SMALL-SCALE WATER PUMPING IN BOTSWANA

VOLUME V: OTHER PUMPING TECHNOLOGIES

Revised Edition

Prepared by:

Jonathan Hodgkin, Richard McGowan and Ron D. White
Associates in Rural Development, Inc.
110 Main Street, Fourth Floor
P.O. Box 1397
Burlington, VT 05402
U.S.A.
Under subcontract number DPE-5942-C-00-4085-00,
WASH Activity 189.

Date: June 1988

CONTENTS

ABBREVIATIONS AND ACRONYMS

ADP	animal-drawn pump
ARD	Associates in Rural Development, Inc.
BEDU	Botswana Enterprise Development Unit
BPC	Botswana Power Corporation
BRET	Botswana Renewable Energy Technology Project
BRS	Borehole Repair Service
BTC	Botswana Technology Centre
CAMU	Communal Areas Management Unit
CWPP	Comparative Water Pumping Project
DWA	Department of Water Affairs
EEC	European Economic Community
GOB	Government of Botswana
kg	kilogram
km	kilometer
kV	kilovolt
kVA	kilovolt ampere
kW	kilowatt
kWh	kilowatt hour
l	liter
m	meter
m^3	cubic meter
MLGL	Ministry of Local Government and Lands
mm	millimeter
MMRWA	Ministry of Mineral Resources and Water Affairs
MOA	Ministry of Agriculture
NGO	nongovernmental organization
P	pula
PMT	pole-mounted transformer
PV	photovoltaic
RET	renewable energy technology
RIIC	Rural Industries Innovation Centre
SIDA	Swedish International Development Authority
UNDP	United Nations Development Programme
USAID	U.S. Agency for International Development
WASH	Water and Sanitation for Health

PREFACE

The Comparative Water Pumping Project (CWPP) was jointly funded by the Government of Botswana and the U.S. Agency for International Development. Technical assistance was provided by Associates in Rural Development, Inc. (ARD), of Burlington, Vermont. The project was implemented under the auspices of Botswana's Ministry of Mineral Resources and Water Affairs (MMRWA). Project field staff included Mr. Jonathan Hodgkin, engineer and field team leader; Mr. Lucas Motsisi, chief technical officer, renewable energy, at the Department of Water Affairs; Mr. Modise Motshoge and Mr. Peter Modimoofile, technicians; and a seconded crew led by Mr. Keberang Goitsemang. Project support was provided by two consultants--Mr. Richard McGowan, senior engineer, ARD; and Mr. Ron White, an economist. This report covers work performed under CWPP from February 1986 through June 1987.

CWPP was a continuation of one component of the Botswana Renewable Energy Technology Project. Future related work will be carried out with assistance from the Swedish International Development Authority.

The project team wishes to acknowledge the assistance and guidance provided by Mr. F. O. Motlhatlhedi, the senior energy officer at MMRWA. In addition, the help and cooperation of the Botswana Technology Centre, Rural Industries Innovation Centre, and the water engineer at the Ministry of Local Government and Lands proved very useful and were gratefully accepted. The support and assistance provided by the REDSO Energy Advisor, Mr. C. Anthony Pryor, in his initial support and ongoing evaluation of CWPP activity were also invaluable.

I. EXECUTIVE SUMMARY

The Comparative Water Pumping Project, a pump testing and evaluation program in Botswana, was jointly funded for the past three years by the U.S. Agency for International Development (USAID) and the Ministry of Mineral Resources and Water Affairs (MMRWA) of the Government of Botswana (GOB). The pump testing and evaluation program began under the auspices of the Botswana Renewable Energy Technology (BRET) Project, managed by Associates in Rural Development, Inc. (ARD). It focused on the installation, testing and evaluation of a wide variety of diesel, wind, solar photovoltaic (PV), grid-electric, bio-gas substitution, and human- and animal-powered pumping systems throughout rural Botswana. The results of this first phase were reported in WATER PUMP FIELD TESTS IN BOTSWANA (McGowan and Hodgkin, 1985).

Because of a perceived need to maximize the benefits from the work completed under the BRET project by gathering longer term data on the recurrent costs of the systems evaluated, CWPP was funded through MMRWA and the Water and Sanitation for Health (WASH) Project of USAID's Bureau for Science and Technology (Office of Health).

The additional data collection and evaluation effort under CWPP allowed a more careful review of all of the technologies considered during the first phase. The results of CWPP are reported in the five-volume series, SMALL-SCALE WATER PUMPING IN BOTSWANA (McGowan and Hodgkin, 1988). VOLUME I: A COMPARISON compares all of the technologies and discusses their appropriateness as potential choices for water pumping in Botswana. The other volumes in the series are II: DIESEL SYSTEMS; III: WINDMILLS; and IV: SOLAR PUMPS.

The major objective of the present volume is to report on the evaluation of four pumping technologies (animal-drawn, bio-gas substitution, alternating-current electrical, and hand-operated pumps). The evaluation aims to provide as clear a picture as possible of the state of technology development, technical and nontechnical constraints, and costs for each. To facilitate comparisons among technologies, the financial and economic evaluations in this report are consistent with those for diesel, wind, and solar pumping systems.

The evaluation of the animal-drawn pump (ADP) and bio-gas substitution technologies are limited by the lack of long-term operating experience over a range of pumping conditions; lack of answers to social and cultural questions concerning use; limited information about fabrication costs, recurrent costs and reliability; and the fact that these technologies, although technically proven, are still in the development stage in

Botswana. The evaluation of electric pumps is limited by the relatively few current installations within the output range of interest and by the limited information on repair and maintenance costs. Handpump evaluation is hampered by the few examples available for testing in Botswana and by the lack of information on the levels of use for those installed.

The major conclusions from the study of the four technologies considered in this report are outlined below.

Animal-Drawn Pumps

ADPs appear to have a role to play in providing water for some private-sector applications. The ADP costs reported by the Rural Industries Innovation Centre (RIIC) indicate that ADPs are a cost-effective alternative to diesel pumps when ADPs can provide sufficient water. They have the distinct advantage of being completely divorced from the need for fuel and from the repair and maintenance infrastructure of diesel engines. However, the cost of the machines is a concern (RIIC's projected cost is more than double that of a small Lister diesel engine), and reliability is still a relative unknown. A number of factors, such as the effect of syndicate organization, supplementary food requirements of the draft animals, animal harnessing techniques, animal ownership, and labor requirements for operation, need further study. Additional funding for the program may be necessary to answer these questions and examine the potential market. Continued work with this technology should be encouraged.

Bio-Gas Substitution

The use of bio-gas as a substitute for diesel fuel in engines used for water pumping does not appear to be financially or economically attractive for small-scale systems (up to 30 m^3/day and 120 m head). The costs for building and maintaining a bio-gas digester for this purpose must be compensated for in fuel savings. For the cases considered, the fuel use is low to moderate, and saving 80 percent of the fuel cost does not appear to be enough to finance digester construction and maintenance. However, the technology is proven, and in larger applications, where the savings from bio-gas use are higher, the technology will be more attractive. Changes in fuel availability and/or price could make the technology more attractive. The use of bio-gas for other purposes has not been included and may be more attractive than for pumping. The potential for bio-gas in small-scale pumping applications does not appear to justify continued activity in this area at the present time. However, larger scale applications, if well organized and operated, may have merit.

Alternating-Current Electric Pumps

The economics of grid-connected electric pumps is very dependent on interconnection distance and cost, and on the tariff structure. The current rate structure does not favor use of these pumps. However, if the interconnect distance is very short (well under one km) and the tariff structure is altered (which is a possibility), electric pumps may be competitive with diesel-driven systems from a financial point of view. If the economic cost of power generated by the Morupule power station is as low as suggested by the Word Bank (P0.062 per kilowatt hour), electrical pumping may be attractive in an economic sense. The lower level of logistical support required by electrical pumps also favors their use. However, a good understanding of borehole characteristics and aquifer potential is required to justify the cost of grid extension for electrical pumping. It must be ascertained that a borehole can be used over a long period of time to justify the financial commitment to overhead lines. Unfortunately, the areas where borehole characteristics are well understood are limited. Grid extension for the sole purpose of rural-village water supplies is not likely to be cost effective. Only for well-characterized well fields, used to supply major villages, are electric pumps likely to be the best choice.

Handpumps

The use of handpumps should be actively encouraged in areas of limited water requirement (less than five m^3/day) and low lift (up to 50 meters). A handpump coordinating group should be established to facilitate this activity. The current practice of locating boreholes well outside village perimeters (to reduce the possibility of water contamination) may limit the use of handpumps if the walking distance is too great. Handpumps should be considered for small settlements and villages of fewer than 200 people, lands areas, and as back-up to diesel engines in rural villages. If handpumps can meet water demand, they can deliver water less expensively than diesel systems. Also, they do not require extensive water storage and reticulation. There are currently several acceptable models of handpumps in use in Botswana, as well as several models that remain untested. A handpump working group should be established to examine handpump use and guide introduction of acceptable models.

II. INTRODUCTION

CWPP was an outgrowth of the pump testing and evaluation component of the BRET project. As the completion date for the BRET project (September 1985) approached, it became apparent that while many pumps had been installed and tested, the data base of long-term operation, maintenance and repair costs was not yet adequate. Fortunately, additional funding for the continuation of the pumping work was made available by the GOB and through USAID's WASH project. Thus, 18 additional months of data monitoring and analysis were possible. This report is the final volume of a five-volume set documenting the results of the CWPP testing and evaluation work.

A. Purpose

The first volume of this report discusses the comparative costs and applications of the various pumps examined during the program. The other three volumes evaluate the technical and economic performance of small-scale diesel engines, solar pumps, and windmills. The present volume discusses the performance of four other small-scale technologies:

- animal-drawn pumps;
- bio-gas substitution pumps;
- alternating-current (AC) electric, grid-connected pumps; and
- handpumps.

The fact that these four water pumping technologies are considered under one cover reflects their minimal impact in Botswana at present and/or CWPP's emphasis on diesel, wind and solar pumping systems. The ADP and bio-gas substitution technologies have been developed over the past several years by RIIC. Although both technologies have been proven from a technical standpoint, efforts are still being made to improve them and successfully introduce them. A careful analysis of several complex social factors and of the potential market for these pumps remains to be completed (RIIC is planning such a study). The use of AC grid inter-tied pumps has attracted attention recently. However, the current use of these pumps is small, due at least in part to the severe limits of the utility grid. Because government programs have emphasized supplying a major part of the rural population with reticulated water pumped by diesel pump sets, the use of handpumps did not receive much attention until recently. There are currently about 50 handpumps in use nationwide.

B. Scope of the Work

The four pumping technologies considered in this volume were not tested as intensively as the diesel, wind and solar pumping systems. However, some firsthand testing was performed on all four either under CWPP or through the BRET project. The limited testing of these technologies was intended to provide field data in a form consistent with that for other technologies, thus allowing comparison of these devices with diesel, solar and wind pumps. The analysis seeks to highlight the economically important parameters and identify the conditions under which these pumping technologies should be considered. The results of this work were incorporated in the comparative analysis of different systems (VOLUME I).

C. Approach

The approach used here is consistent with that for the other technologies. Cost and performance data were collected through:

- interviews with users and those knowledgeable about the pumping systems;
- field-testing; and
- review of the results of tests conducted by BTC, RIIC and Water Unit technicians.

The performance of each technology was calculated based on the results of the tests over a range of conditions. Financial and economic analyses of each type of system were based on the performance and costs, both capital and recurrent.

Unfortunately, there are no reliable long-term data on system costs. In several cases, the technologies are in the prototype development stage and the longer term costs can only be estimated. In addition, current capital costs for prototype development reflect development costs, not probable production costs. For both the handpump and electrical pumping systems, the number of pumps is low and the repair intervals are large. Thus, the data are not sufficient to provide an accurate picture of the long-term costs. In these cases, estimates of long-term recurrent costs were extrapolated from the first several years of operating experience, as well as from conversations with individuals who have had long-term experience with the technologies in Botswana.

D. Report Structure

The technologies covered in this volume are:

- animal-drawn pumps,
- bio-gas substitution,
- AC grid-connected pumps, and
- handpumps.

Sections III through VI, covering the four technologies, include discussions of the current state of the technology in Botswana, its characteristics and performance, financial and economic implications, and conclusions.

III. ANIMAL-DRAWN PUMPS

Animal traction has been used for many years for plowing and transportation. During the last several years, RIIC has sought to apply animal power to the pumping of water as well. This concept, fairly common in some parts of the world, is new to Botswana. The impetus to develop ADPs stemmed from concern about rising energy costs during the mid-1970s, and from RIIC's mandate to work for the improvement of living standards in rural areas.

The original request to consider animal power came from a horticultural cooperative and resulted in installation of the first ADP at Manyana in October 1982. Since work began on this project, the ADP has been through two major design configurations (Mark I and II). Both were developed to drive the Mono pump and use teams of up to eight or nine draught animals to drive the pump through a transmission. Although several Mark I models are in use, the ADP is still in the development stage. Other than one being tested at RIIC, no other Mark II machines have been installed yet. Because the ADP is not yet in widespread use, the analysis here can only be indicative of the machine's potential, not its proven performance.

A. Technology Description

Both the Mark I and Mark II versions of the ADP (see Figures 1 and 2) are essentially nothing more than transmissions. Both allow a large speed increase from the input shaft to the output shaft of the device. The input shaft of the transmission is driven by a team of draught animals pulling drawbars around a circular path. The drawbars are connected to the transmission at the center of the circle. The output speed driving the Mono pump is a large multiple of the input speed. A pulley on the transmission output shaft allows the ADP to be connected to the Mono pump by the conventional V-belt arrangement. The first production prototype ADP (Mark I) consisted of three six-meter drawbars driving a three-step transmission with a total input/output ratio of up to 1:160. The first two steps (of 1:5.9 each) used a horizontal chain and sprockets. For the last step (1:4.6), pulleys and V-belts were used. The final drive from the transmission output shaft to the pump was also accomplished with V-belts. The ratio could be increased by up to 1:6 by selection of the pulley to be used on the output shaft. This meant that if the animals completed one revolution per minute, the pump could operate at 960 revolutions per minute (rpm). This is within the most efficient operating range of the Mono pump.

Figure 1. Mark I ADP in use at Gamorotswana.

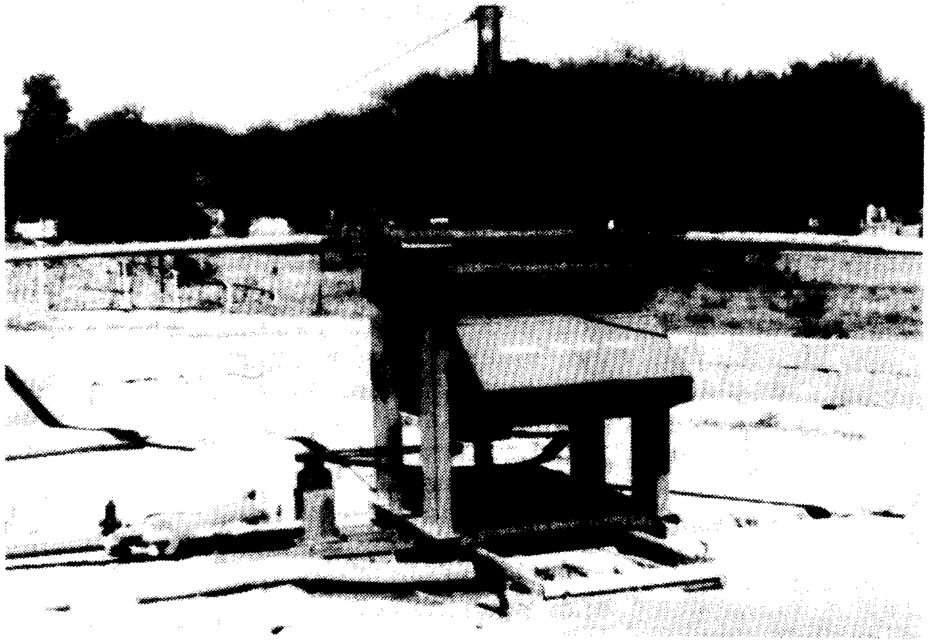


Figure 2. Mark II ADP under testing at RIIC.

During 1985, after some experience with the design, RIIC felt that improvements in the design should be made to address problems resulting from dusty and sandy operating conditions and problems with the idler pulley design. These improvements included protecting the moving parts from dust, improving the lubrication system, and changing the transmission design. A new ADP (the Mark II) was in the final phases of testing as of June 1987. The ADP is driven by teams of animals pulling two (instead of three) drawbars through a transmission and V-belt arrangement to the Mono pump. The transmission of the Mark II design consists of three 1:6 steps, plus a fourth 1:3.8 step (which can be adjusted). All are horizontal chain-and-sprocket drives. This provides an internal step-up of 1:820. The final drive from the transmission to the Mono pump head is also adjustable, within limits, to provide an overall speed increase to over 1:1,500 (the upper limit for Mono speed). In 1985, the Mark I machine cost in the range of P4,000 (not including installation). RIIC estimates the production cost of the improved Mark II design to be P6,700.

Ten ADPs have been installed since the inception of the program in 1982. Two of these are in Swaziland and Zimbabwe; five are currently installed in Botswana; three have been removed. The original ADP at Manyana was removed because the water source dried up. The other two failed--one due to sand and dust abrasion (Khawa), and one to power requirements in excess of what the ADP could handle (Tlhatswe). All currently installed ADPs are the Mark I model with improvements. The ADP in Gamorotswana is the oldest installation in use, dating from May 1984. The others have been installed since January 1986. Two of the ADPs are being used in horticulture projects, the others for stock watering.

B. Water Pumping Applications

ADPs are more labor-intensive than diesel pump sets. A diesel engine requires an operator to start and stop the engine, provide some on-site service such as changing the oil, and contact someone else when major servicing or repair is necessary. For the ADP, each day the power source (the animals) must be collected, harnessed and, in most cases, driven to ensure that water is delivered. This is a labor-intensive process (compared to diesel technology) that requires more than one person.

During ADP development, it was assumed that the owners of the device would use donkeys that were already at their disposal. It was also assumed that the animals would graze for their food and that local harnesses and harnessing techniques would be easily adaptable to ADPs. ADP developers believed that by using already available resources, water could be pumped without reliance on diesel fuel. As the development work continued, some of these initial assumptions had to be modified--primarily assumptions concerning animal ownership, supplemental feeding and harnessing.

To date, only the private sector has used ADPs. Government use is not likely due to the high labor requirements; government wages for unskilled labor are considerably higher than those within the private sector. Private-sector users of water pumping equipment can be subdivided into freehold farmers, private owners of pumping equipment in communal lands areas, and collectives that form syndicates to purchase and maintain equipment. Development of the ADP technology has focused on the collectives. Because collective use of individual property (the animals) is required, it is important that a syndicate be well organized and operated and that there be trust among members. Members may resist using their own donkeys for what they perceive to be the benefit of others. In several cases, it appears that syndicates are seriously considering purchasing animals specifically to operate the pump. If this is required to maintain harmonious relations in the syndicate, the cost of donkeys and their periodic replacement must be added to the cost of the pump and its operation. In some cases, this could mean an additional initial cost for the animals, plus the cost of replacement, which would affect the economic performance of the technology.

Animal feeding and care have also become an issue. It has been observed that after a work shift, donkeys were "inordinately hungry" (Ainley, 1985). There are two concerns--the basic food requirements and the need for supplements to improve the diet. The former is dependent on the natural forage available, site, and time of year. If local overgrazing is a problem, then additional feeding may be required. The second concern is about balance in the diet. RIIC suggests a dietary supplement of a mix of bonemeal and salt. RIIC indicates that an additional P200 per year may be necessary to keep animals fit for the heavy work of running an ADP. However, it reports a resistance on the part of ADP users to meeting these supplementary needs. Traditionally, donkeys have grazed as other animals do. In any case, it seems clear that ADP performance will depend to some degree on these issues, and that further study is needed.

Problems have arisen with harnessing as well. The commonly used harnesses are made from strips of rubber-tire casings stitched together with wire and joined with bolts. Traces are made from chain and attached to the harness and load with bolts. In most cases, little attention is paid to ensuring that loads are balanced, or the harnesses comfortable and efficient in transferring the power of the donkey to the load. These harnesses may be sufficient for light and/or intermittent work, but are not suitable for the continuous heavy work required by an ADP. The tire casings are impermeable, trapping sweat under the breastband, causing the skin to soften and increasing the likelihood of abrasion to a hardworking animal. A newer leatherharness design, intended to more evenly distribute the load over the shoulders, has been introduced, and more care is being taken to ensure that loads are balanced among the animals. These harnesses are more expensive than the ones traditionally used and will increase the cost of operating the pump.

The labor requirements of ADP operation are greater than for other pumping technologies. If syndicate members contribute their own labor, the cash requirement is minimized. However, two people are required at all times for proper operation of the pump using donkeys. The Mark I model has three drawbars and requires at least three people to drive the animals. However, syndicate family members, including older children, have been seen driving the donkeys, and it appears that no money changes hands for the labor of operating the ADP.

ADP operation is clearly free of the need for diesel fuel, and syndicate members who use ADPs seem to appreciate this. However, it appears that some potential costs and organizational constraints were not envisioned when ADP development began. These need to be more clearly understood, as each potentially adds to the cost (and most certainly acceptability) of the technology. Section III.F explores these cost implications in some detail.

C. Testing Program

CWPP did short-term performance testing at one field site only. However, RIIC has been conducting tests of the Mark II model at its facility in Kanye and is also monitoring field installation. In addition, the Botswana Technology Centre (BTC) has conducted tests at the Gamorotswana site. Formal testing and field monitoring are discussed in the following two subsections.

1. Testing at RIIC

RIIC's work with the Mark II ADP has included tests of a range of heads with different numbers of animals. Testing was conducted at each head and team size over at least a three-day period. The total water flow was recorded, along with time of operation and number of animal revolutions. RIIC shared its results with CWPP, and a representative sample is given in Table 1.

Table 1. Selected Results of ADP Testing at RIIC

With Donkeys

Total Head (m)	No. of Donkeys	Output (m^3/hr)	Pump rpm	Power/Donkey (watts)
10	4	4.9	850	33
20	4	5.5	850	75
30	6	4.7	900	64
60	8	3.5	500	72

With Oxen

Total Head (m)	No. of Oxen	Output (m^3/hr)	Pump rpm	Power/Oxen (watts)
20	4	9.4	*	128
60	4	3.5	900	142
80	6	3.4	*	124

*Pump rpm not known.

The variation in output at different heads and pump rpms is due to the different pumps being used. The low power per donkey measured at the 10-meter head is largely due to poor pump selection for this test.

The usable power per animal has been defined as the hydraulic requirement divided by the number of animals, as follows:

$$\text{power/animal} = (Q \times H \times 9.8 / 3.6) / \text{no. of animals}$$

where: power/animal is given in watts
Q = flow rate (m^3/hr)
H = total pumping head (m)

These tests do not isolate the efficiencies of the transmission and pump from the efficiencies of the donkey and harnessing system. RIIC is planning a series of tests to explore these subsystem efficiencies. However, if the system is seen as a whole, the performance of the donkeys can be compared to accepted standards of performance.

Animal performance is a function of species, gender, size, feeding and harnessing, to mention a few factors. The power output of a donkey is expected to range from 70 to 200 watts, depending on the above conditions. If the assumption is made that the average power output is 135 (the average of 70 and 200) watts per donkey, and the average hydraulic power delivered to the pump per donkey is 70 watts per donkey, the overall system efficiencies are in the range of 50 percent. This is within the anticipated range. This figure is very dependent on the assumed output per donkey. The tests conducted by BTC are consistent with these findings.

Although donkeys are in use at all ADP sites, the tests reveal that oxen should be considered, as they can provide about twice the power of donkeys. During testing, it was also noted that oxen, once trained, would work without the constant tending required for donkeys. Oxen will operate the pump without being driven. This has a dramatic effect on operating costs if there is a charge for pump operators. The higher power output of oxen is confirmed by the performance of the oxen-driven ADP in Swaziland.

2. Field-Testing

The performance of the five installed ADPs is being monitored by RIIC. BTC undertook intensive testing at the Gamorotswana site during late 1984. CWPP staff also performed short tests at this site in April 1986. The results of these tests and monitoring are given in Table 2.

Table 2. ADP Field-Test Results

Site	Total Head (m)	No. of donkeys	Output (m^3/hr)	Power/Donkey (watts)
Gamorotswana[1]	38	9	6.0	70
Gamorotswana[2]	38	9	5.2	60
Khawa[3]	70	9	2.5	53
Tidi[3,4]	8	6	4.5	16
Mosung[3]	50	8	3.0	51
Masama[3]	16	6	3.0	22

[1] Tested by BTC and replicated by CWPP.
[2] Reported by Integrated Farming Pilot Project.
[3] Reported by RIIC.
[4] Performance limited by well yield.

These results indicate that ADP efficiency decreases at lower heads. In at least one case (Tidi), this is the result of water resource limitations. In the other cases, the differences appear to be the result of low pump efficiencies due to poor pump selection. During the earlier phases of the RIIC program, the importance of proper pump selection was not fully appreciated. After recent test work, it appears that higher efficiencies in lower head cases can be obtained through more careful pump selection.

D. Performance Estimation

Using the test results for the Mark II ADP, and assuming that donkeys will be used for traction power (true for all current installations in Botswana), the following estimates (Table 3) for pump performance were made. These estimates assume that pumps can be selected so that 70 watts of animal power can be effectively utilized in lifting water.

Table 3. Output of Donkey Teams (in cubic meters per hour)

	Number of Donkeys			
Head (m)	2	4	6	8
15	3.4	6.9	10.3	13.7
30	1.7	3.4	2.3	1.7
45	1.1	2.3	3.4	4.6
60	0.9	1.7	2.6	3.4

It should be noted that the yield of most boreholes in Botswana will not allow high pumping rates. There are relatively few instances where pumping rates in excess of four or five m^3/hr can be sustained. There are, however, a few areas along the Limpopo River where low heads occur in conjunction with high borehole yields.

The results of testing at RIIC and the experience of users at Gamorotswana indicate that the optimal amount of time for a team of donkeys to work in one day is one shift of two to three hours. RIIC's experience indicates that longer shifts (up to 4.5 hours) can be achieved by resting the donkeys for 15 minutes each hour. However, for the present analysis, 2.5-hour shifts are assumed. Thus, if more that 2.5 times the hourly performance of the animals is necessary, a second team of animals must be employed. Further, it is assumed that the maximum pumping time per day is five hours (or two shifts). This means that two teams of six donkeys can pump 25.5 m^3/day from 30 meters (5.1 m^3/hr x 2.5 hrs x two shifts). Since extra time is required for gathering and harnessing the donkeys, a five-hour upper limit appears reasonable for actual daily pumping time.

E. Cost Estimation

Neither the production-scale capital cost nor the long-term recurrent cost of the ADP is known with any degree of accuracy. The device is still in the development stage, and reasonable fabrication costs are difficult to ascertain. This is not only due to the prototype development procedures used at RIIC but also because material waste and labor time can be expected to decline as experience in the fabrication process is gained. The current RIIC estimate for materials and labor for ADP fabrication is P6,700 (P4,900 for materials and P1,800 for labor). The costs of the pump and piping components are additional and will depend on site conditions. It has been estimated, based on limited testing, that RIIC will install the ADP with a skilled crew of three and that casual labor will be hired on site as needed. A seven-ton truck will be required for transportation to the site.

Recurrent costs for the currently marketed Mark II model are unknown, since no Mark IIs are installed yet. The redesign addresses the major difficulties with the Mark I model, so the recurrent costs associated with that design will not be representative of the Mark II. However, the costs for operating Mono pumps are known (see VOLUME II: DIESEL SYSTEMS). They can be expected to be about P200 per year for six hours' use of the pump per day. Although the Mark II has not been field-tested, and costs could be higher until problems are worked out, RIIC expects continuing minor problems to cost in the range of P50 per year. Replacement of donkeys (if they are purchased) is calculated at P40 each at five-year intervals, with harnesses replaced at two-year intervals for P30 each. There are several items for which very little cost information is available, including supplemental feed (estimated by RIIC to be about P200 per year if done properly), labor associated with care and training of the animals, and increased veterinary care because the animals are working harder.

Due to the nature of ADP use to date, the figures used here can only be estimated. However, they will allow preliminary determination of the unit water cost in a way that is consistent with the other technologies being considered. The sensitivity analysis below will help to identify the assumptions that have the most critical effect on water costs.

F. Financial and Economic Analysis

For the ADP to be financially or economically attractive, it must be less expensive to purchase and operate over the long term than a diesel engine. The analysis performed is based on a net present value approach. No effort has been made to determine the financial or economic value of the benefit (the water delivered). The volume of water is used directly as a measure of the benefit.

As is appropriate, future costs and future benefits (the water) are discounted to present value. The present value of the costs are divided by the "discounted" water delivery (in cubic meters). This provides a figure for the cost per cubic meter of water delivered, hereinafter referred to as the unit cost.

The difference between financial and economic analyses is largely one of perspective. A financial analysis considers all of the costs for which money changes hands. An economic analysis makes adjustments (through shadow-pricing) to account for the national or social value of the costs. This becomes particularly important for the ADP because it is likely that many ADP user/operators will not be paid, so their labor has no financial cost. However, their labor does have an economic cost, as this time could otherwise be spent in other productive pursuits. The costs are divided into capital and recurrent categories. All assumptions not discussed in detail here are given in Appendix M of VOLUME II. The figures used in this analysis differ slightly from those in VOLUME I because this analysis attempts to characterize typical use, while the analysis in VOLUME I seeks to identify the most appropriate applications.

1. Capital and Recurrent Costs

To determine the financial and economic characteristics of the ADP, cost estimates for fabrication, installation and operation were obtained from RIIC. For the analysis, the costs associated with the Mono pump itself (both capital and recurrent) are taken to be similar to those incurred for diesel pump sets. The power transmission technology is still in development, and not yet a commercially available product. Thus, the costs are not easily calculated--each example contains some component of genuinely developmental costs.

Reliable cost data are not available for many of the items that will be used in ADP operation. These data are crucial to determining the long-term costs of operating an ADP. In part, the lack of data is due to the fact that there is still a great deal of uncertainty as to how the pump will be operated. Will animals receive supplemental feed? If not, how will there long-term performance be affected? Will existing animals be used as draught animals, or will animals be purchased? Will operators be paid, or will they provide their labor in return for water? Some of these potential costs have been excluded from initial consideration, but will be considered in the sensitivity analysis. In particular, no costs are included in the base-case set of assumptions for:

- pump operator salaries (an economic cost of P0.50 per hour of pump operation is assumed for the economic portion of the analysis);

- supplemental feed for the animals;
- increased veterinary care for the animals; and
- labor associated with care, training and use of donkeys.

The other assumptions in the base-case analysis were chosen to be consistent with the anticipated costs of the ADP and the site conditions assumed for other pumping technologies. The site conditions include installation 200 kilometers from the installation crew's home base, and service 100 kilometers from the service crew's home base (for the foreseeable future, however, these two distances will be the same as RIIC will continue to perform both functions). Estimates of installation labor as well as service and repair costs have been made in consultation with RIIC and are the best current estimates for these costs. The purchase of donkeys and harnesses are included, as it is anticipated that this will be the choice of most ADP users.

Table 4 provides a detailed breakdown of the anticipated costs. Note that the installed cost for the ADP under these conditions (less animals and harnesses) is over P10,000. This is roughly the price of an installed diesel pump using a Lister 8/1 engine--the choice of many engine users in the private sector. However, the ADP cost is significantly greater than a smaller, more appropriately sized Lister LT-1 pump set. Nevertheless, it is clear that the recurrent costs of an ADP are significantly lower than those of a diesel system.

Table 4. ADP Financial Costs (45 m Head)

Capital Costs	
Manufacturing	
materials	P4900
skilled labor	1350
unskilled labor	450
Pump and pipes	
Mono pump and head	1000
column (P21/m)	1155
balance of system	50
foundation	600
Installation	
Labor	500
Transportation	510
Animals and harness	
donkeys (P40 each)--2 shifts of 6	480
harness (P30 each)	180
Total installed cost	P11,175
Recurrent Costs	
Material (annually)	50
Transport (annually)	264
Skilled labor (annually)	72
Unskilled labor (annually)	84
Pump repairs (annually)	200
Harness replacement (every 2 years)	(each) 30
Donkey replacement (every 5 years)	(each) 40

2. Cost Analysis

Based on tests conducted by RIIC and data taken from published sources, outputs have been estimated for teams of two, four, six and eight donkeys (see Table 3). It was assumed that two teams would pump for one 2.5-hour shift per day. No financial cost for pump operation was included. However, an economic cost of P0.50 was included in the economic analysis. These output figures were combined with the costs described above to calculate the unit cost of water pumped. The results are shown in matrix form in Table 5. A 20-year time span was used for the analysis, with replacement of the donkeys after five years and of the harness every two years. The harness replacement interval was estimated by RIIC and refers to an RIIC design specific to this task. The replacement interval for the donkeys could not be verified, but is based on estimates of 10 to

12 years for a donkey's life and a productive working life in this heavy occupation of five years.

Table 5. ADP Costs and Performance*

Head (m)		Number of Donkeys 2	4	6	8
15:	m^3/day	17.0	34.5	51.5	68.5
	financial (P)	.37	.19	.13	.10
	economic (P)	.53	.29	.18	.14
30:	m^3/day	8.6	17.1	25.7	34.3
	financial	.75	.39	.27	.21
	economic	1.07	.59	.37	.28
45:	m^3/day	5.7	11.4	17.1	22.8
	financial	1.15	.59	.41	.32
	economic	1.64	.90	.56	.42
60:	m^3/day	4.3	8.6	12.8	17.1
	financial	1.55	.80	.56	.43
	economic	2.15	1.20	.75	.58

*Based on five hours of pumping (two 2.5-hour shifts).

The above table indicates that the financial unit cost for pumping water is inversely proportional to the amount pumped and is, within the range considered, nearly independent of head, number of donkeys used, or the pumping rate (see Table 3). This is because no financial costs are keyed to the hours of pumping time--a simplifying assumption that is not strictly accurate. However, as there is no financial cost for labor included, it is not a bad assumption. The additional costs for pumping from deeper water levels and for purchase of additional donkeys are not significant when compared to the other costs.

3. Base Case and Sensitivity Analysis

Base Case

A hypothetical "typical" pumping case has been developed in order to analyze the financial and economic implications of using the ADP. The case is for six donkeys pumping 17 m^3/day through a head of 45 meters. In this case, two 2.5-hour shifts are assumed.

A discount rate of 12 percent is used. This reflects private-sector use of this technology and is the interest rate charged by the National Development Bank (NDB). Currently, there are several low-interest loan and grant programs open to certain individuals and groups through Ministry of Agriculture (MOA) programs. Qualification for these programs depends on the size of the loan or grant and the status of the applicant. Cases where these programs are used are not analyzed here.

The financial and economic unit water costs, when analyzed using the unit cost approach, are P0.41 and P0.56 per cubic meter, respectively. The financial installed capital cost for this system is P11,175. The present value of the recurrent costs is P7,914.

Sensitivity

The sensitivity analysis for this case examined changes in manufacturing, installation costs and recurrent costs. Unless otherwise specified, the figures referred to are economic. These sensitivity cases are summarized in Table 6. The assumed costs of the ADP reflect RIIC's estimates of the fabricated cost for the device. It may be possible to reduce the materials cost for manufacturing by P1,000 through bulk purchasing, reduction of waste and careful specification of components. If so, the unit water cost would decline by seven percent. As more units are fabricated, it is reasonable to assume that the skilled labor input could decline by 10 percent. This would reduce the economic unit cost by another one percent. These two changes would decrease the installed capital cost of the ADP by 11 percent (including animal and harness costs). If, on the other hand, the manufacturing cost increases by 10 percent due to increased materials cost, the increase in unit water cost would only be two percent. None of these changes makes as much as a 10 percent difference in the unit water cost.

Table 6. Sensitivity Analysis Results

Variable Name	Change Made	Financial	%	Economic	%
Base-case condition	none	P0.41		P0.56	
ADP lifetime	double to 20 years	.36	-12	.51	-9
ADP cost	mat. cost, less P1000 labor cost, less 10%	.38	-7	.52	-7
ADP cost	mat. only, less P1000	.38	-7	.53	-6
Transportation	installation & service distances halved	.38	-7	.53	-6
Donkey cost	no cost for animals	.39	-5	.54	-4
Labor cost	P0.50/hour	.56	+37	.56	0
Transportation	300 km inst & service	.50	+22	.60	+7
Supplemental feed	P200/year	.44	+ 7	.59	+5
Repair cost	3x annual spares	.43	+ 5	.58	+4
ADP cost	10% increase, materials	.42	+ 2	.57	+2
Donkey cost	20% increase, to P50	.41	0	.56	0
No. of animals	use 8 donkeys	.42	+ 2	.53	-5

The greatest changes in the unit water cost are associated with labor and transportation. Transportation cost changes could be due to use of vehicles that are more expensive to operate, increased distances for installation or servicing, or increased number of service and repair trips. When the installation and service distances were halved (from 200 and 100 kilometers for installation and service, respectively), the financial unit water cost decreased by seven percent. If installation and service trips are increased to 300 kilometers each, the financial unit water cost increases by 22 percent. While this may appear unexpectedly high, transportation costs account for from one-third to one-half of the recurrent costs if no pumper salary or supplemental feeding is included. This should make clear the importance of training service personnel near pump sites in order to reduce this cost.

No financial cost for labor has been included in the base-case analysis because it is assumed that the users who benefit will provide free labor. An economic cost for labor has been included, however. If there is indeed a financial cost equal to the economic cost for labor, the financial unit cost will increase by 37 percent and will equal the economic unit cost. This is the most significant change included in the sensitivity study and underlines the importance of labor in ADP use.

Animal and harness costs influence both capital and recurrent costs. When the cost of each donkey is increased by 20 percent to a total of P50, there is no measurable effect on the water cost. Exploring this cost further, the number of animals per shift was increased to eight. This increases the financial unit cost by two percent if no additional water is pumped as a result of the increased number of animals. Note that the additional animals allow the pumping rate to increase, thereby reducing the number of pumping hours; this causes a reduction in the economic unit cost because of the economic cost for labor. In reality, adding two donkeys should increase output from 17 to 23 m^3/day (when pumping the same number of hours) and reduce unit costs by 25 percent. Adding two animals costs P160, initially, for two animals per shift, and periodic replacement costs must be considered. This implies that over the long term, there is little to be gained from trying to save animal costs by extending shifts or pushing the animals harder. However, animal costs can affect the cash-flow situation of ADP users if animals are purchased to operate the pump. Additional animals will also affect animal collection and harnessing time. Similarly, if the animals are being fed, feeding costs may increase. The effect of using animals already owned by users was also explored. The unit water cost declines by only five percent when no animals are purchased. This indicates that there are limited long-term gains or losses in unit cost as a result of direct animal costs; the issue is largely one of user cash flow.

The consideration of recurrent costs includes the effects of supplemental feeding costs, pumper costs, spare-parts costs, and increased ADP lifetime. Pump-operator costs were discussed above. If supplemental feeding is required, at an annual cost of P200, the unit water cost increases by seven percent. This is a substantial increase and stresses the need to more thoroughly explore this aspect of ADP use. An increase in the spare-parts costs from P50 to P150 per year increases the unit water cost by five percent. This, along with the transportation analysis, indicates that emphasis must be placed on local servicing even if this implies a slight increase in the spare-parts cost. The ADP design lifetime has been estimated to be 10 years. The term of this analysis has been 20 years, with one ADP replacement at the 10-year mark. If the ADP can be built to last 20 years, there will be a 12 percent savings in the unit water cost, because the ADP will not need replacing during the term of the analysis. Increasing the ADP lifetime has a significant impact on unit costs.

For comparison purposes, the unit water cost to deliver 17 m^3/day, through a head of 45 meters, with a Lister 8/1 (the choice of many private-sector diesel-engine users), is in the range of P0.60. This is roughly 50 percent higher than the cost of delivering water with the ADP, assuming the base-case conditions. This cost will be approached with the ADP only if manufacturing costs increase by 10 percent, animal costs increase by 20 percent, supplemental feed must be provided at P200 annually, a pump operator must be employed at P400, the annual cost of materials triples, and the distance for both installation and service increases to 300 kilometers. The capital cost of the ADP is in the same range as that of a diesel system--the recurrent cost savings make the difference. The annual fuel cost alone for the Lister 8/1 will cover all of the recurrent costs of the ADP.

However, if engine users choose the LT-1 instead of the 8/1, they will save one-third of the capital cost and one-half of the fuel cost, and the unit water cost will be in the range of P0.40 to 0.45 per cubic meter delivered. This is only slightly more expensive than the base-case ADP. The ADP is more expensive but has lower recurrent costs. Thus, given the assumptions made, the ADP is competitive in this case, but there is less margin for increased cost due to any of the possibilities listed above.

It seems clear from the analysis that the ADP, as a mature technology, could deliver water competitively with diesel engines, provided manufacturing costs can be reduced. From the information provided in Table 5 and the sensitivity analysis, the cost of delivering water seems quite independent of all factors, except the amount of water that can be pumped, labor costs, and transportation considerations. It is important to note that the financial and economic unit costs will be significantly affected if supplemental feeding is required, pump operators must be paid, or transportation costs increase. Thus, these issues must receive attention as development of the ADP proceeds.

4. Use of Oxen

Given that ADP performance seems to depend heavily on the amount of water that can be pumped, it is natural to consider the use of other draught animals. The use of oxen has several advantages. The RIIC tests involving oxen indicate that the power output of oxen is about twice that of donkeys (tested power drawbar to water pumped), or 130 watts as opposed to 70 watts. Four oxen can pump 3.5 m^3/hr from a head of 60 meters, or over nine m^3/hr over a 20-meter head (Table 1). Using oxen, water can be pumped from deeper boreholes, or at an increased rate from shallower boreholes. If water can be pumped at a faster rate (i.e., if borehole yield is adequate), more water can be delivered per day, or the same amount can be delivered using less of a pump operator's time. With oxen, it is also possible to pump the same amount of water using half the number of animals. The unit cost of water can also be reduced under a variety of conditions; however, borehole yield is usually the factor that limits practical pumping rates. Thus, any consideration of the potential to decrease unit water costs through the use of oxen will require exploration of the potential cost and time savings of using half the number of animals.

The use of oxen would also extend the range of the ADP to greater heads because the ADP's design makes teams of more than eight donkeys difficult to harness and drive. In cases where borehole yield does not limit the pumping rate, the potential to pump greater volumes of water clearly favors consideration of oxen as draught animals. Although donkeys have been the draught animal of choice for ADPs thus far, it is clear that further experiments with oxen are advisable and should lead to positive results.

G. Conclusions

Although the ADP is still in the development stage, the experience to date proves that ADPs have a definite role in water delivery in Botswana. From an energy perspective, the ADP offers the opportunity to be independent of diesel fuel supplies. This is an important strategic as well as practical consideration. From a practical perspective, this independence reduces recurrent costs considerably, as no fuel must be purchased or delivered and no engine servicing is required. Strategically, independence from imported fuel and manufactured spares decreases (however marginally) Botswana's vulnerability to regional discord. In addition, locally made products increase employment and use of local resources. Nevertheless, potential users must be convinced to use the ADP for practical reasons--cost, reliability and ease of use. Longer term costs are not well documented yet. Reliability has not yet been demonstrated over the long term, as no machines have been in use for more than several years. Questions concerning the organization of user groups, operator costs, supplemental feeding costs and animal ownership have yet to be fully explored.

Recurrent costs, the user's ability to pay them, and the effects they have on performance must be more fully understood. As the RIIC ADP program continues, added information must be gathered and analyzed to ensure that questions about animal health and nutrition, and their effect on water pumping--issues which have not yet received primary attention--are clearly addressed and solved. In addition, the work with harnesses and harnessing techniques must continue. To compete with the diesel pumping alternative, the ADP's capital cost must be reduced.

This will decrease the capital outlay required as well as the unit cost of water delivered.

As ADP use continues to be investigated, organizational questions need to be addressed, particularly since the ADP has been aimed at the syndicate market. The nature and stability of syndicates needs to be explored. It is important to have a strong user group, as the character of the ADP technology requires active cooperation among users. This, along with the high initial cost, appears to be the largest barrier to successful ADP use. Continued emphasis must be placed on working with potential customers to ensure that they understand the commitment required by the technology as well as the need to be well organized.

Given the information available, there is little doubt that the ADP can be competitive with diesel pump sets in many applications when water demand is in the range of 20 to 30 m^3/day. There are currently several thousand private-sector engine owners and operators. Thus, the potential market for the ADP is likely to be sufficient to justify additional efforts to further develop and explore the social and animal-related issues involved in ADP use.

IV. BIO-GAS SUBSTITUTION

Bio-gas is an organically produced mixture of methane, carbon dioxide and trace gases. The methane component is combustible and can be used as a substitute for other combustible materials. Bio-gas has been used as an energy source in other parts of the world for many years. However, efforts to explore its use in Botswana began only recently. In the late 1970s, RIIC became interested in the potential of bio-gas technology and undertook a program to build and test several types of bio-gas plants. These included fixed-dome bio-gas digesters (the type typically found in China); a horizontal, cylindrical type; and the floating-dome digester (commonly used in India).

The horizontal, cylindrical digesters proved unsuitable as they needed to be heated and insulated to operate properly. The fixed-dome digesters were plagued by low gas production, probably due to the loss of gas through leaks in the dome. Finally, work with these bio-gas plants was abandoned in favor of the Indian floating-dome model. It offered the distinct advantages of simplicity of construction and the production of gas at a constant pressure. Although it is possible to operate engines entirely with bio-gas, to take advantage of existing equipment and infrastructure, it appeared preferable to design for partial fuel replacement.

After the first successful tests at RIIC of a digester with a tank volume of 10 m^3 (see Figure 3), a digester with a tank volume of 75 m^3 was built at Diphawana. It was to be used to provide bio-gas as a substitute for diesel fuel in an ST-1 Lister engine. Tests conducted by RIIC (Khatibu, 1983) indicated that the digester produced more than 23 m^3/day of bio-gas and that 80 percent of the diesel fuel (by volume) could be displaced. Since these tests were completed, about eight other digesters have been built. These range in size from 15 to 110 m^3. At present, Botswana has three operating digesters that displace diesel fuel in pumping applications (with one more in the planning stages). The rest are being used to provide gas for other purposes.

This report discusses only the displacement of diesel in pumping applications--not other uses of bio-gas, such as for lighting and heating. CWPP was concerned only with the use of bio-gas as a substitute for fuel in the operation of diesel engines for water pumping. Therefore, the present analysis is based on the assumption that the bio-gas system operates only as a fuel displacer. Thus, it does not consider, for example, the value of the sludge by-products as fertilizer. However, the total pumping system will be included in the analysis so that comparisons can be made with other pumping technologies.

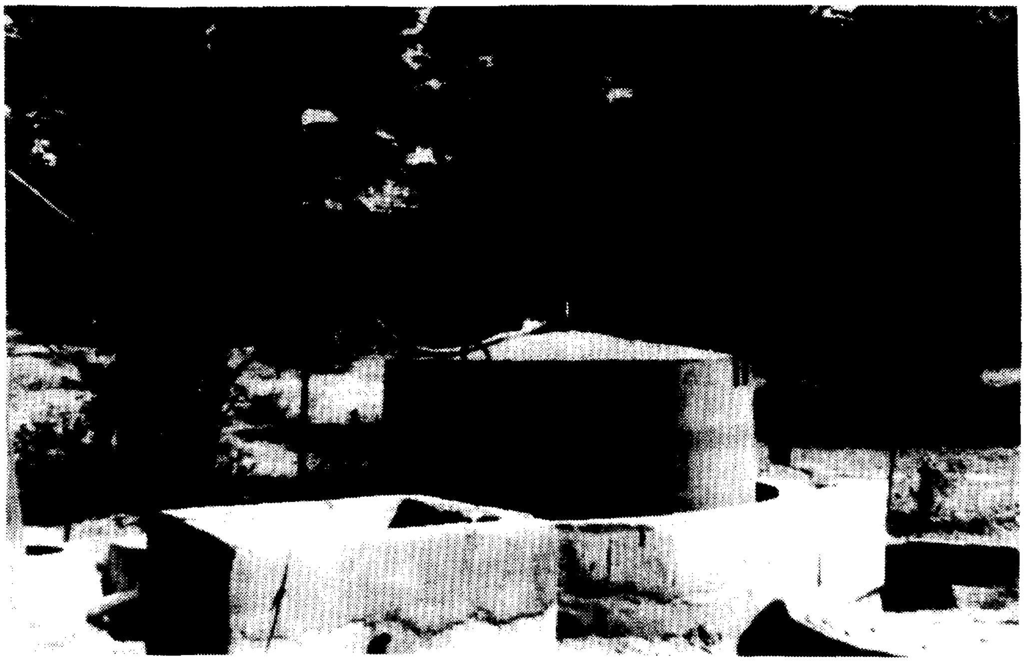


Figure 3. Demonstration floating-dome bio-gas digester at RIIC.

A. Technology Description

The process of bio-gas production takes place in an oxygen-free "digester" environment that allows the action of anaerobic bacteria to break down organic matter in a series of steps. This leads to the creation of bio-gas as well as an effluent that can be used as a fertilizer. Bio-gas is lighter than air and rises to the top of the digester, where it can be collected for use. As gas is created and trapped in the dome, the weight of the dome on the gas causes it to be held at greater than atmospheric pressure. Floating-dome digesters, such as those in use in Botswana, must be continually fed a slurry of water and organic matter, and the effluent must be removed in a flow-through process. In order for the digestion process to be completed, the slurry must remain in the system for a certain period. This is referred to as the hydraulic retention time. The hydraulic retention time is a function of digester size and feeding rate. For Botswana, a retention time of 75 days allows the decomposition of 90 percent of the degradable components of cattle manure into bio-gas. The production of gas depends on the kind of manure used, the freshness of the manure, and the temperature of the slurry.

B. Water Pumping Applications

A general precondition for the use of the technology in Botswana is the ready accessibility of organic matter in the form of cattle dung. This source will clearly exist in stock-watering applications. In addition, the technology is "participatory" in that it requires the active participation of a number of people not only for operation of the pump, but also for dung collection and effluent handling. In the public sector, higher government wage scales and the lack of day-to-day community participation in village water supplies make the use of bio-gas substitution pumping unlikely under present conditions. For these reasons, the use of bio-gas for water pumping will only be considered for private-sector stock watering. A small number of government research facilities could possibly apply the technology, but these are few and will not be discussed here.

For stock-watering purposes, the water requirement and head are the primary considerations in the design of a diesel pumping system. The design and operating conditions of the engine determine the fuel requirement on both a per hour and per unit of water pumped basis. This will continue to be true as bio-gas is substituted for some of the diesel fuel. The replacement rate of diesel fuel will determine the gas requirement, and this in turn enters the equation that determines the digester size and the slurry feeding requirement. One cubic meter of bio-gas substitutes for 0.6 liters of diesel fuel, based on the energy values of the two fuels. In addition, digester size depends on the gas requirement, the conversion efficiency of dung to bio-gas, and the hydraulic retention time in the digester. Based on a typical conversion rate of five kilograms of fresh dung into one cubic meter of bio-gas, and a hydraulic retention time of 75 days, the tank volume of a digester would have to be roughly 3.6 times the daily gas requirement (as indicated by the analysis performed for the Botswana Energy Master Plan). This is a simplification since other factors enter into the equation as well, including the temperature in the digester, the water needed to convert the dung to a slurry of the proper consistency (assumed to be 1.2 l/kg), and a number of other factors.*

The digester design being promoted by RIIC is a brick-lined, subsurface enclosure with an Indian-style, floating steel dome, which pressurizes the gas. A loading chute on one side permits easy charging of the digester, and an outflow pipe permits removal of the slurry. A tube at the top of the dome supplies the gas to the modified engine manifold, where it is taken into the combustion chamber and burned. In addition to the digester tank itself, the following equipment is also required in a bio-gas/diesel system:

---

*For further information on this subject, see BOTSWANA ENERGY MASTER PLAN, Final Draft Report, Vol. 1, March 1987. A detailed evaluation of the potential for bio-gas use is provided in Chapter 3.4 of the report.

- a gas collection dome;
- a pipeline with a water trap, a manometer and a valve for adjusting gas pressure; and
- an adapter to allow mixture of the fuel, air and bio-gas.

All of the other requirements are similar to those for using diesel fuel alone. For a full discussion of the use of diesel-driven pump sets, refer to VOLUME II: DIESEL SYSTEMS.

To use a mix of diesel and bio-gas, the two must be mixed with air in the combustion chamber of a standard diesel engine. This is accomplished with a special adapter that fits between the air cleaner and the air manifold inlet. This low-cost adapter is fabricated at RIIC. In addition, a water trap is required to trap any moisture that collects due to condensation in the pipeline. The manometer and valve allow the gas to be turned off, and, when turned on, adjusted to the proper working pressure. Proper operation depends on the proper working pressure which, in turn, depends on feeding the cattle dung and water mixture into the digester at specified rates. In short, the whole process depends on operators performing a series of tasks on a daily basis to guarantee that gas is formed at a sufficient rate to ensure displacement of the diesel fuel.

C. Requirements for Operation

Operation of a diesel pumping system that substitutes bio-gas for a portion of the diesel fuel requires a few additional skills over and above those used in operation of a diesel engine alone. The differences fall into two categories--digester operation and engine operation. Operation of the digester requires collecting dung, mixing the dung with water to form a slurry, and feeding the slurry into the digester. In addition, the digester effluent must be removed from the outlet tank. The slurry must be stirred to break up the surface scum that forms. Stirring is accomplished by rotating the dome (which has stirrers built into it). The moisture trap should be emptied weekly. Each year, the floating dome must be given a new coat of black paint. The color is important as it captures the radiant energy of the sun, thus helping to maintain the proper temperature.

System operation begins each day by starting the engine without using bio-gas. After five minutes, the bio-gas mixture must be adjusted by opening the valve in the bio-gas pipeline until the proper pressure is observed. The engine will then run unattended. At the end of the day, the bio-gas supply is stopped five minutes before the engine to ensure that all of the bio-gas (and particularly its hydrogen sulfide impurities) is clear of the system. This prevents engine damage due to the presence of gas residues. These procedures, although they add to the time required of the operator, are not difficult.

D. Testing

CWPP did not perform any independent tests of the use of bio-gas for water pumping. However, the BRET project commissioned BTC to perform tests at the Diphawana site. These tests were conducted in August 1984 (Jacobs, 1985). Earlier tests were conducted by RIIC (Khatibu, 1983). At first, these two sets of tests did not appear to be consistent, but the Botswana Energy Master Plan (March 1987) indicates that the results are consistent when test conditions are taken into account. In addition, RIIC conducted tests at its 10 m^3 digester. These results have been taken as representative of the potential performance of bio-gas plants in Botswana. The monthly gas production and digester temperature figures are given in Table 7.

Table 7. Gas Production of Two Floating-Dome Bio-Gas Digesters

	10 m3 Digester		75 m3 Digester	
	m^3/day	digester temp °C	m^3/day	digester temp °C
January	3.3	27.2	26.3	27.5
February	3.0	26.0	24.5	25.5
March	2.7	25.2	22.0	24.5
April	2.6	24.0	20.6	22.0
May	2.6	21.0	19.0	20.0
June	2.0	17.0	18.0	16.0
July	1.8	15.2	19.8	18.5
August	2.0	17.0	23.1	20.8
September	2.3	19.0	23.8	22.0
October	2.4	23.3	28.0	25.5
November	2.6	25.1	28.2	26.0
December	2.9	26.0	30.2	28.0

Source: Khatibu, 1983.

Note that gas production falls off during the winter months as digester temperature declines. This is typical of the performance of bio-gas plants, as the bacteria that produce bio-gas prefer a warmer environment. This makes clear the importance of keeping the dome painted properly and the digester as well insulated as possible. For the 10 m^3 digester, the average daily gas production during the coolest month was 18 percent of the digester's volume. For the 75 m^3 digester, it averaged 24 percent. Indications are that it should be possible to increase this figure to 25 to 30 percent.

All testing at Diphawana indicates that it is possible to displace 80 percent of the diesel fuel (by volume) when bio-gas is used to operate a Lister engine. This displacement potential is typical for bio-gas/diesel engines in other countries. The potential depends on the availability of bio-gas at the proper pressure. As the pressure declines, or if the floating dome is resting on the stops (and thus its mass is not providing pressure), then the substitution rate declines, in the extreme, to zero.

E. Pumping System Design

The design of diesel pumping systems is discussed in Section VI of VOLUME II: DIESEL SYSTEMS. With the introduction of bio-gas as a substitute for diesel fuel, no change is required of this basic design procedure. However, the bio-gas system must be designed to complement the requirements of the diesel engine. No discussion is provided here on the details of digester construction or the detailed considerations regarding sizing. For the present purpose, it suffices to consider digester sizing in general terms.

The design process requires several steps, some of which are common to the design of all pumping systems. These include:

- calculate head and flow requirements, and then pump and engine requirements, as for a diesel pumping system;

- based on de-rating and partial-load fuel consumption, calculate the daily fuel requirement when the most water is being pumped;

- using an 80 percent fuel-displacement rate, and assuming that one cubic meter of bio-gas is needed to replace a liter of diesel fuel, calculate the daily bio-gas requirement; and

- calculate the digester tank size by multiplying the gas volume required by 3.6 (for Botswana), and round the tank size up to the nearest five cubic meters.

Next, it must be determined whether sufficient organic matter exists to fuel the digester. At five kilograms of fresh dung per cubic meter of bio-gas, this will rarely if ever be a constraint for stock-watering applications. However, the choice of design conditions is an important one. As shown in Section IV.D, gas production declines in the winter as the temperature declines. This corresponds to the winter dry season, when cattle are most likely to be watered from borehole sources and use of the diesel engine is at its highest. If 80 percent of the diesel fuel is to be displaced at all times, the digester must be sized to provide sufficient gas during this period of the year. This is clearly a simplification of the design procedure, but the experience and data collected to date cannot justify a more detailed analysis. A complete theoretical analysis is reported as a part of the Botswana Energy Master Plan, and those with more interest are referred there.

F. Analytical Approach

For this economic analysis of the use of bio-gas as a substitute fuel, it is assumed that all of the costs for operating the diesel system remain, with the exception of fuel costs, as if no bio-gas were being substituted. It is assumed that 80 percent of the fuel can be displaced by bio-gas at all times. Further, it is assumed that the pumping system is only used during the time of year when cattle would normally be watered from boreholes, not on a year-round basis. Similarly, no marginal value has been assigned to bio-gas that might have been produced and used for other purposes than pumping.

It is also assumed that digesters are available in increments of five cubic meters (although this is not currently true, the designs could be developed easily). The gas requirement is calculated to displace 80 percent of the de-rated fuel consumption of an ST-1 Lister engine. The appropriate digester tank size is taken as 3.6 times the daily gas requirement, rounded up to the next incremental size.

The cost of the digester is taken to be P75 per cubic meter. This figure, provided by RIIC, is an average for digester construction and appears to be reasonable. Twenty percent of the construction cost is assumed to be labor, again based on discussions with RIIC. All costs for operating the diesel engine (other than fuel) are taken to be the same as for a diesel engine operating without bio-gas. No additional cost is assumed for maintenance of the bio-gas digester, nor is any additional labor included to cover the cost of dung collection and effluent removal.

G. Financial and Economic Analysis

For the bio-gas pumping technology to be economically attractive, sufficient diesel fuel must be saved so that the cost savings more than cover the additional costs of fabricating and operating the digester. There may also be a strategic benefit in the reduced use of imported diesel fuel. However, the bio-gas pump in its present configuration requires the use of at least 20 percent diesel fuel. Thus, this system will still be vulnerable to disruptions in fuel supply.

There are other uses for bio-gas as well, and displacement of diesel fuel burned in small pump sets may or may not be the use of greatest value. Bio-gas may be more valuable in situations where refrigeration fuels are at a premium, or where illumination is needed, for example. Clearly, bio-gas can substitute for a variety of fuels, or possibly be the only fuel available in some situations.

1. Cost Analysis

To calculate the cost and fuel savings associated with investment in the digester, the model used in VOLUME II: DIESEL SYSTEMS was modified to permit inclusion of added capital costs and to account for the displacement of diesel fuel with bio-gas.

For this analysis, the cost of engine modifications is included as part of the digester costs. In addition, the economic cost of gathering dung and tending the digester are included at P50 per year. It is assumed that the users of the system will provide this labor at no financial cost. An annual salary of P450 is included for a pump operator. Based on estimates by RIIC staff, unskilled labor constitutes about 20 percent of system fabrication costs. The prospective user of this system is a private-sector cattle owner--either a syndicate or a private owner.

The engine is a Lister ST-1, single-cylinder engine driving a Mono pump. Although an LT-1 would be less expensive and more cost-effective, use of the ST-1 (and 8/1) is more typical in private-sector applications. This ST-1 case is identical to that considered in VOLUME II: DIESEL SYSTEMS, except for the digester-specific modifications. Namely, a seven-ton truck is used for installation, due to the larger scale of the construction project; transportation costs for the installation were increased by 2.8 trips (to four trips), using the standard distance from the installation center (200 km); and it is expected to take 20 days to complete the project, including building the digester. The remainder of the costs reflect retail prices for system components and common installation and configuration practices for the private sector. This accounts for the fact that costs differ from those for public-sector cases. All assumptions not discussed in detail here are given in Appendix M of VOLUME II. Note that the figures given in this analysis are slightly different from those in VOLUME I. This analysis attempts to characterize typical use, while the analysis in VOLUME I seeks to identify the most appropriate applications.

The cost items for a diesel pumping system, both with and without bio-gas fuel substitution, are shown in Table 8.

Table 8. Summary of Diesel Pumping Costs (60 m Head)

Costs	Without Digester	With Digester
Equipment Costs		
engine--Lister ST-1	P3763	P3763
Mono pump and head	856	856
rising main (Mono column) per meter	1820	1820
pump house	600	600
above-ground piping	50	50
digester cost	0	1125
Installation labor cost	1050	3000
Installation transportation	408	1360
Installed capital cost	8,547	12,574
Present value of recurrent costs	16,094	12,285
Total	P24,641	P24,859

Based on these figures--those normally required for equipping a private borehole with the Lister ST-1 engine--and adding only the cost of the digester itself, a set of unit costs for water delivered was calculated (see Section III.F for a brief discussion of terms and methodology). These unit costs, along with pertinent information regarding the size of unit required to displace 80 percent of diesel fuel for each head and daily output specification, are shown in Table 9.

Table 9. Output and Costs

Head (m)		Daily Output (in cubic meters)			
		5	10	20	30
30:	Financial (P)	1.33	.73	.44	.34
	Economic (P)	1.30	.72	.44	.34
	Bio-gas demand (m^3)	.7	1.4	2.8	4.2
	Digester size (m^3)	5.0	10.0	15.0	20.0
60:	Financial	1.39	.77	.46	.35
	Economic	1.37	.76	.46	.36
	Bio-gas demand	.9	1.9	3.7	5.6
	Digester size	5.0	10.0	15.0	25.0
90:	Financial	1.45	.80	.48	.37
	Economic	1.44	.80	.49	.38
	Bio-gas demand	1.1	2.1	4.3	6.4
	Digester size	5.0	10.0	20.0	25.0
120:	Financial	1.52	.84	.50	.39
	Economic	1.51	.84	.51	.40
	Bio-gas demand	1.3	2.6	5.2	7.7
	Digester size	5.0	10.0	20.0	30.0

2. Base Case and Sensitivity Analysis

A base case with a 60-meters head pumping 20 m^3/day was selected for the sensitivity analysis. Diesel fuel is priced at P0.62 per liter. To understand the changes in costs associated with the bio-gas system, the model was first run without the system being added. The result was a unit cost of P0.45 for both the financial and economic analyses.

At the stated head and flow, assuming an 80 percent displacement of diesel fuel with bio-gas, the demand for bio-gas is 3.7 m^3/day. The design rule for sizing the digester specifies a 13.3 m^3 digester, and it is assumed that digesters will be available in increments of five cubic meters. Therefore, a 15 m^3 digester was chosen for the analysis. The unit cost in both the financial and economic cases is P0.46. This indicates that for the base-case considered, the unit costs are similar with or without the use of bio-gas. Table 8 indicates that the installed capital costs are higher and the recurrent costs lower when bio-gas is used.

Further sensitivity analyses were conducted. These are summarized in Table 10.

Table 10. Sensitivity Analysis Results

Variable Name	Change Made	Financial	%	Economic	%
Base-case condition	no change	P0.46		P0.46	
Base case w/o bio-gas		.45	-2	.45	-2
Digester cost	reduce by one-third	.45	-2	.45	-2
Fuel displacement	reduce to 70%	.47	+2	.47	+2
Labor cost	double the economic cost of digester operation	.46	0	.47	+2
Labor cost	double the financial cost of operation	.52	+13	.49	+7
Repairs	one additional trip	.50	+9	.51	+11
Fuel cost w/ bio-gas	10% escalation rate	.48	+4	.48	+4
Fuel cost w/o bio-gas	10% escalation rate	.54	+17	.55	+20
Fuel cost w/ bio-gas	double the cost	.47	+2	.48	+4
Fuel cost w/o bio-gas	double the cost	.54	+17	.55	+20

The major potential cost reduction would be a decrease in the digester cost to P50 per cubic meter, as earlier reported in the Botswana Energy Master Plan. This cost reduction results in unit costs of P0.45. This reduction of two percent in unit costs (both financial and economic) is not significant for this size digester.

If, on the other hand, the diesel/digester system requires one more repair trip annually than a diesel system alone, the costs increase by nine percent (financial) and 11 percent (economic). If the pumper salary is increased from P450 to P900, the financial unit cost increases by 13 percent and the economic unit cost by seven percent. The unit cost shows little sensitivity to the economic cost of dung collection and effluent removal. Doubling the economic cost of this labor results in an increase of two percent in the economic unit cost.

The quantity of fuel displaced was reduced to 70 percent; this reduction in output increased overall costs by two percent. Even greater reductions, of course, increase costs further. For example, when only 50 percent of the diesel fuel is displaced, the costs rise by four percent. Clearly, it is very important to achieve the maximum diesel fuel displacement to make the digester cost-competitive.

Sensitivity to diesel fuel prices was tested by increasing the cost of fuel by 10 percent each year (a 10 percent fuel cost escalation). The unit cost of water delivered without using bio-gas increases by 17 percent in the financial case and 20 percent in the economic case. When bio-gas is used, the increases are two percent and four percent, respectively. The results are very nearly the same if the cost of fuel is doubled (as may be the case if supplies are disrupted). This indicates that bio-gas substitution is not nearly as sensitive to fuel prices as diesel pumping systems alone are, and that as fuel prices increase, bio-gas systems will appear more attractive from both a financial and an economic perspective.

Because the major advantage of digesters is the displacement of diesel fuel, as might be expected, they are most cost-competitive with diesel pumps at high water demand and high head situations where the greatest amount of diesel fuel is normally required. For the analysis presented in Table 9, that would mean pumping 30 m^3/day at a pumping head of 120 meters. The unit financial cost for that case is P0.39. Under these pumping conditions, a standard Lister ST-1 system would deliver water at a unit cost of P0.43. Bio-gas becomes more cost-effective as the fuel requirement increases.

To test the sensitivity in this setting, the cost of the digester was reduced to P50 per cubic meter and the unit cost was reduced by three percent. In addition, if the price of fuel escalates by 10 percent annually, the financial unit cost for water pumped without bio-gas substitution increases by 36 percent. Use of bio-gas limits this to an increase of 10 percent.

For smaller pumping systems, bio-gas substitution does not offer substantial savings, as the cost of the fuel used is a small portion of the total life-cycle cost (about 20 percent in the base case chosen). As system size increases or as fuel costs increase (and become a larger percentage of total costs), bio-gas becomes a more attractive pumping alternative.

H. Conclusions

The foregoing analysis defines an approach to making decisions concerning potential use of bio-gas as a substitution for diesel in water pumping applications. The results cannot be considered definitive, as the field cost and performance data do not exist to allow careful examination of the actual costs of installation and use of such systems. However, the results can be considered indicative of the potential for bio-gas substitution in small-scale water pumping systems. Several important conclusions can be drawn from the analysis.

The analysis underscores a finding of VOLUME II: DIESEL SYSTEMS--that the fuel cost is a small component of total costs at present. In the base case considered here, the annual diesel cost without the use of bio-gas is less than P700; therefore, the potential annual savings is not more than P560 (at a substitution rate of 80 percent). The present value of the fuel savings over 20 years is about P3,800. This provides some indication of the cost limits for the bio-gas plant. Larger systems, where larger amounts of fuel are used (and where fuel is a larger percentage of the cost), will benefit more from the use of bio-gas substitution. In cases where fuel savings are small, the analysis is sensitive to other assumptions, such as labor and digester installation costs. It is important to quantify the costs of installation and operation of production bio-gas systems more carefully in order to determine costs as accurately as possible.

The Botswana Energy Master Plan provides a provisional estimate that bio-gas for pumping water could be attractive at 200 sites in Botswana. If, in fact, 200 digesters were in use, the total diesel fuel savings to Botswana would be on the order of 200,000 liters, or roughly two percent of diesel fuel used for water pumping country-wide. According to the analysis, the cost to construct these digesters may not be significantly less than the fuel savings over 20 years. This does not include the required steps of setting up technical services in the major villages or providing training so that local fabrication is possible. To ascertain the true potential of the technology for water pumping applications, a detailed market survey of the private sector is needed.

If an investment is made in a digester to provide supplemental fuel for a diesel engine, then it is quite important that the digester be operated at maximum efficiency to displace 80 percent of the fuel. If a lower percentage of fuel is displaced, the benefits of the digester decrease but the cost remains the same. This makes the system less attractive from a financial and economic perspective.

The analysis assumes that the operating costs of the digester are small. It is possible that financial costs for collecting dung, feeding the digester and disposing of the effluent will be incurred because users will not be willing to donate time for the sake of realizing fuel savings. If these costs are found to be of any magnitude, there is little likelihood of the digester being an attractive choice for the range of sizes considered.

The need for considerable organization of labor (for dung collection and digester operation) is a source of significant uncertainty in determining the feasibility of bio-gas substitution pumping systems. A study of the willingness and ability of potential users to successfully manage the system's operation should be undertaken before any substantial investment is made in widespread dissemination of bio-gas pumps.

However, it appears that bio-gas substitution may have a role to play in larger water pumping applications where greater amounts of fuel can be displaced. Larger scale use of bio-gas systems will require closer examination, as it may be limited by the availability of dung and the increasing labor required to collect it. In addition, the displacement of diesel fuel may become more important if fuel is in short supply or if the price rises faster than general inflation. It should be noted that digester start-up time would make it difficult to use these systems as stand-bys for periods of scarce fuel. In these cases, moderate-sized systems may become attractive choices.

Any alternative to diesel must be more than marginally cost-competitive with diesels if it is to generate widespread acceptance. People are unlikely to quickly accept new and unfamiliar technologies if they cost the same as the familiar diesels. There must be demonstrated, significant savings involved if the new technology is to gain many adherents. Bio-gas generation may be more practical in multiple-use situations. The economics of cases where lighting and/or heating applications are also included were not examined. If interest in these multiple-use conditions is significant, additional analysis is warranted.

V. GRID-CONNECTED ELECTRIC PUMPS

At the present time, Botswana has three major power plant sites. These are at Selebi-Phikwe (net capacity 74 MW), Gaborone (net capacity 13.6 MW) and Morupule. The new Morupule generating plant is designed to accommodate six coal-fired units with a net capacity of 30 MW each. Three of these units are scheduled to come on line in the very near future. Botswana also has a 30 MW link to the Republic of South Africa. Plans are being made for interconnection to the Zimbabwe/Zambia electrical networks as well.

One of the GOB's major goals has been to minimize dependence on imported oil by substituting domestic coal for oil in electricity generation. The new power plant at Morupule will contribute to that goal by allowing the retirement of diesel-fired power plants. In addition, the use of electrical equipment in place of stand-alone diesel equipment, including water pumps and isolated diesel gen-sets, will contribute to this goal.

Historically, the use of electric pumps has been very limited. The main reason is that the electricity grid (mains) network has been limited. Electric pumps have been used in the water supplies for towns (under the Water Utilities Corporation), but the major-village water supplies and rural schemes have always relied heavily on diesel-driven systems. DWA has an interest in the use of electric pumps for the major-village supplies and has operated a few such systems over the years. The earliest installations date from 1977, when seven submersible pumps were purchased for application in three villages. In several of these cases, the pumps were improperly specified because borehole characteristics were not well understood. Only two of these installations are still operating as designed.

Due in part to these experiences and to the flexibility of the Mono pump, electrically driven Mono pumps have been installed in several locations. There are currently about 10 electric pumps (of roughly 100 total) in operation in major villages. The remainder are operated by the Water Utilities Corporation and by private individuals along the electricity grid. These are about evenly split between submersible pumps and electric Mono pumps. The repair and maintenance experience has been positive, especially for the submersible pumps (when properly sized), and DWA is interested in expanding their use where appropriate.

The use of electric pumps outside the major villages has been minimal due to the limitations of the electricity grid. There is only one electric pump installed as part of the rural village program--at Ncojane in Ghanzi District, where a crooked borehole dictated the use of a diesel generator coupled to a submersible pump. Private use of electric pumps is limited to several in villages where electricity connections are possible and to residential development areas, such as the Gaborone North Estates. There are a few scattered diesel-driven submersible systems in the country.

There is growing interest in the use of electricity to pump water. This interest increased as plans developed to build the generating facility at Morupule. With local generating capacity, the possibility exists to decrease the cost of water pumping as well as dependence on imported energy. However, increased use of electric pumps depends on the extent of the electricity grid and the connection costs for isolated loads. A recent report (UNDP and World Bank, 1986) examines the technological and economic issues of expanded pump electrification. They conclude that the cost-effectiveness of pump electrification depends heavily on the interconnection distance to the grid. The main conclusion is that there are about 70 boreholes in 23 villages (eight major and 15 rural villages) that should be considered for electrification. The annual economic savings would be about P0.8 million for an investment of P0.96 million. The report also concludes that electrification looked economically favorable for some irrigation schemes. These findings have generated considerable interest, and the government is actively seeking funds to undertake a program of pump electrification.

Private contractors are also involved with installation of electric pumps. This activity is largely limited to submersible pumps in areas that are served by the electricity grid and to a few diesel-generator-driven submersible pumps. At least one contractor believes that there are savings to be realized by using a generator and submersible pump instead of the more common diesel-driven Mono pump system. Total activity in this area does not currently exceed 10 pump installations per year, but the application of electricity to water pumping is expected to rise in the future.

A. Technology Choice

Although electricity can be applied to any pumping application--from large-scale irrigation using axial flow pumps, to high head use of positive displacement pumps--the use of electric pumps in Botswana is limited to three types of systems. These are submersible centrifugal; electrically driven Mono; and surface-mounted, radial-flow pumps. The last of these are only used in a few irrigation schemes and as booster pumps where conditions permit, and will not be discussed further here.

Submersible pumps are designed in such a way that the pump and motor are placed below the water surface in the borehole. The motor is placed below the pump and is connected, via an electrical cable, to the surface. In general, three-phase motors are preferred since they are both more efficient and have lower current requirements, allowing the use of smaller diameter, less expensive wire. The remaining components of the system are an isolator (for circuit protection), a direct-on-line starter (for three-phase systems), lightning arrestor, and low-water disconnect protection. In addition, a transformer is required to reduce the transmission voltage to the motor operating voltage. These pumps are flexible in that they can be specified for a wide range of applications by fitting more or fewer pump stages and by choosing an appropriate motor. Efficiencies can be as high as 70 percent if pumps match the application properly. The limited experience with these pumps in Botswana indicates that, if specified correctly, they provide trouble-free operation and hence have low recurrent costs for maintenance and repair. Submersible pumps can also be used where crooked boreholes preclude the use of Mono pumps. However, they also have several distinct disadvantages. First, the efficiency of these pumps is much more sensitive to pumping head than the Mono pump, and the motor can be severely damaged if the pump runs dry. They depend entirely on the reliability of the electricity grid. The Mono is more flexible in that it can also be operated by a diesel-engine backup if necessary.

An electrically driven Mono pump (see Figure 4) consists of the same components as a diesel-driven Mono, minus the diesel engine. In its place, an electric motor drives the pump through V-belts. The requirements of an isolator, a direct-on-line starter (for three-phase systems) and a transformer are the same as for a submersible system. The system has the advantage that the Mono pump is well known, flexible in terms of applications, and maintains high efficiency over a wide range of pumping heads. In addition, should there be a lengthy power outage, the pump can be driven with a diesel engine. The motor is surface mounted, which provides easy access to it should there be difficulties. Both the Mono and submersible pump systems can also be operated with generator sets.

Figure 4. Surface-mounted AC electric motor connected to Mono pump, Otse.

B. Tests Conducted

Short-term tests were conducted at a limited number of electric pumping sites. Both electric submersibles and Mono pumps driven by surface motors were tested. The major goal of the tests was to determine the energy efficiency of the pumping system. For this purpose, the following short-term measurements were made at each site:

- pumping water level;
- pressure on the delivery side of the well head;
- water flow rate; and
- electricity consumption.

A well dipper was used to measure water level, a pressure gage was installed in the delivery line to measure delivery pressure, and then a stopwatch was used to measure the time required to deliver 100 liters of water. Electrical consumption was measured simultaneously using the kilowatt-hour (kWh) meter installed to meter electrical consumption. The Botswana Power Corporation's (BPC) limits of meter acceptability are 2.5 percent fast and 3.5 percent slow, but most meters are accurate to within one percent. The meters used for the test were assumed to be accurate. The electrical consumption tests were performed by recording the water delivery for a known number of meter disk revolutions. From the information provided on the meter, the relationship between kWh consumption and disk revolutions is known and the electrical consumption per unit of water delivered can be calculated.

The energy efficiency of the pump set can be found by calculating the hydraulic energy required to pump a volume of water and dividing by the electrical energy delivered to the pump motor. The hydraulic energy requirement can be calculated for a known head and water volume as follows:

$$E_h = (V \times H \times 9.8) / 3.6$$

where: E_h = hydraulic energy (kWh)
V = water volume (m^3)
H = total head (m)

The efficiency is then calculated as follows:

$$Eff = E_h/kWh_{del}$$

where: Eff = energy efficiency of the system
kWh_{del} = electrical energy delivered (kWh)

From these efficiency calculations, one can estimate the daily or annual energy consumption of the system (provided the pumping conditions do not change).

In addition to these tests and calculations, existing records were consulted and interviews conducted with government officials and pump installation contractors. The purpose was to identify the capital costs and long-term operating costs. Unfortunately, experience with electric pumps is fairly limited due to the comparatively few installations. As a result, certain assumptions and generalizations are necessary. These will be discussed in further detail later in this section.

C. Test Results

Tests were conducted at three sites equipped with submersible pumps connected to grid electricity--one site with a gen-set and submersible pump, and two sites equipped with surface-mounted, grid-driven electric motors driving Mono pumps. These three configurations are discussed individually below.

1. Grid-Connected Submersible Pumps

Three sites, referred to as sites 1, 2 and 3 (two in Mochudi and one in Molepolole), were tested. The results are given in Table 11.

Table 11. Test Results for Grid-Connected Submersible Pumps

Site	Head (m)	Flow Rate (m^3/hr)	Operating Time (hrs/day)	Energy Consumption (kWh/day)	Efficiency (%)
1	110	9.6	17	116	42
2	94	4.0	16	47	35
3	67	9.4	11	38	50

Sites 1 and 2 were first equipped with submersible pumps in the mid-1970s. Discussions with the engineer in charge of the project at the time revealed that after purchasing the equipment for specific applications, it became clear that the pumps could not be used in the particular boreholes for which they were intended. This was because the total pumping head had been miscalculated due to greater than anticipated drawdown in the borehole. The pumps were eventually installed in different boreholes. No legible markings remain on the pumps. As most commercially available submersible pumps have efficiencies above 60 percent at the optimum design point (see Table 11), even without knowing the pump model number it is clear that these pumps are operating far below optimal design conditions.

The third of these pumps, a Grundfos 16-8, was installed in 1982. It was designed to deliver 13 m^3/hr at a head of 62 meters. Under those conditions, the pump should have been 65 percent efficient. In fact, the actual head is 67 meters and the pump delivers 9.4 m^3/hr at an efficiency of only 50 percent (see Figures 5 and 6). A more efficient pump could be specified for this application. This example shows the sensitivity of the submersible pump to head conditions. It also demonstrates the need to accurately determine drawdown and delivery head conditions in order to specify submersible pumps properly.

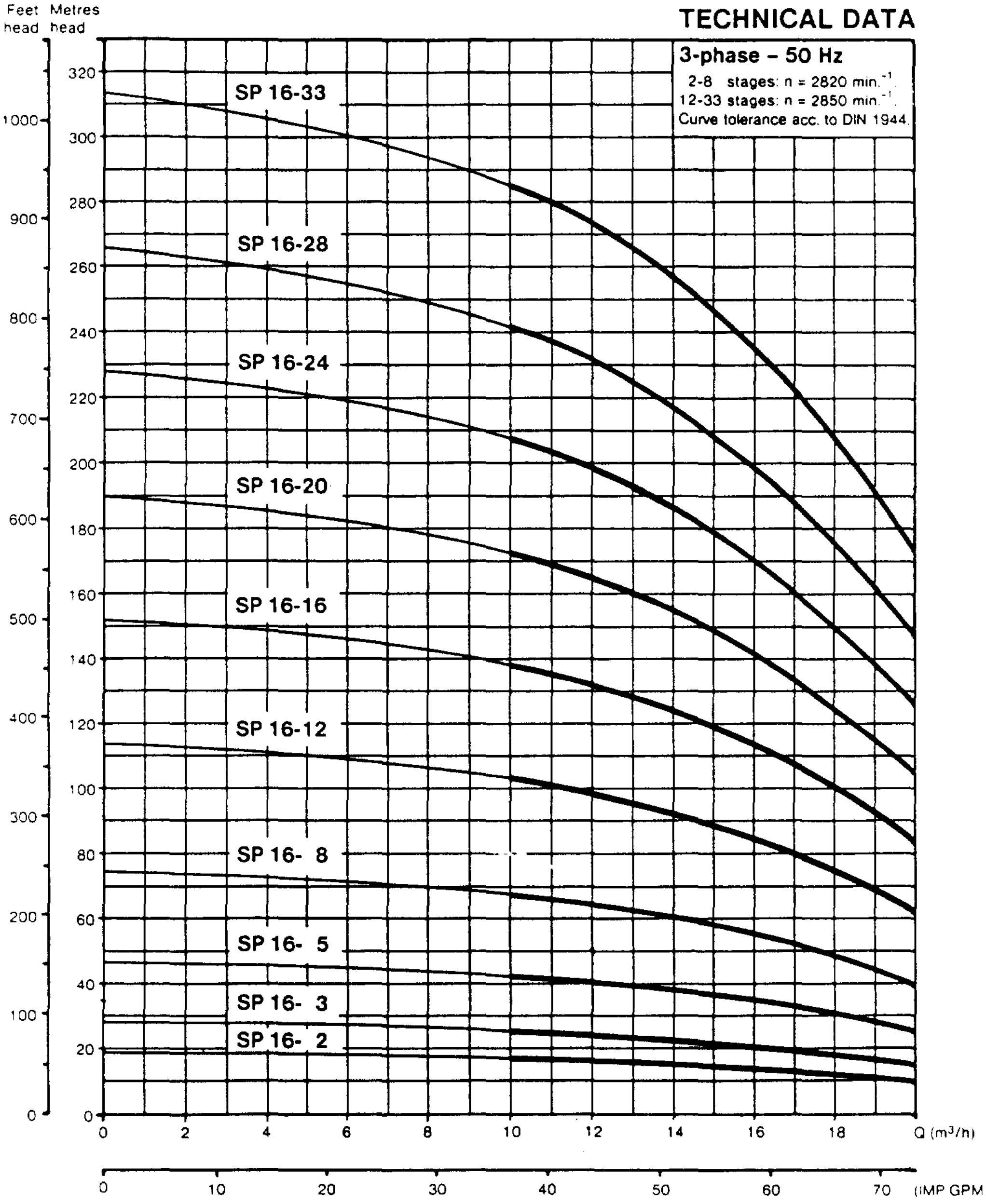
2. Gen-Set Submersible Pumps

Only one test of a diesel-generator-driven submersible pump was undertaken. This installation at Ncojane in Ghanzi District was tested by the Chief Technical Officer-Water for the district. Unfortunately, the borehole is not straight (which was the reason for using an electric submersible rather than a Mono pump in the first place), and it was impossible to measure the head due to

GRUNDFOS **SP 16**

GB **SUBMERSIBLE PUMP** **50 Hz**

TECHNICAL DATA



SP 16 flow range: 10-20 m^3/h (37-74 IMP GPM).

The GRUNDFOS submersible pump range covers flows from 0.1-160 m^3/h (0.4-587 IMP GPM).

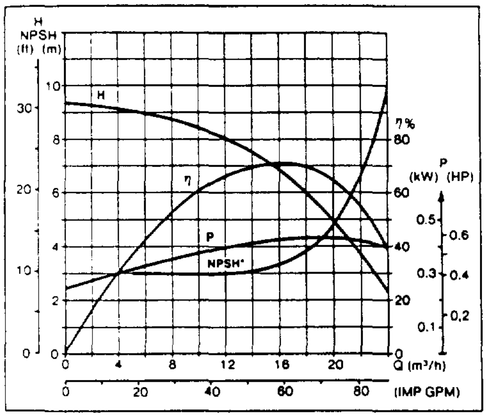
30 EX 12 004 02 83	2
Repl 30 EX 12 002 10 77	

Figure 5

SP 16

50 Hz

PERFORMANCES PER STAGE



* NPSH is determined at 1 percent head loss.

MATERIALS

SP 16 – Standard version:
All main components in stainless steel: DIN W.-nr. 1.4301. Max. water temperature: Pumps with 4" motors, 40°C. Pumps with 6" motors, 35°C.

SP 16-N – Sea water version:
All main components in stainless steel: DIN W.-nr. 1.4401. Max. water temperature: Pumps with 4" motors, 40°C. Pumps with 6" motors, 35°C.

A hot water version is available on request.

MINIMUM INTERNAL DIAMETER OF BOREHOLE: 6" (152 mm).

Connection to riser main: 2 1/2" BSP, length of thread 27 mm.

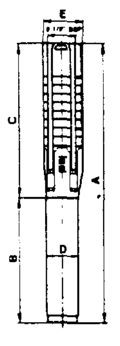
Pumps with larger numbers of stages are available on request: SP 16-40 and SP 16-50.
These pumps are delivered in special stainless steel sleeves (pump section only).

ELECTRICAL DATA

	PUMP TYPE	MOTOR		MAX. OPERATING CURRENT (amps)			FULL LOAD CURRENT $I_{1/1}$ (amps)			POWER FACTOR (full load)			$\frac{I_{start}}{I_{1/1}}$		
		kW	HP	3x220 V	3x380 V	3x415 V	3x220 V	3x380 V	3x415 V	3x220 V	3x380 V	3x415 V	3x220 V	3x380 V	3x415 V
4" MOTOR	SP 16- 2	1.1	1.5	4.5	2.7	2.5	4.6	3.3	3.0	0.84	0.84	0.84	3.8	3.7	3.7
	SP 16- 3	1.5	2.0	5.9	3.4	3.1	6.7	3.9	3.6	0.88	0.88	0.88	4.7	4.7	4.7
	SP 16- 5	2.2	3.0	9.9	5.7	5.3	10.1	5.8	5.4	0.88	0.87	0.87	4.1	4.1	4.1
	SP 16- 8	3.7	5.0	15.2	8.9	8.1	16.1	9.4	8.6	0.88	0.87	0.88	4.3	4.3	4.3
6" MOTOR	SP 16-12	5.5	7.5	20.5	12.4	12.8	21.5	12.8	13.0	0.85	0.85	0.76	5.4	5.2	5.6
	SP 16-16	7.5	10.0	27.5	15.9	16.6	28.5	16.7	17.1	0.86	0.85	0.77	5.5	5.4	5.7
	SP 16-20	11.0	15.0	35.0	21.0	22.0	41	24.5	25.0	0.87	0.86	0.78	6.3	6.0	6.4
	SP 16-24	11.0	15.0	39.5	23.5	24.5	41	24.5	25.0	0.87	0.86	0.78	6.3	6.0	6.4
	SP 16-28	15.0	20.0	50	28.5	31.0	56	32.5	34.0	0.85	0.85	0.76	5.9	5.8	6.1
	SP 16-33	15.0	20.0	55	32.0	33.5	56	32.5	34.0	0.85	0.85	0.76	5.9	5.8	6.1

The electrical data are for SP submersible pumps fitted with GRUNDFOS motors. When using other motor makes, the data can be used as a guide only. Always check the motor name plate. Other voltages are available on request.

DIMENSIONS AND WEIGHTS

	PUMP TYPE	DIMENSIONS mm					WEIGHT kgs.		SHIPP. VOL.	
		A	B	C	D	E*	Net	Gross	m³	
4" MOTOR	SP 16- 2	670	326	244	95	131	20	24	0.04	
	SP 16- 3	755	366	489	95	131	22	26	0.04	
	SP 16- 5	980	501	479	95	131	24	28	0.04	
	SP 16- 8	1259	645	614	95	131	39	44	0.05	
6" MOTOR	SP 16-12	1440	630	810	140	140	75	90	0.12	
	SP 16-16	1675	685	990	140	140	79	95	0.14	
	SP 16-20	1930	760	1170	140	140	90	110	0.16	
	SP 16-24	2110	760	1350	140	140	100	122	0.17	
	SP 16-28	2380	850	1530	140	140	110	134	0.19	
	SP 16-33	2605	850	1755	140	140	116	142	0.20	

* E = Max. diameter of pump incl. cable guard + motor.

BY INQUIRY

Please supply the following information with each inquiry:

1. Q – the quantity of water required.
2. H – the total manometric head required including frictional losses and tank pressure, if any.
3. The diameter of the borehole (the smallest inside dimension).
4. The distance from ground level to water level at rest.
5. The lowering of the water level, when a certain quantity is pumped.
6. The total length of the borehole, less the length of a borehole filter, if any.
7. The type of electric supply, voltage and frequency.
8. Supplementary information concerning the installation, if any.

Subject to alterations

GRUNDFOS®

8850 BJERRINGBRO · DENMARK · TELEPHONE (06) 68 14 00
TELEX 60731 TELEGRAMS: GRUNDFOS

Figure 6

the curvature of the borehole. However, the pump make and model are known (Grundfos SP10-37), and inspection of the curves for the pump indicate a probable total head of 205 meters (implied from the measured flow rate). The pump curve is given in Figure 7. The remainder of the system consists of a 22 KVA x HR-2 Lister generator set. The results of the test, as well as the original design, are given in Table 12.

Table 12. Test Results for Submersible Pump with Gen-Set

Site	Head (m)	Flow Rate (m^3/hr)	Operating Time (hrs/day)	Fuel Consumption (l/day)	Efficiency (%)
Actual	205*	1.8	24	41	~18**
Design	165	7.2	6***	--	~62**

*Head assumed.
**Efficiency does not include diesel conversion.
***Hours required to match current water delivery/day.

It should be noted that the design was based on information that indicated a borehole yield of 17 m^3/hr and a rest level of 125 meters, with less than one meter of drawdown. The test-pump records indicate 40 hours of pumping but only nine readings beyond one hour. In fact, the yield is only 1.8 m^3/hr. This case provides a graphic example of the costs and complications of not completing test pumping properly. If the yield had been known to be so low, this borehole might never have been equipped at all. If it had been necessary to equip the borehole with a diesel generator and a submersible pump, as was done, a significantly smaller engine could have been installed. The efficiency would have been greater and the fuel consumption considerably lower. This information has been brought to DWA's attention, and a reevaluation of the site is in progress.

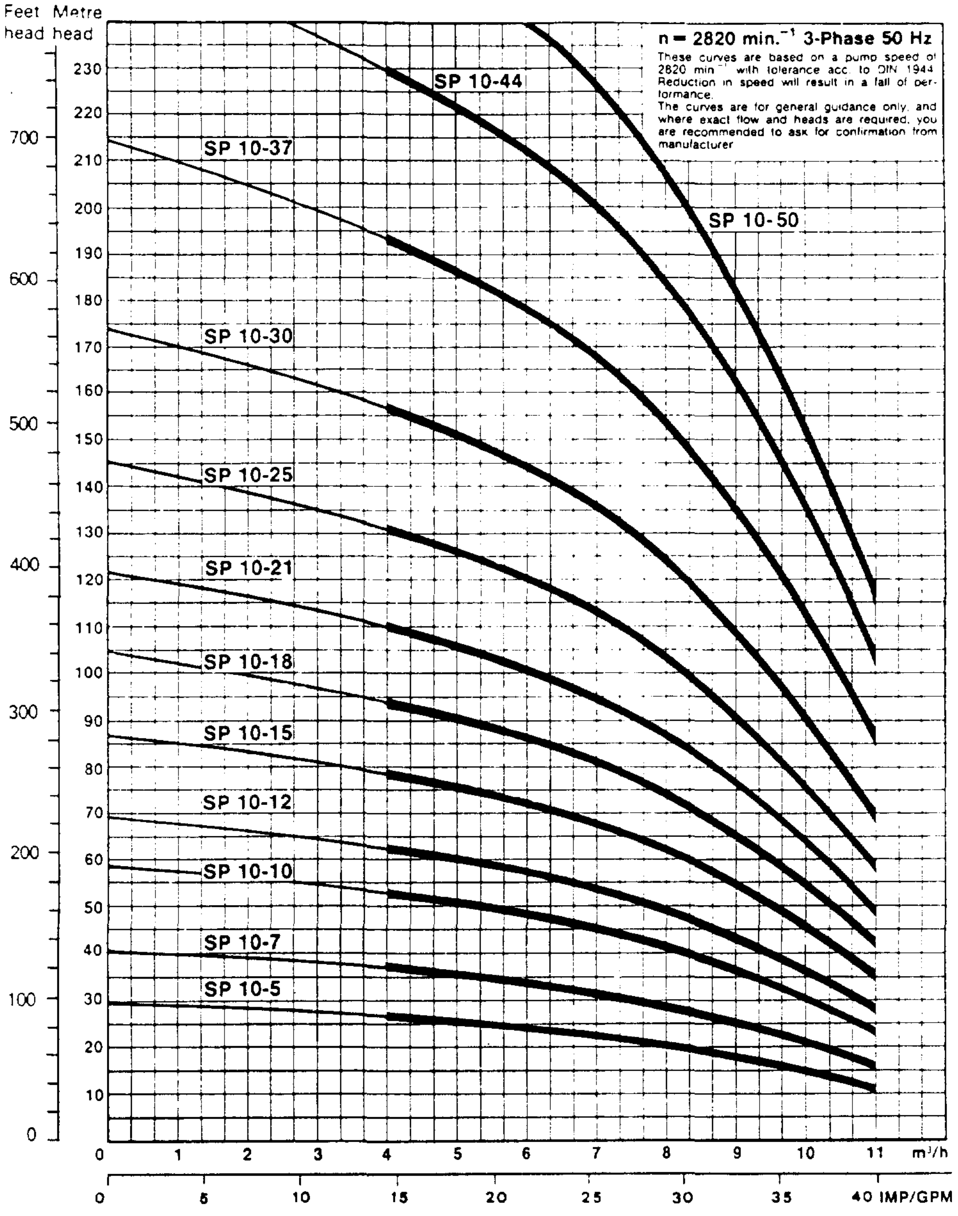
3. Electrically Driven Mono Pumps

Two sites equipped with surface-mounted electric motors driving Mono pumps were tested. These sites, designated 5 and 6, are located in Mochudi and Otse, respectively. The results of the tests are indicated in Table 13.

GRUNDFOS **SP 10**

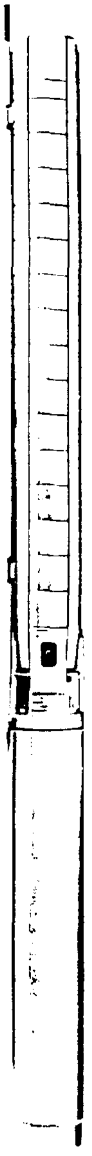
GB **SUBMERSIBLE PUMP** **50 Hz**

TECHNICAL DATA



n = 2820 min.$^{-1}$ 3-Phase 50 Hz

These curves are based on a pump speed of 2820 min^{-1} with tolerance acc. to DIN 1944. Reduction in speed will result in a fall of performance.
The curves are for general guidance only, and where exact flow and heads are required, you are recommended to ask for confirmation from manufacturer.



SP 10-15
Motor 2.2 kW
(3 HP)

Minimum Internal Diameter of Bore Holes is 104 mm (4") for SP 10-5 to SP 10-25 (Motor 95 mm).

Minimum Internal Diameter of Bore Holes is 152 mm (6") for SP 10-30 to SP 10-50 (Motor 137 mm).

Flow Range 4-11 m³/h.

GRUNDFOS SUBMERSIBLE PUMPS are available for capacities varying from 0.5-160 m³/h — 1.8-587 IMP/GPM

30 EX 11 005 10 80	2
Repl. 30 EX 11 000 12 78	

Figure 7

Table 13. Test Results for Electrically Driven Mono Pumps

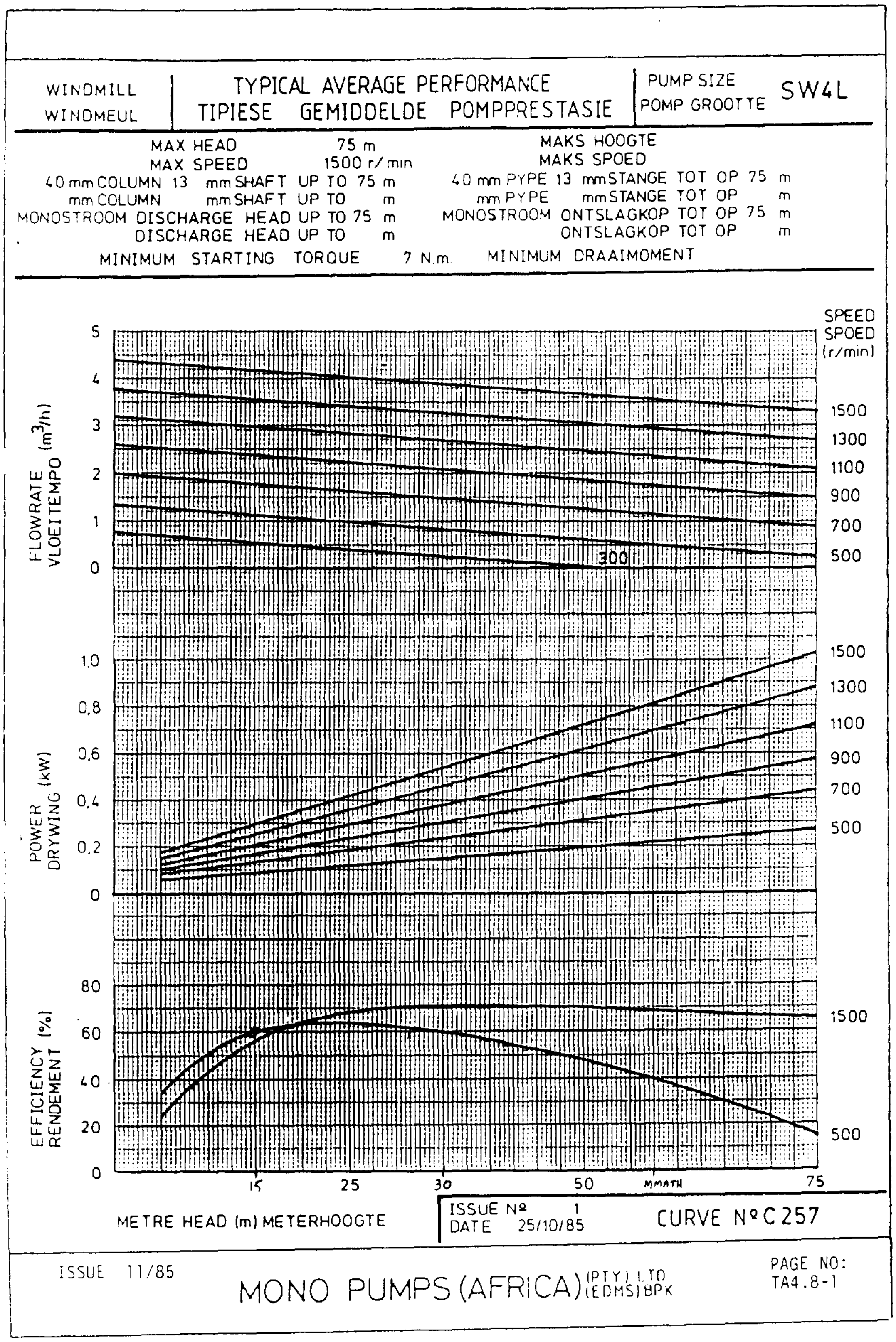
Site	Head (m)	Flow Rate (m^3/hr)	Operating Time (hrs/day)	Energy Consumption (kWh/day)	Efficiency (%)
5	71	4.2	15	77	42%
6	58	2.9	20	29	46%

Both sites were equipped with three-phase, 380-volt motors (4.0 kW GEC and 2.2 kW Siemens, respectively). In each case, a comparison of the hydraulic energy requirement and the nameplate power rating indicated that the motor was designed to deliver four times the operating power requirement of the pump. The over-sizing of the motor allows for the high starting torque of the Mono pump and the starting current for the electric motor (which occur simultaneously with start-up). The tested efficiencies of these systems are higher than those of the submersible pumps. This reflects the lower sensitivity of the Mono pump to fluctuations in pumping head (see Figure 8).

Given the Mono pump efficiencies in the range of 60 to 70 percent, and three-phase electric motor efficiencies (for these small motors) in the range of 70 to 75 percent, the expected efficiency will be below 50 percent. This implies that the tested efficiencies are in a reasonable range for the type of equipment used. It also implies that if submersible pumps can be designed to operate at their design point, their efficiencies will be slightly higher.

D. Installation

The installation of grid-connected systems implies the presence of the electricity grid at or near the borehole. The costs of installing the necessary overhead lines and appropriate step-down transformers must be considered as part of the installation cost. These costs are not insignificant, as overhead lines cost P10,000 per kilometer for 11 kilovolts and P12,000 for 33 kilovolts--the commonly used sub-transmission voltage in Botswana. This figure includes all poles, cable and labor charges. At present, the lowest commonly used pole-mounted transformer (PMT) is 25 KVA. An 11-.38 KV PMT costs P3,600, including installation and connection charges. Smaller transformers are not significantly cheaper. However for small-scale water pump applications, a 25 KVA transformer is considerably oversized and the capacity factor for the installation will be low. This will not affect operation of the pump, but does have load-factor implications for BPC, the company generating the power.



WINDMILL WINDMEUL	TYPICAL AVERAGE PERFORMANCE TIPIESE GEMIDDELDE POMPPRESTASIE	PUMP SIZE POMP GROOTTE	SW4L

MAX HEAD 75 m — MAKS HOOGTE

MAX SPEED 1500 r/min — MAKS SPOED

40 mm COLUMN 13 mm SHAFT UP TO 75 m — 40 mm PYPE 13 mm STANGE TOT OP 75 m

mm COLUMN mm SHAFT UP TO m — mm PYPE mm STANGE TOT OP m

MONOSTROOM DISCHARGE HEAD UP TO 75 m — MONOSTROOM ONTSLAGKOP TOT OP 75 m

DISCHARGE HEAD UP TO m — ONTSLAGKOP TOT OP m

MINIMUM STARTING TORQUE 7 N.m. — MINIMUM DRAAIMOMENT

METRE HEAD (m) METERHOOGTE

ISSUE Nº 1
DATE 25/10/85

CURVE Nº C 257

ISSUE 11/85

MONO PUMPS (AFRICA) (PTY) LTD (EDMS) BPK

PAGE NO: TA4.8-1

Figure 8

On the low-voltage side of the transformer, the required electrical equipment includes an isolator, the appropriate three-phase magnetic starter for the motor, the motor, and the requisite wiring. For a submersible pump, this also includes a lightning arrestor and a low-water disconnect to protect the pump set. Other capital equipment includes a pump house, rising main, water meter, pressure relief valve and associated fittings. If a Mono pump is used, the pump, discharge head, drive shafts, bobbins and stabilizers must be included.

Because so few electric pumping systems have been installed to date, the installation labor and transport requirements cannot be accurately documented. It has been assumed that installation of an electric system will typically require less time than a diesel system, merely because it is a simple procedure. However, the labor cost is assumed to be the same as for diesel because the installation crew must include a trained electrician.

E. Repair and Maintenance

The small number of electric pumping systems installed and their low repair frequency do not provide a significant basis on which to estimate long-term repair and maintenance costs. Interviews were conducted with individuals knowledgeable about electric pumping systems and the use of electric motors for other applications in Botswana. Indications are that submersible-pump lifetimes are in the range of 10 years. However, repairs may well be necessary during this period. A single repair per motor life, at half the cost of a new unit, is assumed. Miscellaneous annual maintenance costs of P100/year are also included for inspection, pipe replacement, etc.

The experience with surface-mounted motors is longer and better documented (although not for pumping applications). These motors can be expected to last about 10 years. They would probably last longer if they were treated carefully and bearings were replaced periodically. Surface-mounted motors can be rewound in Botswana, but it does not seem worth the cost for the smaller motors. P175 per year is assumed for belt and/or drive shaft replacement and other miscellaneous expenses. Mono pump maintenance and repair costs have been found to be similar to these costs when a diesel engine is used (see VOLUME II: DIESEL SYSTEMS).

F. Financial and Economic Analysis

As mentioned above, the option of using grid electric power to pump water has received increased attention in Botswana in recent years. The limits on the use of grid power are usually twofold. First, there is the general question of availability and reliability of power from the grid and, second, the distance to the existing power lines. Historically, the reliability of the electric grid has been high. There is sufficient generating capacity, and new generating units at Morupule are coming on line. The distance to the electrical power network is a more significant issue. Currently, the network serves the larger population centers and the mining towns. Development plans call for extension of the grid to additional towns and several villages. The extent of the electrical power network will remain fairly limited even when this work is complete. Thus, application of electric pumping technologies will be limited to those cases where electrical power is available at a reasonable hook-up cost.

There are potential advantages to electrification of pumping systems, if they are near enough to the existing grid. The cost advantages of electrification have been documented by UNDP and the World Bank (1986). In addition to lower costs under the right conditions, there are other advantages. Chief among these is the switch to a domestic energy source (coal-fired electric) and away from imported petroleum.

On the other hand, some potential risks will be encountered in a program of electrification. Two are of sufficient merit to mention briefly here. First, potential exists for a reduced amount of local control over the reliability of water pumping. With a diesel engine, users and villages have a measure of control over reliability--through maintenance and repair facilities provided by the water units, BRS, or the informal servicing network. With grid electricity, the fact that trained electricians are seldom available in rural areas increases the possibility of an outage that cannot be corrected at the local or district level.

Second, and clearly more important, is the problem of accurate measurement of borehole characteristics and estimation of sustainable yield. While this is a generic problem with the provision of village water supplies in Botswana, the cost of incorrectly estimating borehole yield is magnified many times when the power of choice is grid electricity. This is because the installed capital (i.e., power lines) is not easily moved to a new borehole. On the other hand, with diesel-powered pump sets, if a borehole must be abandoned due to decreasing yield, it can be done more easily and without losing the major capital investment in overhead lines.

In the balance of this section, the electrification option will be analyzed by estimating the costs of pumping water in both rural and major villages under a range of head and output (m^3/day) conditions. These user groups are the most committed to pump electrification now and in the future. Cases have been examined for both Mono and submersible pumps. Since the

UNDP/World Bank pre-feasibility report (1986) dealt with this specific issue, a brief discussion of the differences in the two sets of cost estimates is presented in the following section. Although the details of design, operation and maintenance are different, the financial and economic results for the two types of systems are nearly identical. This will be demonstrated, and further results will not differentiate between pump and motor types. If choices between the two types of systems are necessary, the choice will depend on factors other than cost.

A base-case situation is developed for each of the user groups, based on actual measured data and costs, review and analysis of secondary data, and selection of typical operating conditions. Sensitivity analysis is then performed on major cost assumptions to highlight the important ones, and to point out where cost-reduction strategies are most likely to be effective.

1. Major Villages

A set of general characteristics of major-village water supplies is assumed for this analysis. These characteristics are:

- distance to the water supply from the service center (150 km) and installation center (30 km);
- pumping rate (seven m^3/hr); and
- volume (20 to 100 m^3/day).

These are used consistently throughout the analysis, for the full range of pumping technologies.

The financial costs for both systems (Mono and submersible pumps) are shown in Table 14. As can be seen, the cost of extending the grid for two kilometers (using 33 KV lines) is included in the capital cost of both systems. This is a realistic cost that will surely be incurred. However, it must be pointed out that donor involvement in electrification projects may reduce or eliminate this cost as far as the GOB is concerned. In addition, not all of these costs need be allocated to pumping if there are other electrical applications near the borehole. The sensitivity analysis shows the effect on cost assumptions if the distance to the grid is reduced or if the cost is omitted entirely, for instances in which the grid passes very near a borehole. Another capital-cost item is the step-down transformer (25 kVA). Transformer costs do not change for any case considered in this section. Surface-mounted, three-phase motors and starters are costed individually, depending on head and flow requirements. The cost of the submersible units includes the standard equipment--starter, cable and low-water disconnect.

Submersible-pump prices are based on quotes for Grundfos pumps, which are currently being used by DWA.

Table 14. Capital and Recurrent Costs of Mono and Submersible Pumps--Major Village

	Mono Pump	Submersible
Installed Capital Costs		
Grid extension (2 km)	P24,000	P24,000
Transformer	3,600	3,600
Starter, motor, pump, etc.	2,281	4,007
Downhole pipe/column	2,100	800
Balance of system	490	490
Pump house and civil works	1,000	1,000
Installation labor	4,000	4,000
Installation transport	473	473
Total installed capital cost	P37,944	P38,370
Annual Recurrent Costs (Normal Year)		
Material	350	100
Labor	80	50
Transportation	100	100
Pumper	2,400	2,400
Electrical power	2,090	2,090
Total annual recurrent cost	P5,020	P4,740
Present Value--Recurrent Costs	70,748	69,644
Unit Cost (Base Case)--Financial	.34	.34
--Economic	.30	.30

The downhole pipes are quite different for the two systems, with the submersible using a galvanized steel pipe (PVC rising mains are not used in Botswana) and the Mono using a drive shaft inside a column, which includes bobbin bearings to hold alignment. The balance-of-system costs are those associated with equipping a borehole for use by a village. They include pipe, a brass tap and a water meter. In addition, the pump house and other civil works are included at the same cost for both systems.

Finally, the labor and transport costs for installation are the same. While it might be argued that the submersible is easier to install, there is not sufficient experience in Botswana to support such a contention. It may be possible that costs could be reduced through increased training. Transport costs associated with installation are the final capital-cost item.

Several components of recurrent costs are estimated separately. First, maintenance materials differ for the two pumps. The Mono (with the column that includes a rotating pump rod as well as the pump head above ground) is more expensive to maintain. Transportation and labor differences reflect the increased number of trips required for the Mono pump. The pumper salary is included at P2400; the sensitivity analysis later in this section shows the results of lowering this cost. Electric power costs are calculated at P0.187 per kWh. The price is an average of the current water pumping tariff for the northern and southern divisions. The Botswana Energy Master Plan argues that a tariff based on long-term marginal cost would yield a price of P0.155. The World Bank study used an economic cost for electricity of P0.062. Currently, there is discussion within the GOB concerning a change in the tariff structure. The effects of these differences and a possible change in the structure are explored in the sensitivity analysis below. The quantity of electricity used is proportional to the efficiency of the pump-motor combination.

Base Case

The base case chosen is delivery of 50 m^3/day through a head of 90 meters. The choice of pumps and motors reflects the total head and flow rate required. It is assumed that the efficiency of the pumping system (as defined in Section V.B) is 40 percent, and growth of demand will be five percent.

The figures in Table 14 were used to calculate a set of estimates of both financial and economic costs of pumping water over a range of daily outputs (20 to 100 m^3/day) with pumping heads ranging from 30 to 120 meters. Note that the assumptions used for the analysis in VOLUME I are slightly different from those here. The objective in VOLUME I was to identify applications for alternatives to diesel engines (hence the assumption of more remote locations); the present analysis seeks to characterize typical installations. It is helpful to examine these systems in terms of the two major cost components--capital and recurrent costs. While the sums are nearly identical (within one percent), the Mono pump has the lower capital costs and higher recurrent costs, and the submersible has a higher capital cost and lower recurrent cost. In short, these costs are clearly too close to be of major importance in choosing between the two types of electric pumps.

Sensitivity

The sensitivity analysis on this base case reveals that the financial and economic values are not very sensitive to some changes in cost and performance parameters, but are sensitive to others (see Table 15).

Of particular interest is the electricity tariff, as the current price structure is under review and may be changed during the next year. Other issues addressed in the sensitivity analysis are the penalty for not getting optimum efficiency from the pump set, the cost of extending the electricity grid, pumper costs, and transportation costs.

Table 15. Sensitivity Analysis Results--Major Village

Variable Name	Change Made	Financial	%	Economic	%
Base-case condition	no change	P0.34		P0.30	
Electricity tariff	.062/kWh (WB est.)	.27	-21	.22	-27
Interconnect dist.	none	.27	-21	.22	-27
Interconnect dist.	one kilometer	.30	-12	.26	-13
Pump efficiency	60 percent	.30	-12	.26	-13
Labor	half-time pumper	.30	-12	.28	-7
Electricity tariff	.155/kWh (LRMC est.)	.32	-6	.28	-7
Transportation	halve installation & service distances	.34	0	.30	0
Transportation	double installation & service distances	.35	+3	.30	0
Repairs	double annual trips	.35	+3	.30	0
Pump efficiency	35 percent	.36	+6	.31	+3

The first variable changed was the electric rate. The rate was changed from P0.187 to P0.155 (the long-term marginal cost as calculated in the Botswana Energy Master Plan). This decreased the annual electric bill from P2090 to P693. Thus the unit economic cost was reduced by seven percent. When the electricity tariff was brought to P0.062 (the World Bank's estimate of the economic cost), the unit cost fell by 27 percent from the base case. Of course, the effects will be greater if more energy is used.

The cost of extending the grid the two kilometers considered in the base case was removed and the unit economic cost decreased by 27 percent. This is a result of a P24000 reduction in capital costs. Halving the interconnection distance to one kilometer results in a 13 percent reduction in the unit cost.

Pump efficiencies can vary considerably, particularly for submersible pumps. The base-case assumption of 40 percent was chosen to reflect test results. The unit costs proved to be fairly responsive to changes in the efficiency. A change from 40 percent to 35 percent reduced the unit cost by three percent. However, an increase in efficiency to 60 percent (possible for a reasonably designed submersible pump) reduced the unit cost by 13 percent. This effect will be greater in cases of higher head and larger flow, as the energy cost will be proportionately greater.

The cost of a pumper is included at P2400 in the base case. Reducing the cost to P1200 to reflect multiple duties of major village pumpers decreases the unit economic cost by only seven percent because of the shadow-pricing of unskilled labor. The unit financial cost is reduced by 13 percent.

Finally, the transportation costs for installation, repair and maintenance were doubled. The economic unit cost was not changed by this or by reducing the transportation distances.

Clearly, the extent of required overhead-line installation is a major component affecting cost. Utility rates and pump/motor efficiencies also have a marked effect.

Extended Analysis

Table 16 provides an extended analysis covering a range of water requirements and heads, using the base-case assumptions. The pumps and motors chosen reflect the head shown and a pumping rate of seven m^3/hr.

Table 16. Base-Case Assumptions--Costs and Performance

Head (m)		Daily Output (in cubic meters) 20	30	50	100
30:	Financial	P0.57	P0.40	P0.26	P0.16
	Economic	P0.47	P0.33	P0.22	P0.14
60:	Financial	.62	.44	.30	.20
	Economic	.51	.37	.26	.18
90:	Financial	.67	.49	.34	.25
	Economic	.56	.42	.30	.22
120:	Financial	.73	.55	.40	.30
	Economic	.63	.48	.35	.27

As is to be expected, the unit cost declines as the head decreases and daily water delivery increases. A comparison to the figures given for major-village diesel systems (see VOLUME II) indicates that electric pumps are more expensive in all but the highest head and greatest demand cases at prevailing utility rates, if two kilometers of interconnection costs are included.

2. Rural Villages

The costs of pumping water in rural villages differ from those in major villages in four respects. First, rural villages are usually more distant from the service and installation centers and therefore have a greater proportion of transportation costs in their total costs. Second, the daily output of water is smaller and the unit cost of pumping water is ordinarily quite sensitive to the volume being pumped. Third, the average pumping rate for rural villages (3.5 m^3/hr) is lower than for major villages, due to greater efforts to locate high-yielding boreholes for major village schemes. Fourth, rural village growth (in population and demand) is expected to be only three percent.

A base case for the rural village analysis was chosen to reflect typical rural village conditions. The base case has a water delivery rate of 3.5 m^3/hr and a daily water requirement of 20 m^3/day through a 90-meter total head. In addition, the distance to the service center is assumed to be 100 km to reflect typically greater distances from rural villages to their service centers. Table 17 shows the capital and recurrent costs for both submersible and Mono pump cases for the base-case conditions. Note that these figures reflect the use of slightly different equipment than for the major village case.

Table 17. Capital and Recurrent Costs of Mono and Submersible Pumps--Rural Village

	Mono Pump	Submersible Pump
Installed Capital Costs		
Grid extension (2 km)	P24,000	P24,000
Transformer	3,600	3,600
Starter, motor, pump, etc.	1,906	3,861
Downhole pipe/column	1,800	800
Balance of system	530	490
Pump house and civil works	1,000	1,000
Installation labor	4,000	4,000
Installation transport	408	408
Total installed capital cost	P37,244	P38,159
Recurrent Costs (Normal Year)		
Materials	350	100
Labor	80	50
Transportation	300	300
Pumper	2,400	2,400
Electrical power (first year)	693	693
Total recurrent cost	P3,823	P3,543
Present Value of Recurrent Costs	48,040	47,054
Unit Cost (Base Case)--Financial	.80	.80
--Economic	.68	.68

Sensitivity Analysis

Sensitivity analysis was performed in the same manner as for the major village cases above. The results are given in Table 18.

Table 18. Sensitivity Analysis--Rural Village

Variable Name	Change Made	Financial	%	Economic	%
Base case condition	no change	P0.80		P0.68	
Electricity tariff	.062/kWh (WB est.)	.72	-10	.60	-12
Interconnect dist.	none	.58	-28	.46	-32
Interconnect dist.	one kilometer	.69	-14	.56	-18
Pump efficiency	60 percent	.76	-5	.64	-6
Labor	pumper half-time	.67	-16	.61	-10
Electricity tariff	.155/kW (LRMC est.)	.78	-3	.66	-3
Transportation	halve service distance	.77	-4	.64	-6
Transportation	double service distance	.82	+3	.70	+3
Repairs	double annual trips	.82	+3	.69	+1
Pump efficiency	35 percent	.72	+3	.69	+1

When the electricity rate was decreased to P0.155/kWh (the assumed long-term marginal electricity cost), the economic unit cost decreased by three percent. The first-year electric bill decreased from P693 to P671. The electricity rate was then decreased to P0.062 per kWh (the cost assumed by the UNDP/World Bank consultants). The first-year electricity cost dropped to P230 and the economic unit cost fell by 12 percent. This is less than the 27 percent drop in the base case for major villages (see Table 15). This difference is the result of a lower electricity requirement to satisfy the rural village case considered.

As with the major village case, the capital costs associated with the grid extension were omitted, thus reducing the capital cost by P24,000 and the installed capital cost to about P14,000 (just over 40 percent of the cost is for grid extension). This resulted in a 32 percent reduction of the unit cost (as opposed to a 27 percent reduction for the major village case). As before, the inclusion of one kilometer of overhead line roughly halves the reduction.

Over the range from 35 to 60 percent pump efficiency, the rural village results show less sensitivity than those for the major village. An increase in efficiency from 40 to 60 percent decreases the unit cost by six percent as a result of lower electricity costs when the efficiency is higher. A reduction in efficiency to 35 percent only increases the unit cost by one percent.

A doubling of the transportation costs for maintenance and repair results in an increase of three percent in unit costs. The difference between this and the major village case is that the assumptions about base-case distances are more relevant to rural villages (see Appendix M, VOLUME II). Note that this doubling affects only the recurrent costs, as it is assumed that the installation distance remains unchanged.

For rural village applications, the interconnection distance becomes an important consideration because it represents a larger percentage of the total cost. The same is true for the pump operator's labor cost. The issues of efficiency and electricity cost are less important, since the electrical cost is a smaller percentage of the total.

Extended Analysis

A range of unit costs per cubic meter of water delivered was calculated for a variety of pumping situations (head and demand) using base-case costs. As in the major village cases, the pumps and motors were chosen to reflect the head and pumping rates for each case. The full set of costs is presented in Table 19.

Table 19. Cost and Performance of Electrical Pumps--Rural Village

		Output per Day (in cubic meters)			
Head (m)		5	10	20	30
30:	Financial	P2.63	P1.34	P0.70	P0.49
	Economic	P2.11	P1.08	P0.58	P0.40
60:	Financial	2.71	1.41	.76	.55
	Economic	2.19	1.15	.64	.46
90:	Financial	2.77	1.46	.80	.58
	Economic	2.26	1.20	.68	.50
120:	Financial	2.72	1.52	.86	.64
	Economic	2.20	1.27	.73	.55

When comparing the major and rural village cases, note that the values are not the same for the cases with similar head and water requirements. This is due largely to the differences in assumed flow rates. The flow rate determines the pump and motor choice and will affect the hours of operation required to satisfy demand. Electric pumping is not clearly shown to be more cost-effective than a diesel system for any of the rural village cases considered.

G. World Bank Analysis

The analysis performed during a joint UNDP/World Bank energy-sector management consultancy in 1985 agrees closely with the analysis performed here when differences in assumptions are taken into account. The major differences in the two analyses are the electricity tariff used and the range of system sizes considered. The UNDP/World Bank study did not address the issue of unknown long-term aquifer characteristics.

The above-mentioned study used an electrical energy cost figure of P0.062. The report does not adequately justify the use of a figure of one-third of the current water pumping tariff. The current tariff reflects a cross-subsidy to the BCL mine in Selebi-Phikwe and probably should be lower. However, for the purposes of the current study, the prevailing tariff is used in the base-case analysis.

CWPP's work was aimed at addressing issues of small-scale water pumping. Unfortunately, this excludes most cases where the potential for electrical pumping is currently being examined. The UNDP/World Bank study does identify 15 rural villages that are candidates for electrification because of their proximity to the electricity grid. Due to several practical considerations, this is felt to be an optimistic assessment. The long-term performance characteristics of boreholes serving rural villages are not well known. This is due to poor test-pumping results in the past and to the cost of adequate groundwater studies. Test results have clearly demonstrated that the long-term economic performance of electric pumps heavily depends on adequate test-pump results and known borehole yield. These considerations will reduce the potential for borehole electrification of rural villages. In addition, the Water Maintenance Units and Departments responsible for rural-village water supply do not currently have the capacity to service and repair electric motors or submersible pumps.

H. Conclusions

The cost of pumping water with electric pumps is surprisingly high. Clearly, the current high electricity tariff has an impact. However, lower rates still may not make electric pumps attractive on strictly financial or economic terms. It is clear that interconnect distances also have a major effect. This conclusion was also reached in the UNDP/World Bank study. An inspection of diesel and electric pumping costs indicates that interconnect distances must be very nearly zero, and electricity rates must fall, for electric pumping to be cost-competitive with diesel pumping for the range of applications considered.

However, there are characteristics that make electric pumps attractive. The repair and maintenance costs are lower, and repair trips can be kept to a minimum. This alleviates logistical difficulties of transportation and labor crew allocation. In ordinary circumstances, choices between the Mono and submersible pumps cannot be based on generalized cost information, as the costs are so similar. However, there are specific conditions where the choice may be clear. If a borehole is crooked, a submersible is needed; if the water level fluctuates or if a stand-by diesel is required, a Mono pump system is more suitable.

Investigation of the use of electric pumps should be continued for major villages where the borehole characteristics are well known and water demand is on the high side. The simplification of logistics, lower recurrent costs and independence from diesel fuel suggest that this is a reasonable policy. It appears, however, that the World Bank's suggestion that 70 boreholes could be electrified cost-effectively is optimistic.

VI. HANDPUMPS

Over the last decade, the focus of Botswana's rural water supply program has been on using diesel engines to provide villages with water from boreholes. The water is pumped to elevated water-storage tanks and reticulated to the villagers through a pipe network to standpipes located conveniently throughout the village. Up to this point, there has not been much official interest in handpumps. However, this is changing now that most of the larger villages have such schemes in place. As a result, handpump use in Botswana can be divided into two areas--traditional use and current trends.

A. History

Lifting water by hand from dug wells has been practiced in Botswana for many years. This method has been limited to the areas where it is possible to dig wells--mainly the Okavango Delta region and along dry rivers in the eastern part of the country. There are a number of winch lifting devices in use for stock-watering purposes, but their use has declined over the years with the increasing availability of diesel engines. Over the past 40 years, several types of handpumps have been introduced and used in small numbers. These include the human traction pump, introduced about 40 years ago, the Godwin handpump, the National pump and, more recently, the Mono geared handpump. These have never been widely used; total installations have probably never exceeded 100 pumps. Several of these earlier installations are all that remain in working order. This appears to be due to a lack of maintenance and spares, the increasing availability of water pumped by diesel engines, and the lower priority given to repair of systems serving few users.

B. Recent Interest

Over the past several years, interest in handpumps has begun to increase. The BRET project conducted a comparison test of the Swedish Petro pump and the India Mark II handpump. This study (Hodgkin and McGowan, 1985) evaluated 14 handpump installations over a period of several years. It concluded that the India Mark II appeared to be suitable for use in cases of limited demand (less than five m^3/day) where water need not be pumped from more than 30 meters. These cases include most lands areas in the eastern part of the country. In addition, it was suggested that a handpump could, in some cases, be used as a back-up for a diesel-pumped village water supply. The need to consider handpumps for lands areas had been suggested earlier (Classen, 1980). DWA has not yet focused on these cases, as its emphasis has been to supply reticulated water to villages, this cannot be done with handpumps. As the Village Water Supply Program draws to a close at the end of this decade, water supply for small settlements and lands areas will be considered. DWA, MLGL and MOA currently have a number of initiatives leading in this direction.

Although Hodgkin and McGowan (1985) indicated that the India Mark II handpump was suitable for use in Botswana, the pump has not been readily available in the country. After the second DWA purchase (25 units), efforts to identify a regional supplier were unsuccessful. In response, DWA sought local manufacturers. Due largely to the ready availability of piecework jobs not requiring capital investment and to the potential manufacturers' perception that the market was small, this initiative did not meet with success either. The Serowe Metalworking Brigades eventually came forward to build several examples of the pump as a training exercise. DWA contracted for an initial run of seven pumps at P1100 each. This represents a high price for the initial pumps. The expectation is that the cost will come down if the pumps are of acceptable quality and more are ordered. This first run of pumps had not yet been delivered as of July 1987. In addition, DWA has ordered five Atlas-Copco handpumps (one model based on an improved Petro design and another based on the India Mark II) and several SWEDCO pumps based on the Afridev design. These handpumps are being provided as part of the Swedish tied-aid package. Four Vergnet handpumps donated by the French government are currently being installed.

The District Councils have shown interest in handpumps, and several District Water Units have installed handpumps either as back-ups for villages with reticulated water or in small settlements and lands areas. The 25 India Mark II pumps purchased by DWA have been distributed and most have been installed. The only commercially available handpump is the Mono direct drive (the National pump head can be modified for hand use). The councils have purchased and installed a number of these and report satisfaction with them. In addition to these efforts, the MLGL water engineer has ordered 50 India Mark II copies from a German company (Pumpenboese kg) using EEC funds. These had not arrived as of July 1987.

MOA, through the Communal Areas Management Unit (CAMU), has also been actively exploring the use of handpumps and other water-lifting technologies in communal lands areas. Among the technologies considered is a local adaptation of the human traction pump. This pump, known as the "Thebe" pump, was originally modified by RIIC at BRET's request. The pump is operated by pushing the handle along a circular path. The handle is fixed to a central pivot and a crank mechanism connected to the pump head by a tie rod. The action of the tie rod operates the counterbalanced reciprocating pump. Several of these modified pumps were installed in Lentsweletau, Monwane and, later, Dikgonnye as part of the BRET project (Shields and McGowan, 1985). Over the past several years, there has been little interest in or activity with the Thebe pump. Recently, RIIC made further modifications, and CAMU has ordered five of the pumps to install in the near future.

The Botswana Enterprise Development Unit (BEDU) has been conducting a survey to determine the potential handpump market. This resulted from Grundfos' interest in setting up a joint venture to fabricate a handpump. The pump being suggested is a modification of the Afridev design, which was favorably evaluated by World Bank researchers as a design that truly reflects the village-level operation-and-maintenance approach to handpump design (Arlosoroff et al., 1987). The results of the BEDU study are not yet available. Although significant interest in handpumps is now evident, there may not be a sufficient market to justify the proposed joint venture.

RIIC has been involved in the development of other water-lifting technologies and is interested in testing and evaluating several handpumps that show promise for use in Botswana. Plans for such a program are in the formative stages.

The total number of handpumps in use in Botswana as of early 1987 and their models are listed in Table 20. The total installations are increasing, with only the Mono and the National available locally.

Table 20. Handpump Installations

Pump	Installed	Planned
India Mark II	22	28
Mono direct-drive	11	?
Mono gear-drive	1	0
Vergnet	1	3
DeepWell	1	0
National	4	?
"Thebe" human traction	2	5
Atlas Copco (2 models)	0	5
SWED pump	0	3
"Brigades" Mark II	0	5

C. Technology Description

Other than the cable winch systems, there are three basic handpump types in use in Botswana. These are the reciprocating-piston pump (India Mark II, National and Thebe); the progressive-cavity, positive-displacement Mono pump (Mono direct-drive and geared models); and diaphragm pumps (Vergnet and DeepWell).

The reciprocating pumps use gearing (in the case of the National pump) or a lever arm to enable human power to lift water from boreholes or dug wells. The India Mark II (see Figure 9) is a well-known example of this type of handpump. The lever arm and cylinder size (2.5-inch diameter) on the standard model allow comfortable pumping from about 25 to 30 meters. The counterbalanced rocker arm and leverage of the Thebe pump (see Figure 10) are designed to allow water to be delivered from up to 100 meters. The National pump is designed as a pump head for a mechanically driven system. However, the pump can be fitted with a handle that allows hand operation. This pump is apparently difficult to operate by hand beyond 20 to 30 meters, due at least in part to the uncomfortable pumping motion.

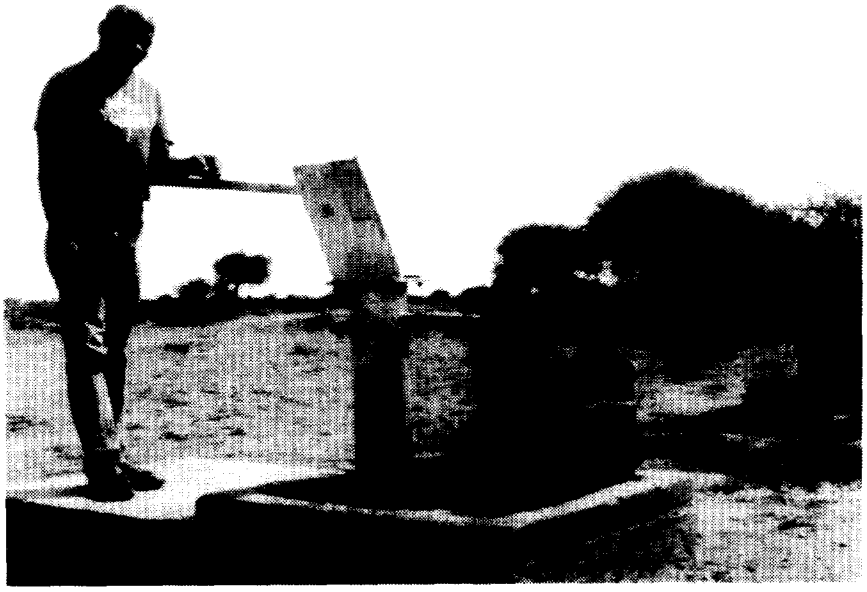


Figure 9. India Mark II installation at Tlhareseleele.

Mono offers two different handpumps. The first is a geared, hand-driven version of its borehole series of pumps. It is driven by vertical hand cranks and is capable of high water-delivery rates. However, it is reportedly difficult to operate and more prone to breakdowns than the newer direct-drive model. The direct-drive handpump (Figure 11) uses a "self-compensating" stator that brings the start-up torque requirement to near zero. This allows the pump to be driven directly via the horizontal circular motion of the pump handle. The Mono direct drive is designed to pump from as deep as 80 meters.

The diaphragm pumps use a pump element consisting of a bladder inside a cylinder. The cylinder has inlet and outlet valves. The bladder is connected to the surface components of

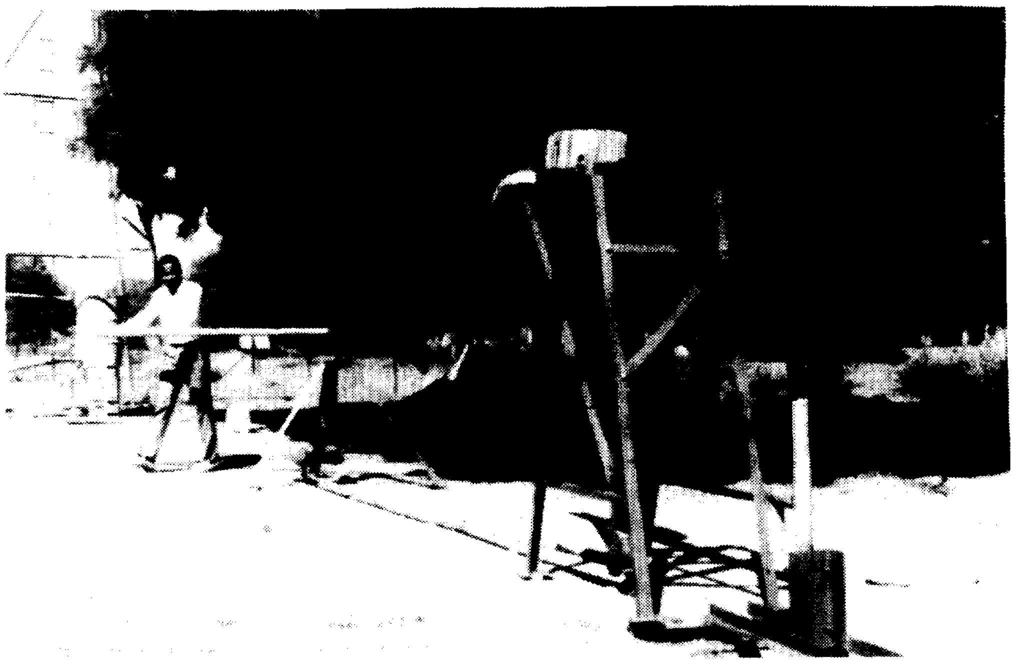


Figure 10. Thebe pump at RIIC.

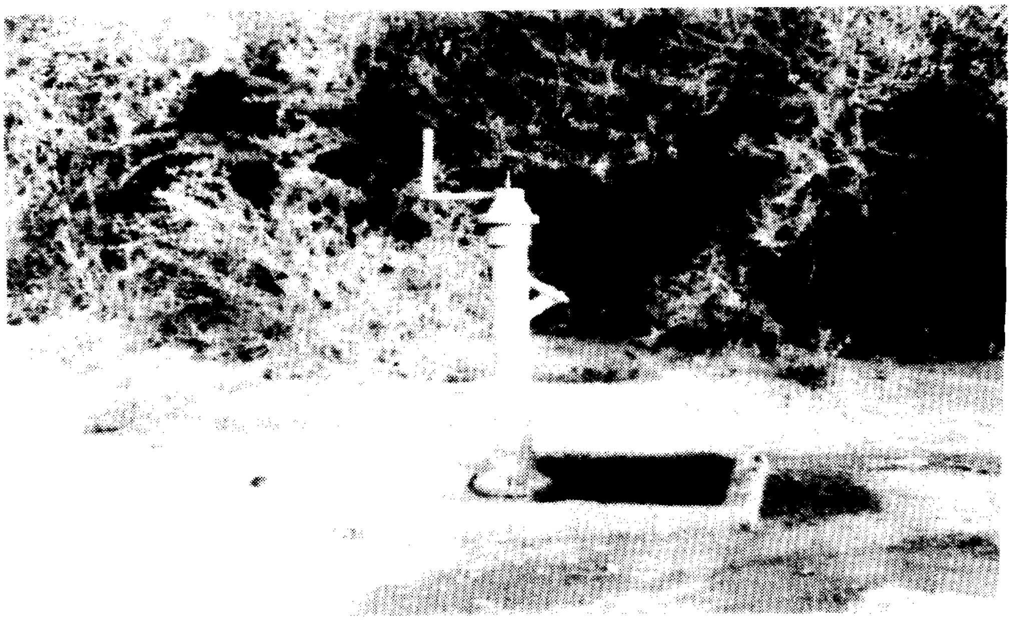


Figure 11. Mono direct-drive handpump at Tsietsamotswana.

the pump with a hose. The action of pumping increases the pressure in the hose and expands the bladder in the pump cylinder. This forces water up a second hose due to the reduced cylinder volume. The return stroke of the pump decreases the bladder volume and allows more water to be drawn into the cylinder. The Vergnet has a foot-operated system, and the DeepWell has a hand-operated hydraulic pumping system.

D. Testing and Evaluation

Handpump testing and evaluation covers several distinctly different, but related, issues: repair and reliability, from the standpoints of frequency and cost; and water delivery from both instantaneous and long-term perspectives. The World Bank, in association with UNDP, conducted a series of laboratory tests on handpumps (Arlosoroff et al., 1986) and is now conducting a handpump field-testing program. The program, active in 16 countries, seeks to provide low-cost, reliable water supply systems. Unfortunately, reports published to date have not included any analysis of repair costs on an annual or "per unit of water delivered" basis. Clearly, the cost to operate and maintain a handpump will be a function of the quality of the pump and the use that it receives.

The sample of handpumps in Botswana is small, and the monitoring has been limited to fewer than half of those installed. The repair records for 10 India Mark II handpumps over a two-year period were provided in an earlier BRET report (Hodgkin and McGowan, 1985). Subsequent to the completion of that report, several other handpumps were installed and/or monitored, including a DeepWell, two Mono direct drives, and a Vergnet.

The DeepWell is not considered a suitable pump for Botswana. It is a complicated, hand-operated hydraulic pump with over 80 parts in the hydraulic component alone. In addition, it would pump only six liters per minute from a depth of 14 meters.

The Vergnet handpump was installed on a borehole with a 40-meter rest water level. The manufacturer claims that this is the limit of the pump's application, and CWPP tests confirmed this. The pump seems robust but is very difficult to operate at this depth.

Several Mono direct-drive handpumps have been monitored for over a year. These pumps continue to operate satisfactorily and no repairs have been necessary yet. These handpumps appear to be suitable for use in Botswana. It is claimed that they will operate at depths of up to 80 meters although, to date, none of those installed pump from this level. The version designed to operate through greater heads uses a different pump from the standard model.

The effective water delivery for handpumps is a function of the pumping rate, pumping head, pump cylinder condition, and pumping continuity. Even when users are lined up, pumping time is lost while each places a water container under the spout and then removes it once the container is full. For these reasons, the effective water delivery rate depends on site and user parameters. Tests were conducted at eight sites to obtain an order of magnitude for the delivery rates. The tests consisted of filling a 200-liter drum with water pumped into 20-liter buckets and poured into the drum. The intent was to simulate a series of users filling a common size of bucket. The results are indicated in Table 21.

Table 21. Handpump Test Results

Site	Model	Head (m)	Liters/hr
Malokaganyane	India Mark II	22	435
Ramogotsi	India Mark II	15	420
Sedibeng	India Mark II	24	480
Segoditshane	India Mark II	43	185*
Tlhareseleele	India Mark II	16	466
Gorakoko	Mono direct-drive	15-20	442
Manyelanong	Mono direct-drive	15-20	636
Tsietsamotswana	Mono direct-drive	15	270

*In need of new cylinder leathers.

The pump at Segoditshane is a particularly deep installation. Since, the first strokes did not produce water. it was determined that the leathers were worn. Hence, these results are not considered to be representative of most installations. On the average, approximately 450 liters per hour could be pumped with the India Mark II. The Mono direct drive also delivered an average of 450 liters per hour. However, there is much wider variation in the test results.

The potential water delivery per day is a function of the number of hours of use and of the pumping rate. Use depends heavily on the handpump's proximity to potential users, as well as seasonal population movements. There are reports of handpumps in other countries being used 18 to 20 hours per day, but this is clearly not the case in Botswana. Most handpumps there are located in lands areas, where the population density is low and use tends to be seasonal. In these cases, the number of users is often 50 or lower. If 50 people each use 15 liters of water per day (a little lower than the measured per capita standpipe use), then only 750 liters per day are pumped. In Keazoa, a Mono direct drive delivers a measured 2,490 liters per day for an estimated population of 150 people (17 liters/person/day). Estimates for National handpump use in Southern District indicate 2,000 liters per day (Ainley, 1985). The range of water delivery from a handpump appears to be from 500 to 2,500 liters per day. If an India Mark II can pump 450 liters per hour, then a population of 200 could be served with just over 7.5 hours of pumping (at 17 liters/person, 3.4 m^3/day). This is in line with average handpump use in much of Africa. Five m^3/day would appear to be an upper limit for handpump use in Botswana.

Repair and maintenance costs are a function of the use a handpump receives and the quality of the original product. The repair requirements of 10 India Mark II handpumps have been documented over a total of 227 months. The repair and service requirements have necessitated nine trips. This amounts to just under one trip per pump per year. The replacement of cup leathers (for reciprocating pumps) is the most common service requirement, although other repairs were necessary. In several cases, the pump rods became disconnected; in one case, the pump head required replacement. Indications from fieldwork conducted by the World Bank are that repair and service requirements vary considerably. In Burkina Faso, repair and service are required roughly twice a year for each installation. Reports from Ghana indicate that roughly 40 percent of India Mark II pumps required minor repairs or had broken down over a one-year period. This would indicate the need for service and repair trips once every 2.5 years per site. The experience in Botswana falls within this range.

Handpump lifetimes are difficult to assess as they depend on model, use and level of care. In addition, none of the handpumps installed recently has required complete replacement (the case of pump head replacement mentioned above can be attributed to poor installation). Given worldwide experience, it would be unreasonable to expect handpumps to last more than 10 years. The sensitivity of pump lifetime will be considered in the economic analysis.

E. Financial and Economic Analysis

To maintain consistency with the other pumping technologies being considered in these volumes, it is important that the financial and economic analysis calculate costs per unit of water delivered. This deviates from the commonly used approach of analyzing the information and simply reporting an annual cost for a handpump installation without regard to water delivery or to reporting a cost per person served. The analysis performed is based on a net present value approach. No effort has been made to determine the financial or economic value of the benefit (the water delivered). The volume of water is used directly as a measure of the benefit. As is appropriate, future costs and future benefits (the water) are discounted to present value. The present value of the costs are divided by the "discounted" water delivery (in cubic meters). This provides a figure for the cost per cubic meter of water delivered, referred to as the unit cost.

There are two major differences between handpumps and the other technologies considered. First, handpumps are complete systems that do not require water storage or reticulation. It is assumed that all other pumping systems have these costs in common. Of course, the existence of a tank and reticulation system allows the pump to be located far from the users, which is not possible with handpumps. This limits the use of handpumps even when they might otherwise be suitable.

The other major difference is that handpumps must be operated by the users. For most technologies considered, labor costs are included as part of the pump's operating costs. The financial analysis takes into account all of the costs for which money changes hands. An economic analysis makes adjustments (through shadow-pricing) to account for the national or social value of the costs. The time and labor do have an economic cost, as the time could be spent in other productive pursuits. There is some opportunity cost for the labor to pump the water; therefore, labor has been included at a nominal rate of P0.32 per hour (the shadow-priced prevailing minimum wage). It has also been argued that borehole drilling costs should be included because it may be more cost-effective to provide two or more handpumps on different boreholes than one diesel system on one borehole. Such cases have not been considered in this analysis.

The pump-repair cost estimates used here are based on one service and/or repair trip per year and the average spare parts cost for those trips. Pump lifetime is estimated at 10 years, with pump cylinder replacement at five-year intervals. The maintenance and repair records are not extensive enough to justify analysis of such costs as a function of use. Nevertheless, since annual water delivery is low, the results will be sensitive to factors that are not yet fully documented. However, the results will indicate order-of-magnitude results, and these will assist in comparisons of handpumps with other technologies. All assumptions not discussed in detail here are given in Appendix M of VOLUME II. Note that the figures given in this analysis differ slightly from those given in VOLUME I. This analysis attempts to characterize typical use; VOLUME I seeks to identify the most appropriate applications.

This section analyzes two handpump models that are being used in and appear appropriate for Botswana. This analysis estimates the extent to which the unit costs vary as output and handpump capital and recurrent costs vary. In addition, there is a brief description of how economic costs might change if a handpump were to be manufactured domestically.

1. Mono Handpumps

The Mono direct-drive handpump is a design variation on the standard Mono pump ordinarily used as a diesel-driven or, less frequently, electrically driven pump in Botswana. The pump is a screw-type or positive-displacement, progressive-cavity pump. The pump available in Botswana is manufactured in South Africa.

For this analysis, the user group is assumed to be rural villages having the same general characteristics as attributed to rural villages in the companion volumes of this report. This assumption is made because the most reasonable handpump service arrangement is through the District Council Water Maintenance Units. The analysis assumes that the pump is 200 km from the installation point and 100 km from the service center. Service is provided by a mechanic and crew who drive a four-wheel-drive Land Cruiser such as those used by the District Councils.

The costs of the Mono pump, including installation and first-year operating costs, are presented in Table 22. A pumping cost is included, as it is assumed that there is an opportunity cost for the time spent pumping.

Table 22. Financial Costs of Mono Handpumps

Installed Capital Costs	
Pump head	P220
Pump (Mono element)	413
Rising main (40 m @ P17/m)	680
Foundation and fence	100
Installation labor	1000
Installation transport	510
Total installed cost	P2923
Annual Recurrent Costs	
Maintenance and/or repair (materials)	25
Maintenance and/or repair (labor)	160
Transportation	188
Pumping labor (3 m^3/day economic cost would be 779)	0
Total annual recurrent cost	P373

There are variations between economic and financial costs. These are accounted for by the shadow-pricing of both materials and unskilled labor. In addition to establishing the first-year costs, costs must be forecast for future years. Future costs were projected at their current levels, with repair and maintenance levels based on the monitored operation and maintenance costs for handpumps in Botswana. Since there was an interest in making the resulting calculated present values comparable with those for the other technologies analyzed in this report, the period of analysis was set at 20 years. In the case of handpumps, the lifetime of the system is estimated to be 10 years. Therefore, the analytic model simply replaces the unit after the tenth year. The analysis was conducted using a discount rate of six percent (consistent with GOB practice).

Table 23 shows the results of the analysis at three levels of total pumping head and at three daily output levels for a pumping rate of 450 liters per hour (7.5 l/min). The pumping rate is derived from the test results reported in Table 21. It should be noted that at 7.5 liters per minute, it takes 2.2 hours to pump one cubic meter, 6.7 hours to pump three cubic meters, and 11.1 hours for five cubic meters. It is assumed that the pumping rate will be the same for each pumping head, although the rate will probably vary somewhat because of the greater difficulty of pumping at higher heads. The changes in unit cost reflect the addition of piping and rod to extend the pump to the lower pump level required. Calculation of these figures at five m^3/day allows comparisons with other technologies in companion volumes of this report.

Table 23. Costs of Pumping with Mono Handpump (at 7.5 l/min)

Head (m)		Daily Output (in cubic meters) 1	3	5
15:	Financial	P1.40	P0.47	P0.28
	Economic	P2.01	P1.14	P0.97
30:	Financial	1.46	.49	.29
	Economic	2.07	1.17	.98
45:	Financial	1.52	.51	.30
	Economic	2.14	1.19	1.00
60:	Financial	1.58	.53	.32
	Economic	2.21	1.21	1.01

Note that the financial cost is significantly lower than the economic cost. This is due to the assumption that the labor to pump water has economic value. There is little reliable information about who pumps water and how much time is allocated to that function. Even though no one may actually be paid to pump water, it is clear that the time should be accounted for and that the hourly rate should approximate the opportunity cost of the individual doing the pumping. The rate assumed, as stated before, is the shadow-priced minimum wage (P0.32/hr). The labor cost amounts to 22 percent of the total cost in economic terms.

Sensitivity analysis was conducted on handpump lifetime (decreased from 10 years to five), number of repair trips (doubled), installed cost of the equipment (increased 10 percent), and installation time (increased from five days to seven). None of these changes made as much as an eight percent difference in the unit cost of water delivered for the three-m^3/day case. Since the pumping labor cost will in all likelihood never be a financial cost, it was omitted. This dropped the financial unit cost to 20 percent of its original value. The allowance made for labor is clearly a significant assumption.

When the above sensitivities were performed with no pumping cost included, the changes were on the order of 30 percent. The most significant factor is repair or maintenance trips. One additional trip per year increases the unit cost by about 30 percent. This is not surprising since these costs now represent a greater portion of the total. The fact that these pumps deliver a relatively small amount of water accounts for the dramatic variation in unit costs when these sensitivities are performed.

To get a sense of the magnitude of the unit costs of handpump water delivery, a Lister LT-1, pumping five m^3/day from 30 meters for a rural village, has a unit cost (financial) of 1.84 (see VOLUME II). This is three to four times the unit cost of this handpump if no pumper cost is included. Even if the economic pumping cost of P0.32/hr is included, the handpump is still less expensive.

2. India Mark II Handpumps

The costs for the India Mark II handpump are shown in Table 24. The pump cost is based on a quote for shipment of a full container of India Mark II pump heads from India. The same set of rural village characteristics used in the Mono pump analysis above was used to generate the cost data given below. Only the pump-specific costs vary, as can be determined by comparing Tables 22 and 24. These costs were used for the first year and projected at the current level over the 20-year time horizon of the analysis.

As indicated in Table 21, the India Mark II delivered water at about the same rate as the Mono handpump. Some tests performed for the World Bank indicate that as much as 1000 liters per hour (16.7 liters per minute) could be achieved by pumping at a high rate of speed. However, for this analysis a rate of 450 liters per hour (7.5 liters per minute), consistent with the tests reported in Table 21, was used.

Table 24. Financial Costs of India Mark II Handpumps

Installed Capital Costs	
Pump head	P420
Pump cylinder	142
Rising main (40 m @ P17/m)	400
Foundation and fence	100
Installation labor	1000
Installation transport	510
Total installed cost	P2572
Annual Recurrent Costs	
Maintenance and/or repair (materials)	25
Maintenance and/or repair (labor)	160
Transportation	188
Pumping labor (3 m^3/day economic cost would be 779)	0
Total annual recurrent cost	P373

The unit water costs have been calculated for only two pumping heads and three output levels, since it is more difficult to pump with the India Mark II from depths greater than 30 meters. Table 25 presents these results. Note that the unit costs are not sensitive to changes in head. This is because the pumping rate is assumed to be the same regardless of the lift. However, this will not strictly be the case, as it does get more difficult to pump as head increases, and the delivery rate will decrease somewhat.

Table 25. Costs of Pumping with India Mark II (at 7.5 l/min)

Head (m)		Daily Output (in cubic meters) 1	3	5
15:	Financial	P1.25	P0.42	P0.25
	Economic	P1.85	P1.09	P0.94
30:	Financial	1.29	.43	.26
	Economic	1.89	1.10	.95

An economic cost for the labor of pumping was included, as in the Mono analysis. The same sensitivity cases were examined as for the Mono handpump (at a head of 30 meters and three m^3/day). As with the Mono, none of the changes (other than removal of pumping costs) caused as much as a 10 percent change in unit costs. Removal of the pumping costs dropped the unit cost by 65 percent. The sensitivity cases were examined without inclusion of a pumper, and these resulted in a unit cost difference of as much as 30 percent. As before, an increase to two repair trips is the most significant change examined.

The analysis reveals that the unit costs of water delivered with a Mono handpump are slightly more than those of the India Mark II, but the disparity is probably insignificant given the uncertainty in the difference in long-term recurrent costs of each model. More important--although the true unit costs for handpumps cannot be known precisely--it is clear that for cases where the head is less than 30 to 50 meters (depending on pump design) and a handpump can deliver five m^3/day, a handpump will deliver water at considerably less cost than a small diesel pump.

3. Domestically Manufactured Handpumps

Two types of handpumps have been fabricated in Botswana over the last several years--a copy of the India Mark II, and the Thebe handpump. The Mark II copy can be compared directly to the imported model. However, the Thebe pump output characteristics are so different from the Mono and India Mark II handpumps that direct cost comparisons without regard for performance are not possible. The Thebe pump analysis uses RIIC's performance projections for the latest model.

India Mark II

DWA recently ordered a trial run of seven locally made India Mark II handpumps at a cost of P1100 each from the Metalworking Brigades in Serowe. It is understood that this represents a prototype cost and that significant savings can be achieved through bulk materials purchase and through experience in fabrication. In the analysis that follows, an effort is made to estimate the savings, in economic terms, that Botswana could realize through domestic manufacturing.

Several assumptions are necessary to allow completion of the analysis. First, for this illustration it is assumed that the financial price will not change--that is, the Brigades can meet the price and quality of pumps that are made elsewhere and shipped to Botswana. This assumption makes it possible to illustrate the advantages of domestic manufacture by maintaining the constant financial price and calculating an economic target price. Second, it is assumed at the outset that the financial price of the pump head (that part which is to be made in-country) is one-third unskilled labor and two-thirds imported materials, so that unskilled labor can be shadow-priced properly.

Table 26 shows the potential economic benefits of making the pump in Botswana compared with importing it. At present, the financial price of the pump head is P420, thus the unskilled labor portion would be P140. If the labor were shadow-priced at 50 percent, it would be entered as P70 in the economic costs. The materials would still be imported and would be valued at P308. Therefore, rather than the present economic price of P462, the new economic price would be P378, allowing a margin of P84 per unit.

The Serowe Metalworking Brigades provided the cost breakdown for handpump fabrication used in Table 26. The economic cost of producing the handpump has been calculated to be P841. This means that a reduction of P379 in the economic value is needed to reach the same economic cost as for an imported pump head. This economic savings can be effected by appropriate reductions in imported materials, skilled labor or unskilled labor. The brigade believes that, with experience, both the skilled and unskilled labor components can be reduced. Bulk purchasing could reduce the materials cost. However, it appears unlikely that a 45 percent reduction, to the economic target, could be reached with the current level of demand for handpumps. Therefore, it does not appear worthwhile to pursue local fabrication of this particular model of handpump unless the demand increases significantly.

Table 26. Potential Gains from Domestic Production

Pump		Financial	Economic
Imported			
Pump head		P420	P462
Domestic			
Pump components:	materials	280	308
	labor	140	70
	margin	——	84
	total	P420	P462
Current Order from Brigades			
Pump components:	materials	160	176
	machine work (contracted out)	390	390
	labor	550	275
	total	P1100	P841
Economic Target Price (from above)			P462
Reduction Needed			P379

Thebe Pump

Unlike the other handpumps considered, the Thebe pump design procedure requires specifying a pump cylinder based on the pumping head and number of people operating the pump. This maximizes the water delivery for the energy available from the pumper(s). The result is a much wider range of possible pumping rates than for the India Mark II or Mono handpumps. To maintain some consistency with the other handpumps considered, the analysis only considers the performance of the pump when operated by one person. This still results in pumping rates from about 1.9 l/min (at 100 m head) to 24 l/min (at 15 m head). The rates used are indicated in Table 27.

RIIC indicates a cost of P901 for fabrication of the Thebe pump. It estimates the materials cost at P466, skilled labor at P58, and unskilled labor at P377. This assumes a mature production process that allows maximum use of materials and minimum labor input. The costs for the operation and maintenance of the pump are assumed to be twice that of other handpumps due to the greater complexity of the mechanism. The results of financial and economic analysis for the three output levels and four head levels considered for the Mono handpump are given in Table 27.

Table 27. Costs of Pumping with Thebe Handpump

Head (m)		Daily Output (in cubic meters) 1	3	5
15 (pumping at 24 l/min):	Financial	P1.94	P0.65	P0.39
	Economic	P1.98	P0.81	P0.57
30 (at 8.1 l/min):	Financial	1.97	.66	.39
	Economic	2.45	1.26	1.02
45 (at 5.3 l/min):	Financial	2.01	.67	.40*
	Economic	2.84	1.62	1.37
60 (at 3.9 l/min):	Financial	2.05	.68*	.41*
	Economic	3.28	1.94	1.74

*More than 12 hours of pumping required.

The results indicate that at a head of 15 meters, the Thebe delivers water more cost-effectively (in economic terms) than either the Mono handpump or the India Mark II. This is due to the large pump cylinders and consequent high pumping rate at this head. The high pumping rate reduces the time required to deliver the necessary water and hence the cost. As head increases, smaller pump cylinders are needed to ensure that one person can operate the pump. This means that the labor required to pump a given amount of water increases, and the unit cost of the water increases. For pumping heads of 45 to 60 meters, the Mono handpump delivers water at less cost than the Thebe pump. Note that as the head increases (and the cylinder decreases to allow pumping by one person), the time required may increase beyond 12 hours. When considered from a financial perspective, the Thebe pump is less cost-effective than the Mono or India Mark II. This is due to the Thebe's higher cost and to the assumption that labor is not a financial cost.

The value of the Thebe pump is its adaptability to two-person use (and hence doubled pumping rate at no additional financial cost) and to deep pumping applications. At a depth of 100 meters, the pump should deliver about 150 liters per hour, or enough water for the needs of about 50 people at Botswana's rate of rural water use. The unit costs for the Thebe to pump one m^3/day from 100 meters are P5.90 (financial) and P3.61 (economic). The unit costs for pumping water with a comparable diesel pumping system are more than 50 percent higher. For the

Thebe pump, if the labor to pump the water is not included, both unit costs are reduced to about P1.50. This should make the pump useful, especially for small settlements in western Botswana where water must be pumped through high heads.

F. Conclusions

Where handpumps can meet the water demand (low-capacity and low- to moderate-head situations), they will be more cost-effective than diesel systems. Clearly, the expanded use of handpumps should be encouraged. Their use would appear to be appropriate for small villages, settlements and lands areas where the head is low and the demand is less than five m^3/day. Use of the Thebe pump should be considered for higher head applications. Handpumps deliver about 500 liters of water per hour. This makes them suitable choices for use on low-yield boreholes when those boreholes are close to the location where the water is needed and the water requirement is small. In addition, due to their low cost and reliance on human power, handpumps have a role to play as back-up pumps in the smaller villages that are already equipped with diesel systems. However, this role will be limited by DWA's current policy to locate boreholes at least one kilometer from a village (to help ensure unpolluted water sources).

There are several reasons for increased interest in the use of handpumps. There is growing concern that the rural population will not be given reticulated water supplies under the present water supply programs. Even within these programs, availability of safe potable water is threatened in cases where only one water source exists. Interest in minimizing the risk of total dependence on imported diesel fuel also plays a part.

A number of organizations are making tentative moves towards handpump promotion. These initiatives should be encouraged. A handpump coordinating group should be established to organize and facilitate these efforts. Soon there will be 10 or 12 models of handpumps installed in Botswana. It will not be in the country's best interest to continue to use so many models. Thus, there is a need to evaluate these models and begin to standardize on one or two. Evaluation should concentrate on field rather than laboratory testing. User acceptance, repair and maintenance costs, and effect of the level of usage should all be considered. Some attention should be given to pumps with a capacity to pump water from more than 30 meters.

Review of existing handpump installations shows that maintenance and repair support is not well organized. The District Council Water Units have greater responsibilities to installations that serve greater numbers of users; thus, handpump servicing may receive a lower priority. The creation of a special unit within MLGL to be responsible for handpump installation and repair (and possibly the drilling of small-diameter boreholes) should be considered by the coordinating group. The unit would be responsible for handpumps throughout the country until such time as sufficient pumps are installed to divide the unit by region and perhaps eventually by district. At the district level, these units would be the responsibility of the Water Departments. Initially, the unit would be responsible to the MLGL water engineer.

Expanding the use of handpumps would be a cost-effective method of providing safe drinking water to many areas of rural Botswana.

BIBLIOGRAPHY

Ainley, M. Water Development at the Integrated Farming Pilot Project. In draft. Gaborone, Botswana: Ministry of Agriculture, 1985.

Arlosoroff, J., et al. Community Water Supply, the Handpump Option. World Bank/UNDP, 1987.

Arlosoroff, J., et al. Handpump Testing and Development. World Bank Technical Paper #29, 1986.

Ashford, R., and Millar, J. SIDA Report on the Needs to Improve District Councils' Capacity to Maintain and Operate Village Water Supplies. Gaborone, Botswana: Ministry of Local Government and Lands, January 1979.

Bailey, C. Keeping Cattle and the Cost of Water in Eastern Botswana. Gaborone, Botswana: Ministry of Agriculture, 1980.

Bhalotra, Y. P. R. The Drought of 1981-1985 in Botswana. Gaborone, Botswana: Department of Meteorological Services, Ministry of Works and Communications, 1985.

Classen, G. A. Consultant's Report on Small-Scale Rural Water Supplies. Gaborone, Botswana: Ministry of Agriculture, May 1980.

Colorado State University. Pumps and Water-Lifters for Rural Development. Fort Collins, Colorado: CSU, June 1977.

CWD. Handbook for Comparative Evaluation of Technical and Economic Performance of Water-Pumping Systems. Amersfoort, Netherlands: CWD Consultancy Services, 1987. (Draft.)

Davidson, N. C. An Analysis of Water-Lifting Devices in Botswana. Gaborone, Botswana: Botswana Technology Centre, October 1984.

Department of Meteorological Services. Climatological Summaries for Botswana. Gaborone, Botswana: Ministry of Works and Communications, 1984.

Department of Water Affairs. Borehole Repair Service Activities, 1984-1985. Gaborone, Botswana: DWA, 1985.

Driscol, F. Groundwater and Wells. 2nd ed. St Paul, Minnesota: Johnson Division, 1986.

Flint, M. E. S. "Water-Point Survey, Winter 1983." Gaborone, Botswana: Ministry of Agriculture, 1984.

Goe, M., and McDowell, R. Animal Traction: Guidelines for Utilization. Ithaca, New York: Department of Animal Science, Cornell University, December 1980.

Hitchcock, R. Kalahari Cattle Posts. Gaborone, Botswana: Ministry of Agriculture, 1978.

Hodgkin, J., and McGowan, R. Two Types of Hand Pumps -- Results of Field Tests in Botswana. Burlington, Vermont: Associates in Rural Development, Inc., 1985.

Hodgkin, J., McGowan, R., and White, R. Small-Scale Water Pumping in Botswana, Volume I: Comparisons. Burlington, Vermont: Associates in Rural Development, Inc., 1988.

Hodgkin, J., McGowan, R., and White, R. Small-Scale Water Pumping in Botswana, Volume II: Diesel Systems. Burlington, Vermont: Associates in Rural Development, Inc., 1988.

Hodgkin, J., McGowan, R., and White, R. Small-Scale Water Pumping in Botswana, Volume III: Windmills. Burlington, Vermont: Associates in Rural Development, Inc., 1988.

Hodgkin, J., McGowan, R., and White, R. Small-Scale Water Pumping in Botswana, Volume IV: Solar Pumps. Burlington, Vermont: Associates in Rural Development, Inc., 1988.

Jacobs, G. Evaluation of the RIIC Biogas Installation at Diphawana. Gaborone, Botswana: Botswana Technology Centre, July 1985.

Jones, W. W. Animal Drawn Pump, An Appropriate Technology. Kanye, Botswana: Rural Industries Innovation Centre, April 1987.

Kenna, J. Rapid Country Review for Botswana. Hants, United Kingdom: IT Power, May 1987.

Kennedy and Donkin. Electricity Tariff Study. Woking, United Kingdom: Kennedy and Donkin, November 1983.

Kennedy, W., and Rogers, T. Human- and Animal-Powered Water-Lifting Devices. London, England: IT Publications, 1985.

Kgosinkwe, B. Annual Report of the Water Hygiene Educational Program, May 1985-May 1986. Gaborone, Botswana: Family Health Division, 1986.

Khandelwal, K. C., and Mahdi, S. S. Biogas Technology, A Practical Handbook. New Delhi, India: Tata McGraw-Hill Publishing Co., Ltd., 1986.

Khatibu, M. Biogas for Water Pumping in Botswana. Kanye, Botswana: Rural Industries Innovation Centre, October 1983.

Larkin, P. "General Hydrogeology for Boreholes." In Proceedings of Photovoltaic Workshop. Gaborone, Botswana: Botswana Technology Centre, 1985.

Maseng, L., and Jacobs, G. Two-Day Test of Animal-Driven Pump at Gamorotswana. Gaborone, Botswana: Botswana Technology Centre, March 1985.

McGowan, R., and Hodgkin, J. Pump Selection: A Field Guide for Developing Countries. Burlington, Vermont: Associates in Rural Development, Inc., 1987. (Draft.)

McGowan, R., and Hodgkin, J. Water Pump Field Tests in Botswana. Burlington, Vermont: Associates in Rural Development, Inc., 15 April 1986.

Merafe, Y. I.F.P.P. Grazing Groups Study. Gaborone, Botswana: Rural Sociology Unit, Division of Planning and Statistics, Ministry of Agriculture, 1983.

Ministry of Finance and Development Planning. National Development Plan, 1969-73 (I). Gaborone, Botswana: Government Printer, .

Ministry of Finance and Development Planning. National Development Plan, 1985-91 (VI). Gaborone, Botswana: Government Printer, December 1985.

Ministry of Finance and Development Planning. Planning Officers Manual. Gaborone, Botswana: Ministry of Finance and Development Planning, June 1986.

Mono Pumps SA. Borehole Pump Curves, ES Series and BP Series.

Nord, M. Sand Rivers of Botswana. Gaborone, Botswana: Government Printer, October 1985.

Roe, E., and Fortman, F. Allocation of Water Points at the Lands. Gaborone, Botswana: Ministry of Local Government and Lands, 1981.

Roe, E., and Fortman, F. Water Use in Eastern Botswana: Policy Guide and Summary of the Water-Points Survey. Gaborone, Botswana: Ministry of Agriculture, 1981.

Shields, J., and McGowan, R. _The Thebe Pump -- A Human-Traction Pump for Botswana_. Burlington, Vermont: Associates in Rural Development, Inc., 1985.

SIDA. _Annual Review of the Rural Village Water Supply Programme, November/December 1985_.

SIDA. _Annual Review of the Rural Village Water Supply Programme, March 1987_.

Tlou, T., and Cambell, A. _History of Botswana_. Gaborone, Botswana: Macmillan Botswana Publishing Company, 1984.

UNDP/World Bank. _Pump Electrification Prefeasibility Study_. January 1986.

Viak. _Eastern Botswana Regional Water Study_. Gaborone, Botswana: Ministry of Mineral Resources and Water Affairs, 1985.

Wilson, B. "A Mini-Guide to Water Resources of Botswana." In _Proceedings of the Botswana Drought Symposium_.