of the well or other water source. This will help minimize the possibility of over-pumping the source and will reduce excessive drawdown, thus decreasing the head and energy requirement. Below 70 percent of the well's yield, the flow rate is determined by the water requirement in cubic meters per day (m^3/d) and number of hours you want to operate the system.

The flow rate for diesel pumps is essentially constant because of the engine's constant operating speed. In most cases, you would simply choose the flow rate (below the 70 percent limit) needed to meet your water requirement if the pump is run six to eight hours per day. Flow rates for handpumps generally do not approach the limit on yield of the water source, but are dependent on the speed at which the pump is manually operated. Because of the cubic relationship between flow rate and wind speed, pumping rates for windmills can be very high during gusts. As a general rule, do not design the output of a wind system to be more than one-third of the source's maximum daily sustainable yield. For example, if the source yield is 3 m^3/h (or 24 x 3 = 72 m^3/d), a windmill should be sized to pump no more than 1/3 of the daily 72 m^3 yield, or 24 m^3/d.

For solar pumping systems without batteries, output varies over the day, with the maximum generally occurring around noon when the sun is highest in the sky. The average daily flow rate (average daily output divided by number of hours of operation) should be no more than about 70 percent of the water source's maximum sustainable yield. For both the solar and wind cases, using these design limits will help prevent over-pumping of the water source (and consequently large drawdown) during periods when the energy resource is strong.

Example 5: Pump Performance at a Given Head

What is the flow rate of the pump in Figure 4a when the total system head is 7 meters? What would it be if the head were increased to 9 meters? What are its efficiency and power requirements?

A. A pump's operating or design point is the value of the point on the pump curve for total system head when the pump is running. From Figure 4a, the operating point (Point A on the graph) of the BP-16 pump is 17 m^3/h at a head of 7 meters.

B. When pumping head is increased (by pumping to a tank, for example), the volume of water output decreases, since it takes more energy to pump to the additional height of the storage tank. Again from Figure 4a, if a ground tank added 2 meters to total system head (making it 9 meters), the pump output would be reduced to about 10 m^3/h (Point B on the graph).

C. As stated above, at 7 meters head the pump delivers 17 m^3/h. Read the value of the efficiency curve at that flow rate to get about 71 percent (reading off the right side scale of the graph to Point C). At 9 meters head and 10 m^3/h, it is only 60 percent efficient (Point D). In both cases, power consumption (shown in the bottom curve) is just below 0.5 kW.

For electric-submersible pump sets, where the pump and its motor are integrated into one unit, pump performance graphs often show multiple head and flow curves and efficiencies for different motor voltages (see the solar pump curves in Figure 5), or for different motors with regular alternating current (AC) submersibles. For PV pumps, an additional parameter that specifies system performance is the level of solar radiation in the plane of the array. For a radiation level, a point on the curve indicates how much water the pump will deliver for a given head. An example of these curves is given in Figure 6.

Various types of pumps have performance curves with very different shapes. Figure 7 shows typical curves for centrifugal and reciprocating pumps. Understanding how these curves apply to a particular situation will help you to choose an appropriate type of pump. For example, if a well has a water level that is seasonally variable (i.e., it depends on rainwater for recharge), there are advantages to choosing a reciprocating over a centrifugal pump. If the centrifugal pump operates at the middle (most efficient) point of its performance curve during the wet season, when the water level drops off in dry months, the total pumping head will increase, thus reducing efficiency and output. However, output for a reciprocating pump is nearly independent of the head. If the water level drops, the system will continue to pump nearly the same amount (as long as the water does not drop below the level of the pump), but at a higher power consumption than if the water level were constant.

4.2 Advantages and Disadvantages of Different Pumps

Many types of pumps are available, but seven are commonly used in diesel, solar, wind, and hand-pumping systems. They are listed below, along with a brief description of their typical use, advantages, and disadvantages. Illustrations of common designs for these pump types are shown in Figure 8. The comments here concern commonly used, commercially available, small-scale pumps (i.e., less than 10 kW). The first three are all centrifugal pumps—they all have a low starting torque and their output and efficiency are very dependent on the operating head.

- Self-Priming Centrifugal

  Use: surface-mounted motor and pump for high-volume, low-head applications.

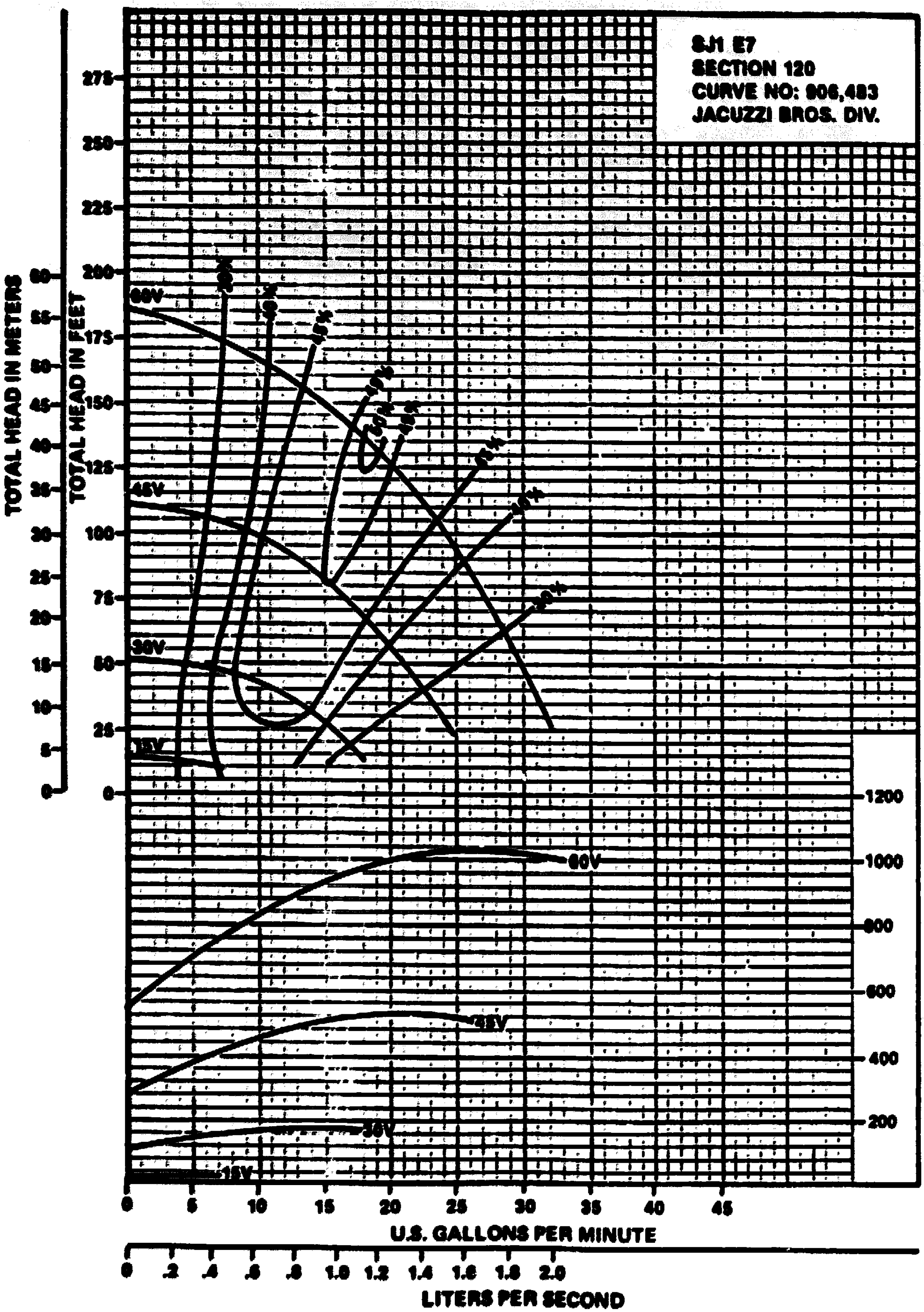
  Advantages: ease of installation, access, and repair, and a low starting torque.

  Disadvantages: limited 5-meter suction head, relatively inefficient compared to centrifugals that have flooded inlets, such as submersible and shaft-driven units.

- Submersible Centrifugal

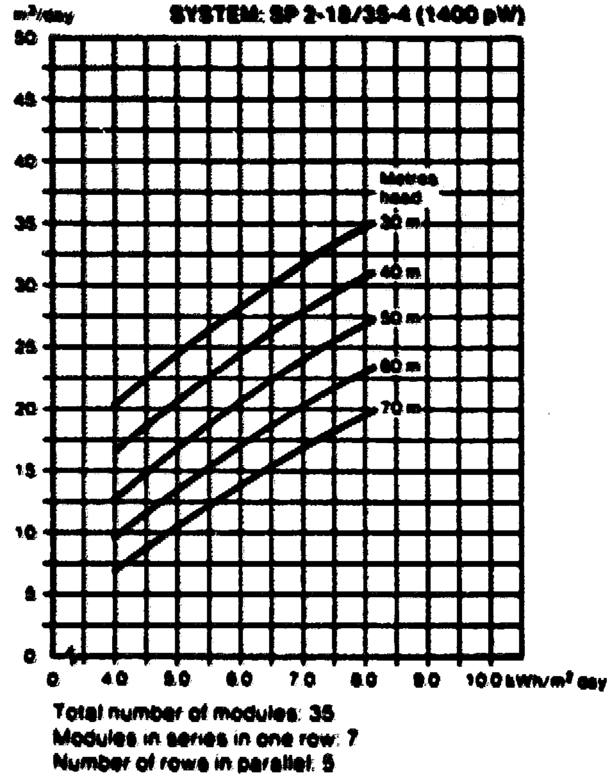
  Use: down-hole, high-volume, high-head, integrated motor/pump unit.

Figure 5. Pump Performance Curves: Submersible Centrifugal Pump at Variable Voltage



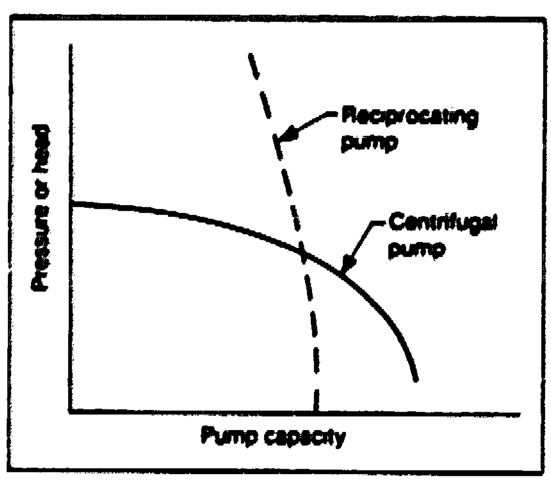
(Jacuzzi Manufacturing Literature)

Figure 6. Solar Pump Performance at Variable Irradiation Levels



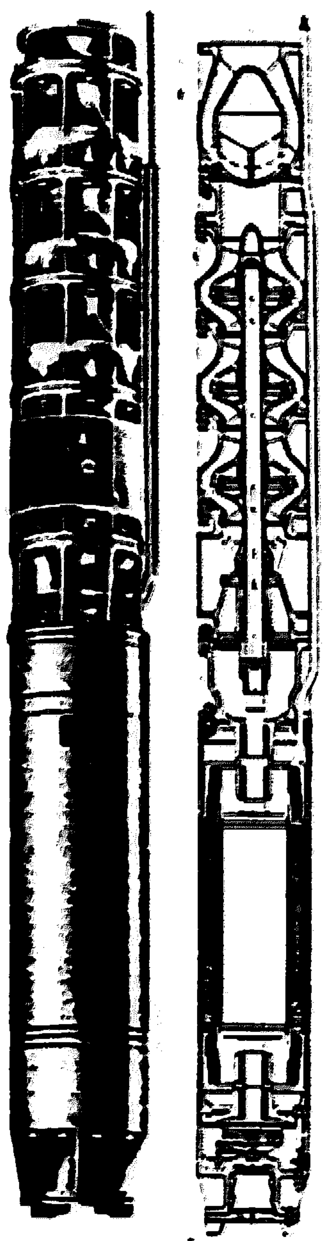
(Grundfos)

Figure 7. Centrifugal vs. Reciprocating Pump Pressure and Capacity Characteristics



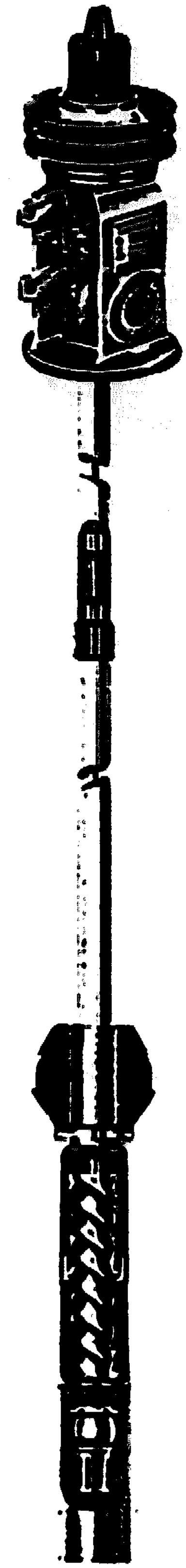
(Driscoll 1986)

Figure 8. Types of Commonly Used Pumps

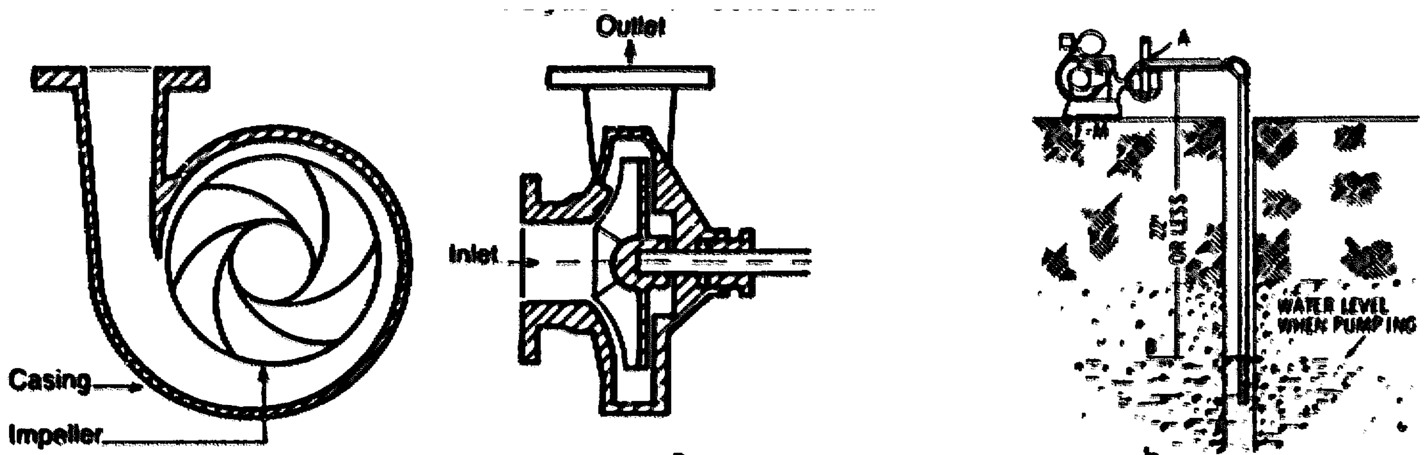


Submersible Centrifugal
(Stewart 1982)

Shaft-Driven Centrifugal
(Grundfos)

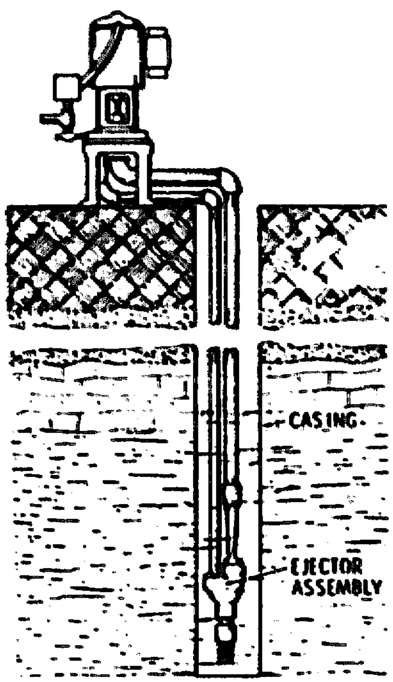


Positive
Displacement Rotary
(Mono Pump)

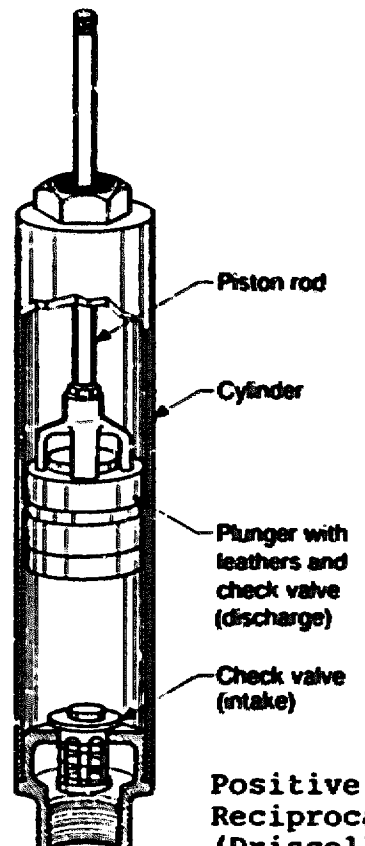


Self-Priming Centrifugal[a] and Typical Installation[b]

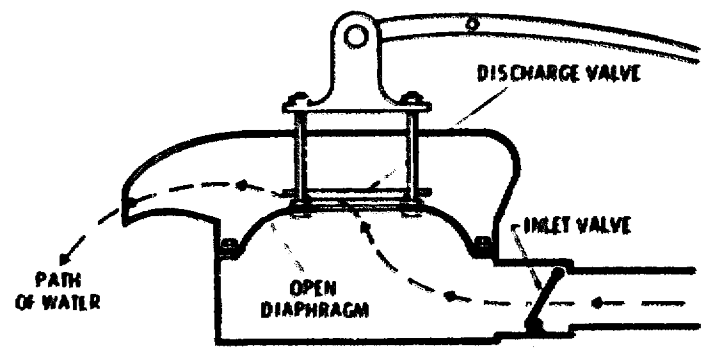
[a] (Hofkes and Visscher 1986)
[b] (Stewart 1982)



Jet
(Stewart 1982)



Positive Displacement
Reciprocating Piston
(Driscoll 1986)



Diaphragm
(Stewart 1982)

Advantages: multi-stage to accommodate a wide range of heads, not restricted.

Disadvantages: sandy or highly saline water causes rapid degradation, water quality affects replacement interval for pump and motor as these are submersed, high capital cost, expensive to repair (pump set requires removing unit from well), requires electricity (i.e., cannot use other drivers), brushless direct-current (DC) submersible motors still in development stage so present DC and AC submersibles must be pulled for periodic brush replacement, inverter losses for AC submersibles when used with PV, limited capacity since currently available units are all nominally one kW.

- Shaft-Driven Centrifugal (Vertical Turbine)

  Use: down-hole, medium-volume, medium-head pump driven by rotary shaft.

  Advantages: surface-mounted motor offers ease of maintenance, not limited in terms of suction so there are no priming problems, high capacities are available.

  Disadvantages: Shaft losses reduce efficiency compared to submersibles, shaft and borehole alignment are critical to proper operation, installation is difficult.

- Jet

  Use: medium-head, medium-flow, down-hole pump and surface-mounted motor.

  Advantages: can be used beyond suction limit, very reliable, easy access to motor for maintenance, low starting torque—least expensive intermediate-head pump.

  Disadvantages: relatively inefficient.

- Positive-Displacement Reciprocating-Piston (Jack)

  Use: high-head, low-flow, down-hole piston and cylinder, driven by sucker rod from surface.

  Advantages: can pump low flows against very high heads, output is independent of head, simple design.

  Disadvantages: maintenance requires periodic replacement of leathers and cylinder, more expensive than centrifugals of same size, relatively inefficient as leathers degrade, most commonly used with windmills, pulsing flow, in PV systems (see Chapter 6) requires batteries or power-conditioning units (PCUs) for high starting current.

- **Positive-Displacement Rotary**

  Use: medium- to high-head, medium-flow, Mono or Moyno pumps.

  Advantages: generally very robust, output fairly independent of head, not confined to suction limit, no priming problems, good efficiency over wide range of heads except for under 20 meters, and no back-flow valve required.

  Disadvantages: sand or very hard water can cause premature degradation of rubber stators, requires gearing, can overload motors if downstream valves are inadvertently closed, installation is difficult. Although newly developed nitrile stators have lower starting torque, standard units require battery or PCU to supply high starting torque.

- **Diaphragm**

  Use: flow produced by flexing diaphragm that is generally used for low-head, low-flow applications.

  Advantages: few moving parts, low internal friction, tolerant of sand or other particulates.

  Disadvantages: constant flexing causes diaphragm wear, fairly uncommon type of pump.

4.3 Pump Selection Considerations

A number of factors to take into consideration when selecting pumps cannot easily be quantified but should be carefully considered in choosing any pump. These include:

- equipment reliability (often a direct function of the complexity of the design);
- frequency and complexity of maintenance requirements and technical skill levels or additional training needed to perform maintenance tasks;
- degree of use in your area--if a pump is commonly used, local mechanics are probably familiar with its operation, and spare parts are likely to be readily available; and
- potential for standardization of equipment, with the goal of minimizing spare parts inventories and technical training requirements.

To some extent, pumps are application-specific. For example, handpumps obviously have a very limited application for irrigation. However, various types of hand-operated pumps—for instance, rower pumps, standard reciprocating-piston handpumps (e.g., Dempster or India Mark II), and rotary pumps (Mono)—have been used in several countries for micro-irrigation. Generally, river-pumping applications for water supply or small-scale irrigation systems, which normally require high flows at low heads, use centrifugal pumps because of their high capacity, reliability, and ease of maintenance. For applications requiring a high capacity system, surface-mounted centrifugals are employed for low heads, and vertical turbine centrifugals for deeper wells—both are relatively inexpensive and their motors are easily serviced. To provide drinking water from wells, submersibles or positive displacement pumps are a more likely choice. They are usually more efficient, but their capacity is lower.

These are just some examples of pump applications. Table 1 shows practical head and output limits with various power sources for these and several other pumps. This information is shown graphically in Figure 9. To a large extent, the choice of a pump will be dictated by constraints associated with the water source—requirements for the head and flow rate, and the variability of the source. In many cases, any one of several different pump types will perform adequately. The important point is to choose a system that will operate efficiently and reliably under the design conditions at your site.

In practical terms, the way to select a particular pump is to first choose the type that is appropriate for your particular application, based on the advantages, disadvantages, and ranges for the flow rate and head given in this section. Then, based on an informal survey of the local availability of makes and models of that type, select four or five models with pump performance curves where your site's operating point is roughly in the middle of the curves (the x-axis represents the flow rate and the y-axis, the head). The final choice is determined by which models require the least energy to pump the amount of water you require from a given head. This can be decided by noting which pumps have the highest operating efficiency for the system's total pumping head. Make sure you are using the correct pump curve in order to reflect the pump's operating speed (e.g., for positive-displacement pumps) or variable voltage conditions (for electric-submersible pumps), if these apply.

4.4 Advantages and Disadvantages of the Drivers Covered in This Manual

As shown in Table 1, certain drivers are suitable for certain types of pumps. This section discusses the qualitative differences between drivers and, where appropriate, the pumps they are best suited for.

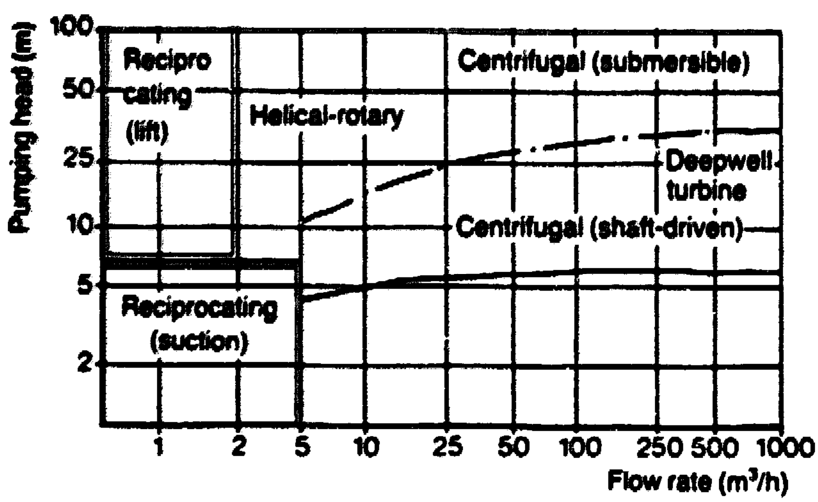
Table 1

Pump Ranges and Power Sources

Type of Pump	Practical Depth Range (m)	Capacity Range m3/hr	Common Power Source
Centrifugal			
single stage	15-20	variable	motor solar
multi-stage submersible	50-500	variable	electric motor solar
multi-stage shaft-driven	15-80	variable	motor wind
Jet			
shallow well	up to 7	1-6	motor
deep-well	20-60	1-3	motor
Recip.ocating-Piston Pumps			
shallow well (suction)	up to 7	2-3	human wind
deep well	15-100	2-6	human motor wind
Rotary Positive Displacement	30-150	1-100	motor human solar
Diaphragm	5-30	1-3	human motor

(adapted from Hofkes and Visscher 1986, 61)

Figure 9. Pump Application Range



(Hofkes and Visscher 1986, 60)

4.4.1 Diesel Systems

Diesel engines are the standard prime mover in most of the developing world (see Chapter 5). They can be used to drive nearly any type of pump, either directly or through a generator. Diesel engines are normally characterized by

- low capital costs, but relatively high recurrent costs for O&M;
- local familiarity with O&M due to existing infrastructural support networks of widely varying quality that include trained mechanics and spare parts supplies (although this can vary widely from country to country, and even by specific area within a country);
- fuel availability that is highly variable and affected by seasonally dependent transportation networks;
- fuel costs that often vary seasonally but are generally increasing in rural areas despite current decreases in world oil prices;
- on-demand pumping capability, as opposed to wind or solar pumps, which are dependent on the availability of variable renewable energy resources;
- equipment that is commonly available for essentially unlimited capacity in terms of head and flow rate, except for small loads (less than 2 to 3 kW);
- relative portability of smaller units, which are generally high-speed; and
- the need for an attendant during operation.

4.4.2 Solar PV Systems

Solar pumping systems typically consist of a PV array (i.e., the power source), power-conditioning equipment, an electric motor, and a pump (see Chapter 6). They are usually characterized by

- relatively high capital equipment costs and low recurrent costs for operation (since there is no fuel requirement), maintenance, and repairs;
- limited capacity for commercially available equipment—up to 2.2 kW peak power input, which can provide about 40 m^3/day from 25 meters of head (although this can vary widely from country to country and even from one area to another within a

country), given solar radiation levels in many developing countries (Note: although it is very unusual, it is possible to install several stacked PV submersibles in one well. However, this is usually not economically viable);

- no on-demand pumping capability, though water storage tanks or batteries can be used to minimize this limitation;
- low portability for most installations because of the PV array—some smaller units of less than about 500 watts peak can be mounted on trailers for portability;
- electromechanical controls, which allow for unattended operation;
- susceptibility to vandalism—stones can easily break the glazing on PV modules; and
- very high reliability for the power supply (i.e., the array), but not always for the energy supply (the sun).

4.4.3 Wind Systems

Mechanical wind pumps typically consist of a horizontally or vertically mounted windmill (i.e., rotor) and transmission (gearbox or other types) mounted on a tower. Most often, rods connected to the transmission drive a down-hole piston pump. Wind pumps are typically characterized by

- high capital equipment costs and relatively low recurrent costs for operation (because there is no fuel requirement), maintenance, and repair;
- limited capacity given the rotor diameter on commercially available machines (up to 7.6 meters) and wind regimes that are commonly encountered (less than 5 m/s under fairly favorable conditions);
- no on-demand pumping capability, which necessitates providing a large amount of storage capacity to increase water availability;
- the possibility of local manufacture;
- no portability; and
- mechanical controls, which permit unattended operation.

4.4.4 Hand-Operated Systems

Hand-operated pumps are commonly simple lever arms that move piston, diaphragm, or rotary down-hole pumps. They are characterized by

- very low capital and recurrent costs;
- ease of installation, operation, and maintenance;
- very limited capacity for single units—less than about 5 m^3/d for up to 40-50 meter heads, but more at lower heads; and
- the possibility of local manufacture for some simpler models.

4.5 Other Types of Drivers

This manual does not deal specifically with other system types besides the four described above. The approximate head and flow limits for the pump drivers discussed here are given in Figure 10. Six other kinds of pump drivers and one other configuration (hybrid systems) might be of potential use to some readers. Thus, the following are briefly described here (see Fraenkel 1986 for coverage of an exceptionally wide variety of pumps):

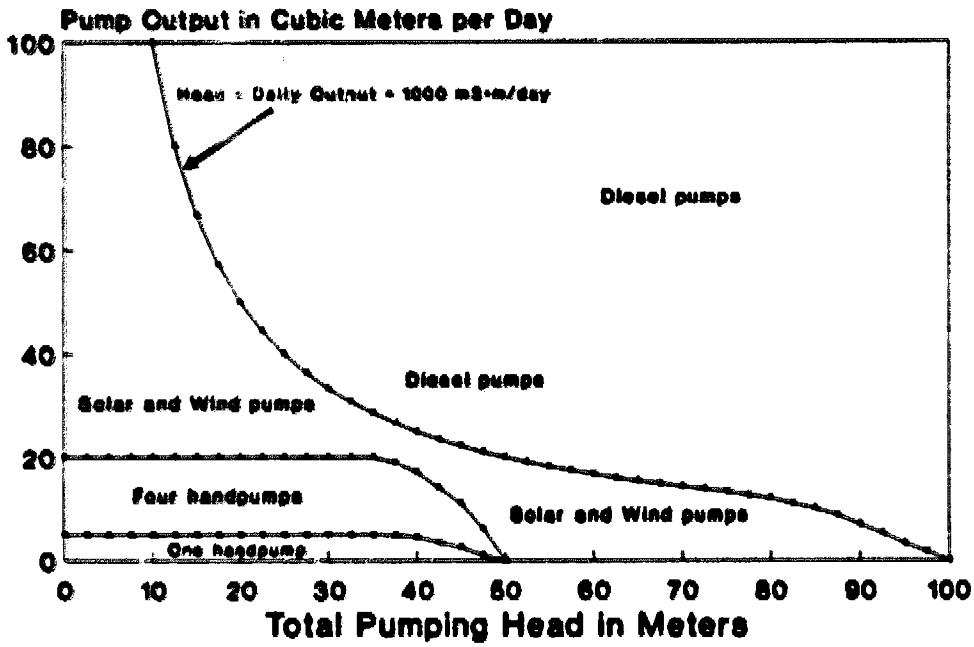
- electric generators and grid-connected pump sets,
- wind-electric turbines,
- animal-traction pumps,
- biogas or dual-fuel pumps,
- river current turbines
- hydraulic rams, and
- hybrid systems.

4.5.1 Electrically-Driven Pump Sets

Where electric power is available, grid-connected pump sets are often the most cost-effective system option for rural water supply. Compared to diesel-driven pumps, electric sets are generally easier to install, require less maintenance, and use cheaper fuel (electricity as opposed to diesel or gasoline). However, for sites without any grid electric power, the high cost of extending an existing grid to more remote areas usually makes other pumping alternatives more cost-effective.

Figure 10. **Approximate Head and Flow Limits for Pump Systems Available in 1988**

(economically competitive applications)



Notes

1. Solar and wind pump outputs depend on radiation and wind speed level.
2. At low head and low flow, all equipment options are possible.
3. Lines indicate technical limits of capacity for existing equipment under normal use conditions.
4. Based on 3.5 m/s wind speed, and 6 kWh/m^2d solar radiation.

In some countries, diesel-driven generators are used to power electric pumps. For sites with other noncompetitive end-uses for the electricity (e.g., village lighting or grinding grain at night), diesel-powered electric generators for water pumping may be cost-effective. In general, such systems offer the flexibility of using electric pump motors, but are inefficient from an energy perspective in that the energy is converted from chemical to mechanical to electrical form and then back to mechanical. Extensive cost data that would permit comparisons with alternatives are unavailable. These systems also require components that are more complex and difficult to repair (e.g., electric generators). They also demand additional skill to maintain and repair and, hence, entail associated training needs. This is a fairly uncommon application in many developing countries, so it will not be discussed further in this manual.

Finally, local "mini-grids" have been suggested as a way of powering electric pumps in rural areas distant from a national grid. Mini-grids—relatively small units in terms of power generation (about 500 kW)—could power a variety of loads in a local area, such as motors and lighting for cottage industry, village lighting and communications, and pumping for the rural water supply. Again, this approach has some merit, but it is fairly rare at present and will not be considered here.

4.5.2 Wind-Electric Turbines

Wind-electric turbines received a considerable boost in popularity in the United States and Europe during the late 1970s and early 1980s when over 15,000 were installed in California. These machines were sited in areas with average wind speeds of more than 7 m/s, a speed that is rare on a regular basis in most areas. Wind-electric turbines are usually designed to operate most efficiently at higher wind speeds than are mechanical wind pumps.

Where high wind speeds prevail (i.e., greater than 6 to 7 m/s), wind-electric turbines can be the most cost-effective choice for power generation at remote sites. However, such high average wind speeds are not usually found in most developing countries. Direct water-pumping applications for wind-electric turbines are still in the development stage, and there is little long-term data on recurrent O&M costs. For these reasons, they will not be discussed further here. However, where windspeeds are sufficient, the potential of this new and interesting application of wind power deserves to be monitored as developments occur.

4.5.3 Animal-Traction Pumps

Animal-drawn pumps (ADPs) have been used to supply water for drinking and small-scale irrigation for thousands of years in countries such as Egypt and Iran. Recent research on ADPs (Kennedy and Rogers 1985) has focused on increasing their efficiency and reliability, lowering their capital costs, and developing units that can be manufactured in developing countries. Work has been undertaken in countries like Botswana (see Hodgkin, McGowan, and White 1988, vol. V) to develop an animal-drawn transmission that can be used in conjunction with a standard pump, such as the Mono. While many low-flow, relatively low-efficiency animal-traction pumps are being used around the world, very little cost data is available on improved versions that might be relevant to the applications covered in this manual.

4.5.4 Biogas and Dual-Fuel Pumps

Biogas pumps are slightly modified internal combustion engines (usually diesels) which burn biogas, a product of the decomposition of a biomass. The main combustible component of biogas is methane, but it also contains other gases such as carbon monoxide. Biogas pumps have been used experimentally in many countries (e.g., India and Botswana) but have not yet achieved widespread commercial acceptance. Dual-fuel engines are also used to drive water pumps. The two fuels are usually diesel fuel (to get the engine started) and biogas or producer gas from a biomass gasifier (to run the engine after it gets warmed up). Gasifier pumps have been used in the Philippines and Thailand for irrigation pumping but, again, have achieved no significant share of the pumping market (nor, it must be said, have wind or solar pumps). The primary advantage of these engines is that they use renewable energy resources and, depending on the country where they are used, show some potential for taking the place of imported fossil fuels. Their primary disadvantage is that they have all the attendant O&M limitations of diesel pump operation, requiring frequent and often extensive maintenance and frequent repair, due to the typical impurity of their fuel.

4.5.5 River Current Turbines

River current turbines are basically modified paddle wheels which are installed in rivers or streams. The water current drives the pump blades in a circular motion, which is usually mechanically converted into a reciprocating motion to drive a piston pump. The pumps are typically used in low-head, low-flow applications. These pumps have been used experimentally in (among other countries) Mali and Southern Sudan but have achieved no significant commercial success. While they have the distinct advantage of being locally manufacturable in many countries, they have not gained a reputation for being robust enough to attract many potential customers. Research on river current pumps is continuing in several developing countries.

4.5.6 Hydraulic Rams

In certain situations, hydraulic ram pumps are an extremely useful technology for pumping water. Relatively simple in design and construction, locally manufacturable in many countries, and very durable, they can effectively lift water up to 150 meters, using no external power. They use the potential energy of water falling a certain distance to lift a smaller amount of water up a greater distance. The major constraint is that their application is severely limited to sites that have the necessary altitude difference between the water source and the pump to drive the ram. This situation occurs often enough in some countries, particularly in South and Central America, that rams are an important, if limited, pumping technology.

4.5.7 Hybrid Systems

One disadvantage of nearly every type of pumping device is that it occasionally runs out of the energy resource used to drive it—diesel fuel is sometimes unavailable, the wind stops, or there are several cloudy days in a row. To address this problem, hybrid systems that use more than one power supply (e.g., diesel/wind, wind/PV, or diesel/handpumping systems) have been employed where the demand for water is critical and outages cannot be tolerated. Hybrid systems are almost always more expensive than traditional systems with a single driver.

An example of a hybrid system is PV/diesel, where PV powers an electric submersible pump whenever solar radiation is sufficient. If the array, which is the main driver, produces insufficient power because of several cloudy days in a row, the diesel engine is automatically engaged by the electronic controller and pumps water until the PV unit can again produce sufficient power. Such systems normally use a single pump with two drivers. Since the diesel unit consumes fuel only when it is running, there is no penalty (aside from the engine's initial capital cost) for having it always available in reserve.

While backup systems are similar to hybrids, they usually use completely redundant components. An example is a village water supply system that has several different water sources. A small diesel engine is installed to pump from the best source as the primary pumping unit. When water becomes unavailable for whatever reason (e.g., breakdown of the diesel engine, need to perform maintenance, or depletion of the water source), handpumps installed at another site(s) are used as backups. However, in most situations, handpumps cannot supply the same amount of water as the diesel engine, so a reduced supply must suffice until the primary diesel system is again operational.

An alternative to purchasing and installing hybrid or backup pumps is using larger storage tanks. If sufficient water can be pumped during normal operation so that enough water for several days is available in a storage tank, users will have an adequate supply in the event of system failure.

The next four chapters discuss detailed procedures for designing diesel, solar, wind, and handpumping systems. All are based on the fundamental pump characteristics discussed in this section.

Chapter 5

DIESEL PUMPS

As the most common type of prime mover in much of the developing world, diesel engines are used to drive a wide variety of pumps. In many countries, there is a broad national network (formal or informal) of equipment distributors, local dealers, mechanics, and transportation facilities that supports diesel engines used for pumping and other purposes. In most cases, diesel pump sets are the standard against which all other types of pumping systems must be compared. The two major factors in choosing an appropriate diesel engine are manufacturer and model. A manufacturer with a good reputation for quality products should be chosen. Also, it is important to consider the local availability of equipment and experienced technicians, engine configurations, and local dealer support in terms of spare parts inventories. The choice of model depends on the site-specific pumping task.

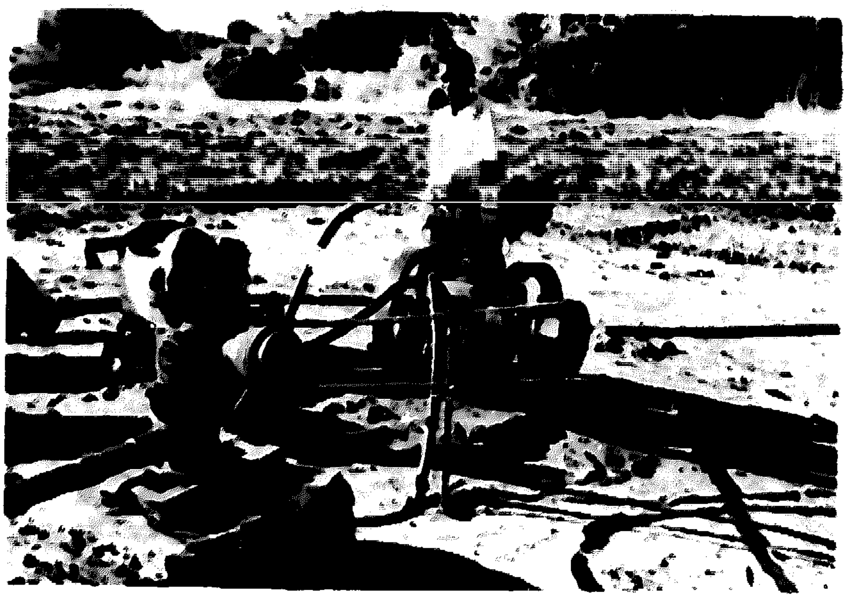
5.1 Engine Description

Through drive shafts or pulleys and belts, diesel engines can be used to drive almost any type of pump. They can also drive electric generators to run electric pump sets, which is a configuration that has advantages in cases where submersible pumps are favored and grid electricity is unavailable. However, this manual addresses only the direct mechanical application of diesel engines to water pumping.

The range of diesel engine output is essentially unlimited, with units available from 2 kW to 20 kW. This manual focuses primarily on the 2 to 10 kW range for small-scale water pumping. Diesel pump sets are usually characterized by moderate capital costs and comparatively high recurrent costs for fuel, maintenance, and repair. They are relatively portable, since engines up to 10 kW normally weigh less than 200 kg. Two typical small engines (under 10 kW) and one larger engine (40 kW) are shown in Photographs 1-3.

Diesel engines are internal-combustion engines that use diesel fuel (also called gas oil) as an energy source. They normally have combustion-ignition systems, meaning that the fuel is ignited by high temperatures in the combustion chamber, which are produced during the engine's compression stroke. Spark plugs are not normally used in diesel engines, except in rare instances that will not be considered here. Diesel engines are generally categorized in the following ways:

- high- or low-speed—operating at greater or less than about 2,000 revolutions per minute (rpm);
- single- or multi-cylinder—bigger, more powerful engines have a greater number of larger cylinders;

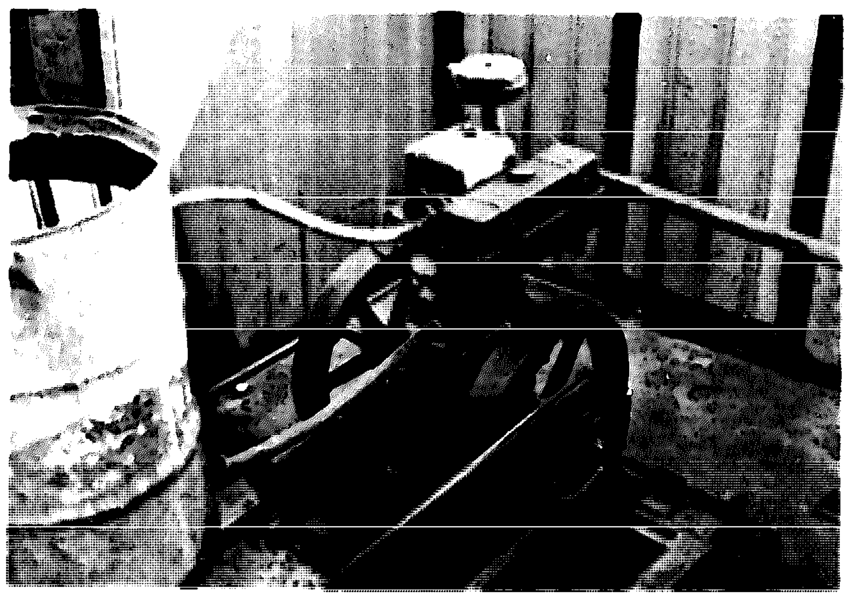


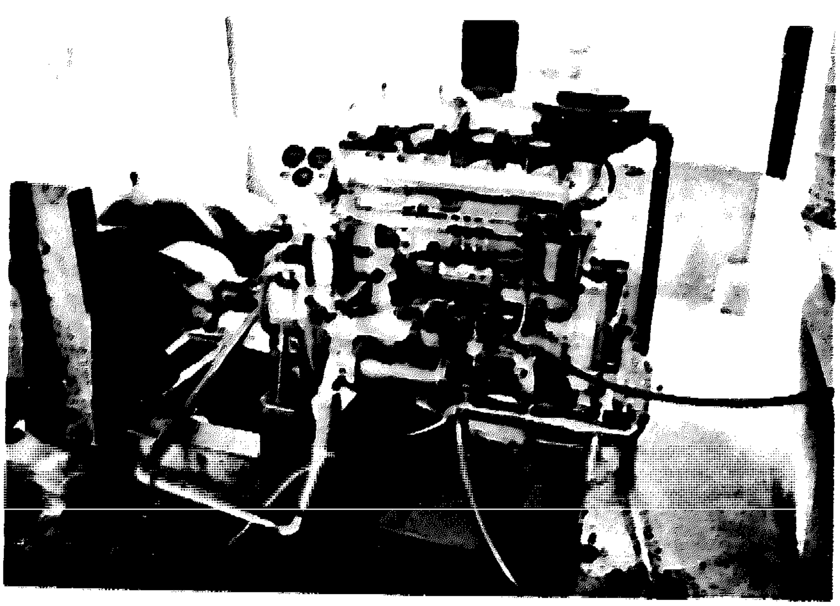
1.

Lister diesel engine with shaft turbine pump for irrigation in Sudan.

2.

Lister diesel engine with Mono pump for village water supply in Botswana.





3.

Italian diesel engine with centrifugal pump for irrigation in Somalia.

- air- or water-cooled; and
- two- or four-stroke.

Traditionally, diesel engines for water pumping have been slow-speed, relatively long-lasting engines. Those that are clearly built for long service are generally heavy; they often run at lower speeds (less than 2,000 rpm) and tend to be more expensive in terms of the initial cost. However, they are often more durable and easier to work on when maintenance or repairs are required because of their simple design. The higher speed, lighter engines that are now becoming available tend to be less expensive initially but also to have a shorter service life. Some lighter, high-speed Japanese diesels fall into this category. From the standpoint of life-cycle costs, it is not always clear which is the best choice. Deciding between low- and high-speed engines will depend on other factors, such as funds available for the equipment purchase, availability of spare parts, and quality of service.

Single-cylinder engines typically have rated power outputs between 1 and 10 kW. Multi-cylinder engines are available in a variety of sizes starting at about 8 kW. They tend to run more smoothly than single-cylinder engines but are normally more expensive. Whether you use a single or multi-cylinder engine depends primarily on power requirements.

Water-cooled engines tend to be larger and somewhat quieter when running; they do not require a cooling fan and/or fins as air-cooled units do but involve the additional maintenance of keeping the coolant at a certain level. Larger air-cooled engines need a cooling fan (very small ones sometimes rely only on fins), the operation of which entails an associated power loss. Most engines under 10 kW are air-cooled.

Both two- and four-stroke diesel engines are available. The former have fewer moving parts, tend to operate at higher speeds and wear out faster, are less efficient, and have a higher power-to-weight ratio (i.e., they produce more power per kilogram of engine weight). Oil must be added to diesel fuel for the proper operation of two-stroke engines. Otherwise, damage to the engine may result. For most water pumping applications, four-stroke engines are preferred.

Diesel engines also differ in the way that power is transferred to the pump. Some are connected to the pump shaft through a gear box and others through belts and pulleys. Such transmissions involve associated power losses that have to be accounted for in engine sizing (see Section 5.3 below).

5.2 Selecting a Manufacturer

Diesel pumping systems are widely used in most developing countries, and many types of engines are usually available. The most important question to ask when choosing a manufacturer is whether you have ready access to adequate spare parts and trained local mechanics who can repair the engine. Careful consideration should be given to the make of the equipment, the product support provided by the manufacturer and its local representatives, and operating and repair capabilities in that particular country.

Extreme caution is suggested when considering "offshore" purchases of mechanical equipment through other than local suppliers, or when buying any equipment that is not already supported locally. Even if some spare parts are included with the original offshore purchase, more will eventually be needed. In addition, any specialized repair tools that may be required and are not available locally will have to be purchased directly from the manufacturer, and local mechanics will not be familiar with the equipment and its particular idiosyncrasies. For all kinds of systems, long-term, trouble-free operation depends largely on local capabilities to service and repair the equipment when necessary. The quality of equipment and service infrastructure vary considerably between countries as well as within a country or region.

It is a good idea to carry out an informal survey of locally available equipment before deciding what to purchase. Discussions with dealers and local engine overhaul shops can help determine spare parts availability and can identify particular makes and models with good reputations as well as those prone to problems. At this stage, you can learn about specific installation and operational features that may affect your choice. Consult several sources to confirm information and opinions, since individuals usually have their own preferences, justified or otherwise. While the initial cost plays an obvious role in selecting a particular manufacturer's equipment, consider that a lower initial cost may mean lower quality equipment that will be expensive to maintain and that will frequently require replacement parts.

5.3 Choosing an Engine Model

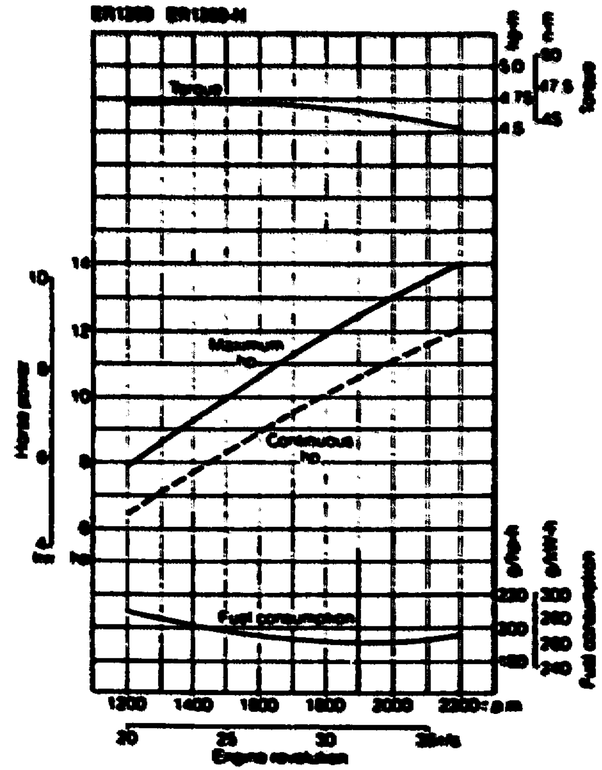
After selecting the appropriate flow rate and determining the total head, the power requirement can be calculated as described in Chapters 2 and 4. A particular model of diesel engine is then chosen on the basis of this power requirement. The performance of any diesel engine is usually specified by manufacturers in terms of three variables:

- torque,
- power, and
- fuel consumption.

All vary with engine speed, so they are quoted for specific speeds or given for a range of speeds in graph form. Examples of typical diesel-engine performance curves for torque, power, and fuel consumption are shown in Figure 11. While fuel consumption (grams of fuel consumed per hour of operation) increases with engine speed, specific fuel consumption (in grams of fuel consumed per kilowatt power output) varies with operating speed. In Figure 11, the Kubota ER 1200 is designed to operate most efficiently (i.e., lowest specific fuel consumption) around 1900 rpm, while the Lister STI operates most efficiently at 1500 rpm.

Figure 11. Diesel Engine Performance Curves

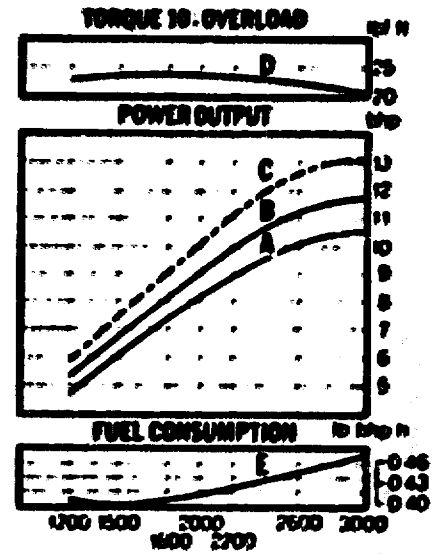
Performance curve



*This performance curve is rated on the basis of JIS (Japan Industrial Standard).

5.1a Kubota ER1200

ST1



5.1b Lister ST1

Power Output--Lister ST-1

Engine Speed	Continuous Power kW (Hp)	Maximum Power kW (Hp)
3000	7.8 (10.5)	8.7 (11.7)
2600	7.5 (10.0)	8.4 (11.2)
2000	6.0 (8.1)	6.7 (9.0)
1800	5.4 (7.3)	6.0 (8.1)
1500	4.5 (6.0)	5.0 (6.7)
1200	3.5 (4.7)	3.9 (5.2)

In the Kubota diagram, there are two power output curves. The upper one is for maximum rated power output and the lower for continuous output. Systems should be sized so engines run continuously at or below the lower output curve. This means the continuous power rating of the engine selected should be the same as or greater than the power requirement of a specific pumping task.

Engine performance is always given for specific conditions of temperature, air pressure, and relative humidity, since these variables also affect performance. Fuel consumption is quoted for a given power output at full engine loading. Engine loading is the ratio of power required by the pump to the maximum power available from the engine. Actual (partial-load) fuel consumption is dependent on the engine's condition and loading. As discussed in the following sections, loading has an impact on fuel consumption and maintenance requirements.

The "nameplate" power rating of a diesel engine, which is stamped on the manufacturer's nameplate, is the power available under continuous full-load conditions (i.e., when the load or pump is drawing the full rated power from the engine) at the engine speed indicated and under specified conditions of temperature, air pressure, and humidity. The power available from an operating engine will normally be less than the manufacturer states because operating conditions are unlikely to match those of the nameplate rating. Diesel engine output is "de-rated" or reduced by a certain percentage to account for such differences in conditions. An engine's power output can be calculated using manufacturer's specifications and then de-rating the engine for the specific site and operating conditions. De-rating recommendations vary by manufacturer and engine, but Lister gives these typical de-rating factors for the following conditions:

- for high engine-air inlet temperature, de-rate the power output by 2 percent for every 5.5° above 30° Centigrade;
- for lower barometric pressure (i.e., higher site elevation), de-rate by 3.5 percent for every 300 meters of elevation beyond 150 meters above sea level;
- for high humidity, which is also dependent on temperature, de-rate up to 6 percent (the precise value has to be chosen from a table supplied by the manufacturer); and
- for power-absorbing equipment, common de-rating factors are up to 10 percent for motor-driven radiator fans, 5 percent for belt drives, and 3 to 5 percent for transmissions.

These de-rating factors are calculated individually and then added. The total de-rating percentage is subtracted from 100 percent and then multiplied by the rated power for a full load to determine the de-rated output for the rpm specified.

Example 6: De-Rated Power Output

A Lister ST-1 has a nameplate rating for continuous output of 6 kW at 2,000 rpm. It will be operated at 1,500 rpm at a site 750 meters above sea level where the temperature can be expected to reach 38° Centigrade in the summer and where the humidity is negligible. A pulley-and-belt system will be used to drive the pump. What is the actual power output that can be expected under these conditions?

At 1,500 rpm, the Lister ST-1 develops 4.5 kW under standard conditions, according to the manufacturer's literature (see Figure 11). The de-rating factor for altitude is:

$$((750m - 150m)/300) \times 3.5 \text{ percent} = 7 \text{ percent}$$

The de-rating factor for temperature is:

$$((38 - 30)/5.5) \times 2 \text{ percent} = 3 \text{ percent}$$

Belt losses call for de-rating by 5 percent. Adding these factors together, the total de-rating factor is 15 percent. Thus, the power that can be delivered by an ST-1 operating under these conditions will be:

$$4.5 \text{ kW} \times (1 - .15) = 3.83 \text{ kW}$$

Each manufacturer's literature should include information on standard conditions and de-rating calculations. The total de-rating factor can easily be 20 to 25 percent. In practice, this means the power that can be expected from an engine may be only 75 to 80 percent of the rated power indicated in the specifications for a chosen speed. Selecting an engine based on nameplate output alone can mean purchasing a unit that will not be able to meet a task's power requirements.

Once the de-rated output for an engine has been calculated and matched to the pump's power requirement, an engine model can be chosen. In doing so, engine loading should also be taken into account. Remember that loading is a measure of the power required of an engine relative to the maximum de-rated power it is capable of delivering. Loading does not depend on the total volume of water pumped, but rather on flow rates and head—it is dependent on power, not energy.

For diesel pumping systems, loading is not a function of time, but it can have a significant effect on time-dependent variables associated with engine operation, such as fuel consumption and maintenance requirements and costs. Under most conditions, an engine should be overpowered by 20 to 30 percent (i.e., run at a loading of 70 to 80 percent). Normally, diesel engines are most fuel-efficient at these levels, and a margin of power is available to meet unusually heavy operating conditions, such as at start-up. Engines operated at lower loading levels run cooler. This decreases fuel efficiency and increases carbon buildup in the cylinder(s) and exhaust manifold, which increases service requirements.

Under-loaded engines—running at less than 50 percent of full-load conditions—are common in many situations in developing countries. The reasons include improper determination of head as well as poor engine and/or pump sizing and matching. Another explanation is that for the very low power demands encountered with some small-scale applications, it may not be possible to select an engine which is small enough and has a slow enough speed to permit proper loading (70 to 80 percent) due to the limited availability of small diesel engines and/or limited yield of the water source. The lower limit of diesel engines that are commonly available is about 2 kW. There are some engines as small as 1 kW, but they are uncommon. In such cases, alternatives to diesel engines should be considered.

5.4 Cost Considerations

Cost considerations include initial equipment and installation costs as well as recurrent costs for operation and preventive and corrective maintenance. The initial installed cost of a diesel pump set is significantly higher than the capital cost of the engine and pump. It also includes labor for the installation, transportation, and the cost of other equipment and materials including cement, fencing, a pump house, water meters, non-return and gate valves, and piping, among other items. Diesel engine costs vary considerably depending on the size and procurement source. In 1988 typical cost ranges were as follows:

- US$300 to US$600 per kW for units between 2 and 10 kW, with smaller engines being more expensive per kW and

- US$200 to US$500 per kW for units between 10 and 25 kW, with smaller engines again being more expensive per kW.

These figures do not include ancillary equipment, such as transmissions, gearboxes, and fuel storage tanks.

Recurrent operating costs include labor for a pump operator (if that individual is paid), fuel, lubricants, and consumables. The cost for a pumper typically falls at the lower end of rates for local skilled labor. In some cases, a pumper's duties can be combined with other related activities (e.g., serving as a caretaker or guard), thereby reducing the cost of employing a pumper. Careful consideration of the magnitude of pumper costs is recommended, as it can be one of the most important recurrent system costs (see Chapter 9).

The fuel and lubricant consumption of a diesel engine accounts for a significant portion of its operating costs. Lubricant use (including oil changes) should be in the range of 3 to 5 percent of fuel consumption by volume. As shown in Figure 11, fuel consumption is dependent on the engine's full rated power (specified by the manufacturer) and loading conditions. Full-load fuel consumption (FLFC) is often given by manufacturers in grams of fuel consumed per rated kWh (g/kWh) or some similar measure such as pounds of fuel consumed per brake horsepower-hour, as in the Lister curve in Figure 11. For small-scale applications, you would normally be interested in the fuel consumption of a specific engine in terms of liters per hour (l/hr). To convert to these units, the calculation is:

$$FLFC = g/kWh \times (.001/SG) \times kW$$

where FLFC = full-load fuel consumption in l/hr
g/kWh = fuel consumption in grams per kWh
SG = specific gravity of diesel fuel (usually 0.87)
kW = engine's rated full-load power output for a specific rpm (not de-rated)

For rough figures, actual fuel consumption can be estimated as the engine's FLFC in l/hr multiplied by the loading, which will be reasonably accurate down to a loading of 20 percent. Below 20 percent, fuel consumption does not decrease much. Note that engine de-rating does not affect this calculation.

Example 7: Engine Loading and Fuel Consumption

The diesel engine in Example 6 is coupled with a pump that is 60 percent efficient and delivers 36 m^3/day from 75 meters of head, running at a constant rpm over a 6-hour period. What is the engine loading and anticipated fuel consumption?

First, determine the power requirement for the load. From the formula for hydraulic energy (E_h) demand given in Section 3.1:

$$E_h = .00273 \times 36\ m^3/day \times 75\ m$$

$$E_h = 7.4\ kWh/day$$

The power (P) input to the pump is then:

$$P = 7.4\ kWh/6\ hours/60\ percent = 2.0\ kW$$

Since the de-rated power output of this engine (from Example 6) is 3.83 kW, the loading will be as follows:

$$loading = 2\ kW/3.83\ kW = 52\ percent$$

This is somewhat lower than desirable. Operating the engine at a lower speed would improve the loading.

From manufacturers' literature, the FLFC for a Lister STI is 240 g/kWh at 1,500 rpm or 1.24 l/hr, using the conversion formula given above. At a loading of 52 percent, actual fuel consumption can be expected to be 1.24 x 0.52 or about 0.64 l/hr. This figure will depend to some extent on the engine's condition, but it is a good approximation.

For a given engine, pump, and site conditions, fuel consumption per cubic meter of water pumped will depend on the loading. At a lower loading, the engine will consume more fuel per unit of water pumped. Using the same procedure given in Example 7, you could calculate the difference that loading makes in fuel consumption per unit of water pumped (using a more precise but complex relationship between fuel consumption and loading than that given above). For example, if you have a Lister ST-1 that is used to pump 30 m^3/day from 90 meters of head, you can vary the flow rate and, hence, the loading by changing the engine speed. Assuming that the head remains essentially constant, annual fuel consumption for the two different loadings would be 1,830 liters at a loading of 34 percent and 1,430 at 73 percent. This represents a savings in fuel and lubricant costs alone (per unit of water pumped) of over 22 percent, not to mention the reduction in maintenance costs associated with running the engine warmer and thereby reducing carbon buildup. An alternative approach is using a smaller engine at a higher loading. In that case, you would also save money on capital equipment costs, in addition to lower operating, maintenance, and (eventually) engine replacement costs. This example shows the importance of proper loading in the design of diesel pumping systems.

5.5 Service Requirements

Service requirements can be categorized as preventive, corrective, or curative. Preventive maintenance includes servicing that should be done on a routine basis to ensure efficient operation of the system. Corrective maintenance is required for occasional problems that may lead to engine or pump failure, but are not part of normal servicing. Curative maintenance is a response to a breakdown. Corrective and curative maintenance constitute unscheduled service.

Preventive maintenance implies that service is carried out on a routine basis, according to the number of hours of engine use or a timed schedule. In practice, servicing is often not performed regularly, so curative maintenance is required after the engine has broken down. This has obvious consequences for the reliability of the system and the lifetime of the equipment. Breakdowns occur for a wide variety of reasons, including poor installation, a lack of operator attention, and failure to provide regular service or poor-quality servicing. The underlying causes of breakdown frequency may be more complicated and can include a poor understanding of the system, lack of incentives for pumpers to perform well, and funding problems.

As a stand-alone mechanical system, a diesel engine requires an operator, regular servicing, and periodic repair. The pumper's skill and the quality and amount of servicing and repairs that are required are completely interdependent. An operator is responsible for day-to-day operation of the pumping system, including starting and stopping the engine, and replenishing the fuel. The pumper is also responsible for preventive maintenance, such as checking the oil and possibly changing it (as required), tightening loose nuts and bolts, and other minor tasks. Corrective maintenance is usually performed by a mechanic, whose tasks include decarbonizing the engine, cleaning injector nozzles, replacing worn belts, adjusting valve clearances, and changing the oil, air, and fuel filters. Checking the fuel-injection system and cooling system and replacing other worn components as necessary are also part of periodic service requirements.

The manufacturer's literature provided with the engine should indicate proper intervals for servicing (see Appendix C). To give a sense of the range of normal service requirements, oil changes are typically required after every 250 hours of engine operation and decarbonization after every 1,500 hours. The actual requirements for a particular system may vary with the operating environment, application, and mechanic's skill and training. For example, if the engine is operating at a low loading, the decarbonization interval should be shorter. Very often, because engines do not receive proper maintenance, the risk of breakdowns is increased, the overhaul interval is reduced (which increases costs), and the lifetime of the engine is shortened. Almost without exception, the routine maintenance aspect of the service infrastructure for diesel engines is the weakest.

Corrective maintenance, which is required when unanticipated problems occur, includes such activities as replacing worn belts or fuel-tank straps and decarbonization or engine overhauls, if these are not performed as part of scheduled preventive maintenance. Proper corrective servicing will eliminate the need for much curative maintenance.

The rate of breakdowns and unscheduled service is heavily dependent on the operator's attentiveness and the normal servicing the engine receives. Routine preventive maintenance, such as changing the engine oil and replacing filters, is one of the most important factors in minimizing repair costs. However, having at least one breakdown per year (and possibly more) that requires curative maintenance is fairly typical, depending on the engine's age and condition and the quality of service it has received.

The cost of unscheduled servicing is highly variable. Estimates of service and maintenance costs, not including fuel and labor, are likely to be in the range of US$0.15 to US$0.25 per cubic meter of water delivered. This figure may be higher or lower depending on labor costs, the operator's skill, and the quality of the equipment, among other factors. Another way of looking at this is that typical annual O&M costs, not including expenses for fuel and operator labor, range between 25 and 75 percent of the engine's initial cost or 5 to 15 percent of the system's installed capital cost (which includes not only the engine, but also the pump, the concrete pad, the transmission, and other items).

5.6 Equipment Life

The service life of any device depends on the conditions under which it is used, which includes installation and maintenance. Under optimum conditions, an engine should be replaced when the cost of maintaining it exceeds the cost of purchasing a new one. However, users' perceptions of engine life also play a role. If users anticipate getting five years of service, a new engine may be purchased at five years even though the old one is still functional. Light, high-speed engines are likely to have shorter lifetimes than heavy, slow-speed models. The best way to estimate values for equipment lifetimes in your situation is to ask other engine users, local equipment dealers, and operators of repair shops about the makes and models you are interested in.

Usually, the lifetime of an engine is given informally in years. The normal range is two to three years for lower quality, heavily used, and/or poorly maintained engines to 20 years or more for higher quality systems that are reasonably well maintained and overhauled at regular intervals. Lifetime hours of operation vary from under 5,000 to over 50,000 hours. About 20,000 hours is a reasonable approximation for planning and costing purposes. A complete list of diesel maintenance needs and a recommended schedule for meeting those needs are given in Appendix C.

Chapter 6

SOLAR PHOTOVOLTAIC PUMPS

r PV cells are used to convert sunlight directly into electricity. While power can be used for a variety of end-use applications (e.g., communications, lighting, and refrigeration at health clinics), it is ming increasingly popular for water pumping in remote areas As of mid-1988, s estimated that between 5,000 and 10,000 solar pumps have been installed nd the world. Successes in PV research and development have significantly ced costs and increased the reliability of this power source, which has orically been very expensive. Multiple cells (30 to 50) are mounted on a le unit (about 0.3 by 1.2 meters) called a module. The individual modules wired together in groups to form arrays. While the PV arrays themselves are ptionally reliable power sources, the primary limitation on the use of solar s has been and continues to be the high initial capital cost of a system. , since water output is directly proportional to the level of solar diation falling on the modules, relatively high and uniform solar irradiation occur at your site for solar pumps to be a cost-effective pumping option.

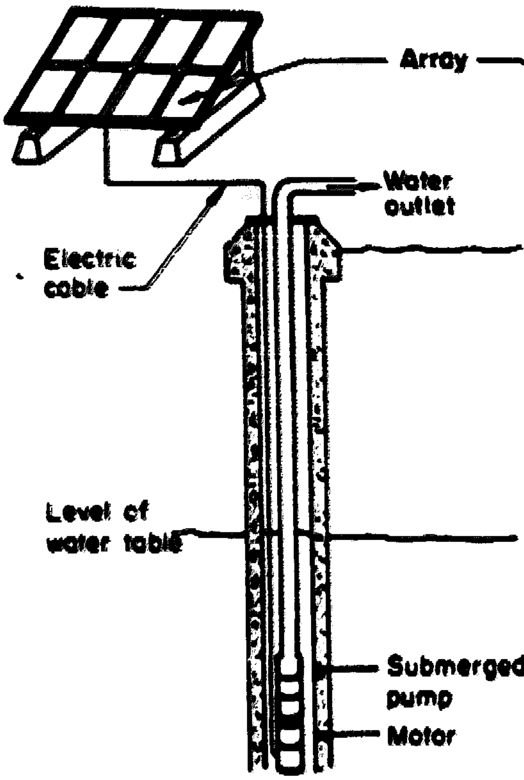
r pumps have been used in field applications for about 10 years. Some early ls were plagued by design and manufacturing problems. Considerable gains ncreasing system efficiency and reliability and reducing production costs lowered the cost per unit of water delivered. Still, solar pumps remain ly expensive compared to other pumps, although they do have the potential eing cost-effective pumping alternatives under certain circumstances. This ion describes typical system components as well as the design, operation, tenance, and repair requirements of solar pumps.

System Description

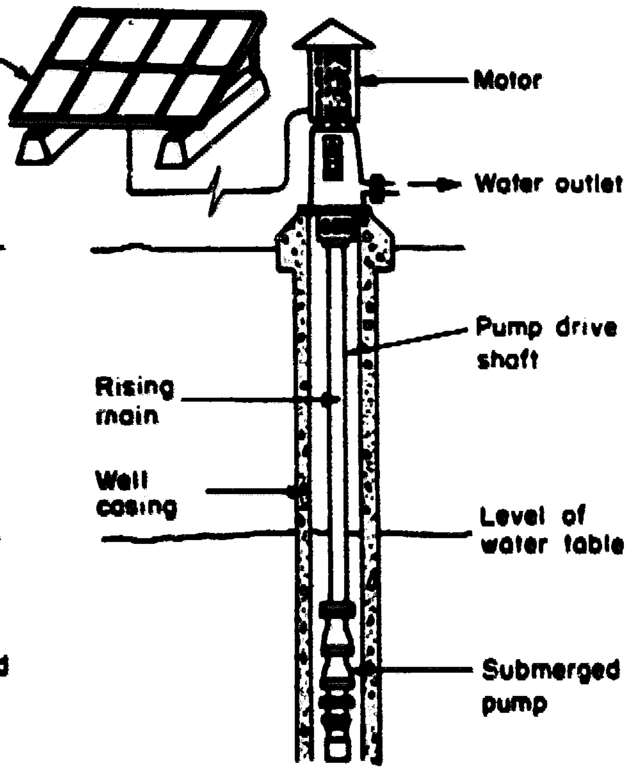
V pumps become more popular, an increasing variety of designs is becoming lable that differ in cost, application, capacity, and reliability. This ion describes the most common kinds of solar pumping systems and several s of optional components. The focus is on systems that have been field-ed in evaluation programs in countries such as Botswana, Mali, Malaysia, and ı.

most basic PV pumping system consists of an electrical power source (i.e., array), a motor, and a pump. The electrical output from the array is rered to the motor, which drives the pump. Many variations of this simplest of system use different optional components. More complex designs are rily intended to increase the efficiency or reliability of the water supply, re water can be pumped with a PV array of the same size. Schematic drawings everal typical solar pumping systems (submersibles, vertical turbines, ting suction, and centrifugal suction pumps) are shown in Figure 12.

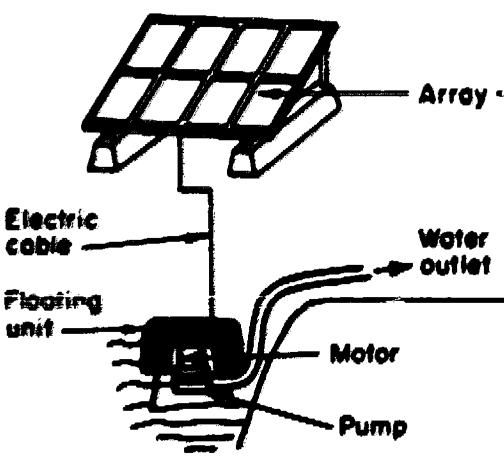
Figure 12. Typical Solar Pump Designs



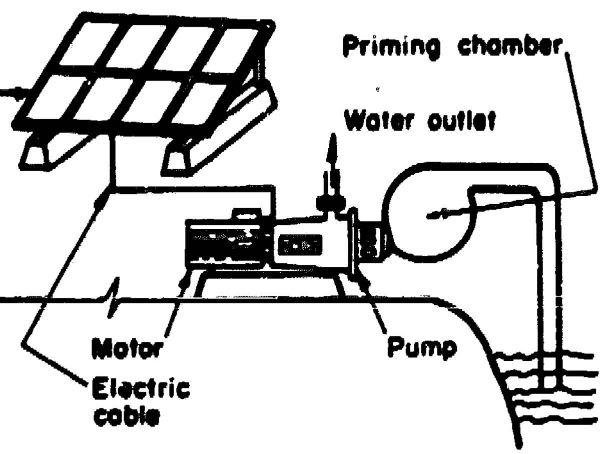
Submersible Unit



Vertical Turbine
(shaft-driven centrifugal)



Floating Suction Unit



Centrifugal Suction Unit

(Kenna and Gillett 1985)

6.1.1 The Power Source

PV modules produce a certain current and voltage under specified sunlight conditions. While several types of PV cells are commonly used (e.g., single crystal, semicrystalline, and amorphous), nearly any power module can be employed in a pumping system. Motors used in solar pumping systems have specific electrical operating characteristics chosen to match those of the array. This increases the overall system efficiency, so more water is delivered per dollar invested in the system. The matching of motors and arrays no longer presents significant problems with equipment standardization among different manufacturers' equipment, since most currently available PV modules have similar electrical output.

Arrays can be wired to produce a wide range of electrical output. Modules are connected in series (i.e., with the terminals minus to plus and plus to minus) to increase voltage and, hence, motor speed at a constant current. Wiring modules in parallel (with terminals minus to minus and plus to plus) increases the current output and motor torque at a constant voltage. Motors are designed to operate most efficiently at a certain current and voltage, so care must be taken to select a motor with electrical input requirements that match array output in order to get the best performance from the system. Similarly, the motor output must match the operating characteristics of the pump in order to use power efficiently. Equipment buyers usually need not match these components themselves, as this is normally already taken care of by PV module and pump manufacturers and system designers. However, because of the importance to proper system operation of correctly matching these components, the procedures necessary to do this have been included in this manual. This will allow you to confirm the specifications given by equipment suppliers.

Equipment distributors will specify the array size and configuration (i.e., wiring arrangement for a specific current and voltage combination) needed to pump a certain quantity of water from a given head, based on manufacturer's recommendations. Array sizes are given in term of peak watts (W_p). This is an indicator of the array's expected power output under peak operating conditions, which are defined as 1 kW/m^2 solar irradiation on the array and an operating temperature of 25° Centigrade. Typical power modules are rated at 40 to 60 W_p. The output of PV modules varies depending on the operating temperature and level of solar irradiance—i.e., the solar energy per unit of area in watts per square meter (W/m^2). The higher the solar irradiance level on a PV cell, the higher the power output is; the higher the operating temperature, which depends on the ambient air temperature, the lower the output.

PV pumping system designs can be varied by adding one or more of the following components:

- Controllers. Their functions include regulating current and/or voltage from the array and to the motor, shutting down the motor for various safety reasons, and controlling the system by means of a float switch that turns the motor off when the storage tank is filled/

- **Inverters.** They change the array's electrical output from DC to AC.

- **Power-point trackers.** These convert sunlight into electricity more efficiently.

- **Batteries.** They provide a constant voltage to the motor and store energy, so the system can pump water even when the array is unable to deliver enough power directly.

- **Sun-tracking devices.** These move the array so it is directly perpendicular to the sun, thereby intercepting more radiation and increasing the power output.

Several types of controllers are used with PV pumps, including inverters, power-point trackers, and battery-charge controllers. The PV array produces DC electricity. Some solar pump motors operate directly on DC, others require AC. An inverter is used to convert DC power from an array into AC power for the pump motor. An inverter can also act as a controller to shut down the motor before overloading or overheating occurs and can help the motor and array operate efficiently in other ways.

Solar cell operating characteristics depicted as current-voltage (I/V) curves are shown in Figure 13. They show a certain current and voltage output for the module under various irradiance (i.e., solar irradiation) levels. There is a particular point on an array's operating curve at which it produces maximum power—the maximum power point. A type of controlling device called a maximum power-point tracker (MPPT) forces the array and motor to operate at or near this point. For example, at an irradiance of 1,000 W/m^2, the module shown has a maximum power point at 16 volts and 3 amps. An MPPT does not make a PV array physically track the sun, but some use devices that tilt the array so it is perpendicular to the sun's rays, thus producing more power. Using an MPPT makes a system more complex and adds to the cost, but under certain circumstances, it can be a cost-effective means for producing additional power from an array.
Batteries are sometimes used with PV systems as storage devices and/or controllers. Solar irradiation is intermittent due to variable cloudy conditions and the sun's movement across the sky during the day. Batteries store electrical energy from the array, which can then be used by the motor to drive the pump when irradiation is inadequate to drive the system directly. In addition, batteries can serve as controllers to provide constant voltage to the motor, so it operates at a more constant and higher average efficiency. Batteries have disadvantages that should be considered in the system design process. These include additional capital costs, higher maintenance requirements, and periodic replacement costs.

Several kinds of sun trackers can be used to move an array so that it is perpendicular to the sun's rays. These vary considerably in terms of complexity, reliability, and cost. Under certain conditions, array trackers have been shown to produce increases in array output of up to 40 percent over the course of a day. This net gain must be weighed against the increased complexity and cost of these devices.

Figure 13. PV Module Operating Characteristics

Power Specifications*

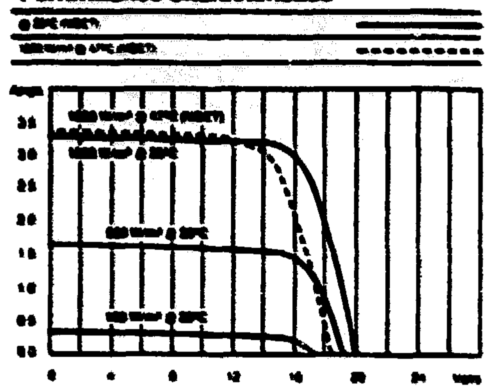
Model	M75
Power (typical ± 10%)	47.0 Watts
Current (typical at load)	2.94 Amps
Voltage (typical at load)	16.0 Volts
Short Circuit Current (typical)	3.27 Amps
Open Circuit Voltage (typical)	19.9 Volts

Physical Characteristics

Length	48 in/1219 mm
Width	13 in/330 mm
Depth	1.4 in/36 mm
Weight	11.6 lb/5.2 kg

*Power specifications are at standard test conditions of: 1000 W/m², 25°C cell temperature and spectrum of 1.5 air mass.

Performance Characteristics



The IV curve (current vs. voltage) above demonstrates typical power response to various light levels at 25°C cell temperature, and at the NOCT (Normal Cell Operating Temperature), 47°C.

(ARCO Solar, Inc., manufacturer's literature)

Particularly in areas where well yields are low and drawdowns high or where water tables vary considerably due to drought or unusually heavy use, safety devices such as low-water cut-out switches and motor overheating/overloading protection should be included in a pumping system. Some commercial PV pumps are already equipped with these safety devices, but you should request that they be included in any quotation on the price of a system. PV systems should also be properly grounded to protect them from lightning--this inexpensive safety measure should never be overlooked.

All of the controlling and storage mechanisms briefly described here have advantages and disadvantages in terms of their complexity of operation and repair, their effects on system efficiency, and their costs. The emphasis in pump design and component selection should be on trying to achieve long-term reliability, rather than the highest possible system efficiency. Reliability has often been shown to be a strong function of a system's design simplicity.

6.1.2 The Motors

Several types of motors are used in solar pumping systems, including DC motors with or without replaceable brushes and AC motors with inverters. DC motors normally use brushes to carry current. These have to be replaced occasionally when they are worn down. This poses no problem for surface-mounted motors that are easily accessible for maintenance (assuming that the replacement brushes are locally available), but for submersible pumps, where the motor and pump are mounted underwater as an integral unit, changing the brushes requires that the whole pump and drop pipe be pulled from the borehole or other water source--a major operation. Recently, some manufacturers (e.g., A.Y. MacDonald in the United States) have developed brushless DC motors for use with submersible pumps. This innovation will reduce recurrent costs for periodic maintenance of submersible pumps, since the brushes will not have to be replaced on these units.

6.1.3 The Pumps

The most typical kind of pumps used in PV systems are listed below. Their operating characteristics, typical applications, advantages, and disadvantages were discussed in Chapter 4. These pumps are listed again here with the names of some well-known suppliers:

- self-priming centrifugal--AEG, A.Y. MacDonald, and SEI;
- submersible centrifugal--Grundfos, A.Y. MacDonald, Warns, AEG, Solar Voltaics, Totale and Franklin; and
- positive-displacement, reciprocating-piston (jack)--Chronar/Tri-Solar, Lamb, Ergo, and Solamotor.

Less common types include:

- positive-displacement, rotary--Mono, and Robbins Meyers/Moyno;
- jet--A.Y. MacDonald; and
- vertical or deep-well turbine--Chronar/Tri-Solar, Guinard.

In general, PV systems that require high flows for low heads (e.g., for micro-irrigation) use surface-mounted, self-priming centrifugal pumps because of their high capacity, reliability, and ease of maintenance. Submersible units (which are by far the most common), positive-displacement pumps (piston and rotary) and vertical turbines are used for deeper wells and boreholes. Piston pumps are typically high-head, low-flow units. Jet pumps are used for moderate head and flow applications, but are not common.

6.2 Operating Characteristics

The amount of water output for a PV pump depends on the intensity of solar irradiation falling on the PV modules, the total pumping head, and the operating temperature of the array. Higher irradiation levels produce greater electrical output and, consequently, more water. As is true for all pumping systems, the greater the pumping head, the lower the water output for a given level of power input. An array's electrical output and a pump's water output drop off as the operating temperature increases—thus, PV pumps are more efficient in cooler climates.

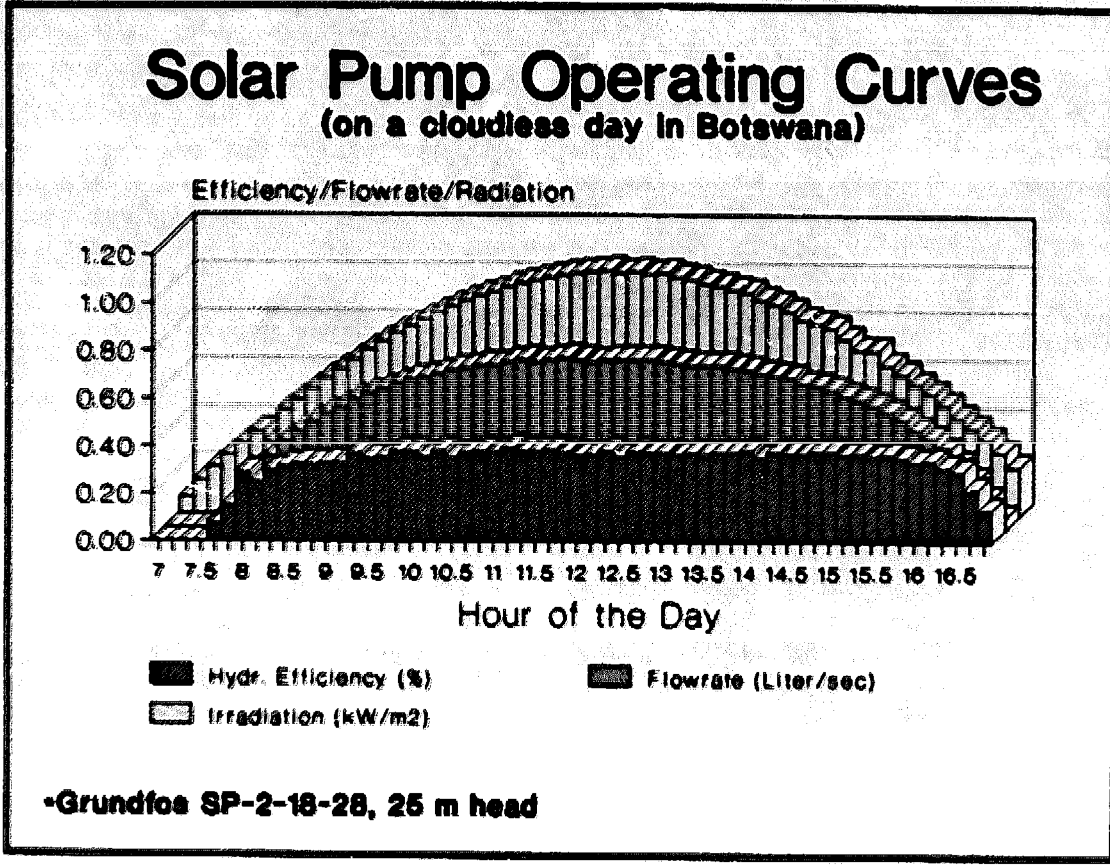
Solar irradiation varies in several ways:

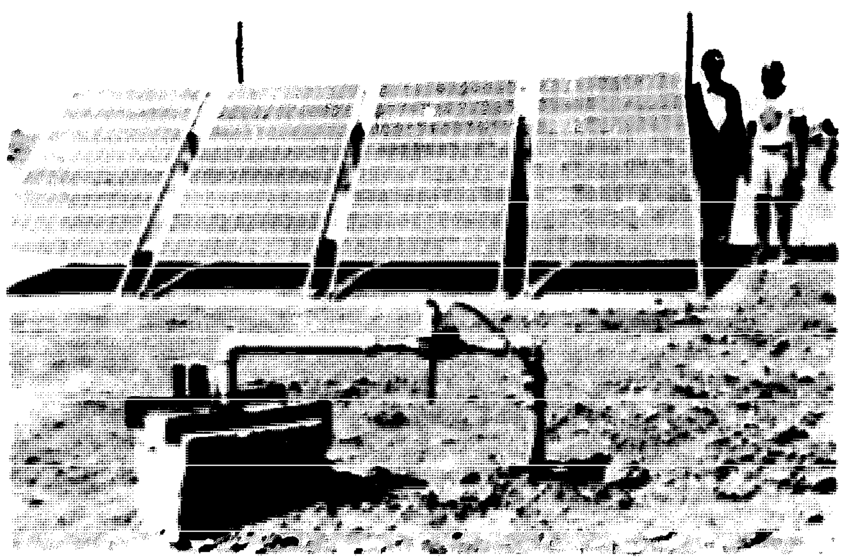
- daily—as the sun rises and sets and as short-term weather patterns cause cloudy or partially cloudy conditions;
- seasonally—as varying long-term weather patterns occur over the year (e.g., monsoons or dry seasons) and as the angle of declination changes (i.e., the angle between the sun's rays and a horizontal surface on the earth), which is reflected in the sun's lower position in the winter sky and higher position in the summer;
- annually—as weather patterns associated with drought conditions, clouds, air pollution, and monsoons vary; and
- geographically—as a function of latitude and microclimatic weather conditions (e.g., local ground fog and dust storms) at the site.

Cloudiness reduces solar irradiation on the array, sometimes to the point where no water can be pumped unless the system has a battery bank for electrical storage. Solar irradiation varies depending on annual variations in weather (such as drought conditions in Sahelian Africa) as well as on seasonal changes such as monsoons (which in some places like India and Malaysia can obscure nearly all usable solar irradiation for up to several months each year).

A typical operating day for a solar pump is depicted graphically in Figure 14, which shows actual measured data for a solar pump on an average sunny day in Botswana. The graph indicates the hydraulic or subsystem efficiency (also sometimes called "wire-to-water" efficiency, but always the ratio of hydraulic energy out of the subsystem divided by electrical energy into the subsystem), the flow rate in l/s, and the solar irradiation intensity in W/m^2. The figure shows how the pump does not turn on immediately in the morning, but only when the cut-in or threshold irradiation level is reached. This is the minimum level of irradiation at which the array produces enough current to overcome the starting torque of the pump and motor starting. It varies with the system and site. A similar system is shown in Photograph 4.

Figure 14





4. Grundfos Submersible Solar Pump for Village Water Supply in Botswana

For poorly designed systems, the cut-in irradiation level may be so high that the pump runs for only a short period during the day or may not turn on at all. By using certain types of controllers (e.g., MPPTs), the system's cut-in irradiation level can be lowered so it operates for a longer period each day. Similarly, for days with low irradiation (for example, a very cloudy day), even a well designed system may never reach its cut-in irradiation level and, hence, will not operate that day.

After the cut-in level is reached, the pump turns on and the flow rate increases until around noon when the sun is at its highest point in the sky. Thereafter, solar irradiation and, consequently, pump output decrease until the cut-out irradiation level is reached in late afternoon and the pump stops. The system's hydraulic efficiency increases early in the day until the unit is in its normal operating range, levels off, and then drops off again in the late afternoon.

Because of the variability in solar irradiation and the consequent variability of pump output over a given period, solar pumps (like wind pumps) require some type of storage system so that water is always available to users. For PV pumps, energy can be stored either electrically (using batteries) or hydraulically (water in a storage tank). Considerable debate has taken place on battery versus water storage, as well as on the amount of each required for any given installation. A general rule of thumb is that systems should be designed with three days of storage. What type of storage depends upon several factors, primarily the respective local cost and availability of storage tanks and batteries, and secondarily the likelihood that the batteries will be properly maintained. Storage tanks require considerably less active maintenance than batteries, and so are less likely to fail over the long run. Batteries in PV pumping systems are not normally serviced properly and thus must be frequently replaced at great expense.

One of the best features of solar pumps is that their normal operating requirements are minimal compared to most other types of systems. A solar pumping system usually operates completely automatically, so pump operators are not strictly required as they are with diesel engines, for example. Nor do solar pumps require fuel.

6.3 Choosing a Solar Pump

Sizing methods for solar pumping systems range from very simple to highly complex. This section covers simpler methods first and then more accurate ones.

6.3.1 A Simple Method of Solar System Sizing

The simplest method of solar sizing calculates the power required, given the estimated head and flow rate requirements. Subsystem efficiency is the ratio of energy out of a system (i.e., water flow for a given head) divided by energy put into the system (electrical energy output from the array). Using a typical estimated subsystem efficiency of 25 to 35 percent, array size can be calculated.

(Note: manufacturers' literature usually quotes this efficiency as measured under ideal conditions, as high as 50 to 60 percent. Our field measurements of subsystem efficiency of many installed solar pumps, including motor, pump and controller, have never been more than 40 percent.)

The actual power required to pump water is defined as

$$P_{req} = (9.81 \times h \times Q)/Eff_{sub}$$

where P_{req} = power required in watts
9.81 = gravitational constant
h = total pumping head in meters
Q = flow rate in liters per second
Eff_{sub} = subsystem efficiency of 0.25 to 0.35

Example 8: Power Requirements

To pump one liter per second (l/s) with 28 meters of head for a system with a subsystem efficiency of 30 percent, what is the electrical output needed from an array?

$$P_{req} = (9.8 \times 28 \times 1)/0.30 = 915 \text{ watts}$$

If a pump set ran for two hours at that rate, energy consumption would be 915 watts multiplied by two hours, which is 1,830 watt-hours or 1.83 kWh. This is the hydraulic energy demand, which was discussed in Chapter 3. The next step is to determine the size of array in W_p that could supply that 915 watts of power under peak solar irradiation conditions.

Example 9: Rough Array Sizing

For the system in Example 8, assume that ARCO Solar M-53 modules are going to be used in the array. Each typically produces about 2.2 amps of current at 15 volts when driving a pump under 1,000 W/m^2 of solar irradiation. The required motor voltage is 105 volts. How should the array be wired, and how many modules should be used?

Since wiring modules in a series increases voltage, the motor voltage of 105 is divided by the module voltage of 15, so seven modules must be wired in series to produce the required voltage. Together, those seven modules have an output of 105 volts multiplied by 2.2 amps, or 231 watts. The required number of series strings of seven modules each is thus the system's overall power requirement (915 watts) divided by the output of each series string (231 watts) or four strings of seven modules, for a total of 28 modules.

This rough calculation assumes a solar irradiation level of 1,000 W/m^2 or 1 kW/m^2. Solar irradiation data are often given in terms of kWh per square meter per day or kWh/m^{2}d. In the simplest method of system sizing, if your site has a daily solar irradiation level of 6 kWh/m^{2}d, the pump in Example 9 would produce the same water output over the course of an entire day as if it were running for 6 hours at a constant flow rate equal to the total volume of water pumped during the day divided by the total daily solar irradiation or about

$$6 \text{ hrs/day} \times 1 \text{ l/s} \times 3{,}600 \text{ sec/hour} = 21{,}600 \text{ l/day} = 21.6 \text{ m}^3\text{/day}$$

This rough method of system sizing oversimplifies the real situation in several ways:

- The level of solar irradiation actually varies continually over the course of a day--starting at zero, irradiation increases to its maximum about noon and then drops off to zero again after sunset.

- System efficiency varies with irradiation level and temperature--efficiency improves as irradiation increases (up to a point, again see Figure 14) but drops as the temperature rises in the afternoon.

- It is assumed that all of the 6 kWh/m^{2}d can be used by the system--in fact, for systems without batteries, irradiation below the cut-in level is wasted because the pump is not running.

6.3.2 A More Accurate Sizing Method

A somewhat more accurate way of estimating the size of the solar array needed to pump a given amount of water is to use the following formula:

$$\text{array size in } W_p = \frac{9.81 \times h \times Q}{H_t \times 3.6 \times F_m \times F_T \times Eff_{sub}}$$

where W_p = peak watts
9.81 = gravitational constant
h = total pumping head in meters
Q = water output in m^3/day
H_t = global solar irradiation in the array plane (kWh/m^2d)
3.6 = conversion factor (kWh to MJ)
Fm = array/load matching factor, 0.9 for centrifugal pumps, 0.8 for others
FT = de-rating factor for operating temperature of array output cells (0.8 for warm climates and 0.9 for cool)
Eff_{sub} = subsystem efficiency

This formula better approximates the actual operation of a solar pump, except that it does not take into account the cut-in and cut-out radiation levels mentioned above, below which the pump will not operate in the early morning and late afternoon. However, these are relatively small errors which tend to overestimate the daily output by 5 percent or so.

Virtually every variable except array size and the gravitational constant changes with the time of day and the season. The array/load matching factor is a measure of the electrical impedance mismatch between a PV array and the subsystem load (i.e., the subsystem controller or pump motor in a direct-coupled system). Simple computer programs are available that can be used to estimate quickly the water output using this formula, including cut-in irradiation levels to reflect the fact that the pump is not operating in the early morning and late afternoon (McGowan and Hodgkin 1985).

Example 10: More Accurate Array Sizing

Use the more accurate formula given above to calculate the size of the array needed to pump 20 m^3/day from 28 meters of head, using the equipment described in Examples 8 and 9.

$$\text{Array Size in } W_p = \frac{9.81 \times 28 \times 20}{6 \times 3.6 \times 0.9 \times 0.8 \times 0.30} = 1,177\ W_p$$

where gravitational constant = 9.81
h (pumping head) = 28 meters
water output = 22 m^3/day
solar irradiation = 6 kWh/m^2d)
conversion factor (kWh to MJ) = 3.6
F_m = 0.9
F_t = 0.8
Eff_{sub} = .30

A 28-module array (one module = 43 W_p) would be adequate here.

In order to give you a better feel for PV system sizing, Table 2 shows the array size needed to pump a given amount of water (10 to 30 m^3/day) at a given head (10 to 60 meters) for three different irradiation levels. The array sizes were computed using the formula above for more accurate array sizing.

Table 2

Sample Solar Pump Sizing Table

Array Size (Watts Peak) to Pump Given Volume at Given Head
(Subsystem efficiency = 30%, and irradiation of 4, 5, and 6 kWh/m²d)

	Water Demand (cubic meters per day)								
	10			20			30		
	Solar Irradiation (kWh/m²d)								
Head (m)	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0
10	315	252	210	631	505	421	946	757	631
20	631	505	421	1,262	1,009	841	1,892	1,514	1,262
30	946	727	631	1,892	1,514	1,262	2,839	2,271	1,892
40	1,262	1,009	841	2,523	2,019	1,682	3,785	3,028	2,523
50	1,577	1,262	1,051	3,154	2,523	2,103	4,731	3,785	3,154
60	1,892	1,514	1,262	3,785	3,028	2,523	5,677	4,542	3,785

For example, to pump 20 cubic meters per day at 30 meters head given a 30 percent subsystem efficiency, if your solar irradiation level is 6.0 kWh/m²d, then you would need a 1,262 watt peak array.

6.3.3 Using Data on Irradiation Conditions

To design a cost-effective system properly, historical data on local solar irradiation conditions should be used, where available. Unfortunately, such information is seldom collected in many areas of most developing countries. Thus, estimates of monthly irradiation levels over the year must be used. Possible sources of local irradiation data (e.g., meteorological data and PV manufacturers' world or area maps) are discussed in Chapter 2. The average daily irradiation level used in array sizing should be based on the design month. The concept of design month for solar pumps is similar to that for windmills--it is the month in which it will be most difficult to meet the water requirement at the site given the available solar energy.

When drawing up bid documents for solar pumps, specify the water requirement as a certain average daily amount from a given head, and supply whatever local irradiation data are available. When reviewing dealers' quotes, use the example given above to check that the systems being proposed are reasonably sized to meet the water demand at the site. Bidders' estimates of water output should be within 15 percent of your calculations from the method described here. Otherwise, the system being proposed will probably be improperly sized to meet your requirements.

The following example illustrates the complete procedure for sizing a solar pump and its components.

Example 11: Detailed Solar Pump System Selection

A solar pump is being considered for use at a village site in rural Sudan, where an elevated tank (5 meters high) stores water pumped from a nearby borehole. The distance from the borehole to the storage tank in the village is 250 meters. The borehole currently has a 4-inch diameter casing. It has been test-pumped for 72 hours by a local drilling contractor, and a yield of 5 m^3/h was measured. The depth from the top of the borehole to the water surface during the test-pumping was 13 meters. Irradiation on a solar array during the design month would be 6 kWh/m^2d (or 21.6 MJ/m^2d). The village currently has 680 people, and the sheikh has determined that the population increases by about 2 percent annually. Currently, people use about 30 liters each per day, but the availability of diesel fuel has been so irregular and its price has been increasing so rapidly that the community has begun to consider buying a solar pump. What type of solar pumping system is appropriate?

<u>First, determine water demand</u>. The current population of 680 is growing at 2 percent per year (F_{PG}). The system should be sized to provide an adequate supply of water over its entire useful life (N), which is expected to be 20 years (some components will have to be replaced as not all of the equipment will last this long). From the formula given in Section 2.1.2, the demand in year 20 will be

$$\begin{aligned} \text{future demand} &= (\text{current demand}) \times (1 + F_{PG})^{(N-1)} \\ &= (680 \text{ people} \times 30 \text{ l/day}) \times (1 + .02)^{(20-1)} \\ &= 30 \text{ m}^3\text{/day} \end{aligned}$$

<u>Second, determine total pumping head</u>. Begin by calculating friction losses. Assume that the maximum pumping rate can be estimated by considering that the 30 m^3/day output requirement will be pumped over 6 "peak sun-hours" (6 kWh/m^2d), so the peak flow rate will be

$$(30 \text{ m}^3\text{/day})/(6 \text{ peak sun-hours/day}) = 5 \text{ m}^3\text{/h} = 1.4 \text{ l/sec}$$

Assume that a 60-millimeter galvanized iron pipe will be used down the borehole and that the pump will be set 5 meters below the dynamic water level. The total length of piping in meters will be

13 (borehole) + 250 (pipe run) + 5 (pump set) + 5 (tank) = 273 meters

Example 11: Detailed Solar Pump System Selection (continued)

From Figure 3 (in Chapter 2) and the tables in Appendix B, the friction loss under these conditions--273 meters of 60-mm galvanized steel pipe with negligible losses due to bends and valves--is 2.2 meters. The total pumping head would then include the dynamic head of 13 meters, the discharge head to the elevated unpressurized tank of 5 meters, and friction losses in the pipes of 2.2 meters for a total of 20.2 meters.

Note that the 2.2-meter friction loss is somewhat greater than 10 percent of the total head. Therefore, you should use slightly larger pipe to reduce the friction loss (thereby reducing the amount of energy required to pump your water). With 100-millimeter pipe, the friction loss is 1 meter. The total head is then 18 + 1 = 19 meters.

Third, determine the array size needed. Following exactly the same procedure as given in Example 10 and using a subsystem efficiency of 32 percent, which is typical of Grundfos submersibles available in Khartoum, and a water demand 30 m^3/d for 19 meters of head, you can compute the array size needed:

$$\text{array size in } W_p = \frac{9.81 \times 19 \times 30}{6 \times 3.6 \times 0.9 \times 0.8 \times 0.32} = 1{,}124\ W_p$$

This figure is the minimum array size in W_p that can meet your water requirement. However, other requirements must be taken into account. The Grundfos submersible you are looking at runs at 105 volts. You are considering using Solarex modules, specifically the MSX-53 version that a dealer in Khartoum has given you a quote on. These 56 W_p modules have a typical operating voltage of 15 volts. This means you will have to wire 105/15 or seven modules in series to get the right voltage.

To find the total number of modules, the last step, divide 1,124 W_p by 56 W_p per module or about 21 modules (rounding up to the nearest multiple of seven). Your array would then be wired as three parallel sets of seven modules each. This system size should match the one described in the dealer's quote. To select the individual pump set, review the pump curves for the types of submersibles the dealer carries, and pick the unit that operates most efficiently at the head for your site (19 meters). Your system sizing is now complete.

6.4 Cost Considerations

Solar pump costs depend primarily on two components—the array size and the pumping unit. Solar module costs usually make up 60 to 85 percent of the total system cost and are usually quoted in terms of dollars per W_p or US\$/W_p. In 1983, module costs were about US\$10/W_p, shipped from the country of manufacture. In 1988, they were being quoted as low as US\$4/W_p to US\$5/W_p. These prices usually do not include freight and insurance charges to ship to developing countries, which can easily add 50 percent or more to the price. For example, in 1988 modules with a U.S. price of \$5/W_p were quoted in Botswana for \$8/W_p. Pump sets (i.e., a pump and motor) designed for use with PV systems range in price from US\$1,000 to US\$3,000 (FOB the manufacturer), with the units rated for lower power output costing less and often used at lower heads (e.g., surface-mounted centrifugal and jet pumps). Units with higher power output for deeper wells run from US\$2,000 to US\$3,000. Submersible AC pumps are generally the most expensive because in addition to the pump and motor, they must have an inverter to convert DC power to AC. Often, the higher cost of these units is more than offset by greater reliability and, consequently, lower recurrent costs.

Other costs associated with solar pumping systems include the array mounting structure, wiring, other types of controllers, water meters, civil works (e.g., a concrete pad for the array and piping), and storage tanks. These costs can vary considerably depending on whether the equipment and/or materials are made locally or imported. Check with local dealers for estimates of these costs.

6.5 Operation, Maintenance, and Repair

Normal operating procedures for PV pumps usually require minimal user interaction, but this does not mean they require no attendance whatsoever. Dust should be washed from the collector array, as required (i.e., when it is obviously coating the modules), and for surface-mounted motors, belt tightness and any overheating of the motor or transmission should be noted. If float switches are used in the system's storage tank, they should be checked periodically for proper operation. Water output should be recorded by reading the flow meter on a daily basis. This will permit a more rapid diagnosis of any problems occurring with the system.

One person should be assigned the responsibility of monitoring pump operation, recording water-use data, and determining the nature and extent of any breakdowns that occur. This individual could be trained to deal with simple repairs, such as loose or broken wires. He or she should also know exactly how to call for a repair crew if repairs are required. Because of the complexity of most of the components in PV pumping systems, it is much more likely that the first response to breakdowns will be to replace a component rather than to make an on-site repair.

In many circumstances, particularly at unattended or remote sites, vandals may break the modules or rip out the wires. Qualified personnel performing periodic maintenance should also check for natural degradation, such as corroded terminals and worn insulation. The equipment should definitely be fenced in to protect it from children and animals and to protect them from electric shock. Animals can easily shut down an unprotected system by scratching on the array's mounting supports and knocking them over or chewing through the insulation on wiring and short-circuiting the system. Representatives from user groups should be chosen and charged with notifying repair crews promptly so that any necessary repairs can be accomplished quickly to minimize downtime.

PV pumps require little maintenance during most of their useful lives. However, like any other piece of equipment, they do require periodic care. The type of maintenance depends on the type of system. DC motors require periodic brush replacement unless they are brushless. Pump seals fail and must be replaced occasionally. Belt-driven pumps must have the belts tightened and eventually replaced. For piston pumps, the cylinder cup leathers must be replaced about every 12 to 24 months.

Maintenance problems will be worse when systems are installed on low-yield wells, in water sources that have wide fluctuations in water level, or where the water quality is marginal. If low-water or overheating cut-off switches are not used, down-hole equipment, including pumps and motors, can be destroyed when water levels drop below the depth of the pump installation. Under very low-flow conditions where the pump continues to operate, an insufficient flow of water past a submersible pump may not provide sufficient cooling and may result in damage to the pump.

Under typical conditions for properly designed systems, monthly or bimonthly maintenance will consist of visually inspecting electrical connections, tightening nuts and bolts, cleaning the array, checking the array electrically on a quarterly basis to make sure it is working properly, and checking the battery bank, if there is one. This entire process should take no more than one to two hours of a mechanic's time, not including any travel that may be required.

Most problems in PV pumping systems occur with components other than the array. Unless they are vandalized, modules very seldom fail. If they are severely damaged, they may have to be replaced, at great expense (US$250 to US$350 each). It is much more cost-effective to educate users about the importance of teaching children and others not to damage the water supply system.

Most problems occur with the pump, motor, and controller. Generally, the design philosophy behind solar pumps has been to manufacture components that will be replaced rather than repaired, at least for most situations in developing countries. Dealer representatives (who are usually assigned only to developing countries with large numbers of solar pumps) for U.S. or European PV pump manufacturers often carry spare parts for pumps (e.g., impellers and seals) or will replace the unit if it is under warranty.

Motors are more problematic. Depending on the level of technical skills in your area, the rewinding of electric motors can be performed locally. Local mechanics or mechanically inclined users can easily replace the brushes, if the motor is easily accessible. Local mechanics can also replace pump or motor seals, assuming that similar types of equipment are used locally (e.g., grid-electric submersible pump sets). With the exception of brush replacement, most procedures should be carried out in a clean electrical shop in the nearest large town, not in the field.

Of course, appropriate spare parts must be available. If not, considerable time and effort may be required to find the necessary parts locally or to have them shipped from the manufacturer. The importance of a complete spare parts inventory cannot be overemphasized. The biggest problem in system maintenance and repair is the time it takes to address the problem from abroad. When choosing a supplier, remember the importance of local dealers who maintain supplies of spare parts and can fix or are willing to replace failed or defective equipment.

There is little, if any, local manufacture of PV pumping equipment in developing countries. Battery-charge controllers are made in some developing countries, and the number of Spire Corporation's turnkey PV cell and module assembly plants in the developing world is slowly increasing. Given the highly automated and sophisticated manufacturing techniques that are typically used to make PV equipment, all of it will probably be imported. In many countries, there are simply no local dealers. In those with local dealers, their knowledge of the product and proper system design procedures may be minimal, so potential customers must either have access to design guidelines (such as this manual) or look elsewhere for equipment. If this is the case in your area, you might reconsider the possibility of using systems that are already available locally. In other countries, knowledgeable, well-equipped dealerships can provide accurate system design, prompt procurement from existing inventories or as a result of good relations with manufacturers, and trained crews for installation and user training. At present, this type of situation is the exception rather than the rule.

6.6 Equipment Life

Since PV pumps are a relatively new technology (compared to diesel engines, windmills, and handpumps), little is known about the economic lifetime that users can reasonably expect of most systems and components. While field tests have been conducted for certain types of systems, few (if any) PV pumps have been in actual use for more than several years. Module manufacturers now commonly guarantee their products for 10 years against significant loss of power output, and accelerated tests have indicated that modules will retain up to 90 percent of their original power-generating capacity for up to 20 years after the initial installation. The need for module replacement because of damage is very dependent on the site.

Other components are not so robust. The motor will probably have to be replaced every three to seven years, depending on the level of operating power (i.e., the higher the power, the sooner the motor will need replacement), the quality of the water (for submersibles, poor water quality tends to corrode casings and ruin seals more quickly), and the quality of the installation. Electronic components, such as controllers, may also need replacement every three to five years, depending on the quality of the equipment. Array mounts should never need replacement.

Chapter 7

WIND PUMPS

Wind pumping systems or windmills convert the energy in wind into mechanical or electrical energy to drive a pump. This section covers what you need to know to

- gather the necessary information to determine whether a windmill will meet the demand for water at your site and
- select a properly sized windmill and pump if this type of system is appropriate for your site.

Since the vast majority of all wind pumps used in developing countries are mechanical windmills driving piston pumps, that configuration is the primary focus of this chapter. Other types of wind pumps will be mentioned only briefly.

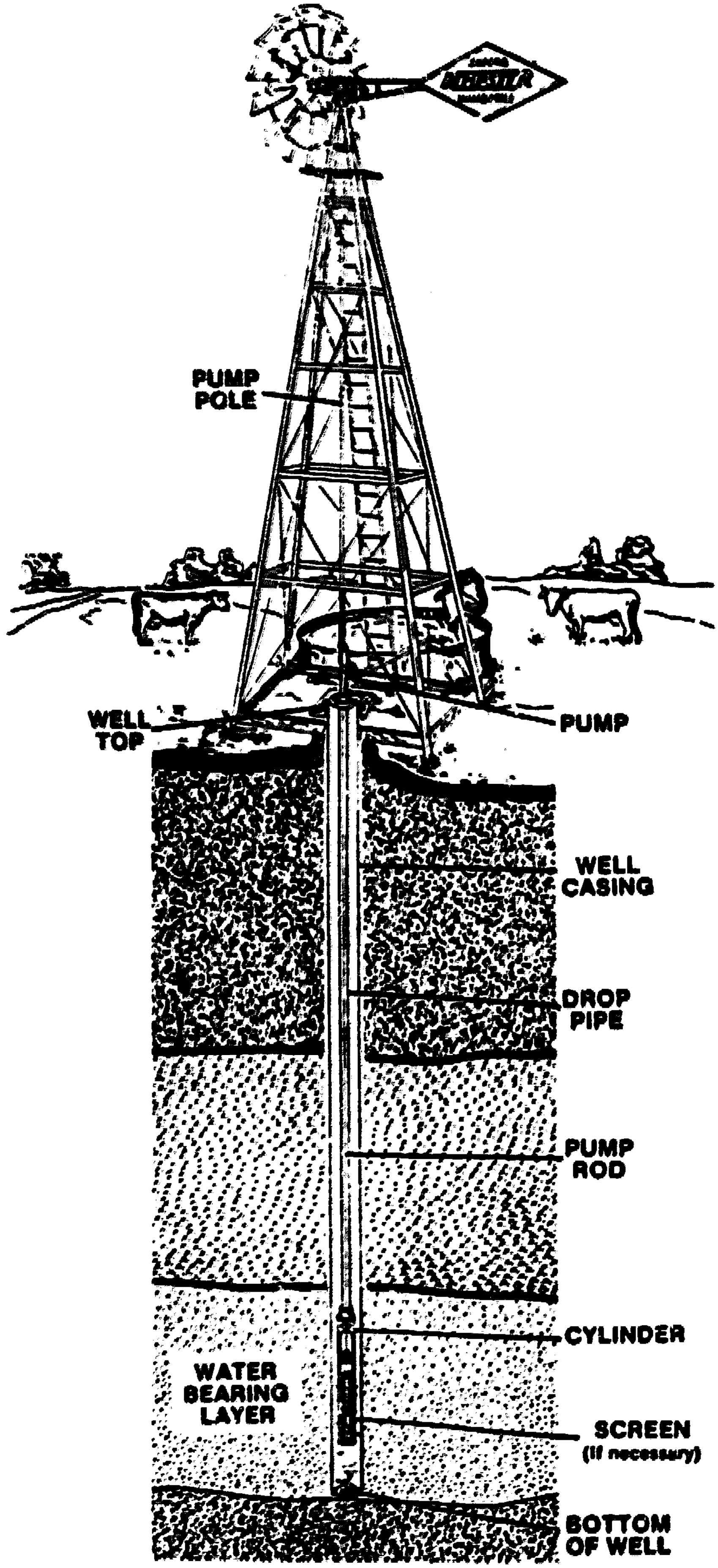
7.1 System Description

Wind energy systems are generally subdivided in two ways--horizontal- or vertical-axis machines (referring to the axis of the rotor) and electrical or mechanical. While it is possible to pump water using the energy produced by any of these four possible configurations, the most common type is the horizontal-axis, mechanical system, which is usually referred to as a steel-bladed, farm-type windmill or, simply, a farm windmill. Dempster, Aeromotor, Fiasa, and Southern Cross windmills are examples of this system design. Figure 15 shows a schematic diagram of this type of wind energy system.

A typical farm windmill has four main parts:

- a horizontal-axis wind wheel, which converts power in the wind into the rotary shaft power of the axis;
- a windmill "head," which changes the rotary motion of the axis to a vertical reciprocating motion and makes any necessary gear reductions;
- a tail attached to the head, which has two purposes--it allows the windmill to track changes in the wind direction and, along with a brake, permits the windmill to be furled (i.e., taken out of the wind and stopped) during high winds or when desired; and

Figure 15. Typical Windmill Installation



(Dempster Manufacturir
Literature)

- a tower, usually fabricated of steel, on which the windmill head is mounted.

This design is nearly always used with a reciprocating-piston pump. The typical multiblade configuration is designed to provide the required high torque to start the pump at low wind speeds. At higher wind speeds, the efficiency of a system is somewhat reduced due to rotor aerodynamics and load characteristics.

For a fixed wind speed, a windmill's power output is proportional to the diameter of the rotor. Commercial farm windmills vary in diameter from 3.0 to 7.3 meters. Water output depends on the amount of energy delivered to the pump cylinder. Cylinder sizes for reciprocating pumps vary in terms of diameter and length of stroke--the larger the cylinder diameter and the longer the stroke, the more water pumped per stroke. Commonly available cylinders run from 2.25 to 4.0 inches in diameter, although larger sizes can be obtained. The stroke length is generally determined by the design of the windmill head. Towers typically come in heights of 9, 12, and 15 meters.

Recent efforts at improving the design, reducing the weight, and simplifying fabrication procedures for windmills have resulted in a new generation of windmills. These differ from traditional designs in many ways, including the elimination of gears and castings, which permits simplified fabrication techniques, and improved rotor efficiency based on a better understanding of aerodynamic design. Photographs 5 and 6 show two examples of new-generation machines.

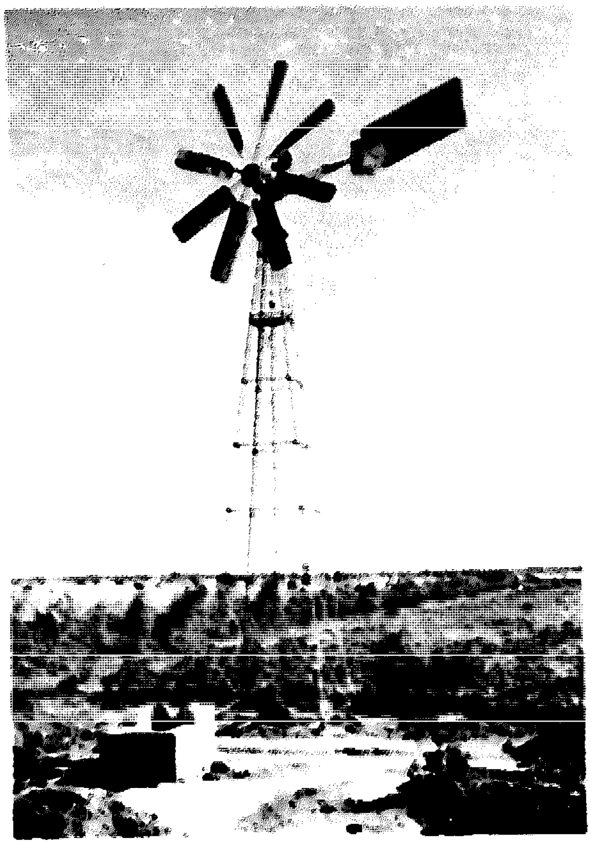
Another type of windmill that has been tested and demonstrated on a much smaller scale than the farm windmill is the Savonious vertical-axis design. The rotor consists of several curved metal blades mounted around a central, vertical axis of rotation. Initially, this design showed promise as a simple, inexpensive, easily constructed device for utilizing wind energy. However, for water pumping applications, it has not proven effective. It is inefficient; problems have arisen in controlling its speed to protect it from high winds; towers that are strong and large enough to get the rotor up into the wind-stream are too expensive; and coupling the vertical shaft to a pump that will operate efficiently at the rotor's low rotational speeds has proved difficult.

Other mechanical windmill designs are relatively uncommon, particularly in developing countries. Thus, this section focuses on the steel-bladed, farm-type windmill and recent improvements in this traditional design.

7.2 Operating Characteristics

Water delivery for a wind pumping system depends on a variety of factors, the most significant being

- the wind regime at the site,
- the pumping head,



5.

CWD-5000 Windmill for Water and Micro-irrigation near Khartoum, Sudan

6.

Kijito 20-Foot in Botswana

- the diameter of the windmill rotor selected, and
- the pump cylinder.

The single most important factor is the wind speed at the site. The power available in wind varies as the cube of the wind speed--if the wind speed doubles, the power available increases by a factor of eight. Because of variations in wind regimes (e.g., gusts and variable directions), wind speeds can only be measured and predicted in a statistical sense, and water delivery can only be estimated statistically. There is no guarantee that a specific amount of water will be delivered per day, week, or month. This characteristic limits practical windmill use to applications with flexible water requirements or some sort of backup system. It also means that for most applications, a storage tank will be needed, typically holding enough water for three to four days.

Although the other factors listed above are important in the design process, they do not have the same influence on performance as wind speed. The output of a specific windmill/pump combination at a given site is inversely proportional to the pumping head--as the head increases, the output decreases. All other factors being equal, the water output increases as the size of the rotor increases (a larger rotor offers a larger area for wind capture) and the height of the tower increases (winds are faster further from the ground).

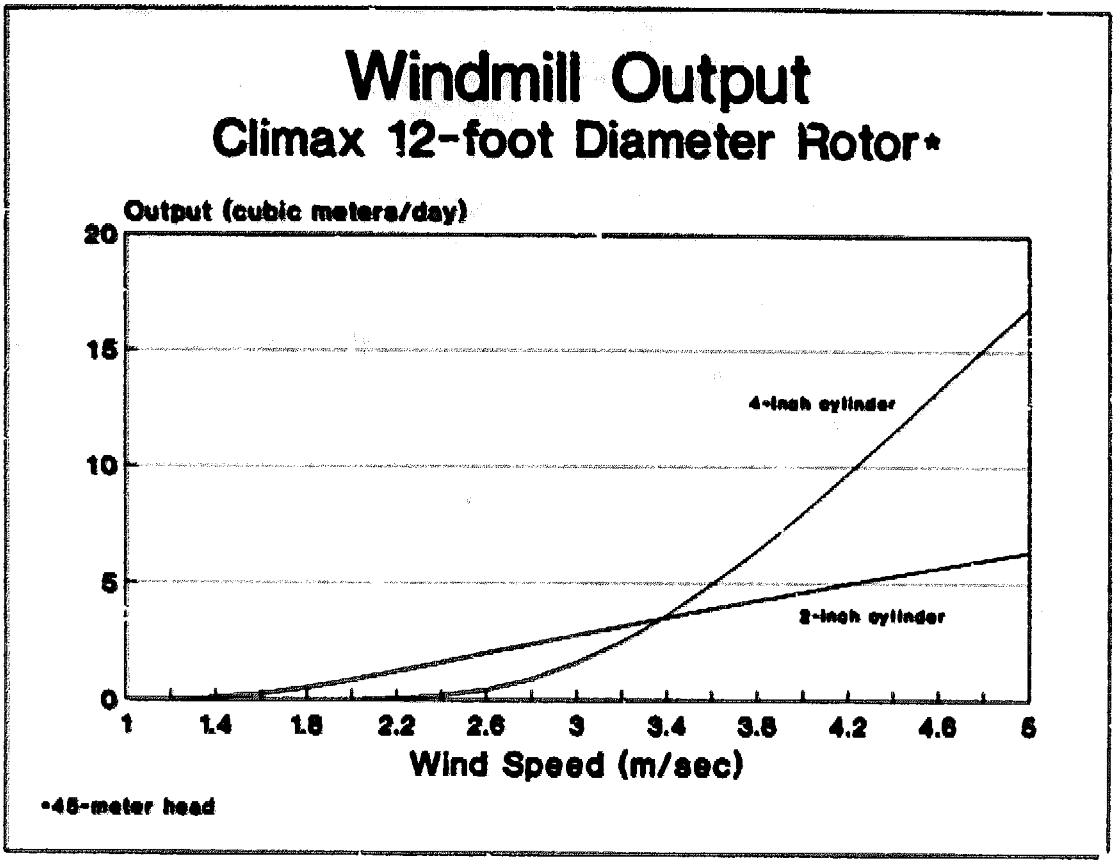
Rotor sizing is a fairly simple procedure (see below), but selecting a pump cylinder is more complex. Larger cylinders require greater power to initiate pumping, but once started, they deliver more water per stroke. For each combination of windmill, pumping head, and wind regime, there is an optimum point at which a balance is reached between the longer pumping hours required with smaller cylinders and the higher pumping rates for larger ones. At lower average wind speeds, smaller cylinders are usually selected to maximize total water delivery.

The relationship between wind speed, head, and amount of water pumped for a given size of windmill is shown in Figure 16. (Photograph 7 shows the windmill on which Figure 16 is based.) The two lines show daily water output in cubic meters for a Climax 12-foot diameter machine and 45 meters of head, using 2- and 4-inch cylinders. For example, at an average daily wind speed of 3 m/s, the 4-inch cylinder will pump only about 1.6 m^3/d, but the 2-inch will pump about 2.8 m^3/d because the windmill starts the smaller cylinder moving in lower wind speeds. However, in winds that are 4 m/s and above, the larger cylinder will deliver considerably more water, pumping 8 as opposed to 4.6 m^3/d. This difference increases as the wind speed goes up.

7.3 Choosing a Windmill

In most countries, there is not a wide selection of locally available windmills. It is not so important to have a local dealer for windmills as it is for diesel engines because windmills require less maintenance; nevertheless, a local source

Figure 16



7.

Climax 12-Foot in Botswana used for Village Water Supply and Small Stock Watering for spare parts is needed. Moreover, if a reputable windmill is manufactured locally in your country or region (e.g., the Kijito in Kenya or the Sanit in Thailand), it is suggested that these makes be considered first. Windmills are usually procured directly from a manufacturer or its agent. The most common approach is to purchase the windmill and tower directly from the manufacturer and the pump cylinder, rod, and pipe from local suppliers. Buying these three components locally is preferable since this ensures that if any parts are omitted or incorrectly specified, they can be replaced locally. It is also a good indicator that spare parts and knowledgeable mechanics will be available if and when they are needed. Finally, purchasing local products for the pump rod and pipe will probably be considerably cheaper.

To follow the design procedures outlined in this section, it is not essential to understand all the aspects of the theory behind wind energy use. Necessary concepts will be introduced as they arise. The general approach in wind system design is to

- determine wind speeds at the site,
- figure the design wind speed,
- calculate the necessary rotor size, and
- choose the proper cylinder.

7.3.1 Site Wind Speeds

There are two ways to estimate average wind speeds at your site. The first assumes that no wind data have been collected at the site but that long-term data is available from a meteorological station relatively nearby. The second method assumes you have recorded several months of wind data at the site, but have no long-term annual data except for information from a nearby meteorological station. In the first case (i.e., no site data), certain correction factors can be applied to estimate wind speeds at your site from meteorological information:

- a height correction, if the windmill will be at a different height than the recording instruments;
- a correction for local terrain conditions; and
- a correction factor if the data has been recorded over a short duration.

These correction factors (described in detail below) should be used with caution. Because the power in the wind is proportional to the cube of the wind speed, small errors in estimating wind speed can lead to large errors in estimating wind-pump output. Where possible, you should always try to gather at least several months of wind-speed data at your proposed site at the actual planned height of the windmill rotor. These short-term data can then be correlated with longer-term data from the nearest meteorological station. Site-specific data will help you more accurately determine whether a windmill is a good investment or only a marginal one.

Wind data are recorded with an instrument called an anemometer, which is basically an electrical switch that counts the rotations of a multiple cup or propeller rotating at a speed proportional to the surrounding wind speed. The number of rotations are counted, multiplied by a conversion factor, and then divided by the time elapsed to give an average wind speed in meters per second (m/s) or miles per hour (mph).

Anemometers are mounted on poles at a fixed height above the ground, usually 2 or 10 meters. Under normal conditions, wind speeds are greater at higher distances above the ground. This is largely because the effects of surface features and turbulence diminish as the height increases. The variability depends on the distance from the ground and the roughness of the terrain. The wind speed data should indicate the height at which the data were collected (i.e., the height of the anemometer). The most commonly accepted measure of the difference that can be expected in wind speeds between the anemometer's reference height and the proposed height of the windmill is given by the "one-seventh power law":

$$V_2 = V_1 \times (h_2/h_1)^{1/7}$$

where V_2 = unknown wind speed at the windmill's height (h_2)
V_1 = known wind speed at the anemometer's height (h_1)

It is much more difficult to predict average monthly wind speeds if the reference height at which the data were recorded is less than 6 meters. Data collected at heights of less than 6 meters should not be used to select a windmill or predict performance.

In relatively flat areas with no trees or buildings in the immediate vicinity, site selection is not critical. However, in mountainous areas or places where obstacles may block the flow of wind, differences in surface roughness and obstacles between the anemometer and pump site must be taken into account when estimating wind speeds for the site. As a general rule, a windmill tower should be tall enough so that the lowest part of the rotor is at least 9 meters off the ground or 15 feet above any obstruction within a radius of 400 feet.

A correction for local terrain must be used to modify predicted wind speeds if surface conditions at the reference and pumping sites are significantly different. For all practical purposes, terrain characteristics can be divided into three groups:

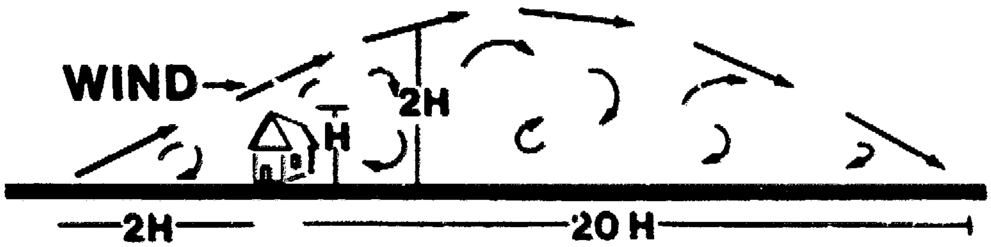
- smooth—empty cropland and exposed airport locations,
- moderately rough—areas with small bushes or crops, and
- rough—woodland or areas with buildings.

In adjusting estimates between any two of these terrain categories, a 25 percent correction factor should be applied, decreasing the wind speed as surface roughness increases. Figure 17 shows the effects of various obstacles on wind speed, along with the estimated reduction in power at different points behind the obstruction. For example, if a building has a height of H, at a distance of 5H downwind from the building, the turbulence caused by the building reduces power by 43 percent. At a distance 10H downwind, the reduction in power is only 17 percent.

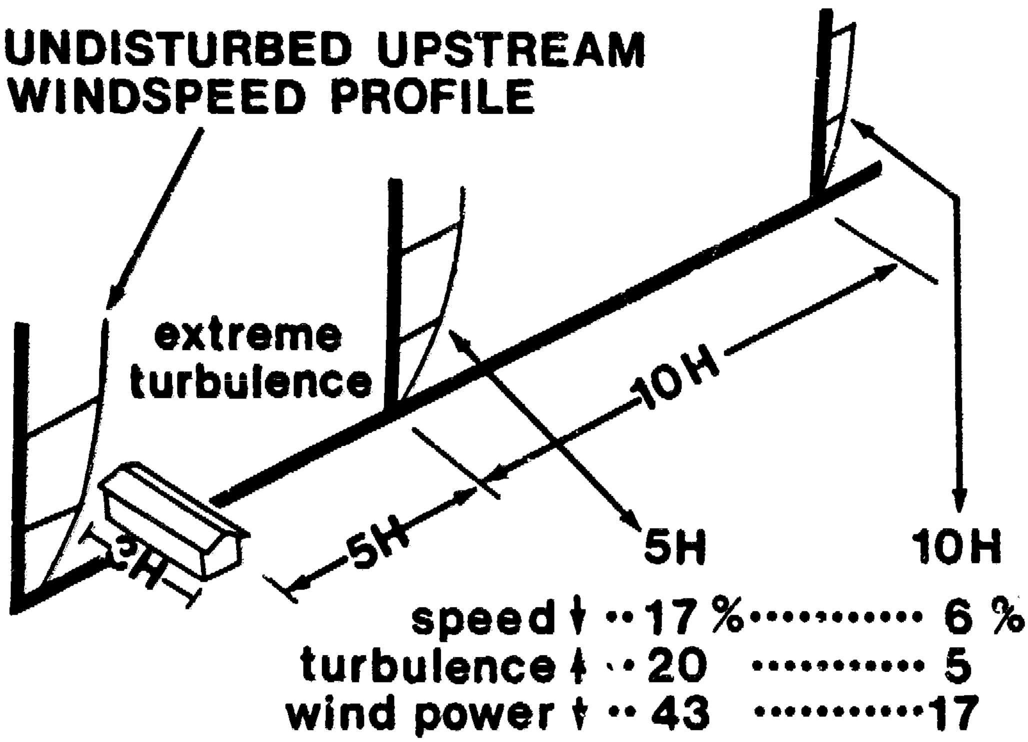
If the length of the recorded data is short, there is a chance that average wind speeds based on the data are not truly representative of long-term averages. If only one year of information is available, average speeds may be in error by 10 percent. Averages for longer periods (three years or more) are likely to be no more than 3 percent in error. If the duration of recorded data is only one year, it is suggested that average wind speeds be discounted by 10 percent as a safety factor to ensure that the windmill will not be undersized.

There is a another simple, but useful, technique for extrapolating from meteorological data to a specific site, if long-term data are available from a nearby meteorological station and you have recorded wind speeds for several months or more at your site (if possible during what you expect will be the design month) (see below). Divide the monthly average wind speeds at the site by the long-term averages for the same months measured at the meteorological site to obtain a correlation factor. Then, use this factor with the meteorological data to estimate the average monthly wind speeds at the site for months with no site-specific data.

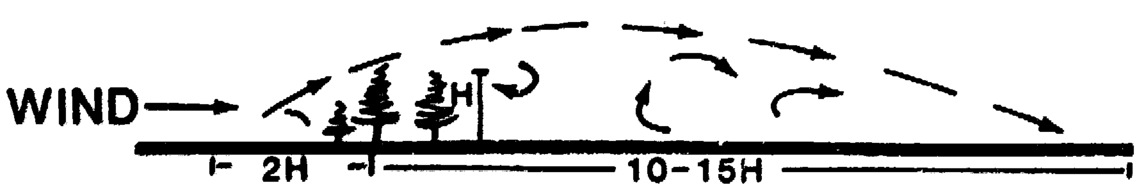
Figure 17. Effects of Obstacles on Wind Speed
(See text for explanation.)



Zone of disturbed flow over small building.



The effects of an undisturbed airflow encountering an obstruction.



Airflow near shelterbelt.

(Nelson)

Example 12: Windspeed Extrapolation from Another Site's Data

You have installed an anemometer at your site to measure wind speeds for several months. You recorded an average monthly wind speed of 5.0 m/s in April. A nearby meteorological station (with an anemometer at the same height and similar terrain) measured 4.0 m/s for the same month. Estimate the wind speed at your site for a month in which the meteorological station measured 3.5 m/s.

The correlation factor is 5.0/4.0, or 1.25. You can then estimate that the average wind speed at your site was about 3.5 x 1.25, or 4.4 m/s. The accuracy of this sort of extrapolation depends on how closely seasonal variations in wind at the site follow those at the weather station.

7.3.2 Design Month

During the course of a normal year, there are periods of high and low winds. Over a number of years, the pattern of these periods will usually be fairly predictable and should be apparent from an examination of average monthly wind speeds for the region.

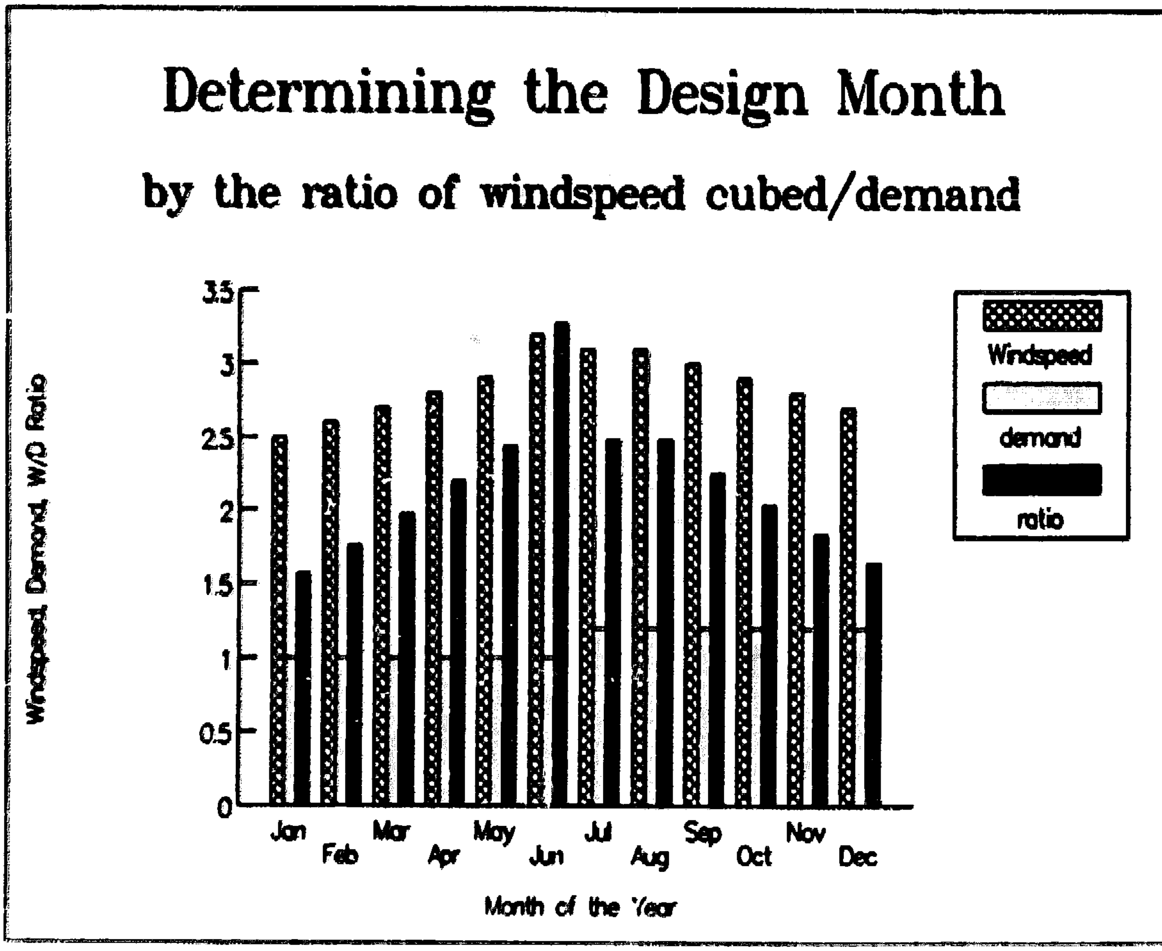
In addition to average wind speeds, the water-demand profile at the site must be determined (see Chapter 2), so the design month can be determined. This is the month when it will be most difficult to meet the water requirement utilizing wind energy. If the demand is constant, the design wind speed will be the average for the month with the lowest average speed. If demand fluctuates from month to month, the design wind speed is determined by dividing the average speed cubed by the average daily demand in cubic meters per day (i.e., $V^3/m^3/day$) for each month and then selecting the month with the lowest value—the design month.

Example 13: Design month

If monthly average wind speeds in m/s for the year starting with January are 2.5, 2.6, 2.7, 2.8, 2.9, 3.2, 3.1, 3.1, 3.0, 2.9, 2.8, and 2.7, and the water requirement is 10 m^3/day from January to June and 12 m^3/day for the remainder of the year, which is the design month?

A quick inspection of the graph shown in Figure 18 below reveals two likely candidates, January and December. Calculations show that the value for V^3/m^3/day is 1.56 in January and 1.64 in December. Thus, the design month is January.

Figure 18. Determining the Design Month



7.3.3 Required Rotor Diameter

The rotor area needed for a specific site depends on the pumping head, design wind speed, water requirement, and overall system efficiency, also called energy efficiency. Windmill output also depends on the pump cylinder chosen. At this stage, it will be assumed that an appropriate cylinder size is available. A method for choosing the proper cylinder size is given in Section 7.3.4. The calculation for selecting an appropriate rotor diameter is

$$D_r^2 = (Q \times H)/(p \times 7.9 \times v_d^3 \times n)$$

where D_r = required windmill rotor diameter in meters
Q = water required in m^3/day
H = total pumping head in meters
p = local air density in kg/m^3
v_d = average wind speed for design month in m/s
n = assumed overall system efficiency as a percentage
7.9 = units conversion factor

For a standard farm-type windmill and average wind speed of 3.5 m/s or greater, use a system efficiency of 6 percent. This figure should be progressively reduced to 4 percent as the average wind speed declines to 2 m/s. For speeds over 4 m/s, a reasonable value for efficiency is 5 to 6 percent. For improved windmills, such as the Kenyan Kijito or Dutch CWD-5000, an efficiency of 8 percent should be used if wind speeds are 3.5 m/s or higher, but this figure should be progressively reduced to 4 percent as the average wind spoed declines to 2 m/s. Air density is closely related to air pressure and temperature. In most cases, altitude (i.e., pressure) is the largest factor in air-density calculations. A secondary factor is air temperature. Table 3 below gives correction factors for altitude (K_A) and temperature (K_T). To estimate air density for any altitude and temperature, multiply the density of standard air (1.22 kg/m^3 at sea level and 20° Centigrade) by both factors shown in Table 3. Consult local weather services to get a representative air density for your proposed site.

Table 3

Air Density Correction Factors*

Altitude (m)	=	0	750	1,500		2,250	3,000	
KA	=	1	0.913	0.835		0.760	0.692	
Temperature (oC)	=	-20	-10	0	10	20	30	40
KT	=	1.271	1.125	1.073	1.020	0.989	0.958	0.925

* Adapted from: J. Leki et al., <u>More Other Homes and Garbage</u> (San Francisco: Sierra Club Books, 1981).

Example 14: Estimating Air Density

Estimate the air density at 1,500 meters above sea level at 40° Centigrade. Under these conditions, $K_A = 0.835$ and $K_T = 0.925$. Therefore, air density $= 1.22\ kg/m^3 \times 0.835 \times 0.925 = 0.94\ kg/m^3$. (This means that for a climate like that in Botswana, the power available in the wind is only 77 percent of that at sea level and 10° Centigrade).

Example 15: Rotor Diameter

What is the required rotor diameter for a standard farm windmill if conditions during the design month are $V_d = 3.6$ m/s, H = 25 meters, and $Q = 7m^3$/day, with an air density of 1.0 kg/m^3?

$$D_r^2 = (Q \times H)/(1 \times 7.9 \times V_d^3 \times n)$$
$$D_r^2 = (7 \times 35)/7.9 \times 3.6^3 \times .06)$$
$$D_r^2 = 1.1m^2$$

Thus, D = 3.3 meters or 10.9 feet. So, choose a windmill with a 12-foot diameter, the next largest available size.

7.3.4 Pump Cylinder

To size a pump cylinder properly for a windmill, the concept of system design ratio (X_d) must be introduced. This is the ratio of the system's design wind speed (v_d) to the average wind speed at the site for the design month. The system's design wind speed is the instantaneous operating wind speed at which system efficiency reaches a maximum. For steel-bladed, farm-type windmills, the design wind speed can be approximated as

$$v_d^2 = .15 \times (S \times H \times D_c^2/(D_r^3 \times G))$$

where vd = average wind speed for design month in m/s
S = stroke length in centimeters
H = total head in meters
D_c = diameter of the pump cylinder in inches
D_r = rotor diameter in meters
G = windmill gear ratio

Note that D_r and G are machine parameters that will depend on the windmill selected, and H varies with the site. A pump cylinder can be chosen based on the sizes available. The cylinder diameter (D_c) is given in inches because this is how cylinders are usually measured. All other measurements are in metric units.

A wind pump that is well matched to a site should reach its optimum efficiency around the average wind speed there. This is the case when X_d is 1.0. In many instances, this is indeed true. However, the designer should know that for values of X_d that are slightly below 1.0, the windmill will operate for slightly longer periods because it runs in lighter winds, but it will deliver less water overall, which may have an impact on the size of storage tank required. For values of X_d above 1.0, a windmill may deliver slightly more water on the average, but less during lower wind periods.

The recommended value for X_d is usually between 0.7 and 0.9. Your choice will depend to some extent on the elasticity of demand at the site, but a reasonable compromise is to use a design parameter for X_d of 0.8. The required cylinder size will depend on the value of X_d selected for your site and can be determined using the following formula:

$$D_c^2 = ((X_d \times v_d)^2 \times D_r^3 \times G)/(.15 \times S \times H)$$

where X_d = system design ratio
and all other variables are as defined above.

Example 16: Cylinder Size

A Dempster windmill is to be installed at the site in Example 15. If X_d is 0.8, what is the proper cylinder size? Note that complete machine specifications should be given in the manufacturer's literature on the windmill. For a 12-foot Dempster, they are a stroke length of 18.4 centimeters and gear ratio of 3:1.

$$D_c^2 = ((X_d \times v_d)^2 \times D_r^3 \times G)/(.15 \times S \times H)$$

$$D_c^2 = ((0.8 \times 3.6)^2 \times (3.65)^3 \times 3.0)/(.15 \times 18.4 \times 35)$$

$$D_c^2 = 12.5$$

$$D_c = 3.53 \text{ inches}$$

Therefore, choose a 3.5-inch cylinder.

The sizing method given here is adequate for choosing a windmill and pump cylinder. However, it is possible to make more accurate estimations if more reliable information on the wind resource is available. Computer programs have been developed that permit more accurate and detailed estimates of wind pump output.

7.4 Cost Considerations

This section gives representative costs for several types of windmills and associated equipment, as well as typical recurrent O&M costs and requirements. For models from the same manufacturer, the capital cost of a windmill increases with increasing rotor diameter. As a general estimate, windmills cost between US$200 and US$500 (not including towers) per square meter of rotor area, depending largely on the country of manufacture. Tower costs are proportional to height. For the same-size rotor, traditional designs (e.g., Southern Cross and Fiasa) are sometimes less expensive than "improved" models (Kijito or CWD-5000), but the price is highly dependent on the country of origin. For example, a 16-foot Fiasa on a 40-foot tower costs about US$13,600, shipped from Fiasa Windmills in the United States, and a 12-foot model on the same tower costs US$6,500. In contrast, a Kijito from Kenya costs about US$11,000 for a 24-foot diameter rotor on a 40-foot tower, shipped from Mombasa, while a 12-foot Kijito costs US$5,000.

The price of a pump cylinder depends on the manufacturer, the diameter, and the material. Cylinders manufactured in developing countries are generally less expensive but can be of good quality depending on the source. They are typically available in the 2- to 4-inch range for US$200 to US$800, with larger sizes costing more. The cost of even larger cylinders increases greatly. Most cylinders are made of brass. Stainless-steel cylinders can be purchased for sites with very corrosive water, but they are often prohibitively expensive.

The prices given here for windmills and cylinders are current as of the summer of 1988, but may vary with new design and manufacturing developments. They also depend on the country of origin—for instance, Kijitos are made in both Kenya and Pakistan but are sold for different prices. The prices quoted here do not include shipping and insurance or local import tariffs and restrictions. If possible, contact a local distributor to get more accurate prices for your area.

7.5 Operating Requirements

As is true of all pumping equipment, the quality of windmill operation and preventive, corrective, and curative maintenance (defined in Section 5.5) will have a definite impact on the reliability of the system, the magnitude of recurrent costs, and the life of the equipment. These aspects of windmill use are closely interrelated, such that following proper procedures in one area will favorably affect other O&M requirements.

Most wind systems do not need a full-time operator, unlike diesel pump sets. When the wind blows, the windmill pumps water. All farm windmills and most of the improved designs have safety mechanisms to turn the rotor out of the wind to protect it during periods of high wind. Despite these self-regulating design features, a part-time operator or caretaker may be advisable for a number of reasons. His or her tasks would include the following:

- periodically checking the windmill and storage tank,
- performing light maintenance,
- manually furling the windmill when the storage tank is full and unfurling it when more water can be added, and
- reporting major repair needs to repair crews.

The issue of paying a part-time operator or caretaker will vary depending on the pump application and community structure. It should be noted that the cost of this item can make a difference in determining the economic and financial feasibility of a wind pump.

7.6 Maintenance and Repair

While normal preventive maintenance requirements for windmills are minimal, they are important. They include routine tightening of all nuts and bolts, changing the lubricating oil, greasing certain parts, and periodically changing the pump-cylinder leathers as they wear out. Ignoring any of these small tasks, can damage the machine and, at best, will decrease its expected service life. If these tasks can be accomplished by a local caretaker instead of an area mechanic, operating costs will be reduced because labor and transportation costs will be saved. In addition, the system is likely to be more reliable if the responsibility for maintenance rests with someone who benefits directly from its proper operation. This is not possible with some tasks, however, such as changing pump-cylinder leathers, which usually requires tools for pipe lifting.

The frequency of routine maintenance depends on conditions at the site. It is recommended that windmills be checked visually at least once a month and remaining maintenance tasks be carried out annually. The life of cylinder cup leathers depends to some degree on water quality (i.e., grit or sand in the water) and may range from less than a year to over two years. In the absence of other information, an average replacement interval of one year is a reasonable estimate for planning purposes.

Minor problems that do not cause a system to break down require corrective maintenance. The most common problems typically involve the windmill's manual furling mechanism. Broken furling cables do not disable the windmill and, in most cases, the problem can be rectified at the local level. However, if left unrepaired, a broken furling mechanism will prevent the windmill from being manually turned out of high winds, which could cause irreparable damage.

When curative maintenance is required for breakdowns, outside assistance is often needed to restore the windmill to operation. The most common curative maintenance problems are broken or disconnected pump rods. How often this problem arises is highly dependent on the quality of the original installation. Improperly installed rods or crooked borehole casings can cause regular breakage of sucker rods. The problem may arise only every several years or as often as every few months. A typical rate for a reasonably well installed system is once a year.

Field experience has indicated that an average windmill installation will have three to four maintenance problems annually. The reliability and serviceable life of the windmill system will be increased and costs decreased in proportion to the amount of maintenance and repair work that can be handled at the local level as well as the responsiveness of outside help, when it is required.

7.7 Equipment Life

The long-term cost-effectiveness of windmills depends on a system having low recurrent costs and a long useful life. Historically, the popularity of steel-bladed, farm-type windmills in many areas was due to the fact that they possessed these attributes, with typical lifetimes often in excess of 20 years and occasionally as long as 40 to 50. Windmills have not had such a favorable record in developing countries. Often, the first or second breakdown has been the end of a windmill's useful life, because local people were not often trained in proper operation and repair procedures before the system was installed. This situation emphasizes the importance of identifying a capable maintenance and repair organization before installing a wind pump and establishing a satisfactory, cooperative, and responsive relationship between that organization and the users of the system to ensure a long, useful life for the machine.

Chapter 8

HANDPUMPS

Considerable research and development have been undertaken over the last 10 years in an effort to produce more efficient, reliable, low cost handpumps that can be manufactured locally. As part of the United Nation's International Drinking Water Supply and Sanitation Decade, the World Bank has funded comparative studies of handpumps (Arlosoroff et al. 1987) that have focused on the concept of village-level operation and management of maintenance (VLOM). VLOM pumps can easily be installed, operated, and maintained by village mechanics and technicians without expensive tools.

It is increasingly apparent that handpumps are the least expensive, most reliable technology for many applications, particularly for low-demand sites (about 5 m^3/day). When properly maintained, handpumps can be very reliable, but community involvement in maintenance and repair is usually required to ensure their long-term performance. Such involvement decreases the need for O&M support from outside the local community, which often makes handpumps a more attractive option in the eyes of development planners and, more important, users. Handpumps that can be maintained locally are likely to result in much higher water availability for the community, compared to other systems where maintenance or repair depend on the intervention of centrally based repair crews which are usually overburdened.

This chapter discusses the technical characteristics, costs, and support requirements of handpumps used for domestic water supply. Sizing is a much less complex design issue for handpumps than the other systems discussed in this manual, so the selection criteria presented here focus more on other issues related to maintenance and repair. There is a wide variety of human-powered pumping systems that are used primarily for agricultural purposes, including foot-powered treadles, shadoofs, and chain-and-washer pumps, but these will not be discussed further here. Kennedy and Rogers (1985) and Fraenkel (1986) offer in-depth discussions of these other types of human-powered pumps.

8.1 Types of Handpumps

Over 50 makes and models of handpumps are available worldwide. All depend on human power and, thus, have a limited pumping rate and head range compared to the other mechanical systems considered in this manual. Handpumps can be divided into four categories:

- high lift—positive-displacement pumps capable of pumping from depths of up to about 45 meters,
- intermediate lift—for lifts of up to 25 meters,
- low lift—up to 12 meters, and

- suction pumps—up to 7 meters.

These categories include high-lift reciprocating, diaphragm, progressive-cavity, direct-action, and suction pumps. Illustrations of several common types of pumps are shown in Figure 19. Two typical installations are shown in Photographs 8 and 9.

Deep-well reciprocating-piston pumps are the best-known type of high-lift pumps. They usually have immersed pump cylinders and are operated with lever-arm pump handles. The most common designs are the India Mark II and Afridev. These pumps can lift water from up to about 45 meters, although some other designs are more suitable for lifts of less than 25 meters. Typically, high-lift piston pumps are

- more difficult and expensive to maintain at the village level than low-lift pumps,
- operated at a decreased pumping rate as head increases, and
- generally less suitable for local manufacture in developing countries.

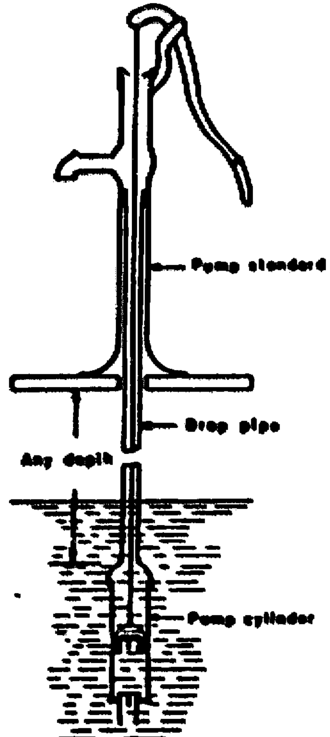
A second design suitable for high-lift pumping is the progressive-cavity pump. Similar to a screw pump in its operation, this design incorporates a rotor turning within a stator that progressively forces water up the drop pipe. The Mono and Moyno brands are examples of this design.

A third type of high-lift pump is the deep-well diaphragm design. It uses a flexible membrane that is repeatedly stretched and relaxed mechanically to provide the pumping action. The French Vergnet is perhaps the best example of this type. These pumps are especially suitable for sandy or silty water. However, compared to reciprocating-piston pumps, they are generally more complex and expensive and often require specialized parts and tools for maintenance and repair.

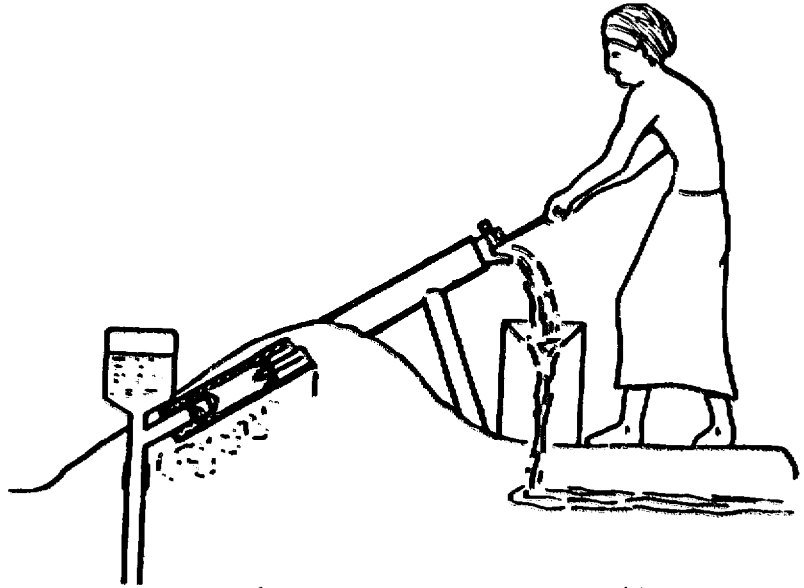
Direct-action systems, such as Blair and Kangaroo pumps, are suitable only for lifts of up to about 12 meters because the pumper acts directly on the pump, without the advantage of a lever arm. Compared to the designs mentioned above, these pumps tend to be

- low in cost,
- more suitable for village-level maintenance, and
- inappropriate for heavy use—they should probably not be considered for sites where the water demand is above 1.5 to 2 m^3/day.

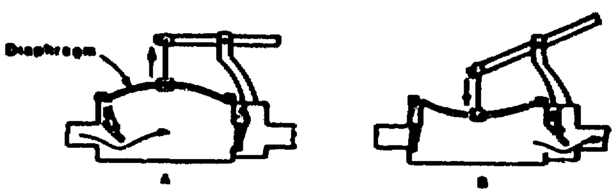
Figure 19. Different Types of Handpumps



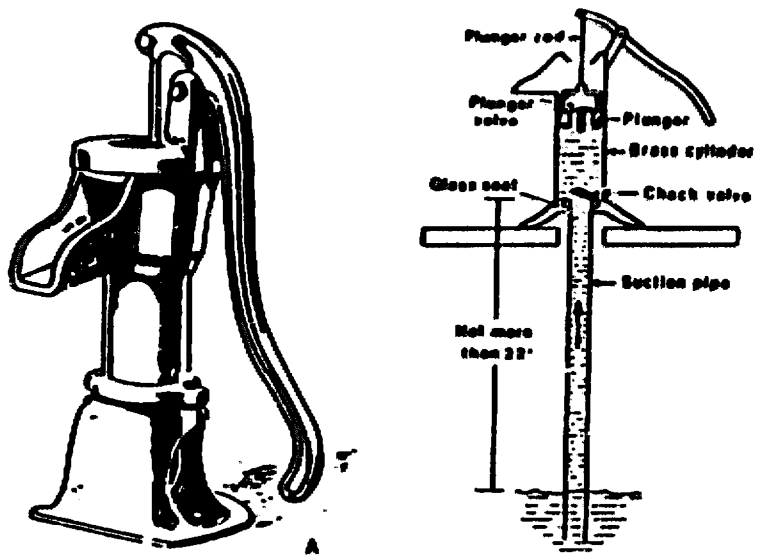
Deep Well Piston Pump*



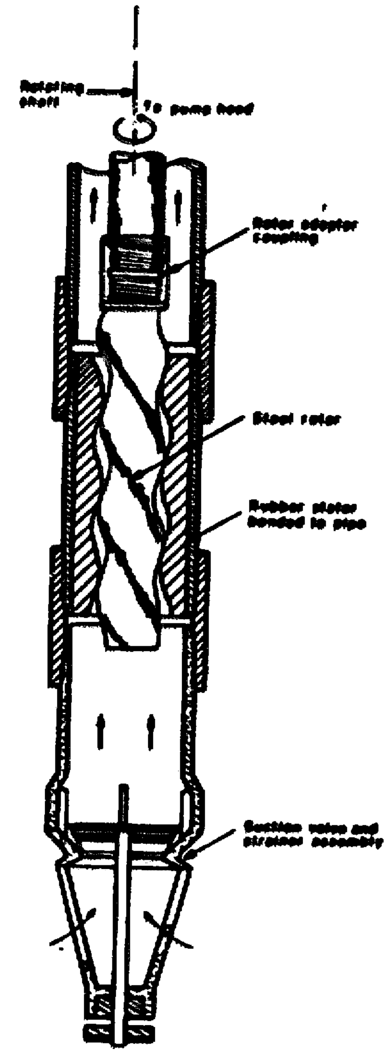
Direct Action Power Pump**



Surface Mounted Diaphragm Pump*



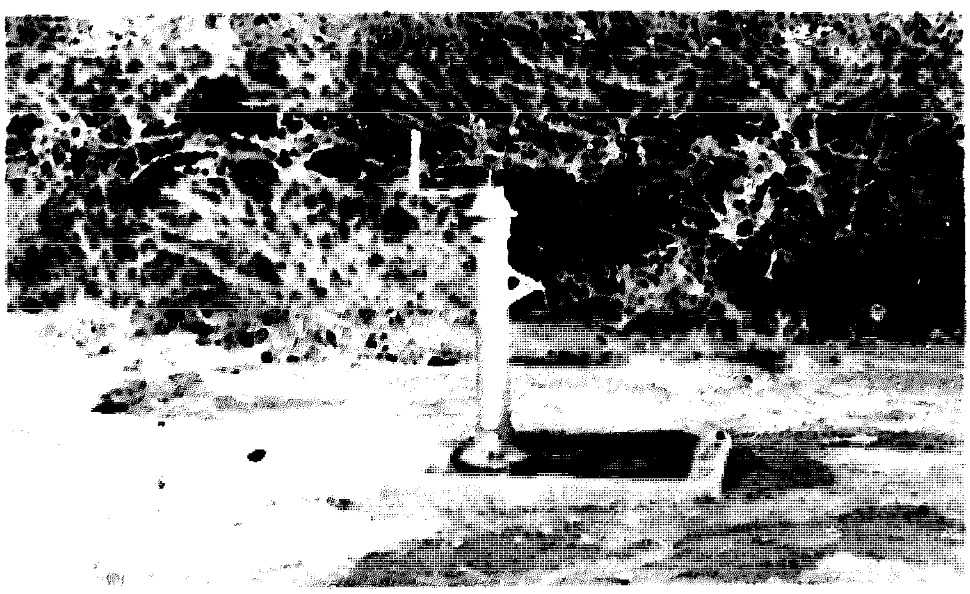
Shallow Well Suction Pump*



Helical Rotary (Mono) Pump*

*(McJunken 1983)
**(Fraenkel 1986)

8. India Mark II Piston Handpump in Botswana



9. Mono Direct Drive Handpump in Botswana

Suction pumps operate by creating a partial vacuum to pull water upward. Thus, they are useful only for lifts of no more than 7 meters, a limit that decreases at higher altitudes. Suction pumps must also be primed before use by pouring water into the space above the plunger. Still, these pumps are very popular in areas where heads are low. This type of pump tends to be

- low in cost,
- easy to service and repair because all moving components are at ground level, and
- primarily suited to meeting fairly limited water needs.

Since low- and intermediate-lift pumps are essentially simplified versions of high-lift pumps, only high-lift and suction pumps will be discussed further in this chapter.

8.2 Operating Characteristics

The operating characteristics and requirements of handpumps are significantly different from those of diesel, solar, and wind systems. These differences between handpumps and the other systems include both advantages and disadvantages. The most important advantages of handpumps are their simplicity of operation, low cost, and potential for local maintenance. The significant disadvantages of handpumps are that their capacity is very limited and they generally cannot be used with piped distribution systems. To some extent, these drawbacks can be overcome by using more than one pump. Of course, this would usually require additional water points, which would entail high costs for drilling or digging more wells at sites where groundwater is pumped.

The capacity of handpumps varies from 5 to 20 liters per minute, or 0.3 to 1.2 m^3 per hour on a continuous basis, depending on the head and pump type. In practice, output is often more dependent on the users than on the capacity of the pump—even if people are organized, lined up, and ready to begin pumping as soon as the preceding person finishes, it still takes time to remove the full container under the discharge pipe and replace it with an empty vessel. Output is also affected by the speed (i.e., effort) with which a pump is used, a factor that varies considerably from user to user. Under typical conditions, a single handpump can deliver 4 to 5 m^3/day, enough for 200 to 250 people. This capacity limits the use of handpumps to villages and settlements with small populations, even if multiple pumps are installed. Depending on particular site constraints, a system of four or five handpumps may provide a reliable water supply that is cost-competitive with other options. This, of course, depends on the costs of digging the wells for each pump.

Usually handpumps deliver water only to the wellhead and cannot easily be adapted to central-standpipe or yard-tap distribution systems. This fact has two implications. First, water sources should be within a convenient walking distance for users. Any economic analysis of the number of water points to be included in a system should consider the opportunity cost of time required to collect water. Second, compared to distributed water supplies, significant capital savings are realized when a storage and distribution system is not needed.

8.3 Operation, Maintenance, and Repair Requirements

Maintenance programs for pumping systems are usually handled by the community or a centrally based organization. In the former (e.g., VLOM), the community takes direct responsibility for the pumping system and only contacts outside help for repairs if necessary. In centrally based programs, responsibility for a system rests with an outside agency, contacted by the community whenever any servicing is required. Studies over the last several years have repeatedly shown that community involvement is an important factor in successful long-term operation of handpumps. To the greatest extent possible, community participation in pumping projects should be encouraged from the earliest planning stages.

As is true for more complex technologies, the proper design, procurement, and installation of handpumps are necessary, though not sufficient, conditions for successful long-term use. Correct operation, maintenance, and repair procedures are equally important. The VLOM approach to handpump design focuses on reducing users' dependence on external support. This approach can save money and time and can also minimize other problems (e.g., communication, transportation, and improper repairs) often associated with centrally supported maintenance and repair programs. Since handpumps are relatively simple pumping systems, they lend themselves to the VLOM approach.

VLOM programs provide an O&M structure that is more directly responsive to community needs. However, centralized programs with mobile mechanics that serve specific geographic areas can complement the VLOM model by mobilizing trained mechanics, tools, and transportation when more complicated repairs are required. VLOM water supply programs include training components to identify and develop the capability of a village caretaker to perform light maintenance, prevent abuse of the pump through improper operation or vandalism, and quickly summon outside help for maintenance and repairs as required. Caretaker effectiveness is the critical component in successful handpump use.

Regular preventive maintenance for handpumps--for instance, tightening nuts and bolts, and keeping the area clean--should be performed at the local level by the village caretaker. As previously defined, curative maintenance includes actions that are necessary to restore pumping following a breakdown. Most handpumps are not truly VLOM designs, so it is frequently impossible to handle all maintenance and repair at the village level. Often, repairs are required when below-ground components fail due to poor water quality, heavy use, or simple wear. This type of work usually involves the transportation of a repair crew with appropriate tools from a central workshop. In such cases, a prompt response is necessary to ensure a steady supply of water.

Down-hole components that occasionally require maintenance, repair, or replacement are the cylinder, cylinder or cup leathers, drop pipe (through which water is pumped), and sucker or pump rods, which drive the piston inside the cylinder on piston pumps or turn the rotor on Mono-type pumps. Replacing cup leathers is the most common repair. Depending on the type of cylinder, this may involve pulling the entire cylinder or just the piston. Periodically (with greater frequency at sites with poor water quality), the drop pipe will need to be replaced. Sometimes, pump rods become disconnected and must be replaced if they cannot be fished out of the well.

The most common maintenance problem encountered above ground is the occasional need to replace worn bearings on the pump handle. Other problems invariably arise with the pump head or other components. The frequency of such repairs will depend on the particular pump selected for the site and the care it has received during use. The amount of lost pumping time and repair costs will be a function of the nature of the problem, the availability of necessary spare parts, and the responsiveness of the maintenance structure.

A reasonable range for frequency of repairs is three to four times a year to once every two years. The level that is acceptable will depend on the responsiveness of the repair infrastructure and the total amount of time the pump is out of service. If repairs can be done at the local level, outages will be shorter and a higher breakdown frequency may be acceptable to users. If repairs must be done by a centralized maintenance unit, it may take several days to a week or more before problems are addressed, and a greater frequency of repairs is not as likely to be tolerated.

The expected lifetime for handpumps is difficult to estimate as it depends on the conditions and amount of use as well as care the equipment has received. However, typical ranges are anywhere from 5 to 10 years.

8.4 Choosing a Handpump System and Model

People are often reluctant to consider handpumps because of their obvious limitations, despite the equally obvious potential for cost savings. The following sections offer some basic recommendations regarding constraints on handpump use to assist you in determining whether or not handpumps are the right choice for your site.

8.4.1 Application Limits

Handpumps should not be considered if the total head at your site is more than 45 to 50 meters, due to the physical difficulty of pumping water from greater depths. You should also take into account whether the maximum anticipated head will be further increased by drawdown in low-yield wells or seasonal fluctuations of the water source—both are likely with shallower sources that are more dependent on seasonal recharge.

If the maximum anticipated pumping head is less than 45 meters, the next concern is the water requirement. Given that a typical handpump can serve 200 to 250 people (i.e., provide 4 to 5 m^3/day), the number of handpumps and wells needed for larger sites can easily be calculated. In some circumstances (e.g., very remote sites where diesel fuel may be expensive or difficult to obtain and where qualified technicians may not be available), four to five handpumps may be a more attractive option than a single diesel pump that has greater pumping capacity and its associated water storage and distribution system. Certainly, the cost of developing additional wells, water storage and distribution systems, and the maintenance associated with these components must be considered in deciding which type of system to use (see Chapter 10 for an economic analysis of pumping systems).

Convenience and health concerns should be considered in system design and siting. Well siting and user convenience are not as important for pumping systems that can distribute water through central standpipes or private connections. However, for handpumps to be a viable option, they should be located no more than a reasonable walking distance from users--400 to 500 meters. At sites where water sources are located well outside village boundaries (perhaps to reduce the risk of pollution), handpumps are probably not suitable because of the distance and time that would be required to collect water. The need to prevent well pollution is also important. Pollution may occur through direct entry, as occurs with open, hand-dug wells, or the migration of contaminants from the surface. Provisions should be made for a well apron and "soak-away" or drain to keep the area around the well as clean and dry as possible.

8.4.2 Selecting a Handpump Model

In terms of equipment, the process of system design for handpumps consists mainly of choosing the pump and, in a few cases, an appropriate cylinder. Pump selection depends on a number of factors, including anticipated maximum lift, water requirements, discharge rate, ease of maintenance and reliability, and resistance to corrosion and abrasion. Additional concerns are the availability of the pump locally and, where appropriate, the potential for local manufacture. When selecting a pump consider these factors in the following order:

- operating conditions--head and output requirements,
- ease of maintenance--dependent on local O&M infrastructure,
- reliability--see the ratings given below,
- resistance to corrosive or abrasive water conditions, and
- potential for local manufacture of the entire pump or some of its components.

In many areas, handpumps can be purchased only through agents from abroad. In others, imported handpumps can be ordered through a local dealer or distributor. Occasionally, local suppliers stock imported pumps or even models manufactured locally. There is increasing interest in promoting the local fabrication of handpumps in countries where the industrial capacity is sufficient to ensure high-quality products. The advantages of in-country manufacturing include:

- cost savings, as the result of lower labor and shipping costs;
- local technicians' familiarity with the units, thereby ensuring better maintenance and repair capabilities;
- increased availability of spare parts; and
- local income generation.

In addition to a moderately developed industrial capability, an adequate local or regional market must exist before local manufacturing of handpumps should be considered. At the project level, the decision to use handpumps should include an evaluation of the potential for future fabrication of the entire pump or some components. If local manufacturing is seriously being considered, various associated needs must be studied. High-quality manufacturing of pumps and/or spare parts can be an expensive, time-consuming project. The implications and cost of such a program must be carefully considered within the overall context of a country-wide water resources development strategy.

If you determine that handpumps are the most appropriate technology, based on the water demand at the site, the operating constraints, and other factors discussed above, the best single source of information on choosing a particular pump manufacturer and model is Arlosoroff et al. 1987. The section titled "Handpump Compendium" contains summary descriptions of over 100 makes, 86 of which were tested during the World Bank's handpump project. Each description includes an overall assessment and ratings on discharge rate, ease of maintenance, reliability, corrosion resistance, abrasion resistance, and manufacturing needs. After first determining which pumps can be procured locally, use this reference to choose between the available models. The book also contains a set of four pump selection tables organized according to head limits--7, 12, 25, and 45 meters. Within these four categories, pumps are rated on each of the six areas listed above. These summary selection tables are reproduced in Appendix D.

8.5 Cost Considerations

When comparing water costs for handpumps with those for other technologies considered in this manual, special care must be taken to include all relevant costs. Only those items that are common to all systems can be overlooked in such comparisons. For example, if you consider using multiple handpumps to meet a demand for distributed water, you must include the cost of developing multiple water sources. Similarly, if this is to be weighed against the cost of a distributed water supply provided by a diesel pump, remember to include costs for piped distribution, water storage, and associated maintenance and upkeep.

The installed capital cost of a handpump varies depending on the type of system and its location. Prices given here are for 1988. Low-head pumps typically cost US$200, but may be as low as US$50, particularly when they are manufactured locally. Pumps for higher heads, which are usually imported, can cost considerably more, between US$300 and US$1,000 per unit plus shipping. Pump or sucker rods cost about US$2 to US$3 per meter and drop pipe about US$5 to US$7 per meter. The cost for a well cap and concrete drain varies considerably depending on local labor and cement costs, but averages around US$50 to US$100.

8.5.1 Operating Costs

Handpump operation is fairly straightforward. The only "fuel" cost is the pumper's salary, if any. Handpumps do require attended operation, but in most cases, pump operators are the water users themselves and so are not paid. Even so, a proper economic analysis of handpumps should consider the labor cost of pumping water. When considering different system options, be sure to include all the costs of supplying water. For example, some handpump sites may be located outside the village. If you are comparing a handpump system (where water users must carry water from the pump site to their village) to a diesel or other system which pumps water to public, centrally located standpipes, the cost of any additional labor for carrying water from the handpump site to the central location should be included in the analysis (as should the cost of the distribution system for the diesel system).

Handpumps require a time and labor commitment from users, who could use that time in other ways if another pumping option were chosen. This is not usually a factor when considering diesel, solar, or wind pumps. As mentioned above, daily care of a handpump should be entrusted to a caretaker, who has some skills and perhaps enough tools to permit him or her to fix minor problems. This person may or may not be paid by the community or as an employee of some public agency.

8.5.2 Maintenance and Repair Costs

For convenience, maintenance and repair needs have been divided into nine potential problem areas:

- the pump handle;
- the fulcrum or bearings;
- the rod hanger, where the sucker or pump rods attach to the bottom of the fulcrum;
- the pump rods, becoming disconnected from each other or the pump element;
- the rising main or drop pipe;
- the piston seal, often referred to as the leathers;

- the pumping element--for example, the piston in reciprocating pumps and the diaphragm in diaphragm pumps;

- the foot valve, which prevents water from draining out of the drop pipe and causing a loss of priming in suction pumps); and

- other problems.

For piston pumps (including high-lift reciprocating, low-lift suction, and direct-action types), the leathers are typically the most common item needing repair. They will probably require replacement every six months to two years, depending on the quality of the water and the degree of pump use, with heavy use increasing the frequency of replacement. The cylinders will likely last five to seven years, depending on the same factors. A typical maintenance and repair crew can replace the leathers or cylinders in one day (not including transportation to the site), even if the cylinder and drop pipes have to be pulled. If the drop pipes have to be pulled, a special rig or tripod may be needed to lift them from the borehole.

The bearings are the second most common problem area in piston pumps. Depending on the design, the replacement of bearings can be very difficult. New pump designs, such as the Afridev, use plastic bearings that can be easily replaced in order to minimize this problem.

For Mono-type pumps, the bobbins holding the pump rods in place will have to be replaced periodically, in addition to the pump rods and drop pipes. In general, the pump itself is very long-lasting and will probably require replacement only every seven to ten years under normal use. For diaphragm pumps, the part that is most likely to need periodic replacement is the diaphragm, every three to five years. Typical frequencies for the maintenance and repair needs of many pumps are given in the "Handpump Compendium" section in Arlosoroff et al. 1987.

A reasonable estimate for a typical cost range for the maintenance of handpumps is US$25 to US$200 per year, assuming the pump is used regularly for about eight hours per day.

Chapter 9

OPERATION, MAINTENANCE, AND REPAIR

Technical selection of pumping equipment has been explained in detail in the preceding chapters. By now, you should be able to determine which systems meet or fail to meet the pumping requirements at your site. If no systems meet the selection criteria, a reevaluation of the criteria, site, or project is necessary. Assuming that you have narrowed the choice down to one or more system options that are technically acceptable, you must now make certain that these pumping systems can be operated and maintained properly.

Before further selecting systems from among the remaining equipment options you must weigh a number of additional factors involving the complex inter-relationship between the physical equipment, pump users, and infrastructural support network that keeps the equipment operating over the long run--system designers, equipment dealers, installation personnel, operators, and maintenance and repair crews. These factors are not nearly so easy to quantify as the head, the flow rate, and the various cost issues discussed in previous sections. As a decision-maker, you must determine what these factors are and weigh their relative importance.

The first important criterion in equipment selection is the technical question of whether the system can deliver the desired amount of water. The next is that proper operation, maintenance, and repair support will be available to ensure that the system will continue to supply water reliably over the long term. This requires an infrastructure that can provide the following important needs:

- spare parts inventories,
- skilled operators and mechanics,
- transportation networks,
- communication, and
- clear lines of authority and responsibility.

In each of the five broad categories of maintenance requirements covered in the following sections, a series of questions are posed that can be used to determine whether or not the local or regional infrastructure will be able to respond to the needs of the specific type, make, and model of equipment you are considering.

9.1 Spare Parts

Probably the most important determinant of whether a pumping system can be maintained over the long run is the availability of spare parts. All parts required for the pump set you select must be available at some location that is relatively near (i.e., can be reached within a reasonable time) or the pump's first failure may mean the end of its service life. Servicing guidelines for diesel engines (often provided by manufacturers) usually divide spare parts into two groups--fast-moving spares and other parts. Fast-moving parts include items needed for preventive procedures and common corrective maintenance, such as gaskets, belts, and injector nozzles. These should be readily available at a nearby location for the engine make and model you choose. Other spare parts that are less commonly needed include cylinder heads, crankshafts, and flywheels. These must also be available, but since the need for them is likely to be less frequent, you may be able to tolerate a longer delay in obtaining them.

For handpumps and windmills, fast-moving spare parts that are often needed are essentially limited to cup or cylinder leathers and wooden sucker rods for windmills. Since these are few in number and relatively inexpensive, these systems are less vulnerable to outages caused by a lack of parts than diesel engines, which require many fast-moving parts. Solar PV pumps do not typically require any fast-moving spare parts, although all hand, wind, and PV pumping systems will occasionally require unexpected repairs (such as replacement brushes for some PV motors). The parts needed to complete these repairs--e.g. a handpump head, windmill blade, or invertor--may only be needed every three, five, or ten years. However, when breakdowns occur, these spare parts should be available in local or nearby regional inventories, since it is highly unlikely that they can be fabricated locally under most circumstances found in developing countries. The more fast-moving the part, the more widely it should be distributed. For example, diesel belts should be available at the local level, but pump cylinders or PV modules need only be available at the district or perhaps national level.

It is possible that parts may only be available at greater distances from the site (i.e., from a central or regional, rather than a local, inventory), so a longer period may elapse before repairs are completed. In that case, the system designer and users must decide how they will meet water requirements until the system can be repaired. In some instances, especially if the part is very expensive and the number of systems being supported is small, it may be too expensive to maintain a regional inventory, so high-cost spare parts will have to be imported on an as-needed basis. If this is the case, it is essential that there be a communication and distribution network in place already, including import agents and distributors, and that planners and water users understand how much time is required to procure imported parts. One solution is to maintain a local inventory of at least one complete set of all spare parts for a system. These can be replaced as they are used.

To get a clear picture of the possible difficulties in obtaining required spare parts for the remaining equipment options, answer the questions below.

1. Are all spare parts available locally at the pump site? List the name of local shop(s) or agent(s) and the types of spare parts they carry.

2. How far is the nearest location outside the village where fast-moving spare parts for your pump set are available? List the name of the village, the distance from the site, and the name of the shop or agent.

3. Where do you have to go to get uncommon spare parts (usually the same location where full service and overhauls are available)? List the names of the agents and the spare parts and service they can provide.

4. How long does it take to get spare parts when they must be ordered or imported?

9.2 Skilled Operators and Mechanics

The second broad category under O&M requirements is skilled personnel. The skills required to operate a pumping system are very different from the technical and diagnostic skills needed to ensure a long service life and proper repairs. Tasks for operators or caretakers typically include

- starting and stopping the pump set, as required;
- performing daily checks of fluid levels (where necessary) and equipment condition;
- handling limited preventive maintenance, as the operator's training and authority and the available parts and tools allow; and
- contacting the proper authority to explain specific problems, when needed.

Operators and caretakers are the most important human component in successful system operation. They form the first line of defense in the ongoing effort to keep a pumping system operational.

Mechanics are necessary when the required maintenance or repair procedure is beyond the operator's authority, capability, or capacity. Typically, mechanics must have

- mobility to travel to the pump site,
- the ability to accurately diagnose problems in the system,
- access to necessary tools to complete minor and major repairs, and
- the skills needed to make complicated repairs in the field.

If individuals in the community possess repair skills, this will help assure that a broken down system is returned to service promptly. Handpumps and windmills are most suitable for local repairs. Since the skills needed are fairly limited, people in the community can be trained to perform most maintenance and repair tasks. The widespread use of diesel engines for pumping water and generating electricity in isolated areas means that there are usually some area mechanics who are at least partly skilled. If the level of local repair capabilities is doubtful, skilled personnel from outside the immediate community may be necessary to ensure that proper maintenance procedures are followed.

Solar pump repairs can require specialized skills that are not normally found in rural areas. Individuals with basic skills in electricity may be available, but the specialized nature of PV technology may mean that suitable technicians will not be available even within the region. Although solar pumps rarely need curative maintenance, it is still important to consider who will perform such repairs. If mechanics are only available regionally, you should also consider how far they may be willing to travel.

To determine the availability of qualified operators or caretakers and trained technicians as well as their potential ability to handle maintenance and repair functions, you should answer the following questions.

Operators

1. Do the people nearby that might serve as potential operators or caretakers have any experience or familiarity with the equipment you are considering?

2. Are there individuals with sufficient education and mechanical aptitude that could be trained to perform these functions well?

3. Are operators likely to have the tools needed to operate the system properly and handle minor repairs?

Mechanics

1. Are skilled mechanics and/or electricians available in the village who have general mechanical, engine-repair, and/or electrical skills?

2. How far must mechanics trained in engine and/or electrical repairs travel to assist with maintenance of the pumping system?

3. Are mechanics from outside the community available year-round, or would transportation problems or other responsibilities make them unavailable sometimes?

4. Can arrangements be made to provide training to mechanics and technicians so that the necessary skills are available when needed?

For all of the above items, you should also consider: How much will this cost? Who will pay for it?

9.3 Authority and Responsibility

The ultimate authority and/or responsibility for a water supply system may rest with a local community leader or organization or a regional or central government agency. When local persons or groups are responsible, they must have sufficient funds and the capacity to mobilize resources to respond to problems, as necessary, if their authority is to be meaningful. If a regional or central organization is responsible, it must be responsive to local needs for maintenance and repair that cannot be handled at the local level.

Regardless of where the formal authority lies, some degree of community responsibility is always important in the successful operation of water supply systems. The choice of technology should take into consideration the capacity of a village to be responsible for a pumping system and the availability of outside sources of periodic assistance. In general, less complex technologies are more suitable for situations where local authorities have responsibility for a system. More complex technologies that require higher levels of O&M support are more appropriate when authority for a system is more centralized.

For example, if care is taken in selecting a handpump, it is likely that most maintenance functions can be carried out locally. At the other extreme, most repairs of solar pumps must be performed by outside agents, who should be clearly identified prior to making a commitment to that technology. This does not mean that solar pumps are necessarily a bad choice, only that there must be responsive mechanisms for maintenance and repairs to ensure the long-term reliability of the system. Diesel systems usually require the largest ongoing commitment of resources because of the complexity of engine O&M relative to other technologies. Sometimes, a community will have a qualified mechanic who is available to perform service functions, assuming that spare parts are available. Since the quality of local mechanics varies considerably, it is important to check thoroughly the experience of the person designated as a local mechanic. Sometimes, "repairs" can leave the system in worse shape than before. For the most part, windmills can be serviced locally, with the possible exception of changing the pump leathers.

To clarify the lines of authority and responsibility for your system, answer the questions below.

1. What person or organization has ultimate authority over the water supply system? Is this authority local or centralized?

2. Does this person or agency have control of the financial resources necessary for successful O&M? If not, which organization does? Is obtaining funds a major problem for the community or user group when the need arises? Does any other group, in the private or public, formal or informal sectors, have the capacity to respond when problems occur? Are existing cost-recovery schemes (e.g., user fees) adequately enforced at the local level, so as to ensure the availability of O&M funds when they are required?

3. What group or individual in the community or nearby area has responsibility for the water supply system at the local level? Is the group or individual responsible to a local or central authority? Is the responsible party paid or a volunteer? Does it have other functions (e.g., village development or health) that may reinforce or get in the way of its responsibilities for the water system? If an organization is responsible, is it likely to represent a faction of the community or the whole village?

4. Does this responsible party feel it can effectively bring resources to bear on operational problems when needed? If it must call on an outside organization for O&M assistance, will this other organization respond in a timely fashion?

5. If there is a backup system or secondary water source, is it under the same authority as the primary system?

9.4 Transportation

As long as spare parts, skilled labor, and/or fuel must be brought in from outside a village for some or all O&M functions, the quality of the local and regional transportation network must be considered in equipment selection. Factors to be considered include distance, travel time, the quality of roads and whether they are passable year-round or only seasonally, and the availability of vehicles or other means of transportation. For systems that have great needs for outside support, these are very important issues. That is why it is an advantage if skilled personnel and spare part inventories are available locally.

Since the transportation network is critical in moving technicians, parts, and materials to a pump site quickly and efficiently, answering the following questions will give you an understanding of what characteristics of that network affect the long-term operation of a system.

1. What means of transportation are readily available for travel to nearby towns or villages to obtain spare parts or technical assistance--bus, official transportation, private vehicles, other modes?

2. What distances must be traveled to obtain spare parts and to summon mechanics?

3. How long do these trips typically take?

4. Are light- and heavy-duty trucks (four-wheel drive, if necessary) available to transport heavier equipment and spare parts to the site? If not, how can they be made available?

5. How much do these different means of transportation cost per kilometer or trip?

6. Are fuel and parts for vehicles readily available on a year-round basis?

9.5 Communication

Ineffective communication is often a factor in long periods of system downtime, but it is frequently overlooked. There are generally two types of communications problems--response time and inaccurate or incomplete information. If it takes two days to summon assistance, every service requiring such communication requires at least two days plus the time needed for a response. In addition, because messages are often incomplete or inaccurate, maintenance and repair crews might bring the wrong personnel, parts, or tools. A simple message like "there is no water" is not very helpful to a maintenance crew that is trying to decide what spare parts and tools will be required. The crew may have to make an additional trip to complete the repair. The need for rapid, accurate communication of the nature of a problem to the proper person or agency is important in assuring a timely, appropriate response. One suggestion is that all site operators be given written forms (perhaps postcards) with the address and telephone number of the repair crew dispatcher, along with several questions which need to be answered when reporting problems.

The following questions focus on important communication issues.

1. Are the proper steps for summoning maintenance and repair assistance clear to the operator/caretaker and users?

2. Does the operator/caretaker have the training and skills to report most problems accurately to the maintenance/repair crew?

3. When outside assistance is needed for maintenance and repair, how is assistance summoned? Are these channels of communication open year-round? Do they depend on verbal, written, or radio messages?

4. Is assistance requested from different sources, depending on the nature of the problem? If so, list the various types of problems and the corresponding sources of assistance.

5. When assistance is summoned, how long is it likely to take to get a response from each source of help?

9.6 Summary

Evaluating the capability of a maintenance structure is neither simple nor straightforward. It requires an assessment that is based on specific local conditions and the type of equipment being considered. In the process of such an evaluation, there are several important points to keep in mind:

- local capability (e.g., for operation, maintenance, repair, and/or spare parts inventories) is always an advantage;
- complex systems are likely to need more maintenance than simple ones;
- well-known technologies and systems that are easily understood increase the possibilities for local repairs;
- the acceptable length of time for skilled technicians to get to your site with appropriate tools and spare parts depends on water availability requirements and backup sources of supply;
- to the extent possible, maintenance functions should be integrated into the existing infrastructure, either government-operated or private--do not try to set up new organizations to support new types of equipment; and
- be sure to consider the need for and cost of ongoing training in O&M procedures.

While it is impossible to guarantee that an existing maintenance and repair infrastructure will be responsive in the future to needs associated with the equipment you choose, careful consideration of answers to the questions listed in this section should give you a good indication of the likelihood for successful long-term operation of the system.

The final section of this manual addresses the major remaining issue involved in pump selection—costs. An analytical method called present-worth analysis is applied to the two major components of pumping system costs (i.e., capital and recurrent costs) to compare the costs of pumping water with different types of systems.

Chapter 10

FINANCIAL AND ECONOMIC ANALYSIS

The first step in choosing a pump is to select one or more options that will meet the technical requirements at your site. This will probably narrow down the choice. The next step is to find out which of the remaining options can be successfully supported by the O&M infrastructure available in your area. This will probably reduce the number of choices even further. Finally, you need to develop a comparative cost analysis that will allow you to compare the few viable systems left on the basis of life-cycle cost. Life-cycle cost is the basis for an economic comparison called present-worth or present-value analysis. It takes into account all costs incurred over the useful life of your system, including those for the initial equipment (capital costs), installation, operation, maintenance, and repair.

10.1 Present-Worth Analysis Method

While there are many kinds of comparative economic methods, present-worth analysis is a convenient method for assessing the relative costs of different pumping systems. This method analyzes all costs associated with installation and use of a pumping system by reducing them to a single number called the present worth or value. Dividing the present value by the total volume of water pumped over the system's lifetime gives a unit cost for water, referred to here simply as unit cost. Calculating unit costs for two different pumping systems that are designed to deliver the same volume of water from the same head allows you to make direct financial and economic comparisons between the two. This approach can only be used to compare systems that are delivering the same daily output for roughly the same head range. It does not address the question of benefits, so you cannot determine whether the benefits of the pump installation (in terms of increased health benefits or number of gardens irrigated, for example) will be worth the cost.

This chapter describes the method for present-worth analysis by discussing typical cost components (capital costs, recurrent costs for operation, maintenance, and repair), discussing the analytical method, and then taking you through an example showing how it is applied. The distinction between financial and economic costs is discussed, with an example that shows the difference between those two concepts. In general, a system's financial cost is determined from the user's viewpoint, while the economic cost is based on the perspective of the government or society as a whole. Since financial and economic unit costs can vary considerably, it is possible that selection of the most cost-effective system may depend on which perspective you take.

10.2 Types of Costs

Present-worth analysis divides system costs into two basic groups--installed capital and recurrent costs. Installed capital costs are all assumed to occur at the start of a system's lifetime (i.e., time zero). All later costs (e.g., for operation, maintenance, and spare parts) are recurrent costs.

To determine whether potential owners or users of a pumping system can afford to own and operate it, it is important to estimate all costs as accurately as possible and then examine the cash flows needed to meet future recurrent costs. Some systems (e.g., diesel pump sets) have low capital costs, but high recurrent costs. Others, such as wind and solar systems, have high capital costs, but low recurrent costs. Who will pay these different costs may have a significant impact on the choice of a system. If a system is not going to be wholly dependent on outside funding (e.g., completely subsidized by the government or paid for by a donor organization), it is important to know what cost-recovery mechanism(s) will be used. Will recurrent costs be funded by water-user fees? Are users willing to pay them? Up to how much? Will the government or some other funding source cover a fixed percentage of recurrent costs? Careful consideration of these questions is crucial when selecting a system.

A system's installed capital cost is the total figure for all equipment, materials, labor, and transportation needed for complete installation of a functioning system. Recurrent costs generally include:

- an operator's salary;
- wages for a mechanic to handle regular service and breakdowns;
- spare parts and replacement components;
- transportation, including a driver; and
- overhauls, when necessary.

Recurrent costs can be subdivided into fixed annual, variable annual, and non-annual costs, which are defined in the sections below. Each category can include costs for materials, labor, and transportation. A matrix showing all the different types of system costs is as follows:

	Installed Capital Costs	Recurrent Costs fixed	Recurrent Costs variable	Recurrent Costs non-annual
Materials				
Labor				
Transportation				

It is not necessary to consider costs that are common to all of the systems analyzed. For example, assume you are considering using one small diesel engine, one solar pump, or two handpumps to meet demand. For the diesel or solar system, you only need one well or borehole. For the two handpumps, you may need to dig a second well or borehole. If the cost of water source development varies between alternatives, include those costs in your analysis. Depending on the particular application, you may need to consider other additional costs, such as:

- well construction or drilling;
- field surveys;
- design work, including engineering drawings; and
- water storage tanks, which may or may not be needed for different systems and can vary in size.

Where appropriate, these costs should be included in the matrix shown above. Sections 10.2.3 and 10.2.4 give detailed descriptions of how to estimate costs for each part of the matrix.

10.2.1 The Discount Rate

The present worth of recurrent costs is determined by making assumptions about the discount rate and useful life of the system, also called the term of the analysis. The discount rate is used to calculate the present worth of future costs (for instance, replacing a windmill cylinder after five years of operation). It is based on what economists would consider the buyer's best alternative investment. If the best alternative is investing money in a bank at 10 percent interest, the assumed discount rate is 10 percent. This rate may vary for different investors, since deciding on the best alternative depends on personal circumstances and their willingness to take risks.

Discount rates differ according to the user. You have to estimate the return on the best alternative investment given local conditions and users' perceptions. Individuals in the private sector may be reluctant to borrow money because of uncertainty about the future, in which case discount rates may need to be as high as 20 percent. For economic analysis, suitable rates are determined by government economists. The World Bank often uses economic discount rates of 10 to 12 percent. The discount rate can have a large effect on the results of analysis, particularly when competing alternatives differ markedly in their capital and recurrent costs.

10.2.2 The Term of the Analysis

The term of the analysis must be ascertained. Usually, this is the same as the useful life of the major system component that will last the longest. For example, with solar pumps, the longest lasting component is the PV array, which has an estimated life of 20 years. Obviously, not all of the other components will last that long. They will have to be replaced periodically as they fail. The cost of repair or replacement for these components is included in the recurrent costs. Similarly, for a diesel pump, the term of the analysis is the engine's useful lifetime. It can be overhauled several times, but eventually it will have to be replaced. To compare different systems using present-worth analysis, you have to use the same term of analysis for all of them. For example, you want to compare a solar pump and a diesel system. The term of the analysis is assumed to be 20 years, and diesel engines in your area are expected to last only 10 years. You can still use this method by simply assuming that you replace the diesel engine at the end of the tenth year, considering it as a recurrent cost.

10.2.3 Installed Capital Costs

In this section, ranges are given for typical capital and recurrent costs associated with the installation of each type of system. In some cases, these ranges are wide because of the degree of variability in power and differences in where the equipment is purchased and used. When possible, it is best to get more precise cost information from local distributors before doing a present-worth analysis. The installed capital cost for a pumping system includes equipment costs for the power source (driver) and pump, other materials, civil works, and associated labor and transportation costs. The driver could be a diesel engine, a solar array and controller, a windmill head with a tower, or a handpump head. Be sure to include the cost of required accessories. All capital equipment costs also depend on import taxes, duty requirements, and freight charges from the country of origin, but these should be kept separate for the economic analysis.

<u>Diesel Systems</u>

Costs for diesel engines are affected by the rated output, quality of the equipment, and location of the manufacturer. They range from US$500 to US$1,000 per kW. Other major items for diesel systems include:

- the pump and transmission, if any;
- pump houses and fencing, for security and protection of equipment and materials; and
- other components for water storage and distribution, such as tanks, piping, and valves. Under some conditions, the need for a completely reliable system involves considering the purchase of a spare engine and/or pump. In most cases, a good water

meter and pressure gauge should also be purchased for diagnostic purposes.

In addition to these more expensive components, lower cost items needed to install a functioning system can add up to a total that is a significant portion of the overall materials cost. They include engine frames, foundation bolts, non-return valves, unions, gate and pressure-relief valves, spare pulleys, belts or drive shafts, and some tools for operator servicing. Required materials also include cement, sand, gravel, reinforcing mesh, and/or "re-bar" to make a concrete foundation for the engine (or windmill tower, solar array's mounting frame, or handpump base), as well as fencing. These can amount to 10 percent of the equipment's total capital costs. A complete list of parts and materials for each of the four system types is given in Appendix E. Typical costs for diesel pumping systems are given in Table 4.

Table 4

Typical Capital Costs for Diesel Pumping Systems
(in US $)

diesel engine (2 to 10 kW)	1,000 to 4,000
pump (complete)	500 to 3,000
civil works (pad, pump house)	500 to 1,000
other (valves, fuel tanks)	1,000 to 3,000
Total System Cost (CIF*)	3,000 to 11,000

* Cost/insurance/freight (delivered price)

Solar-Powered Systems

For solar pumps, PV modules are the most expensive component. Other system components include the pump, motor, array support structure, wiring, and controller and/or batteries. Array costs are in the range of US$4.0 to US$4.5 per W_p, from the point of manufacture. This cost can easily rise to US$9/$W_p$ or more where distribution and shipping costs are high. In most cases, motors and pumps for a solar system are purchased together because solar pump manufacturers design and match pumps and motors to maximize subsystem efficiency. Controller costs vary considerably depending on the type of control system chosen and the country of manufacture. Some manufacturers may specify controllers that are designed to operate with their systems. Array support structures cost from US$100 to US$200 for racks that hold four to six modules. Wiring costs are usually US$50 to US$200. Unlike diesel pumps, neither PV nor wind systems normally require pump houses, but all three require fencing.

Table 5

Typical Capital Costs for Solar Pumping Systems
(in US $)

PV array (0.6 to 2.2 kW_p)	3,600 to 20,000
pump (no submersible motor)	200 to 700
motor (0.5 to 2 kW)	200 to 800
submersible pump set (motor, pump, and invertor, if needed)	1,500 to 4,000
controllers (where needed)	100 to 1,600
civil works (pad, fencing)	300 to 1,000
other (wiring, racks, rods, meters)	200 to 1,400
Total System Cost (CIF)	4,600 to 28,000

Wind Systems

Windmill and tower costs are highly dependent on shipping charges, as these machines tend to be heavy. In general, units are supplied complete, with no additional or optional parts to be considered. The cost for a windmill head will generally be higher for rotors with larger diameters. The range of costs is US$200 to US$500 per square meter of rotor area. Simpler designs that are fabricated locally or regionally are likely to be less expensive than American or European windmills of similar size. Tower costs are proportional to the size and to the quality of construction; they range from US$1,000 to US$3,000, depending on whether the tower is made locally or purchased and imported with the windmill. Cylinder costs are often dependent on design, with high-quality, ball-valve cylinders being more expensive than those with flap or spool valves. Other items include the drop pipe, pump rod, pipe clamp at the wellhead, cement for the foundation, and fencing.

Table 6

Typical Capital Costs for Wind Pumping Systems
(in US $)

windmill head (cost is a function of size)	600 to 8,000
tower and associated hardware	1,000 to 4,000
pump cylinder with spare leathers	100 to 800
other (foundation, tank, piping)	500 to 2,000
Total System Cost (CIF)	2,200 to 15,000

Handpumps

Handpump costs vary considerably depending on the country of origin. You might assume that locally fabricated units would be the least expensive, but this is not always the case. Handpump costs range from US$300 to US$1,000.

Table 7

Typical Capital Costs for Handpump Systems
(in US $)

handpump head	300 to 1,000
pump cylinder with spare leathers	100 to 400
pump rod (depends on depth)	10 to 150
other (foundation, drain, piping)	100 to 400
Total System Cost (CIF)	510 to 2,000

Besides equipment and materials, capital costs also include the labor and transportation associated with installation. Labor costs are often divided into skilled, semiskilled, and unskilled components. This is partly because the daily or hourly rates are different for these groups and because the unskilled portion is often valued below the wage rate in the economic analysis (see Section 10.4). You should have some idea of labor costs or daily rates for these three groups, including any relevant per-diem or other allowances. Remember to include the preparation associated with collecting tools and equipment in your estimates for installation time.

Time Required for Installation

Assuming that the well is already developed, the minimum amount of time required for installation of a diesel pump is about three to five days and includes pouring a foundation, lowering the pump, installing the engine, and building a prefabricated metal pump house. Solar pumps often take a bit longer but should require no more than seven to eight days, unless the crew is very inexperienced. For the first few installations of any system, the need for on-the-job training will increase installation time somewhat. Windmill installation can easily take up to ten to twelve days in typical developing country situations. Handpumps can typically be installed in two to three days, if all goes well. These figures should be used only as general guidelines for estimating the actual time needed for an installation at your site. Your estimate will depend on the number of people in an installation crew as well as on their training and familiarity with the particular type of system being installed. The size of a typical crew varies from three to ten, of which one to three are usually skilled laborers.

Transportation Costs

Transportation costs are affected not only by the distance to the site, but also by the type of vehicle used and the number of trips. Remember that it may be necessary to make more than one trip to the site to move all the equipment, gear, and personnel needed to complete the installation. Thus, the total transportation distance can easily be two to three times the round-trip distance from the installation center to the site. The type of vehicle(s) affects transportation costs because light, two-wheel drive trucks are less expensive to operate and maintain than heavier four-wheel drive vehicles and trucks, which may be needed for some installations, such as windmills. To get some idea of transportation costs, talk to vehicle rental agencies or truck users in the private sector. Often it is possible to get a daily rental figure plus a mileage charge, which will probably not include fuel costs. Rental agencies usually have a good estimate of typical fuel use per kilometer.

Once these cost components have been calculated separately, they are added together to determine the installed capital cost. All other costs associated with operation, maintenance, and repair are recurrent costs.

10.2.4 Recurrent Costs

As mentioned above, recurrent costs can be divided into fixed annual, variable annual, and non-annual costs. This section discusses these cost components for all four system types considered in this manual.

Fixed Annual Costs

Fixed annual costs for a pumping system are annual recurrent costs that are not affected by the amount of use a system receives. The major types of fixed costs do not fall neatly into the materials, labor, and transportation categories used above. Rather, they include such items as overhead, finance charges (e.g., interest on a loan used to buy the system), and labor costs for an operator, if any. For example, fuel is not a fixed cost since it depends on how much the engine is run.

Whether or not there are overhead costs and how high they are depends on the way a pumping system is managed and maintained. Overhead can include costs for such things as record-keeping or maintaining a vehicle, office, warehouse, spare parts inventories, or headquarters staff. These costs are often omitted from comparative analysis on the assumption that they will be similar regardless of the system chosen, but this is not necessarily the case. If a system was paid for with cash from business operating funds, personal monies, or a grant, there will be no interest charges.

The labor cost for an operator is usually a fixed cost that depends on the type of pump and daily average use of the system. It rarely changes with hourly usage of the pump each day. For example, diesel pumps are often run by a full-time salaried (i.e., not hourly) operator. In instances where the operator may have additional unrelated responsibilities (e.g., a maintenance person for a school or a driver), the allocation of some time to non-pumping activities can reduce labor costs somewhat. Handpump operation does not require an actual operator. However, it is important to value the time spent pumping water in the economic analysis. Typically, this time is costed at the prevailing wage rate for unskilled labor.

Variable Annual Costs

Items falling in the variable annual cost category include all materials (i.e., fuel, oil, and parts), labor (except for the operator), and transportation required for normal operation, servicing, and repair of the system. These are all the items whose use depends on the amount of time the system is operated during the year. Estimates for these costs can be made by modifying the information provided in Chapters 5 through 8 to meet the specific conditions at your site. These requirements and their associated costs are summarized here.

Annual labor costs are a function of the number and duration of trips made in response to normal service requirements and breakdowns as well as the crew's size and skill levels. Of the four systems considered here, diesel pumps will likely require the most maintenance and repair trips. For planning purposes, count on at least four such trips per year up to as many as one per month, depending on the situation. For solar, wind, and handpump systems, the number of maintenance/repair trips will probably be many fewer, in the range of one to three annually if the installation is properly done. Fewer trips may be needed if the pump operator can perform some minor servicing.

Maintenance and repair crews typically consist of a mix of skilled, semiskilled, and unskilled labor. In estimating annual labor costs for service and repair, consider the specific skill mix required for your system. In the absence of other information, assume a repair crew of three--one skilled and two unskilled--plus a driver for 70 percent of all necessary repairs. Larger crews of as many as eight will be needed for jobs like pulling pipe, replacing engines, or repairing breaks in the pipeline. Labor costs can then be estimated by calculating the total daily wage rate for smaller and larger crews, and then multiplying by the number of days required for each crew. Remember, if all labor arises from salaries included in the overhead figure discussed above, you need not calculate labor costs here.

Annual transportation costs include trips made for service and repair, as described in the preceding paragraphs. In addition, they should include trips to deliver fuel for diesel systems. The cost of such trips will depend on the distance and the type of vehicle used. The distance traveled may or may not be the same as the installation distance--it depends on the relative locations of service facilities and the pump site. You should also consider that it may be possible to combine trips in some cases (e.g., regular servicing and a delivery of diesel fuel).

The type of vehicle used will depend on what is available, plus the requirements of the job and the condition of the roads to the pump site. Of course, lighter vehicles should be used when possible, but this may not always be practical given other constraints. As described above, vehicle charges are often given as a daily rate plus a mileage charge plus fuel. As appropriate, include these figures in calculating transportation costs. Again, if the cost of vehicles is figured into the overhead, the variable annual transportation costs should be reduced or eliminated. Typically transportation costs range from US$0.25 to US$1.00 per kilometer.

Non-Annual Costs

Non-annual costs are those that do not usually recur every year. Costs in this category are treated differently because of their intermittent nature. They include such items as major or minor overhauls for diesel systems, or the replacement or repair of any major system component during the term of the analysis.

For diesel systems, non-annual costs include the overhaul and replacement of the engine, pump, and down-hole components, as necessary. Non-annual costs for solar pumps include the overhaul or replacement of batteries, controllers, electric motors, and down-hole equipment, as well as the replacement of solar modules in case of vandalism or theft. For windmills, non-annual costs will likely be limited to the replacement of the pump and down-hole components--the drop pipe, sucker rods, leathers (if these are not replaced annually), and pump cylinder. The only non-annual costs for handpumps will probably be the replacement of the down-hole components and possibly the pump-head or bearings. For all systems, other non-annual costs may include the repair or replacement of civil works, storage tanks, fences, pump houses, and wells (particularly if hand-dug wells are used).

Summary estimates of recurrent costs for the four types of systems considered in this manual are given in Tables 8 to 11.

Table 8

Recurrent Costs for Diesel Pumps

Fixed Annual	
interest on loan	if applicable
pump operator	varies
Variable Annual	
diesel fuel	
oil and filter changes (monthly)	1 day of labor + US$5 to US$15 each
minor repairs (3-6 times annually)	1 day of labor each + US$10 to US$100
Non-Annual	
engine ove.haul	every 2 to 5 years
replace/repair pump and/or pipes	every 5 to 10 years

Note: Fixed costs must be determined based on local practices and specific site conditions. Fuel costs can be calculated using the method given in Chapter 5. The oil and filters (if any) may need to be changed more or less often depending on engine use and operating conditions. For an engine that is used eight to nine hours a day, the oil and filters should probably be changed once a month. Repair costs are highly variable and will be affected by the quality of preventive and curative maintenance. The values given above are typical. Engine overhauls and repair or replacement intervals for the pump and piping are also highly variable. The values shown are indicative of average conditions in developing countries.

Table 9

Recurrent Costs for Wind Pumps

Fixed Annual	
interest on loan	if applicable
pump caretaker, if any	varies
Variable Annual	
replace leathers and oil or grease	1 day of labor + US$5 to US$15
repair 1 to 4 times annually	1 day of labor each + US$0 to US$100
Non-Annual	
replace cylinder and pipes	every 5 to 10 years

Note: Depending on water quality and the extent of pump use, leathers may need to be replaced more often than annually. Other repairs may be required more or less often depending on the quality of the installation and the users' care of the windmill. The replacement interval for the pump cylinder and piping will depend largely on water quality. If the water has highly aggressive or abrasive characteristics, the cylinder and pipes will have to be replaced often, perhaps even more often than indicated in the range.

Table 10

Recurrent Costs for Solar Pumps

Fixed Annual	
interest on loan	if applicable
pump caretaker, if any	varies
clean array, check wiring	1 hr of labor per week
Variable Annual	
replace leathers (for piston pumps)	1 day of labor + US$5 to US$15
minor repair 1-2 times annually	1 day of labor each + US$0 to US$300
Non-Annual	
repair or replace motor/pump	every 3 to 5 years
repair or replace electronic parts	every 3 to 5 years
replace cylinder (if any) and pipes	every 5 to 10 years

Note: Predicting the long-term frequency of repairs and replacement for solar pump components is difficult because few systems have been in operation for more than three to five years. Many early units required the replacement of major components every year or two, particularly for electrical components such as controllers, inverters, and motors. Newer units have surmounted most of those early problems, and much longer component lifetimes are becoming more common. Minor annual repairs consist primarily of replacing poor electrical connections or vandalized modules, if necessary.

Table 11

Recurrent Costs for Handpumps

Fixed Annual	
interest on loan	minor, if applicable
pump caretaker, if any	varies
Variable Annual	
replace leathers	1 day of labor + US$5 to US$15
repair 1 to 4 times annually	1 day of labor each + US$0 to US100
Non-Annual	
repair handle/replace bearings	every 1 to 4 years
replace cylinder, pipes, and rods	every 5 to 10 years
replace pump-head	every 5 to 10 years

Note: Generally, the maintenance and repair requirements for handpumps will be easier to meet, and costs will be lower if the drop pipe does not have to be pulled to replace the leathers or fix the cylinder. Handpumps designed using the VLOM concept will have fewer needs for more expensive repairs by personnel from outside the immediate area.

10.2.5 Filling Out the Cost Matrix

The cost matrix for capital and recurrent costs shown at the beginning of this section should be completed based on the information given above. Two matrices will be necessary if a financial and an economic analysis are carried out. Differences between the two matrices are discussed in Section 10.4.

Note that, for the sake of simplicity, inflation of specific costs over and above the general rate of inflation has not been discussed in this section. While it is true that any or all of the costs discussed here can change (increase or decrease) at a rate different from the general rate of inflation, it is often very difficult to predict the magnitude (or often, even the direction) of those changes. If you have information which convinces you to believe that one or more of the capital or recurrent costs of operating your pumping system will change over the period of the analysis, factor that information into the analysis. Better yet, make several calculations of the unit cost using different assumptions about the change in one or more variables. This "sensitivity analysis" will allow you to see what effect your assumptions have on the unit cost.

10.3 Present-Worth Analysis

This section discusses the analytical method for present-worth analysis. It requires that all future costs be discounted to their present worth, which is most easily accomplished by grouping costs in such a way that simple formulas can be used to calculate the present worth of each group. A list of all relevant formulas used in present-worth analysis is provided in Appendix F.

For the purpose of the analysis, installed capital costs are already present costs. Fixed and variable annual costs for materials, labor, and transportation should be combined to get a total for annual recurrent costs that will be the same for each year of the analysis, if it is assumed that the equipment is operated for the same amount of time every year. Use Equation One to calculate the total present value of these costs.

Equation One:

$$P = A \times \frac{(1 + d)^n - 1}{d \times (1 + d)^n}$$

where P = present worth of a uniform series of future costs
A = annual amount or payment
d = discount rate, as a decimal
n = term of the analysis in years

Note: To simply this calculation, a table of factors which can be used to calculate the present worth of a uniform series of future payments (or costs) are given in Appendix F. To use them, take the annual payment (A) and multiply by the "F1" value given in the tables for a particular interest rate and term of analysis ("N") (see Example 17 below).

Non-annual costs must be treated individually. For each occurrence of a non-annual cost, Equation Two should be used to calculate its present value. It should also be used instead of Equation One to calculate the present worth of individual total annual costs if they vary from year to year over the term of the analysis (i.e., if pump operation varies from year to year). Example 17 demonstrates the method.

Equation Two:

$$P = F \times (1 + d)-y$$

where P = present worth of future cost
F = future amount
d = discount rate, as a decimal
y = year of occurrence for the future cost

Note: To simplify this calculation, tables of the present worth of a single future payment (same as calculated in Equation Two) are given in Appendix F. See Example 17 below for their use.

Example 17: Calculating Present Worth

Assume that the discount rate is 12 percent over the 20-year term of this analysis. The following table shows expected costs over the life of the pumping system you are considering.

	Installed Capital Costs	Recurrent Costs			
		fixed	variable	non-annual	
Materials	3,000		750	1,000	500
Labor	500	1,000	100	100	75
Transportation	300		50	50	50
Total	3,800	1,000	900	1,150	625

Of the non-annual costs shown, the first (totaling $1,150) occurs in year 10. The second ($625) occurs in years 5 and 15. What is the present worth of this system? The present worth of installed capital costs is $3,800. The present worth of fixed and variable (here assumed to be constant) annual costs is given by Equation One:

$$P = A \times \frac{(1 + d)^n - 1}{d \times (1 + d)^n}$$

Substituting values from the table above:

$$P = (\$1,000 + \$900) \times \frac{(1 + .12)^{20} - 1}{.12 \times (1 + .12)^{20}} = \$1,900 \times 7.47 = \$14,192$$

Note: you could simply look up the corresponding value in Appendix F as follows: Look down the term of analysis ("N") column to 20 years, go across to the "F1" column and the appropriate interest rate (12 percent) and read the value 7.4694. Multiply $1,900 (from above) by 7.4694 to get $14,192. The present worth of each of the three non-annual costs must be calculated separately.

Example 17: Calculating Present Worth (contined)

At year 5: $P = \$625 \times (1 + .12)^{-5} = \$355$
At year 10: $P = \$1,150 \times (1 + .12)^{-10} = \$370$
At year 15: $P = \$625 \times (1 + .12)^{-15} = \$114$

Note: You could simply look up the multiplier value for these three calculations in the table in Appendix F as follows: Look down the term of analysis ("N") column to 5 years, go across to the "F2" column and the appropriate interest rate (12 percent) to get the value 0.5674. Multiply the year-5 value of $625 (from above) by 0.5674 to get $355. Similarly, multiply the year-10 value of $1,150 by 0.3220 to get $370, and the year-15 value of $625 by 0.1827 to get $114.

Therefore, the present worth of all costs is:

$$\$3,800 + \$14,192 + \$355 + \$370 + \$114 = \$18,831.$$

Note that this example did not consider the amount of water pumped, nor was a unit cost calculated. This procedure will be shown in the example in the next section.

10.4 Financial Versus Economic Analysis

The basic difference between financial and economic analysis is one of perspective. Financial analysis relates to private costs and benefits, while economic analysis is concerned with social costs and benefits to a community or nation. Usually, the private sector is more concerned with financial analysis. Analysis done to address public-sector needs is often economic. Whether you should perform one or both depends on who provides the money and what the objectives of the pumping system are.

The major difference in calculating financial and economic present worth is making allowances for factors that have social impact, such as,

- foreign-exchange costs and interest rates,
- taxes and subsidies,
- employment generation, and
- training costs.

These allowances are commonly called shadow prices. For example, in most developing countries, the economic cost of labor is less than the actual financial cost. This means that when there is a labor surplus (in most developing countries, this pertains only to unskilled labor), the economic cost to the country or society as a whole is less than the market price or current wage level. Shadow prices are used to reflect the difference between the market price and the true value of goods, services, and other production factors. The shadow price for unskilled labor is a multiplier (usually between 0.4 and 0.7) that decreases the actual cost of unskilled labor in an economic analysis. Its value is usually determined by government economists and planners.

You should note that when the economic cost for labor is less than the financial cost, labor-intensive systems--those with proportionally higher labor requirements--become more attractive than capital-intensive ones from an economic perspective. For instance, this means that the unit cost of a diesel system, which has a higher proportion of labor costs and lower proportion of capital costs than other systems, is lowered by the shadow-pricing of unskilled labor. Similarly, the unit costs of capital-intensive systems such as wind or solar are increased when foreign exchange is shadow-priced at a value greater than one.

In some countries, foreign-exchange costs and real interest rates do not reflect true economic costs. This is evident in the large differences frequently seen in official versus free-market exchange rates. Interest rates used in economic analysis may be dictated by government economists and, thus, may not necessarily reflect the true cost of borrowing capital. In addition, the export earnings of some countries are based on the depletion of resources (e.g., mining). In these cases, funds may be available for import purchases in the short run, but not over longer terms as foreign earnings decline. Circumstances such as these lead to shadow-pricing for foreign-currency requirements that better reflect the real cost of foreign-exchange expenditures. Such shadow-pricing typically increases the cost of imported items by 5 to 15 percent.

From the standpoint of a private user or business person, taxes are part of the cost of doing business, and any government subsidy is considered a benefit. These costs and benefits are likely to influence some activities in the private sector. However, from the government's perspective, they do not represent costs or benefits at all, but merely a transfer of money and control over resources. Economic analysis does not include taxes paid as costs or subsidies as benefits. Actually, taxes and subsidies are often used as mechanisms to help manipulate private-sector activity to bring it more in line with what the government believes is the greater national good. Interest paid on domestic loans and depreciation allowances also fall into this category of transfer payments and, hence, are included in financial but not economic analysis.

Training costs incurred by firms in the private sector are costs from their perspective. Private businesses train individuals with the expectation that they will benefit from their employees' increased skills and ability. However, since employees do not always remain with the firm providing the training, benefits may not always accrue to those firms. This constitutes a disincentive to the private sector to provide training. In most countries, development of a more highly skilled work force is a clearly stated goal. Training costs may not be considered in an economic analysis, if the benefits of a more skilled work force are considered to be equal to or greater than the financial cost. Private-sector training costs may be shadow-priced to reflect potential economic benefits. Example 18 shows the effect of shadow-pricing on economic analysis.

Example 18: Economic Costs

Using the information given in Example 17, calculate the economic cost for that system. The economic price of unskilled labor is one-half of the financial price. Assume that half of the labor cost is unskilled. All equipment and materials are imported, including transportation, since trucks, fuel, tires, and all spare parts must be imported. The shadow price multiplier on foreign exchange is 1.15.

First, determine the economic cost entries for the matrix given in Example 17. Multiplying the financial values of various costs by appropriate shadow price multipliers gives:

	Installed Capital Costs	Recurrent Costs fixed	variable	non-annual	
Materials	3,450		863	1,150	575
Labor	375	750	75	75	56
Transportation	345		58	58	58
Total	4,170	750	996	1,283	689

Again, the first non-annual recurrent cost listed ($1,283) occurs in year 10. The other ($689) occurs in years 5 and 15. The present worth of installed capital costs is $4,170. The present worth of fixed plus variable (here assumed to be constant) annual costs is given by Equation One:

$$P = A \times \frac{(1 + d)^n - 1}{d \times (1 + d)^n}$$

Substituting values from the matrix gives:

$$P = (\$750 + \$996) \times \frac{(1 + .12)^{20} - 1}{.12 \times (1 + .12)^{20}} = \$1,746 \times 7.47 = \$13,042$$

The present worth of each of the three non-annual costs must be calculated separately.

At year 5: $P = \$689 \times (1 + .12)^{-5} = \$391$
At year 10: $P = \$1,283 \times (1 + .12)^{-10} = \$413$
At year 15: $P = \$689 \times (1 + .12)^{-15} = \$126$

Therefore, the present economic worth of all costs (i.e., the system's life-cycle cost) is:

$$\$4,170 + \$13,042 + \$391 + \$413 + \$126 = \$18,142$$

The financial and economic present worth calculated in Examples 17 and 18 do not differ appreciably. The economic cost is slightly less (US$689). In other circumstances, however, these two costs can vary considerably. When comparing different system options, one may be cheaper economically and the other financially. In that case, the choice of a system would depend on the perspective of the potential purchaser.

10.5 Unit Cost of Water

Finally, the unit cost needs to be calculated, which depends on the amount of water pumped. For simplicity, assume that the system delivers a constant 30 m^3/day over its useful life. (Growth in water demand can be included by using a slightly more complex procedure). The economic unit cost is determined by annualizing the system's life-cycle cost and dividing that number by the annual water output, as shown in Example 19.

Example 19: Calculating Unit Cost

Calculate the unit cost of water for the installation described in Examples 17 and 18, assuming that an annual average of 30 m^3/day of water is pumped.

Solve Equation One for "A" to annualize life-cycle costs:

$$P = A \times \frac{(1 + d)^n - 1}{d \times (1 + d)^n} \quad \text{or} \quad A = \frac{P \times d \times (1 + d)^n}{(1 + d)^n - 1}$$

Substituting values from Example 18 gives:

$$A = \frac{\$18{,}142 \times .12 \times (1 + .12)^{20}}{(1 + .12)^{20} - 1} = \$18{,}142 \times 0.1339 = \$2{,}429$$

Dividing this value for annualized life-cycle cost (ALCC) by the annual volume of water pumped gives the economic unit cost:

$$\text{unit cost} = \frac{\text{ALCC}}{365 \times 30\ m^3} = \frac{\$2{,}429}{10{,}950\ m^3} = \$0.22/m^3$$

This final value--the economic unit cost of pumping water over the system's lifetime--is the figure you should use to compare this system with other options. Note that this is a somewhat simplified example, since no growth in demand has been assumed.

When evaluating capital costs and the present worth of different technology options, several other points should be considered:

- International donors are more likely to be able to provide funds to cover high capital costs than private individuals or host governments.
- Host governments are often not in a position to cover recurrent costs, even if the capital cost is provided by a donor.

- Governments may or may not be able to justify higher capital costs to benefit from lower life-cycle costs because of short-term monetary constraints.

- In most places, private-sector purchases are very sensitive to initial capital costs, such that low capital costs often influence the choice of technology regardless of the long-term implications.

It is important to make one final point in this section on comparative costs. If you are considering introducing a type of pumping system that is unfamiliar locally because it has the potential for long-term cost savings, remember that simple cost parity is not enough to convince potential buyers to adopt a new or unfamiliar type of system. There would probably have to be a significant price difference to get potential users even to consider the new system.

For example, if you are considering solar or wind pumps in an area that has historically used only handpumps or diesel systems, buyers are not likely to purchase the former simply because they are equal or slightly cheaper in cost than conventional systems. There would probably have to be clearly substantial savings associated with using the new systems to make it worthwhile for users to take the risk of installing unfamiliar equipment. The definition of substantial savings undoubtedly varies depending on the user group, its level of sophistication, education, and willingness to take risks. It may mean that new systems would have to be as much as 10 to 30 percent cheaper in terms of unit costs to be appealing. Even so, to many users the promise of future savings (even in the near future) is not enough to offset the obvious appeal of a system like a diesel pump set that has a low initial cost.

10.6 Summary

This manual has taken you through the essential steps involved in properly selecting a pumping system for a small-scale, rural water supply. Its underlying assumption is that the use of equipment which is already locally available should be the *first* strategy considered in most cases. It is most likely that the systems commonly found in your area can be serviced locally and thus meet the most critical requirement for ensuring successful long-term operation.

In summary, the approach to pump selection described here is to

- calculate the pumping requirement,

- determine what kind of equipment is available,

- review the local O&M infrastructure to see what types of equipment can be supported,

- determine which kinds of available equipment meet your site requirements and can be supported over the long term.

- calculate how much the remaining viable equipment options will cost to use, and

- select the one with the required cash flows that best fit the needs of the community or agency which will be using it.

While the technical requirements for a pumping system must obviously be met, it should be remembered that skilled labor, the availability of fuel and spare parts, good transportation facilities, and the importance of planning for future cash outlays needed to keep the system operating properly are also very important factors in selecting a pumping system.

It is hoped that this manual has clarified the procedures for determining these requirements and for comparing costs, thus assisting you to make a well-informed choice of a pumping system and components. However, the method given in this manual has been oversimplified in some ways. There are more refined tools available to assist you in selecting a pumping system. Reviewing the annotated bibliography (Appendix A) will give you some insight into areas of further interest. There are also computer programs available that are relatively easy to use and can facilitate certain parts of the method presented here, especially the financial and economic analysis. Finally, remember that additional assistance with pump selection and comparative analysis is available through activities funded by international donors, such as the WASH Project, and a variety of institutions and private firms.

APPENDIX A

Annotated Bibliography

APPENDIX A

Annotated Bibliography

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Most recent comprehensive work published by the World Bank handpump development program. An excellent reference manual for policymakers and professionals on technical, social, and economic aspects of handpump use.

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CIDA, DGIS, GTZ, USAID, and FAO. Handbook for Comparative Evaluation of Technical and Economic Performance of Water Pumping Systems. Amersfoort, Netherlands: Consultancy Services Wind Energy Developing Countries (CWD), March 1987. (Draft.)

Detailed methodology for pump testing as well as technical, institutional, and socioeconomic evaluation of diesel, wind, solar PV, grid-electric, hand, and animal-traction pumps.

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Excellent technical reference on all important aspects of groundwater development, including aquifers; well hydraulics; designing, drilling, and developing wells (boreholes); pump selection and maintenance; and water quality and treatment.

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Very comprehensive descriptions of the entire range of pumping and water-lifting devices used around the world. Gives operating characteristics and system design criteria for pumps and prime movers. Includes brief discussion of equipment selection.

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Excellent summary of power equipment costs, capacities, and descriptions, including solar, wind, water, biomass and thermal energy, internal and external combustion engines, and electrical generators, as well as instrumentation, monitoring, and control equipment. Somewhat dated on certain topics.

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Good practical reference on domestic water system design and construction, with useful sections on options for hardware and system configurations.

Helvig, O.; Scott, V.; and Scalmanini, J. Improving Well and Pump Efficiency. Denver, Colorado: American Water Works Association, 1984.

Stresses efficiency concepts in water system design. Contains detailed practical strategies for improving the efficiency of wells and water pumping systems.

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Good reference on solar pump operation and system sizing. Gives methodology for choosing PV systems based on technical selection criteria.

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Lancashire, S., Kenna, J.; and Fraenkel, P. Windpumping Handbook. London, England: Intermediate Technology Publications, Ltd., 1987.

Good practical reference on wind-pumping technology, including sizing for water supply and irrigation, and information on procurement, installation, and maintenance.

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McGowan, R., and Hodgkin, J. Water Pump Field Tests in Botswana. Burlington, Vermont: Associates in Rural Development, Inc. (ARD), 1985.

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Provides checklists for identifying sites and projects and planning and designing community piped water supplies. Useful coverage of system design process, with general focus on most relevant technical issues and good discussion of infrastructural support/planning requirements.

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A practical guide to water system design with emphasis on electrical and mechanical aspects of domestic water supplies, including sections on troubleshooting and repairs.

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Good brief summary of all aspects of village drinking-water supply projects. Covers technical aspects, costs (in summary fashion), financial aspects, organization and management, justifying investments, policy issues, and project and program design.

APPENDIX B

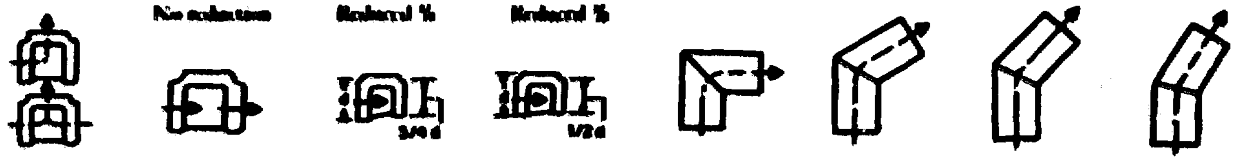
Friction Losses

* Theodore Baumeister, Euguene A. Avallone, and Theodore Baumeister, III (eds.), Marks' Standard Handbook for Mechanical Engineers, 8th ed. (New York : McGraw-Hill Book Company), pp. 12-106 and 12-109

Valve Losses in Equivalent Feet and Meters of Pipe for Screwed, Welded, Flanged, and Flared Connections

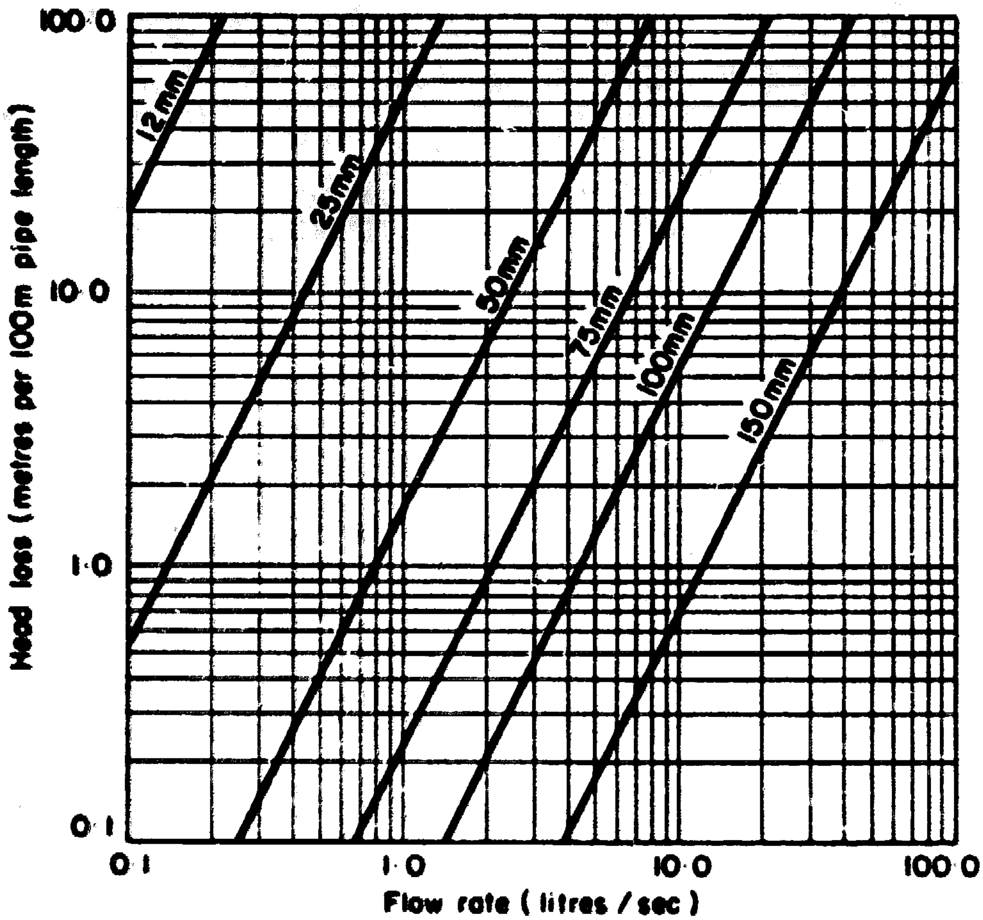
Nominal pipe or tube size		Globe*†		60° Y		45° Y		Angle*†		Gate*‡		Swing check§		Lift check
in	mm	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	
3/8	10	17	5.2	8	2.4	6	1.8	6	1.8	0.6	0.2	5	1.5	
1/2	12	18	5.5	9	2.7	7	2.1	7	2.1	0.7	0.2	6	1.8	
3/4	20	22	6.7	11	3.4	9	2.7	9	2.7	0.9	0.3	8	2.4	Globe and
1	25	29	8.8	15	4.6	12	3.7	12	3.7	1.0	0.3	10	3.0	vertical
1 1/4	32	38	11.6	20	6.1	15	4.6	15	4.6	1.5	0.5	14	4.3	lift
1 1/2	40	43	13.1	24	7.3	18	5.5	18	5.5	1.8	0.5	16	4.9	same as
2	50	55	16.8	30	9.1	24	7.3	24	7.3	2.3	0.7	20	6.1	globe
2 1/2	65	69	21.0	35	10.7	29	8.8	29	8.8	2.8	0.9	25	7.6	valve¶
3	80	84	25.6	43	13.1	35	10.7	35	10.7	3.2	1.0	30	9.1	
3 1/2	90	100	30.5	50	15.2	41	12.5	41	12.5	4.0	1.2	35	10.7	
4	100	120	36.6	58	17.7	47	14.3	47	14.3	4.5	1.4	40	12.2	
5	125	140	42.7	71	21.6	58	17.7	58	17.7	6	1.8	50	15.2	
6	150	170	51.8	88	26.8	70	21.3	70	21.3	7	2.1	60	18.3	
8	200	220	67.1	115	35.1	85	25.9	85	25.9	9	2.7	80	24.4	
10	250	280	85.3	145	44.2	105	32.0	105	32.0	12	3.7	100	30.5	
12	300	320	97.5	165	50.3	130	39.6	130	39.6	13	4.0	120	36.6	Angle lift
14	350	360	109.7	185	56.4	155	47.2	155	47.2	15	4.6	135	41.1	same as
16	400	410	125.0	210	64.0	180	54.9	180	54.9	17	5.2	150	45.7	angle
18	450	460	140.2	240	73.2	200	61.0	200	61.0	19	5.8	165	50.3	valve
20	500	520	158.5	275	83.8	235	71.6	235	71.6	22	6.7	200	61.0	
24	600	610	185.9	320	97.5	265	80.8	265	80.8	25	7.6	240	73.2	

*Losses are for all valves in fully open position.
†These losses do not apply to valves with needlepoint-type seats.
‡Regular and short pattern plug cock valves, when fully open, have same loss as gate valve. For valve losses of short-pattern plug cocks above 6 in., check manufacturer.
§Losses also apply to the in-line, ball-type check valve.
¶For Y pattern globe lift-check valve with seat approximately equal to the nominal pipe diameter, use values of 60° Y valve for loss.

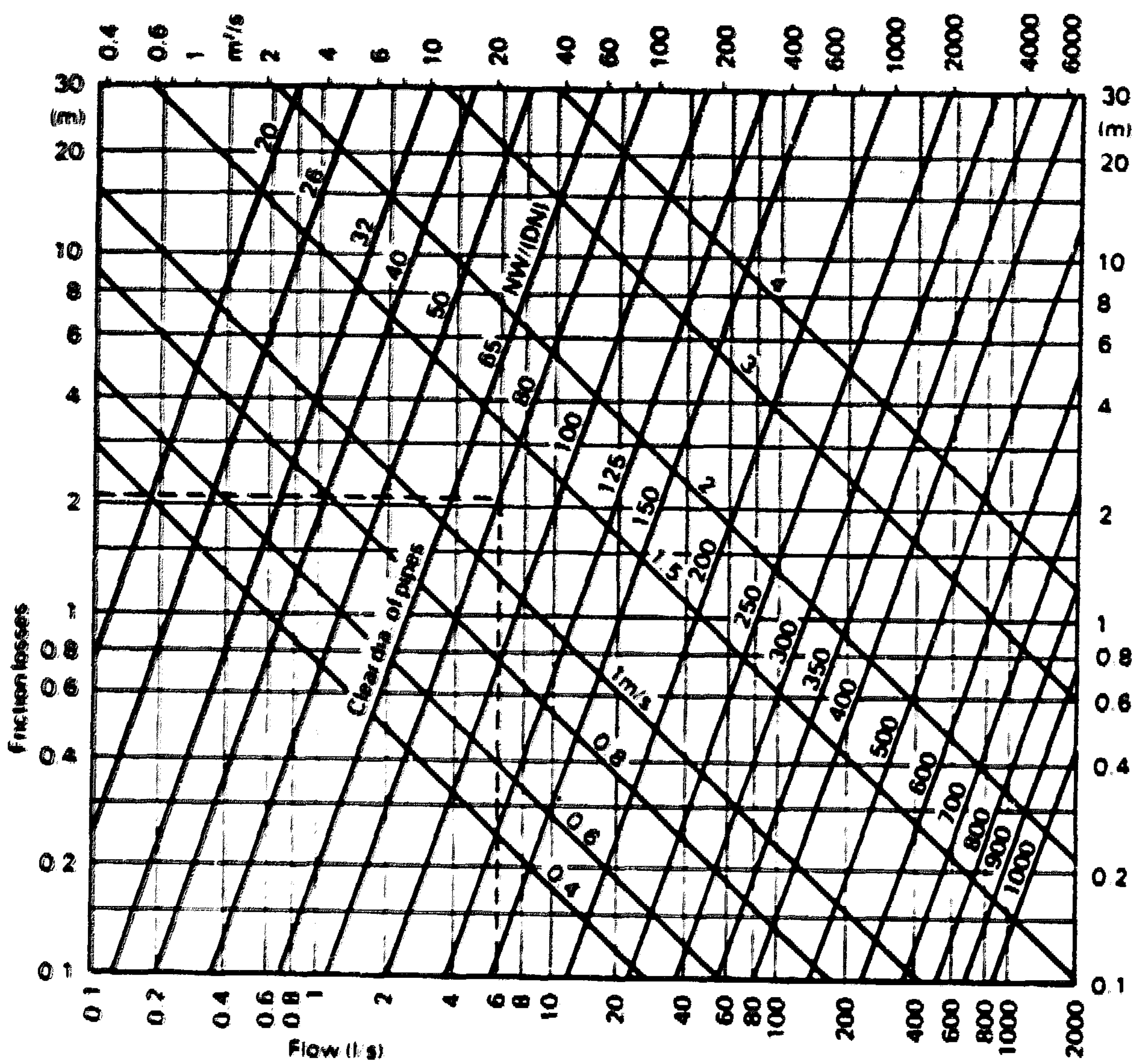


Smooth-bend tees								Mitre elbows							
Flow-through branch		Straight-through flow						90° ell		60° ell		45° ell		30° ell	
		No reduction		Reduced ¼		Reduced ½									
ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m
2.7	0.8	0.9	0.3	1.2	0.4	1.4	0.4	2.7	0.8	1.1	0.3	0.6	0.2	0.3	0.1
3.0	0.9	1.0	0.3	1.4	0.4	1.6	0.5	3.0	0.9	1.3	0.4	0.7	0.2	0.4	0.1
4.0	1.2	1.4	0.4	1.9	0.6	2.0	0.6	4.0	1.2	1.6	0.5	0.9	0.3	0.5	0.2
5.0	1.5	1.7	0.5	2.4	0.7	2.6	0.8	5.0	1.5	2.1	0.6	1.0	0.3	0.7	0.2
7.0	2.1	2.3	0.7	3.1	0.9	3.3	1.0	7.0	2.1	3.0	0.9	1.5	0.5	0.9	0.3
8.0	2.4	2.6	0.8	3.7	1.1	4.0	1.2	8.0	2.4	3.4	1.0	1.8	0.5	1.1	0.3
10	3.0	3.3	1.0	4.7	1.4	5.0	1.5	10	3.0	4.5	1.4	2.3	0.7	1.3	0.4
12	3.7	4.1	1.2	5.6	1.7	6.0	1.8	12	3.7	5.2	1.6	2.8	0.9	1.7	0.5
15	4.6	5.0	1.5	7.0	2.1	7.5	2.3	15	4.6	6.4	2.0	3.2	1.0	2.0	0.6
18	5.5	5.9	1.8	8.0	2.4	9.0	2.7	18	5.5	7.3	2.2	4.0	1.2	2.4	0.7
21	6.4	6.7	2.0	9.0	2.7	10	3.0	21	6.4	8.5	2.6	4.5	1.4	2.7	0.8
25	7.6	8.2	2.5	12	3.7	13	4.0	25	7.6	11	3.4	6.0	1.8	3.2	1.0
30	9.1	10	3.0	14	4.3	16	4.9	30	9.1	13	4.0	7.0	2.1	4.0	1.2
40	12.2	13	4.0	18	5.5	20	6.1	40	12.2	17	5.2	9.0	2.7	5.1	1.6
50	15.2	16	4.9	23	7.0	25	7.6	50	15.2	21	6.4	12	3.7	7.2	2.2
60	18.3	19	5.8	26	7.9	30	9.1	60	18.3	25	7.6	13	4.0	8.0	2.4
68	20.7	23	7.0	30	9.1	34	10.4	68	20.7	29	8.8	15	4.6	9.0	2.7
78	23.8	26	7.9	35	10.7	38	11.6	78	23.8	31	9.4	17	5.2	10	3.0
85	25.9	29	8.8	40	12.2	42	12.8	85	25.9	37	11.3	19	5.8	11	3.4
100	30.5	33	10.1	44	13.4	50	15.2	100	30.5	41	12.5	22	6.7	13	4.0
115	35.1	40	12.2	50	15.2	60	18.3	115	35.1	49	14.9	25	7.6	16	4.9

*R/D approximately equal to 1.
†R/D approximately equal to 1.5.



Head loss in smooth pipes of different internal diameter

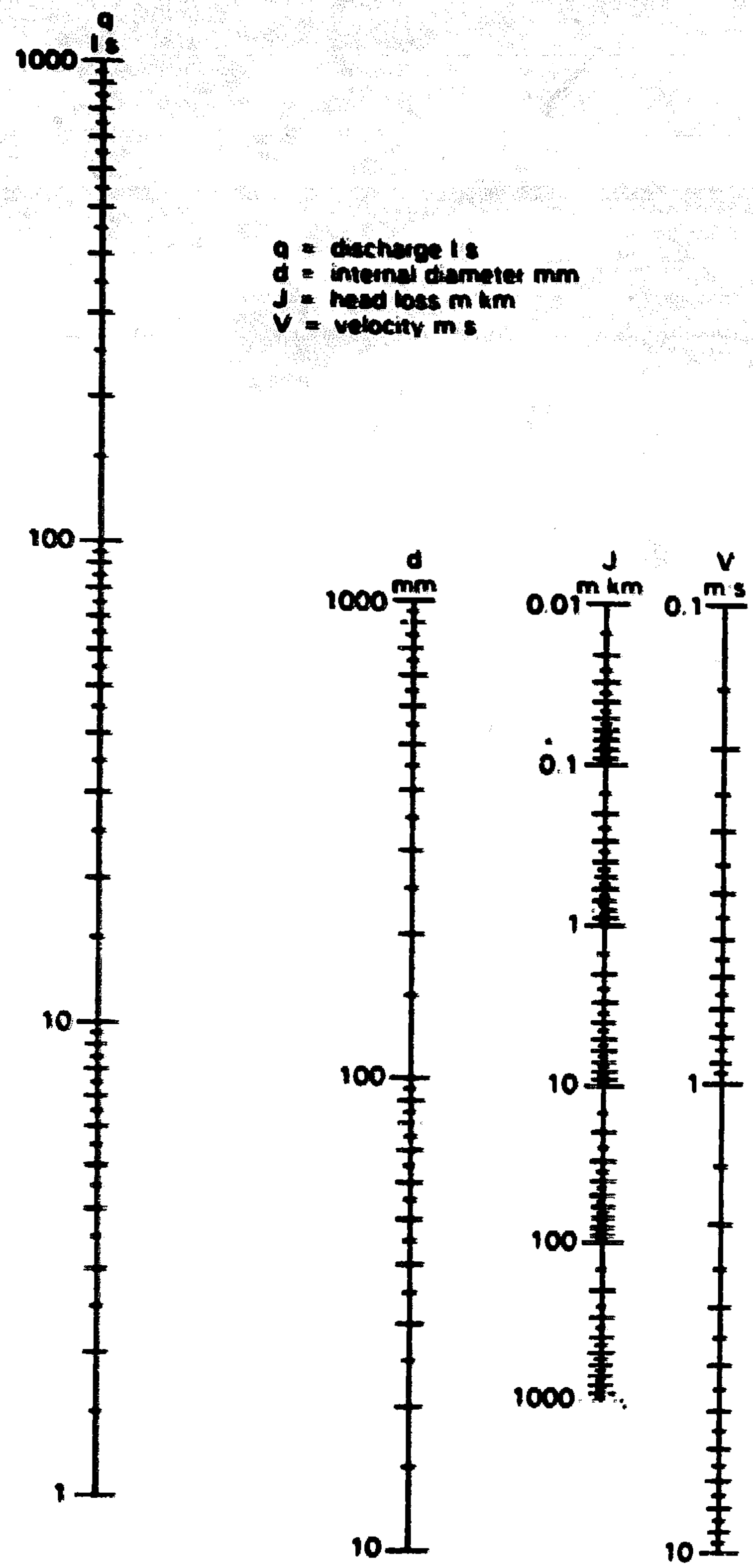


Friction losses in metres per 100m for a new pipeline of cast iron

For other types of pipe multiply the friction loss as indicated by the table by the factors given below:

New Rolled steel	-	0.8
New plastic	-	0.8
Old rusty cast iron	-	1.25
Pipes with encrustations	-	1.7

Determination of head friction losses in straight pipes



Head loss nomogram calculated for rigid PVC pipes using Blasius formula

APPENDIX C

Typical Recommended Service for Diesel Engines

APPENDIX C

Typical Recommended Service for Diesel Engines

The following summarizes the recommended service intervals for Lister engines. The engine model is given in parentheses (e.g., ST, LT, 8/1). Where no model is specified, the procedure applies to all.

Daily	Check supply of diesel fuel and oil level Check air filter (in dusty conditions)
125 hrs	Check air filter (in moderately dusty conditions, renew if necessary) Check for oil and fuel leaks Check and tighten nuts and bolts as necessary Clean engine and mounting
250 hrs	Change engine oil Clean the restrictor banjo union in the lubricating oil feed line Renew oil filter if fitted (ST) Clean injector nozzle if exhaust is dirty Renew fuel filter if necessary Check belt tension
500 hrs	Decarbonize if necessary (LT) Renew fuel filter element (ST) Adjust valve clearances (LT) Change oil in oil bath air filters (8/1 so equipped)
1000 hrs	Decarbonize (8/1) and if necessary (ST) Change filter elements (8/1) Adjust valve clearances (LT)
500 hrs	Decarbonize (LT) Examine and clean fan blades (LT) Check governor linkage and adjustment (LT) Drain and clean fuel tank (LT) Renew fuel filter (LT) Clean and test the injector nozzle (LT) Check fuel pump timing (LT) Check oil pump and its valves (LT) Renew the air filter element (LT)
2000 hrs	Decarbonize (ST) Clean inlet and exhaust system (ST) Examine and clean fan blades (ST) Check governor linkage and adjustment (ST) Drain and clean fuel tank (ST) Renew fuel filter (ST) Clean and test the injector nozzle (ST) Check fuel pump and its valves (ST) Renew the air filter element (ST)

APPENDIX D

Handpump Selection Tables*

* Arlosoroff et al. 1987, 80-87

GUIDE TO PUMP SELECTION TABLES

THE RATINGS

Ratings in the Pump Selection Tables are based on evaluation of pump performance in the laboratory and field trials. Three ratings are used:

●● = Good
● = Adequate
— = Does not meet minimum requirements

A more detailed interpretation of the ratings for specific headings can be found in the earlier part of this Chapter.

Column 1 — Pump Name

The pumps are listed alphabetically in four sections, according to the maximum pumping lift recommended by the manufacturer. The reference number which precedes each pump name indicates the order of the pumps in the Handpump Compendium.

Column 2 — Data Source

L = The pump has been tested in the laboratory
F = The pump has had a minimum of 2 years' field trials
(F) = The pump has had limited field trials

Column 3 — Discharge Rate

The discharge rate deemed "adequate" for each pumping lift is noted at the top of the appropriate table. The rate reduces as depth increases, for the reasons explained in Box 5.1. Some deepwell pumps thus achieve lower ratings for low-lift applications, where users will opt for pumps giving greater discharges. A special note is made where a pump is available with a range of cylinder sizes or adjustable stroke length, to suit different depths.

Column 4 — Ease of Maintenance

Ratings indicate the ease with which maintenance can be carried out by:

A — A village caretaker
B — An area mechanic
C — A mobile maintenance team

Column 5 — Reliability

Reliability ratings are an indication of the proportion of the time that the pump is likely to be functioning properly. Separate ratings are given for different daily outputs. The ratings combine judgments of the "mean time before failure" (MTBF) and the probable "downtime" when the pump is waiting to be repaired. They thus take account of the fact that pumps which are suitable for village maintenance and can be repaired quickly may be more "reliable" than those which require more complex maintenance, even if the latter break down less frequently.

Column 6 — Corrosion Resistance

Ratings are based primarily on the materials of the downhole components. Galvanized steel pumprods and rising mains are not corrosion resistant in aggressive water and earn a — rating.

Column 7 — Abrasion Resistance

Ratings indicate the pump's capability to pump sand-laden water. Performance in laboratory and field trials is combined with assessment of the seal and valve types. For non-suction pumps, leather cupseals are rated — , though the extent of abrasion damage will be related to the daily output of the pump. Analysts may therefore accept lower rated pumps for light duty applications.

Column 8 — Manufacturing Needs

Ratings indicate the ease with which a pump could be manufactured in a developing country with the specified level of industrial development.

1 — Low industrial base, limited quality control
2 — Medium-level industry, no special processes
3 — Advanced industry, good quality control

Column 9 — Short List

The Analyst develops a short list by entering a check mark against those pumps meeting his selection criteria.

Column 10 — Capital Cost

Analysts should obtain current prices for short-listed pumps.

Column 11 — Remarks

Special features of individual pumps are noted in this column. Amplification of the notes is given below.

Amplification of the ratings for individual pumps can be found in the Handpump Compendium

NOTES ON TABLES

The notes relate to pumps with the same reference number — i.e. Note 14 refers to Pump 14, the Maldev. In the tables, ratings to which the note refers are highlighted [●]

Note 1. The ●● corrosion rating for the Abi-ASM is based on current models. Earlier models did suffer from corrosion.
Note 2. The ● corrosion rating for the Afridev is based on the use of stainless steel pumprods, offered as an option.
Note 7. The Duba Tropic 7 is a high-discharge pump designed for two-person operation.
Notes 9 and 10. The India Mark II uses a gravity return on the plunger, and requires a minimum cylinder setting of 24 meters (one manufacturer offers a fixed-link system for shallower settings).
Note 14. The Maldev is a pumphead only. All ratings are based on the use of conventional downhole components.
Note 16. Reliability ratings for the Monolift are based on pumps with metal gears. Plastic gears were less reliable.
Note 21. The ●● corrosion rating for the Vergnet is based on current models. Earlier models did suffer from corrosion.
Note 23. The ●● discharge rating for the Volanta takes account of the pump's adjustable stroke length. Present designs require a minimum well diameter of 110mm.
Note 30. Downhole components of the Kangaroo are corrosion resistant. The ● rating relates to the pedal return spring.
Note 40. The Rower is designed as an irrigation pump, and has a high discharge. It is widely used for domestic water supply in Bangladesh.

1	2	3	4			5			6	7	8			9	10	11
			Ease of maintenance			Reliability for (m³/d)					Manufacturing needs					
Pump name	Data source	Discharge rate	A	B	C	1.5	4	8	Corr. res.	Abr. res.	1	2	3	Short list	Price (US$)	Remarks
HIGH LIFT PUMPS (0-45 meters)																
1 Ab-ASM	L (F)	—	—	●●	●●	●●	●	—	●●	●	—	●	●			See Note 1
2 Afridev	(F)	●	●●	●●	●●	●●	●●	●	●	●	●	●●	●●			See Note 2
3 AID Derv. Deepwell	L F	●●	—	●●	●●	●●	●	—	—	—	—	●●	●●			
4 Bestobell	L	●	—	●●	●●	●●	●	—	●	●	●	●●	●●			
5 Climax	L	●●*	—	—	●●	●●	●●	●	—	—	—	—	●●			
6 Dragon 2	L	●	—	●●	●●	●●	●	—	—	—	—	●	●●			
7 Duba Tropic 7	F	●●*	—	●	●●	●●	●	—	—	—	—	—	●●			See Note 7
8 GSW	L (F)	●*	—	●●	●●	●●	●●	●	—	—	—	●	●●			
9 India Mark II (standard)	L F	●	—	●●	●●	●●	●●	●●	—	—	—	●	●●			See Note 9
10 India Mark II (modified)	(F)	●	—	●●	●●	●●	●●	●●	—	●	—	●	●●			See Note 10
11 Jetmatic Deepwell	L	●	—	●●	●●	●●	●●	●	—	—	—	●	●●			
12 Kardia	L (F)	●	—	●●	●●	●●	●●	●	●●	●	—	●	●●			
13 Korat	L F	●●*	—	●●	●●	●●	●●	●	—	—	—	●●	●●			
14 Maldev	L F	●●*	—	●●	●●	●●	●●	●	—	—	●	●●	●●			See Note 14
15 Monarch P3	L F	●●*	—	●●	●●	●●	●●	●	—	—	—	●	●●			
16 Monolift	L (F)	—	—	—	●●	●●	●●	●	—	●●	—	—	●●			See Note 16
17 Moyno	L F	—	—	—	●●	●●	●●	●	—	●●	—	—	●			
18 Nira AF84	L	●	—	●●	●●	●●	●●	●	●●	●	—	●	●●			
19 Philippines Deepset	(F)	●	—	●●	●●	●●	●	—	—	—	●	●●	●●			
20 SWN 80 & 81	F	●●*	—	●●	●●	●●	●●	●●	●●	●●	—	●●	●●			
21 Vergnet	L F	—	●	●●	●●	●●	●●	●	●●	●	—	●	●			See Note 21
22 VEW A18	L	●	—	●	●●	●●	●	—	●●	—	—	—	●			
23 Volanta	L F	●●	●	●●	●●	●●	●●	●●	●●	●●	●	●	●●			See Note 23
INTERMEDIATE LIFT PUMPS (0-25 meters)																
24 Consallen LD6	L F	●●*	—	●●	●●	●●	●●	●	●●	●	—	●	●●			
25 DMR (Dempster deriv.)	F	●●*	—	●●	●●	●●	●	—	—	—	—	●●	●●			
26 Nira AF76	L F	●●*	—	●●	●●	●●	●	—	—	●	—	●●	●●			
LOW LIFT PUMPS (0-12 meters)																
27 Blair	F	●	●●	●●	●●	●●	●	—	●●	●	●	●●	●●			
28 Ethiopia BP50	L	●●	●	●●	●●	●●	●	●	●	—	●	●●	●●			7m max. lift
29 IDRC UM	L	●●	●	●●	●●	●●	●	—	●●	—	●	●●	●●			
30 Kangaroo	L F	●●	—	●●	●●	●●	●	—	●	●●	—	●	●●			See Note 30
31 Malawi Mark V	F	●●	●	●●	●●	●	—	—	●●	●	●	●●	●●			7m max. lift
32 Nira AF85	L F	●●	●●	●●	●●	●●	●●	●●	●●	●	●	●●	●●			
33 Tara	L F	●●	●●	●●	●●	●●	●	—	●	—	●	●●	●●			
SUCTION PUMPS (0-7 meters)																
34 AID Suction	F	●●	●	●●	●●	●●	●	—	—	●	—	●●	●●			
35 Bangura	L	●●	●●	●●	●●	●●	●●	●	●	●	—	●●	●●			
36 Ingalsa Suction	F	●●	●	●●	●●	●●	●	—	—	—	—	●●	●●			
37 Jetmatic Suction	(F)	●●	●	●●	●●	●●	●	—	●	●	—	●●	●●			
38 Lucky	F	●●	●	●●	●●	●	—	—	—	●	—	●●	●●			
39 New No. 6	L (F)	●●	●●	●●	●●	●●	●	—	—	●●	—	●●	●●			
40 Rower	L (F)	●●	●●	●●	●●	●●	●●	●	●	●	●●	●●	●●			See Note 40
41 SYB-100	F	●●	●	●●	●●	●●	●●	●	●	●●	—	●●	●●			
42 Waso	F	●●	●	●●	●●	●●	●	—	—	●	—	●●	●●			
ADDITIONAL PUMPS																
A1																
A2																
A3																
A4																

* Indicates that discharge ratings are based on choice of the correct cylinder size from a range offered by the manufacturer.

GUIDE TO PUMP SELECTION TABLES

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- L = The pump has been tested in the laboratory
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The discharge rate deemed "adequate" for each pumping lift is noted at the top of the appropriate table. The rate reduces as depth increases, for the reasons explained in Box 5.1. Some deepwell pumps thus achieve lower ratings in low-lift applications, where users will opt for pumps giving greater discharges. A special note is made where a pump is available with a range of cylinder sizes or adjustable stroke length, to suit different depths.

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Ratings indicate the ease with which maintenance can be carried out by:

- A — A village caretaker
- B — An area mechanic
- C — A mobile maintenance team

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Ratings indicate the pump's capability to pump sand-laden water. Performance in laboratory and field trials is combined with assessment of the seal and valve types. Leather cupseals are rated — , though the extent of abrasion damage will be related to the daily output of the pump. Analysts may therefore accept lower rated pumps for light duty applications.

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Note 7. The Duba Tropic 7 is a high-discharge pump designed for two-person operation.

Notes 9 and 10. The India Mark II uses a gravity return on the plunger, and requires a minimum cylinder setting of 24 meters (one manufacturer offers a fixed-link system for shallower settings).

Note 14. The Maldev is a pumphead only. All ratings are based on the use of conventional downhole components.

Note 16. Reliability ratings for the Monolift are based on pumps with metal gears. Plastic gears were less reliable.

Note 21. The ●● corrosion rating for the Vergnet is based on current models. Earlier models did suffer from corrosion.

Note 23. The ●● discharge rating for the Volanta takes account of the pump's adjustable stroke length. Present designs require a minimum well diameter of 110mm.

Note 30. Downhole components of the Kangaroo are corrosion resistant. The ● rating relates to the pedal return spring.

Maximum pumping lift — 12 meters
"Adequate" discharge rate — 16 liters/minute

1 Pump name	2 Data source	3 Discharge rate	4 Ease of maintenance A	B	C	5 Reliability for (m⁴/d) 1.5	4	8	6 Corr. res.	7 Abr. res.	8 Manufacturing needs 1	2	3	9 Short list	10 Price (US$)	11 Remarks
HIGH LIFT PUMPS (0-45 meters)																
1 Abi-ASM	L (F)	●	—	●●	●●	●●	●	—	●●	●	—	●	●			See Note 1
2 Aindev	(F)	●●	●●	●●	●●	●●	●●	●	●	●	●	●●	●●			See Note 2
3 AID Dem. Deepwell	L F	●●	—	●●	●●	●●	●	—	—	—	—	●●	●●			
4 Bestobell	L	●	—	●●	●●	●●	●	—	●	●	●	●●	●●			
5 Climax	L	●●*	—	—	●●	●●	●●	●	—	—	—	—	●●			
6 Dragon 2	L	●	—	●●	●●	●●	●	—	—	—	—	●	●●			
7 Duba Tropic 7	F	●●*	—	●	●●	●●	●	—	—	—	—	—	●●			See Note 7
8 GSW	L (F)	●*	—	●●	●●	●●	●●	●	—	—	—	●	●●			
9 India Mark II (standard)	L F	●	—	●●	●●	●●	●●	●●	—	—	—	●	●●			See Note 9
10 India Mark II (modified)	(F)	●	—	●●	●●	●●	●●	●●	—	●	—	●	●●			See Note 10
11 Jetmatic Deepwell	L	●	—	●●	●●	●●	●●	●	—	—	—	●	●●			
12 Kardia	L (F)	●	—	●●	●●	●●	●●	●	●●	●	—	●	●●			
13 Korat	L F	●●*	—	●●	●●	●●	●●	●	—	—	—	●●	●●			
14 Maldev	L F	●●*	—	●●	●●	●●	●●	●	—	—	●	●●	●●			See Note 14
15 Monarch P3	L F	●●*	—	●●	●●	●●	●●	●	—	—	—	●	●●			
16 Monolift	L (F)	●	—	—	●●	●●	●●	●	—	●●	—	—	●●			See Note 16
17 Moyno	L F	—	—	—	●●	●●	●●	●	—	●●	—	—	●			
18 Nira AF84	L	●	—	●●	●●	●●	●●	●	●●	●	—	●	●●			
19 Philippines Deepset	(F)	●	—	●●	●●	●●	●	—	—	—	●	●●	●●			
20 SWN 80 & 81	F	●●*	—	●●	●●	●●	●●	●●	●●	●●	—	●●	●●			
21 Vergnet	L F	—	●	●●	●●	●●	●●	●	●●	●	—	●	●			See Note 21
22 VEW A18	L	●	—	●	●●	●●	●	—	●●	—	—	—	●			
23 Volanta	L F	●●	●	●●	●●	●●	●●	●●	●●	●●	●	●	●●			See Note 23
INTERMEDIATE LIFT PUMPS (0-25 meters)																
24 Consallen LD5	L F	●●*	—	●●	●●	●●	●	—	●●	●	—	●	●●			
25 DMR (Dempster deriv.)	F	●●*	—	●●	●●	●●	●	—	—	—	—	●●	●●			
26 Nira AF76	L F	●●*	—	●●	●●	●●	●	—	—	●	—	●●	●●			
LOW LIFT PUMPS (0-12 meters)																
27 Blair	F	●	●●	●●	●●	●●	●	—	●●	●	●	●●	●●			
28 Ethiopia BP50	L															7m max. lift
29 IDRC UM	L	●●	●	●●	●●	●●	●	—	●●	—	●	●●	●●			
30 Kangaroo	L F	●●	—	●●	●●	●●	●	—	●	●●	—	●	●●			See Note 30
31 Malawi Mark V	F															7m max. lift
32 Nira AF85	L F	●●	●●	●●	●●	●●	●●	●	●●	●	●	●●	●●			
33 Tara	L F	●●	●●	●●	●●	●	—	—	●	—	●	●●	●●			
ADDITIONAL PUMPS																
A1																
A2																
A3																
A4																

* Indicates that discharge ratings are based on choice of the correct cylinder size from a range offered by the manufacturer.

GUIDE TO PUMP SELECTION TABLES

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Ratings in the Pump Selection Tables are based on evaluation of pump performance in the laboratory and field trials. Three ratings are used:

●● = Good
● = Adequate
— = Does not meet minimum requirements

A more detailed interpretation of the ratings for specific headings can be found in the earlier part of this Chapter.

Column 1 — Pump Name

The pumps are listed alphabetically in four sections, according to the maximum pumping lift recommended by the manufacturer. The reference number which precedes each pump name indicates the order of the pumps in the Handpump Compendium.

Column 2 — Data Source

L = The pump has been tested in the laboratory
F = The pump has had a minimum of 2 years' field trials
(F) = The pump has had limited field trials

Column 3 — Discharge Rate

The discharge rate deemed "adequate" for each pumping lift is noted at the top of the appropriate table. The rate reduces as depth increases, for the reasons explained in Box 5.1. Some deepwell pumps thus achieve lower ratings for low-lift applications, where users will opt for pumps giving greater discharges. A special note is made where a pump is available with a range of cylinder sizes or adjustable stroke length, to suit different depths.

Column 4 — Ease of Maintenance

Ratings indicate the ease with which maintenance can be carried out by:

A — A village caretaker
B — An area mechanic
C — A mobile maintenance team

Column 5 — Reliability

Reliability ratings are an indication of the proportion of the time that the pump is likely to be functioning properly. Separate ratings are given for different daily outputs. The ratings combine judgments of the "mean time before failure" (MTBF) and the probable "downtime" when the pump is waiting to be repaired. They thus take account of the fact that pumps which are suitable for village maintenance and can be repaired quickly may be more "reliable" than those which require more complex maintenance, even if the latter break down less frequently.

Column 6 — Corrosion Resistance

Ratings are based primarily on the materials of the downhole components. Galvanized steel pumprods and rising mains are not corrosion resistant in aggressive water and earn a — rating.

Column 7 — Abrasion Resistance

Ratings indicate the pump's capability to pump sand-laden water. Performance in laboratory and field trials is combined with assessment of the seal and valve types. Leather cupseals are rated — , though the extent of abrasion damage will be related to the daily output of the pump. Analysts may therefore accept lower rated pumps for light duty applications.

Column 8 — Manufacturing Needs

Ratings indicate the ease with which a pump could be manufactured in a developing country with the specified level of industrial development.

1 — Low industrial base, limited quality control
2 — Medium-level industry, no special processes
3 — Advanced industry, good quality control

Column 9 — Short List

The Analyst develops a short list by entering a check mark against those pumps meeting his selection criteria.

Column 10 — Capital Cost

Analysts should obtain current prices for short-listed pumps.

Column 11 — Remarks

Special features of individual pumps are noted in this column. Amplification of the notes is given below.

Amplification of the ratings for individual pumps can be found in the Handpump Compendium

NOTES ON TABLES

The notes relate to pumps with the same reference number — i.e. Note 14 refers to Pump 14, the Maldev. In the tables, ratings to which the note refers are highlighted [●]

Note 1. The ●● corrosion rating for the Abi-ASM is based on current models. Earlier models did suffer from corrosion.
Note 2. The ● corrosion rating for the Alndev is based on the use of stainless steel pumprods, offered as an option.
Note 7. The Duba Tropic 7 is a high-discharge pump designed for two-person operation.
Note 14. The Maldev is a pumphead only. All ratings are based on the use of conventional downhole components.
Note 16. Reliability ratings for the Monolift are based on pumps with metal gears. Plastic gears were less reliable.
Note 21. The ●● corrosion rating for the Vergnet is based on current models. Earlier models did suffer from corrosion.
Note 23. The ●● discharge rating for the Volanta takes account of the pump's adjustable stroke length. Present designs require a minimum well diameter of 110mm.

1	2	3	4			5		6	7	8			9	10	11
Pump name	Data source	Discharge rate	Ease of maintenance A	B	C	Reliability (for m^4/d) 4	8	Corr. res.	Abr. res.	Manufacturing needs 1	2	3	Short list	Price (US$)	Remarks
HIGH LIFT PUMPS (0-45 meters)															
1 Abi-ASM	L (F)	●	—	●●	●●	●	—	●●	●	—	●	●			See Note 1
2 Afridev	(F)	●●	●●	●●	●●	●●	●	●	●	●	●●	●●			See Note 2
3 AID Deriv. Deepwell	L F	●	—	●	●●	—	—	—	—	—	●●	●●			
4 Bestobell	L	●	—	●	●●	●	—	●	●	●	●●	●●			
5 Climax	L	●●*	—	—	●●	●●	●	—	—	—	—	●●			
6 Dragon 2	L	●	—	●	●●	—	—	—	—	—	●	●●			
7 Duba Tropic 7	F	●●*	—	●	●●	●	—	—	—	—	—	●●			See Note 7
8 GSW	L (F)	●●*	—	●	●●	●	—	—	—	—	●	●●			
9 India Mark II (standard)	L F	●●	—	●	●●	●	—	—	—	—	●	●●			
10 India Mark II (modified)	(F)	●●	—	●●	●●	●●	●	—	●	—	●	●●			
11 Jetmatic Deepwell	L	●	—	●	●●	—	—	—	—	—	●	●●			
12 Kardia	L (F)	●●	—	●●	●●	●	—	●●	●	—	●	●●			
13 Korat	L F	●●*	—	●	●●	●	—	—	—	—	●●	●●			
14 Maldev	L F	●●*	—	●	●●	●	—	—	—	●	●●	●●			See Note 14
15 Monarch P3*	L F	●●	—	●	●●	●	—	—	—	—	●	●●			
16 Monolift	L (F)	●	—	—	●●	●●	●	—	●●	—	—	●●			See Note 16
17 Moyno	L F	●	—	—	●●	●●	●	—	●●	—	—	●			
18 Nira AF84	L	●	—	●	●●	●●	●	●●	●	—	●	●●			
19 Philippines Deepset	(F)	●●	—	●	●●	●	—	—	—	●	●●	●●			
20 SWN 80 & 81	F	●●*	—	●	●●	●	—	●●	●●	—	●●	●●			
21 Vergnet	L F	●	●	●●	●●	●●	●	●●	●	—	●	●			See Note 21
22 VEW A18	L	●	—	—	●●	●	—	●●	—	—	—	●			
23 Volanta	L F	●●	●	●●	●●	●●	●●	●●	●●	●	●	●●			See Note 23
INTERMEDIATE LIFT PUMPS (0-25 meters)															
24 Consallen LD5	L F	●●*	—	●●	●●	—	—	●●	●	—	●	●●			
25 DMR (Dempster deriv.)	F	●●*	—	●	●●	—	—	—	—	—	●●	●●			
26 Nira AF76	L F	●●*	—	●	●●	—	—	—	●	—	●●	●●			
ADDITIONAL PUMPS															
A1															
A2															
A3															
A4															

* indicates that discharge ratings are based on choice of the correct cylinder size from a range offered by the manufacturer.

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Note 1. The ●● corrosion rating for the Abi-ASM is based on current models. Earlier models did suffer from corrosion.

Note 2. The ● corrosion rating for the Afridev is based on the use of stainless steel pumprods, offered as an option.

Note 7. The Duba Tropic 7 is a high-discharge pump designed for two-person operation.

Note 12. The manufacturer recommends a maximum depth of 40 meters for the Kardia.

Note 14. The Maldev is a pumphead only. All ratings are based on the use of conventional downhole components.

Note 16. Reliability ratings for the Monolift are based on pumps with metal gears. Plastic gears were less reliable. A 2:1 gear ratio is supplied for deepwell applications.

Note 21. The ●● corrosion rating for the Vergnet is based on current models. Earlier models did suffer from corrosion.

Note 23. The ●● discharge rating for the Volanta takes account of the pump's adjustable stroke length. Present designs require a minimum well diameter of 110mm.

Maximum pumping lift — 45 meters

"Adequate" discharge rate — 7 liters/minute

1	2	3	4			5	6	7	8			9	10	11
			Ease of maintenance			*Reliability for (m³/d)*			*Manufacturing needs*					
Pump name	*Data source*	*Discharge rate*	*A*	*B*	*C*	*4*	*Corr. res.*	*Abr. res.*	*1*	*2*	*3*	*Short list*	*Price (US$)*	*Remarks*
HIGH LIFT PUMPS (0-45 meters)														
1 Abi-ASM	L (F)	o	—	oo	oo	—	oo	o	—	o	o			See Note 1
2 Afridev	(F)	oo	oo	oo	oo	o	o	o	o	oo	oo			See Note 2
3 AID Demp. Deepwell	L F	o	—	o	oo	—	—	—	—	oo	oo			
4 Bestobell	L	o	—	o	oo	—	o	o	o	oo	oo			
5 Climax	L	oo*	—	—	oo	o	—	—	—	—	oo			
6 Dragon 2	L	o	—	o	oo	—	—	—	—	o	oo			
7 Duba Tropic 7	F	oo*	—	o	oo	—	—	—	—	—	oo			See Note 7
8 GSW	L (F)	oo*	—	o	oo	—	—	—	—	o	oo			
9 India Mark II (standard)	L F	oo	—	o	oo	—	—	—	—	o	oo			
10 India Mark II (modified)	(F)	oo	—	oo	oo	o	—	o	—	o	oo			
11 Jetmatic Deepwell	L	oo	—	o	oo	—	—	—	—	o	oo			
12 Kardia	L (F)	oo	—	o	oo	—	oo	o	—	o	oo			See Note 12
13 Korat	L F	oo*	—	o	oo	—	—	—	—	oo	oo			
14 Maldev	L F	oo*	—	o	oo	—	—	—	o	oo	oo			See Note 14
15 Monarch P3	L F	oo*	—	o	oo	—	—	—	—	o	oo			
16 Monolift	L (F)	o	—	—	oo	o	—	oo	—	—	oo			See Note 16
17 Moyno	L F	o	—	—	oo	o	—	oo	—	—	o			
18 Nira AF84	L	o	—	o	oo	o	oo	o	—	o	oo			
19 Philippines Deepset	(F)	oo	—	o	oo	—	—	—	o	oo	oo			
20 SWN 80 & 81	F	oo*	—	o	oo	—	oo	oo	—	oo	oo			
21 Vergnet	L F	o	o	oo	oo	o	oo	o	—	o	o			See Note 21
22 VEW A18	L	o	—	—	oo	—	oo	—	—	—	o			
23 Volanta	L F	oo	o	oo	oo	o	oo	oo	o	o	oo			See Note 23
ADDITIONAL PUMPS														
A1														
A2														
A3														
A4														

* Indicates that discharge ratings are based on choice of the correct cylinder size from a range offered by the manufacturer.

APPENDIX E

Checklist for Materials, Labor, and Transportation

APPENDIX E

Checklist for Materials, Labor, and Transportation

This appendix contains a checklist of materials, labor, and transportation. It can be used to ensure that all items have been considered in the technical and economic analysis.

<u>Diesel</u>

pump
pump head
shafts
pipe engine
clutch
shaft
extension
pulley
belts
pressure relief
water meter
non-return
hose tap
union
gate valve
pipe and fittings (elbows, nipples, couplings, etc.)
cement
sand
gravel
reinforcing
mesh
engine
frame
foundation bolts
lock for pump house
fuel storage tank
labor: skilled supervisory and mechanic semiskilled pipefitters, mechanic helpers unskilled labor
labor per diem allowances
transportation

Delivery pipe network

pipe
elbows, tees, and connections
gate valves
unions
labor: skilled supervisory semiskilled tank installers, pipefitters
unskilled labor
labor per diem allowances
transportation

Distribution pipe network

pipe (more than one size?)
elbows, tees, and connections
distribution boxes and valve chambers
shut-offs and gate valves
standpipes and taps
labor: skilled supervisory semiskilled tank installers, pipefitters
unskilled labor
labor per diem allowances
transportation

Storage tank

storage tank
tank stand
tank liner
water level indicator
inflow and outflow connections
pipe from borehole to tank
labor: skilled supervisory
semiskilled tank installers, pipefitters
unskilled labor
labor per diem allowances
transportation

Solar pumps

modules
array support structures
wiring connections
foundation bolts
array foundation
grounding rod
controller
batteries
battery storage and protection
pump
pump motor
submersible pump cable
safety wire
borehole clamp
sand
gravel
cement
labor: supervisory, skilled electrician
semiskilled pipefitters, electrician helpers
unskilled labor
labor per diem allowances
transportation

Windmills

windmill head
tower
pump cylinder
piping
pumprod
sand
gravel
cement
clamp of forcehead
fence (gate, wire corner posts, regular posts, barbed wire?)
labor: skilled supervisory
semiskilled pipefitters, installers
unskilled labor
labor per diem allowances
transportation

Handpumps

pump head
pump
piping
pumprod
cement
sand
gravel
labor: skilled supervisory
semiskilled or unskilled labor
labor per diem allowances
transportation

Annual costs

financing charges for capital costs
pump operator
fuel and oil
consumables (cleaning materials, etc.)
spares: maintenance (filters, belts, etc.)
spares: repair (pumpset, pipelines, storage)
labor: skilled mechanic/electrician
semiskilled pipefitters
unskilled muscle
labor per diem allowances
transportation (no. of trips)

Non-annual costs

pump replacement
engine replacement
module replacement (damage or theft)
controller replacement
battery replacement
tank replacement
rebuild well/redrill borehole

APPENDIX F

Formulas Used in Present-Worth Analysis

Formulas Used in Present-Worth Analysis*

To Find:	Given:	Factor by Which to Multiply "Given"	Factor Name	Factor Functional Symbol[b]
For single cash flows:				
F	P	$(1+i)^N$	Single payment compound amount	$(F/P, i\%, N)$
P	F	$\frac{1}{(1+i)^N}$	Single payment present worth	$(P/F, i\%, N)$
For uniform series (annuities):				
F	A	$\frac{(1+i)^N - 1}{i}$	Uniform series compound amount	$(F/A, i\%, N)$
P	A	$\frac{(1+i)^N - 1}{i(1+i)^N}$	Uniform series present worth	$(P/A, i\%, N)$
A	F	$\frac{i}{(1+i)^N - 1}$	Sinking fund	$(A/F, i\%, N)$
A	P	$\frac{i(1+i)^N}{(1+i)^N - 1}$	Capital recovery	$(A/P, i\%, N)$

[a]i, effective interest rate per interest period; N, number of interest periods; A, uniform series amount (occurs at the end of each interest period); F, future worth; P, present worth.
[b]The functional symbol system is used throughout this book.

*E. Paul DeGarmo, William G. Sullivan, and John R. Canada, Engineering Economy, 7th ed. (New York, New York: Macmillan Publishing Company, 1984), p. 75.

Compound Interest Factors (Based on annual compounding)

Where:

N = Term of Analysis (years)
F1 = Factor for Present Worth of Uniform Series of Future Payments
F2 = Factor for Present Worth of Single Future Payment

Interest Rate (%)

	6		8		10		12	
N	F1	F2	F1	F2	F1	F2	F1	F2
1	0.9434	0.9434	0.9259	0.9259	0.9091	0.9091	0.8929	0.8929
2	1.8334	0.8900	1.7833	0.8573	1.7355	0.8264	1.6901	0.7972
3	2.6730	0.8396	2.5771	0.7938	2.4869	0.7513	2.4018	0.7118
4	3.4651	0.7921	3.3121	0.7350	3.1699	0.6830	3.0373	0.6355
5	4.2124	0.7473	3.9927	0.6806	3.7908	0.6209	3.6048	0.5674
6	4.9173	0.7050	4.6229	0.6302	4.3553	0.5645	4.1114	0.5066
7	5.5824	0.6651	5.2064	0.5835	4.8684	0.5132	4.5638	0.4523
8	6.2098	0.6274	5.7466	0.5403	5.3349	0.4665	4.9676	0.4039
9	6.8017	0.5919	6.2469	0.5002	5.7590	0.4241	5.3282	0.3606
10	7.3601	0.5584	6.7101	0.4632	6.1446	0.3855	5.6502	0.3220
11	7.8869	0.5268	7.1390	0.4289	6.4951	0.3505	5.9377	0.2875
12	8.3838	0.4970	7.5361	0.3971	6.8137	0.3186	6.1944	0.2567
13	8.8527	0.4688	7.9038	0.3677	7.1034	0.2897	6.4235	0.2292
14	9.2950	0.4423	8.2442	0.3405	7.3667	0.2633	6.6282	0.2046
15	9.7122	0.4173	8.5595	0.3152	7.6061	0.2394	6.8109	0.1827
16	10.1059	0.3936	8.8514	0.2919	7.8237	0.2176	6.9740	0.1631
17	10.4773	0.3714	9.1216	0.2703	8.0216	0.1978	7.1196	0.1456
18	10.8276	0.3503	9.3719	0.2502	8.2014	0.1799	7.2497	0.1300
19	11.1581	0.3305	9.6036	0.2317	8.3649	0.1635	7.3658	0.1161
20	11.4699	0.3118	9.8181	0.2145	8.5136	0.1486	7.4694	0.1037