Aspects of Irrigation with Windmills

by A. van Vilsteren

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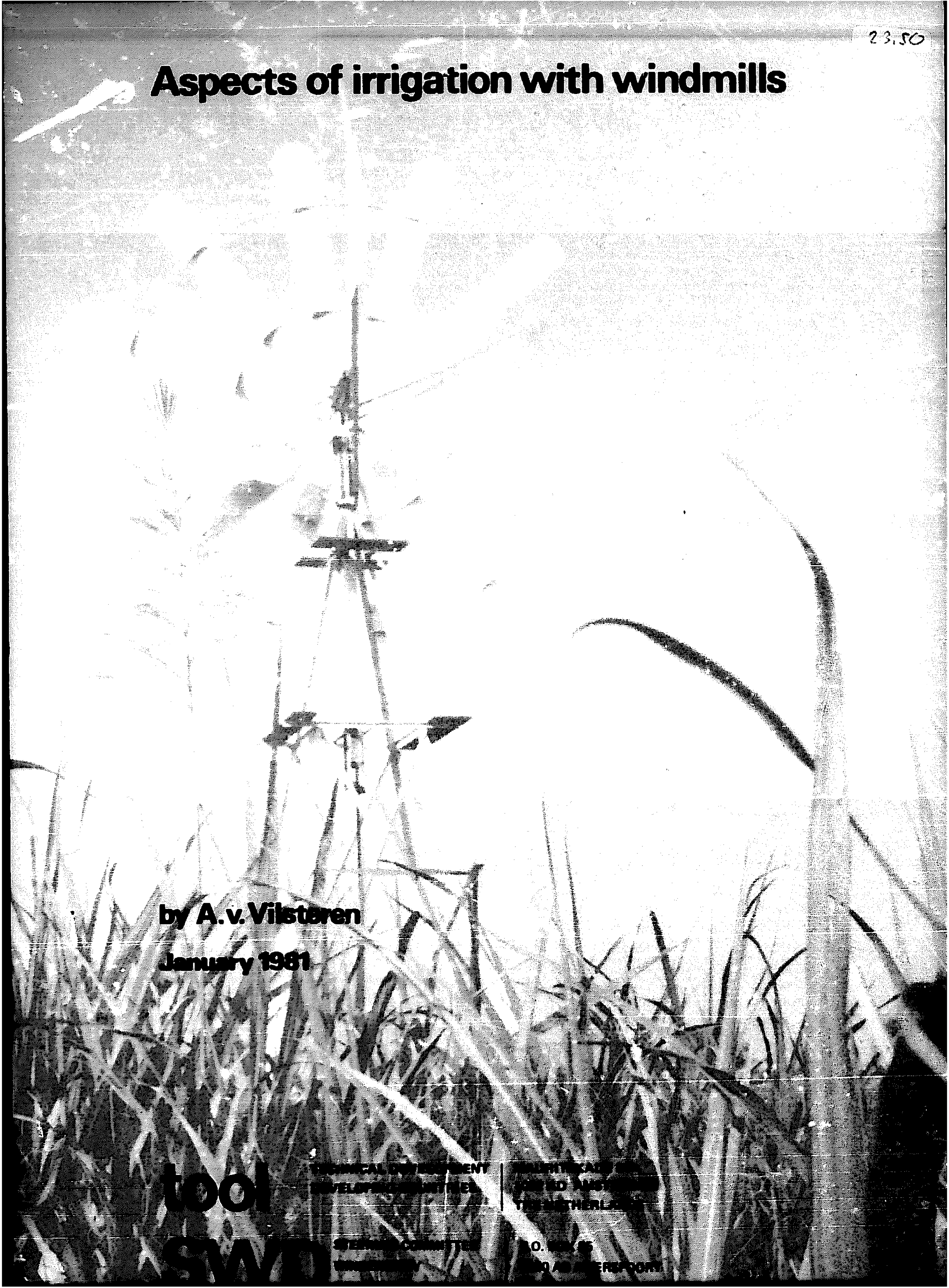

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The S.W.D. tries to help governments, institutes and private parties in the Third World, with their efforts to use wind-energy and in general to promote the interest for wind-energy in Third World Countries.

ASPECTS OF IRRIGATION WITH WINDMILLS

By:

Anton van Vilsteren

January 1981

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Hopefully this study will contribute to the further application of windmills for irrigation, so reducing the small farmers' dependence on fossil fuels and contributing to the alleviation of poverty and the production of more food in the developing countries.

Anton van Vilsteren.

SUMMARY

The sharply rising prices of fossil fuels increased the interest in alternative energy resources in the seventies. This combined with rising interest for infinitive, environmentally sound technologies has resulted in the development of quite a number of windmill prototypes and other alternative energy converters. Since the late seventies several prototypes have reached the implementation stage. Due to further improvements in performance, dependability and cost effectiveness (partly due to new price rises of fossil fuels), windmills can be applied in irrigation and may under certain conditions provide a more attractive solution than comparable small diesel-, petrol-, or electrical pump sets.

This study deals with aspects of this special kind of lift-irrigation, in the context of small holder agriculture in third world countries. The context in which small holder windmill irrigation has to be placed is discussed as well as how such projects can be planned. Irrigation, agricultural and social aspects are considered, and general economic calculation methods are given.

The analysis of the wind potential for water lifting is worked out. Special emphasis is laid on the correlation between wind, precipitation and evaporation and its impact on irrigation.
With the help of probability analyses of the soil water balance, the command area per windmill can be calculated. Optimization of the usage of the water pumped (by crop plan adjustments) is another important aspect.

The correlation between the daily evaporation and windspeed is significant. This, combined with the increase in instantly available soil moisture at lower evaporation rates, allows a delay in irrigation of several days for most crops, when windspeed drops for a few days. Guidelines are derived for increasing the flexibility of the crop plan with regard to the irrigation interval.

The Annexes provide formulae and tables that will enable the user to perform the necessary calculations with data from his own environment. Some working examples are also given to illustrate the calculation methods discussed in this paper.

CONTENTS page

REFERENCES

ANNEX I : Panevaporation method and Penman method, including tables and calculation examples.

ANNEX I-A : Determination of the relative influence of windspeed on the evapotranspiration.

ANNEX II : Table of salt tolerance of crops.

ANNEX III : Calculation example of the probability analysis of the windmill command area.

ANNEX IV : Formulae and calculation examples for economic analysis of windmill irrigation.

1. INTRODUCTION

In the wake of the increasing world energy crisis, which hits the least developed countries most, the interest in alternative energy resources has increased considerably.
Windmills have good potentials in many areas in the world, since they are relatively efficient energy convertors and their construction is relatively simple, cheap and can often be carried out locally.

This study discusses some specific aspects of small scale irrigation with windmills, for application by individuals or groups of small and marginal farmers, with the primary aim of improving their living conditions. However the general information provided will probably be useful to all people who apply windmills for irrigation.

It should be borne in mind that the study, based on literature and three years of experience with windmill irrigation, is primarily aimed at people already working in this field. Basic knowledge of irrigation principles and windmill construction are required for sound interpretation of the suggestions made in this paper.
These suggestions can provide a basis for assessment of the potential for windmill irrigation in a certain area.

However, the study is not to be used as a manual for design and operation of windmill irrigation projects. The examples and figures given here are just examples and mostly restricted to the situation given. Therefore it is recommended to seek expert advice if windmiils for irrigation projets are seriously considered.

1.1. Alternatives for irrigation

In this section it is stressed that despite the interest in windmills, irrigation and irrigation in general is not necessarily the most appropriate solution for the improvement of the living conditions of small and marginal farmers in a certain area. Especially in areas where gravitational irrigation is not possible, the rising energy costs and the required skill for operation and maintenance may make irrigation a costly and uneconomical affair. Pressure to boost national food production often leads to optimistic projections with regard to fuel prices and other costs and skills required for an irrigation project.

There are other alternatives for improvement of the living conditions of small and marginal farmers and increase of food production, such as: land reform, improved dry farming, erosion control, water saving activities and supply of, for instance, fertilizers and pesticides. Infrastructural improvements might also be more appropriate in certain areas. Under specific conditions rainwater catchment may be an alternative.

Introduction of irrigation is often justified on economic grounds, all other inputs being taken to be optimally available, including infrastructure for the supply of inputs and the marketing of the crops.
But farmers are often unable to change all their agricultural practices at once and the authorities and other parties are also often unable to supply all services and inputs at once.
A step by step approach may be more appropriate in such cases, input- and output-levels first being improved, after which new farming practices are gradually adopted and infrastructural improvements realized.
Irrigation, especially lift irrigation, is a costly affair and should therefore in fact only be applied if all other cheaper alternatives for improvement of agricultural production have been investigated. (History of irrigation projects Hagan, 1967, Vreede 1978).

1.2. Selection of irrigation device

Let us assume that detailed need assessment studies and surveys have shown small scale irrigation to be a logical next step for further improvement of the living conditions of the small and marginal farmers in a certain area.
Next comes the selection of the irrigation device (electrical pump sets, pumps driven by internal combustion engines, windmills).
A direct economic comparison is made in chapter 4; other aspects that deserve consideration are discussed in this section.

Windmills depend directly on an natural resource (wind) and are unknown in most rural areas in developing countries.
These factors have consequences for their application in several ways: social, agro-economical, technical and political.
The most important elements of these aspects are considered below.

Social

1. Many developments in the augmentation of agriculatural production are characterized by decreasing dependence on natural forces (fertilizers to improve natural fertility, new varieties and hybrids to replace traditional low yielding varieties, irrigation to supplement or replace the natural rainfall).
   Dependence on windmills for irrigation however, means increasing dependence on natural forces. This is in significant contrast with the developments in the last century. This aspect may reduce the acceptability of windmills by farmers as well as by the local authorities. Especially in developing countries all efforts and hopes are placed on "modernization" of agriculture.

However, with the increasing cost of the fossil fuels on which many of these improvements depend (fertilizers, insecticides, energy for water lifting and mechanization), the dependence on nature may become a sound economic alternative and therefore easier to accept.
An additional advantage in this respect, especially for small and marginal farmers is that the energy source "wind" cannot be monopolised, whereas with the fossil energy sources this is becoming more and more the case, due to their scarcity and increasing prices.

2. If a few small farmers have to share the water pumped by one windmill, difficulties may arise with regard to distribution of the irrigation water, since windmills cannot be started at any moment. For example, it is the turn of farmer B to irrigate his wheat, but he has to wait for 2 days since there is not sufficient wind. The third day there is some wind; at that moment however, it can be more essential to irrigate first the potatoes of farmer A, since that crop is much more sensitive to water shortage in a certair growing stage. This unpredictability of the day to day output of a windmill also restricts its suitability for selling irrigation water to neighbours. Selling irrigation water is widely practised by (small) farmers with pump sets in many places in Asia and elsewhere and is often a sound source of cash income.

Agro-economical
----

1. Besides the economic components of the above mentioned social implications, it should be mentioned that as the availability of sufficient windenergy in a certain period often cannot be relied upon, safety factors have to be taken into account with regard to command area and crop choice. For realistic planning, it is recommended to make probability analyses of the combined figures of evaporation, rainfall and windspeed, since these phenomena are intercorrelated. If insufficient data are available for such an analysis, the windmill irrigation unit has to have an overcapacity to compensate for partial or total failure of rains, because this cannot be overcome by running a few extra hours, as with a pump set. However, a large tank for storage of the pumped water to meet crop water requirements at a later stage may be uneconomical due to the cost of construction and the loss of land which it occupies. Even small tanks to meet short windless periods during the growing season are often uneconomical. Chapter 3 deals in detail with this subject of meeting short windless periods.

2. The crop plan has to be adjusted to the existing annual wind regime. This may lead to reduction of the command area during the low wind seasons or to growing more drought resistant crops during such seasons.
Drought resistant crops are often not the most renumerative crops. It will be clear that the crop plan cannot be selected solely on the basis of the capacity of the windpump, but that many other factors will be of influence (see Chapter 3).

However, recent studies in India, Indonesia and Kenya show that the economic viability of windmills as an irrigation medium depends largely on a (to the wind regime) adjusted crop plan for the entire year. Than maximum use can be made of the water pumped by the windmill (van Vilsteren 1978, 1979, 1980).
A crop plan determination in accordance with the actual wind regime may also imply that further crop plan adjustments to future market changes will be difficult or impossible. But this is also often a limitation of large irrigation schemes within flexible farm supplies.

The lower reliability of windmills may also affect the level of the other inputs (high yielding varieties, fertilizers, pesticides etc....) and consequently the output level (yield). The same symptoms have often been reported in evaluations on the introduction of the "green revolution" in areas with uncertain availability of irrigation water (risk minimization).
Due to the worldwide energy crisis and the consequent scarcity and high prices of diesel oil and electricity, the reliability of these irrigation sources has decreased as well.
Also unsound management of large irrigation schemes may cause unreliable watersupply and consequently, farmers will grow less and or fewer risky crops and apply fewer inputs compared with areas with good irrigation water supply.
E.g. farmers in the Ganga-plain of North India who get their water from government tubewells grow fewer risky crops (no vegetables, no potatoes) and obtain lower yields than farmers with private pumping sets.

3. On the other hand, if the cost per m^3 water pumped by windmills is considerably less than the cost of water from other irrigation sources, this may compensate the limitations with regard to its reliability.
In the same Ganga-plain of North India, farmers with diesel pump sets grow hardly any crops during the hot summer season.
The water requirements of crops in that season is so high that economic crop production with high (variable) cost per m^3 water is hardly possible. Yet this is the main season for the windmills due to prevailing high windspeeds during that period.

The variable cost of water pumped by windmills is almost negligible, since it consists only of repair and maintenance costs (see figure 1.1.), most of which may also be regarded as fixed costs as wear and tear of the windmill structure (e.g. corosion) continues even if the mill is not running. Only the wear and tear on the transmission (e.g. bearings) can be regarded a true variable cost, because it is directly related to the running of the windmill.

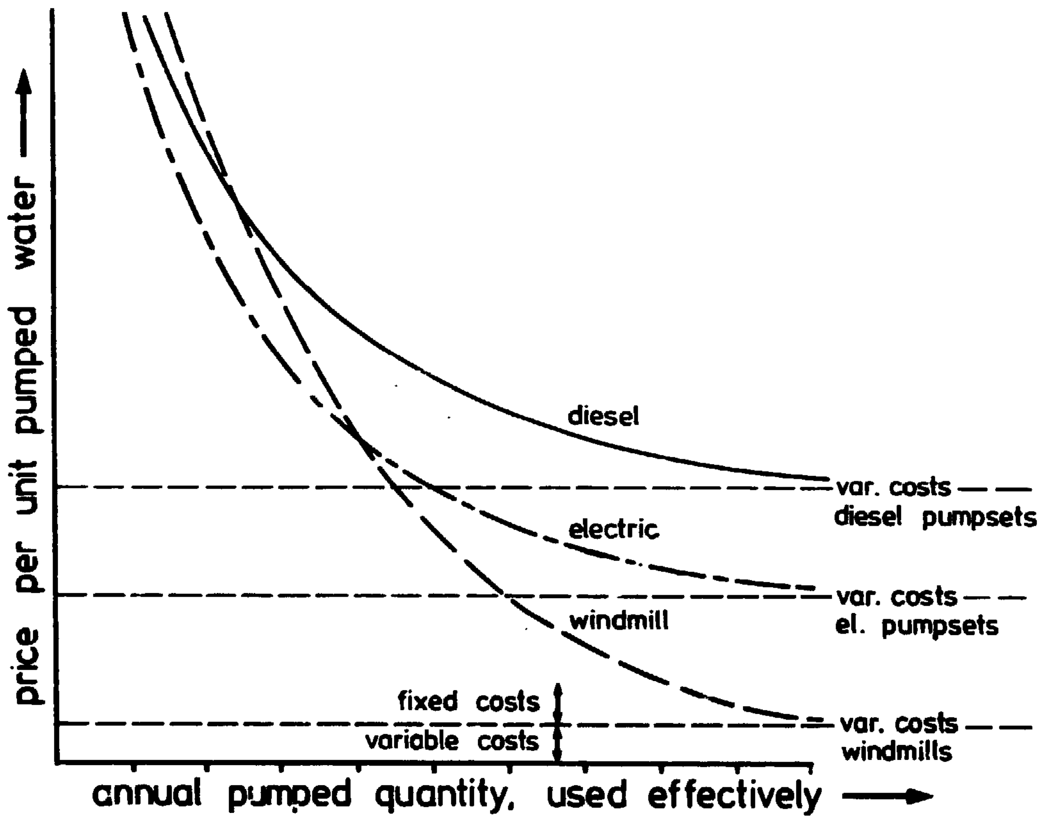


Fig. 1.1. General relation between the price per unit of water pumped and the annual output for small diesel and electrical pump sets and windmills.
Any additional amount pumped by the windmill is much cheaper than for the other pump sets due to the low level of variable costs (no fuel costs).

Technical
----

1. Windmills can only be applied in windy areas (see chapter 2 for wind analysis).
   It is recommended that the initial introduction of windmills in an country takes place where there is abundant wind and the water source is reliable and not too deep (E.g. average monthly windspeed above 2.5 m/sec., total elevation head less than 15 m).

2. At present, windmills have a relatively small capacity, comparable with a small pump set. Windmills with larger capacities may be constructed in the future but this is likely to be accompanied by increasing costs and technical problems.
   Windmills should be placed far from each other (more than 10 times the rotordiameter) and their water source should be nearly under them (direct mechanical transmission). In some places windmills generate eletricity for an electric pump set elsewhere. Energy losses and increasing costs limit the economic application of such systems. Consequently, if the number of water sources is limited, and their capacity is large, it may be more economical to install an electric or diesel powered pumping station and irrigate a larger area from the same source. For example in case of a river or lake, irrigation with windmills will only supply water to a very small area along the shores of the source. Even a well with a large capacity may be more economically pumped by electricity or diesel, provided there are no other limitations (topographical, land property, availability of energy etc....).
   However, as can be seen in fig. 1.2, windmills can sometimes provide an attractive solution. In the future they may also be used in large schemes with low lift irrigation.

3. Windmills need an open surrounding of about 20 times the rotor diameter free of trees and houses. Yet, in the nature of things, water sources are usually surrounded by trees. Removing them is often difficult and sometime even prohibited by governmental or religious authorities. Moreover surrounding trees often have an economic value (coconut, fruit trees etc.).

4. In most rural areas, diesel and electric pumps are already in use. Consequently the technology is familiar, there may be a network for marketing and spare parts and skills are available for repair and maintenance.
   However in the case of windmills, production has to be started, a marketing network has to established for the mills and their spare parts; local blacksmiths have to be trained for repair and maintenance work.

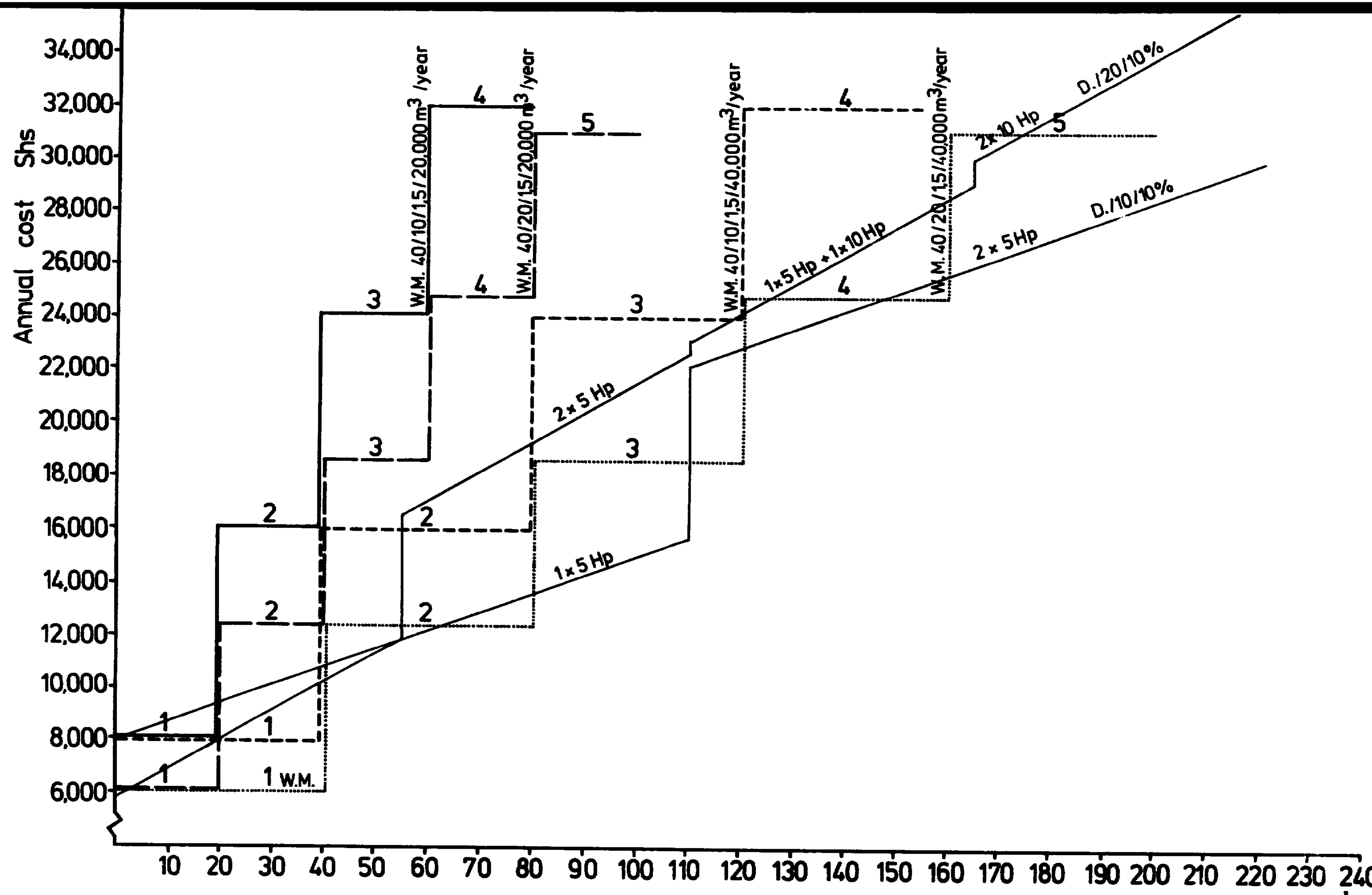


Fig. 1.2. Comparison of annual costs for larger schemes in Kenya, using a number of windmills of a certain annual capacity or a diesel pump set plant. Time span 10 and 20 years; elevation head 5 m. (Vilsteren, 1980)

W.M. 40/10/1,5/20,000 m3/yr means:
Windmill plus tank: Shs. 40,000; Lifespan, 10 years; Repair and maint, Shs. 1,500 per year; Output, 20,000 m3/yr

D/10/10% means : Dieselpumpset; lifespan 10 years; annual fuel pricerise 10%

If the windmills prove to be viable all these activities will expand automatically.

Political
----

1. Whether windmills will be accepted by governmental bodies depends on policies with regard to rural electrification, fuel import and fuel prices, and the general policy with regard to the area concerned, such as plans for hydropower plants, large gravitational irrigation schemes, employment generation etc.....

2. In areas where small scale irrigation already takes place (electricity, diesel) there are often all kinds of subsidies and credit schemes for pumpsets, such as interest subsidy on credits, subsidy on fuels etc..... These facilities should be made eligible for windmills as well, as the non availability of subsidies and credit-facilities for windmills limits their acceptance by the potential users.
   This process of acceptance can take several years, during which the windmill irrigation system has to prove its viability.

3. In general, the faith of governments in windmills for irrigation is not yet great. This can only be improved by successful windmill-irrigation pilot projects.

1.3. Planning of a windmill irrigation project

As has been made clear in the previous sections, the introduction of windmills in a certain area is fairly complicated. A planning chart is presented here to review the many aspects that can influence the introduction of windmills and to show at what phase of the project action must be taken. This chart is based on a survey of the implementation of an Appropriate Technology Programme in Indonesia. (De Iong, 1980)

Since the philosophy of Appropriate Technology emerged, windmills have been regarderd as a suitable possibility for this approach. At this moment a small number of simple, low cost windmill designs are under testing or in operation at several places around the world.
A characteristic of Appropriate Technology is that it is not easily transferable to other areas. The technology has te be appropriate to the specific conditions of the area in which it is to function.
In the first place with regard to its social appropriateness.
Are windmills the step for further development that is wanted next by the target group?
Secondly are the required skills, materials and infrastructure sufficient available locally? Appropriate Technology is not automatically

simple. Recent experiences with windmill projects show that although the principles may be quite simple, that if the windmill is to function optimally for a number of years, it is essential to produce it with skill and precision.

The planning chart given is only functional if the need for small scale irrigation has already been assessed.
Moreover, it should be discussed before each subsequent step whether windmills can still be considered to provide the most appropriate solution.
It should be realised that windmills for irrigation, like any other technology, will not provide (indeed cannot provide) the sole solution for improvement of the living conditions of the weaker sections of the community.
Introduction of windmills should preferably be decided on and planned in the framework of an integrated rural development scheme. Here we limit ourselves to the planning of the "windmill part" of such projects.

FEASIBILITY STUDY

Long term goal setting	
Selection pilot area	- need for irrigation - favourable wind conditions - favourable water sources
Surveys	- social - economic (macro-micro) - agricultural - technical
Target group selection	- counterpart organization - producers of windmills - users of windmills

Need assessment and target group study

Target group segmentation	short term goal setting	selection participants of target group

DISCUSSION

- Does the realisation of the longterm objective seem to be feasible?
- If not, is a modification of the long term objective desired or required?
- Should the project be started or not?

PILOT PROJECT

Hardware selection, development and testing

Data collection - detailed wind analyses - detailed water source study - calculation cropwater requirement - detailed survey of available material and skills	windmill design	prototype construction
	pump design	improvements

Implementation on small scale

selection of sites selection of farmers	guidance of farmers data collection	training mechanics transfer of technoligy

Evaluation pilot project

evalutation social appropriateness	evaluation technical/agricultural feasibility	evaluation economic feasibility

DISCUSSION

- Will the realisation of the long term objectives be feasible?
- If not, is a modification of the long term objectives desired or required?
- Should the project be continued or not?

IMPLEMENTATION

Short term goal setting

Fixation project area

Project implementation

1. windmills production quality control standardization price control	marketing advertizing credit facilities subsidy facilities	servicing spare parts servicing contracts quarantee period

2. agriculture
   extension service
   field worker
   demonstration farm
   mass media

Applied research/further data collection
Transfer of technology

Evaluation

2. SMALL SCALE IRRIGATION WITH WINDMILLS

Chapter 1 of this report comprises a review of the general aspects to be considered before a windmill project can be started. In Chapters 2 and 3 attention is given to specific aspects of irrigation with windmills . As an introduction, the main principles of irrigation are briefly outlined and references are given. The use of windmills for water lifting is discussed more extensively. Readers with a limited knowledge of agriculture and irrigation are advised to read:
"Small scale irrigation by P. Stern" 1979. *

The determination of the command area is the main subject of this chapter. The command area is the acreage that can be irrigated by the water lifting device (e.g. windmill) under the given conditions. A simple example:

crop water use 300 mm/month.
rainfall 100 mm/month.
windmill output 200 mm/month. (=2000 m^3/ha since 1 mm = 10 m^3/ha).
In this situation the command area is 1 ha, since windmill output and rainfall can just compensate the crop water need.

The elements: evapotranspiration, rainfall, windmill output and crop selection are discussed in detail. A simple probability analysis is introduced to predict the probability of occurrence of a certain command area with windmills under the given climatological conditions. Finally a few remarks are made about the irrigation water source.

In Chapter 3 attention is given to typical aspects of irrigation with a variable energy source (wind) and to the calculation of the irrigation interval. Also the way in which the effects of the variable daily windmill output can be minimized (relation wind-evapotranspiration; evapotranspiration-crop production; other input levels; storage tank) is dealt with.

2.1. Water balance

Before assessing the amount of irrigation required to grow a crop, it is necessary to evàluate the elements which can influence the balance of the water in the soil.
This water balance can be expressed as follows:

$$\Delta W = P + I + C - DR - RO - E.$$

in which: ΔW: change in amount of water present in the soil
P: precipitation

* P. Stern: "Small scale irrigation; Intermediate Technology Publications Ltd. Kingstreet Londen, WC 2, 8HN U.K.
(Also to be ordered from TOOL, Mauritskade 61 A, Amsterdam (NETHERLANDS.)

I: irrigation
C: capillary rise
DR: drainage to lower soil layers
RO: run off
E: evapotranspiration

Precipitation, evapotranspiration and irrigation are discussed in detail in the following sections. Those terms are often the main components of the water balance of the soil for which irrigation is needed. The remaining factors are briefly considered below.

Capillary rise

Capillary rise is the transport of water from the subsoil to the topsoil through the capillaries of the soil. As is common in all flow processes, the capillary rise depends upon the length of the pathway, the resistance of the pathway and the difference in potential between the outer ends of the pathway.

A significant contribution from capillary rise only occurs when the groundwater table lies within 1-2 m. below soil surface. Lighter soils (loamy soils or loams) allow a delivery of 2-4 mm/day at 60-100 cm above groundwater table, whereas in clay soils, these quantities can only be delivered at less than 40 cm above the groundwater table (Rijtema, 1970).

These figures show, that the contribution of capillary rise to the water balance of the soil is negligible in most cases.

Drainage

Drainage is the loss of water due to percolation beyond the reach of plant roots. If the amount of rainfall or irrigation exceeds the storage capacity of the rootzone, drainage occurs.
If this excess of water cannot be removed naturally (percolation to the subsoil) or artificially (drains, ditches, canals etc.) water logging will occur, causing damage to the crop due to insufficient aeration of the rootzone.
If, due to percolation of excess rainfall or irrigation, the groundwater table rises within 2 m of the ground surface, artificial drainage has to be applied to avoid salinization caused by high groundwater tables (Unesco/FAO, 1973).
Drainage facilities are also required when the irrigation water contains salts which can accumulate in the rootzone. Additional irrigation water is applied for leaching purposes and then has to be drained from the rootzone. For leaching requirements and drainage capacities see Unesco/FAO, 1973.

In water balance studies it is often difficult to estimate the loss of water due to drainage. By measuring groundwater tables and the discharge from drains, an impression can be obtained about the drainage of the area studied.

Run-off

Water which does not penetrate in the soil but flows over the soil surface is called run-off. If the rainfall intensity, or irrigation intensity exceeds the infiltration capacity of the soil, water remains on the soil surface and will start to flow if there is any gradient. This process can cause erosion in sloping areas and water logging in small depressions in fields. The infiltration rate of the soil can be improved and erosion reduced by cultural practices (contour plowing, mulching, strip cropping, contour ditches etc.). Single fields should be properly levelled.
In the case of furrow- and border-irrigation, run-off at the end of the field is almost inevitable. Drainage ditches have to be applied in such cases to prevent water logging and salinization. In paddy growing areas the run-off of one field is often used to meet the water requirements of the lower fields.
Measuring the run-off is almost as difficult as measuring drainage. Drainage and run-off are often discounted in irrigation- and rainfall efficiency. Inevitable irrigation losses such as deep percolation and run-off are accounted for by introducing irrigation efficiency factors. (See section 2.3.2.).
With the abovementioned modifications for irrigation and rainfall the water balance equation can be simplified as follows:

$$\Delta W = P + I - E.$$

If W has to be constant over a certain period, the following balance has to exist over that period:

$$E = P + I$$

Evapotranspiration, rainfall and irrigation are considered in more detail in the following sections.

2.1.1. Evapotranspiration

Evapotranspiration is a combination of evaporation from the soil surface and transpiration from the crop, and is dependent on many factors.
In the first place, the reference evopotranspiration ETo is defined as

> "the rate of evapotranspiration from an extensive surface of green grass cover of uniform height (8-15 cm), actively growing, completely shading the ground and not short of water".

As can be concluded from this definition many factors, other than the climate, influence the evapotranspiration (crop height, colour, uniformity, growing conditions, ground cover etc.).

Several methods are available to calculate the ETo (Blaney and Criddle, Radiation, Penman, Pan Evaporation) (FAO, 1977).
The modified Penman methods offers the results with the lowest error (about 10%). However, this method requires a number of measured meteorological data and the calculation is not simple.
Calculation tables for the Penman method and the Pan evaporation method can be found in Annex I and in the literature (Penman 1948, Kijne and Baars 1971, FAO 1977).

Evapotranspiration can be divided into 2 main components:
The radiation component (sun) provides in general the energy for the evapotranspiration.
The aerodynamic component (wind) transports the water vapour.
By transporting warmer air over a cooler surface, this aerodynamic component also provides energy for evapotranspiration. This is called advection and occurs regularly in semi-arid and arid regions.

Wind is the agent for air transport. So the windspeed will influence the evapotranspiration. At low windspeeds the water vapour resulting from evapotranspiration will not be transported and consequently the evaporation will decrease.
At high windspeed the water vapour will be removed immediately and the total evapotranspiration will increase. If the wind comes from a drier and warmer area, the effect of windspeed on the evapotranspiration will be even higher.
The effect of windspeed on the total evapotranspiration can be as much as 30% (see Annex I-A). The relation between evapotranspiration and windspeed is important for the calculation of the command area (sec. 2.3.) as well as for the irrigation interval (sec. 3.2.) when irrigation with windmills is envisaged.

Crop evapotranspiration (ETcrop)

The reference evapotranspiration (ETo) refers to grass of 8-15 cm height. Other crops with other characteristics can be related to ETo with the following formula:
ETcrop=kc.ETo.

Crop Coefficients (kc)

CROP	Crop Development stages					
	Initial	Crop development	Mid-season	Late season	At harvest	Total growing period
Banana						
tropical	0.4 -0.5	0.7 -0.85	1.0 -1.1	0.9 -1.0	0.75-0.85	0.7 -0.8
subtropical	0.5 -0.65	0.8 -0.9	1.0 -1.2	1.0 -1.15	1.0 -1.15	0.85-0.95
Bean						
green	0.3 -0.4	0.65-0.75	0.95-1.05	0.9 -0.95	0.85-0.95	0.85-0.9
dry	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7 -0.8
Cabbage	0.4 -0.5	0.7 -0.8	0.95-1.1	0.9 -1.0	0.8 -0.95	0.7 -0.8
Cotton	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.9	0.65-0.7	0.8 -0.9
Grape	0.35-0.55	0.6 -0.8	0.7 -0.9	0.6 -0.8	0.55-0.7	0.55-0.75
Groundnut	0.4 -0.5	0.7 -0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize						
sweet	0.3 -0.5	0.7 -0.9	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
grain	0.3 -0.5*	0.7 -0.85*	1.05-1.2*	0.8 -0.95	0.55-0.6*	0.75-0.9*
Onion						
dry	0.4 -0.6	0.7 -0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8 -0.9
green	0.4 -0.6	0.6 -0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4 -0.5	0.7 -0.85	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
Pepper, fresh	0.3 -0.4	0.6 -0.75	0.95-1.1	0.85-1.0	0.8 -0.9	0.7 -0.8
Potato	0.4 -0.5	0.7 -0.8	1.05-1.2	0.85-0.95	0.7 -0.75	0.75-0.9
Rice	1.1 -1.15	1.1 -1.5	1.1 -1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.7	0.2 -0.25	0.65-0.7
Sorghum	0.3 -0.4	0.7 -0.75	1.0 -1.15	0.75-0.8	0.5 -0.55	0.75-0.85
Soybean	0.3 -0.4	0.7 -0.8	1.0 -1.15	0.7 -0.8	0.4 -0.5	0.75-0.9
Sugarbeet	0.4 -0.5	0.75-0.85	1.05-1.2	0.9 -1.0	0.6 -0.7	0.8 -0.9
Sugarcane	0.4 -0.5	0.7 -1.0	1.0 -1.3	0.75-0.8	0.5 -0.6	0.85-1.05
Sunflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.7 -0.8	0.35-0.45	0.75-0.85
Tobacco	0.3 -0.4	0.7 -0.8	1.0 -1.2	0.9 -1.0	0.75-0.85	0.85-0.95
Tomato	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.95	0.6 -0.65	0.75-0.9
Watermelon	0.4 -0.5	0.7 -0.8	0.95-1.05	0.8 -0.9	0.65-0.75	0.75-0.85
Wheat	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.2 0.25	0.8 -0.9

CROP	Crop Development stages					Total growing period
	Initial	Crop development	Mid-season	Late season	At harvest	
Alfalfa	0.3 -0.4				1.05-1.2	0.85-1.50
Citrus						
clean weeding						0.65-0.75
no weed control						0.85-0.9
Olive						0.4 -0.6

First figure : Under high humidity (RHmin >70%) and low wind (U<5m/sec).
Second figure : Under low humidity (RHmin <20%) and strong wind (>5m/sec).

Table 2.1: k_c-values of different crops for different growing phases under different conditions of relative humidity and windspeed. (FAO, 1979).

Many studies have been carried out to analyse the influences on crop-water requirement (Rijtema, 1970, 1975, Salter, 1969).
The following factors influence the kc-value:

- plant physiological features (closure of stomata, waxy or hair leaves)
- crop height and crop roughness
- growing phase and ground cover.

A procedure for determination of kc-values of different crops at various growth phases has been developed by FAO (FAO, 1977); kc-Values are listed in table 2.1.

ETcrop is defined as: "The evapotranspiration of a disease-free crop, grown in large fields under optimal soil, water and fertility conditions".
This ETcrop can be used in the water balance equation. The evapotranspiration under non-optimal growing conditions is discussed in section 3.4.
Attention should be given to advection winds and their effect on the ETcrop. Fields irrigated by windmills can be regarded as green spots in barren surroundings.
Corrections will have to be made, depending on the location of the meteo-station from which the data used for determining ETcrop, have been obtained (FAO, 1977).

2.1.2. Precipitation

Precipitation means rainfall in this case. Only in exceptional cases do dew, hail or snow contribute directly to the water balance of the soil in irrigated areas. To predict the contribution to the water balance, two aspects of rain are important: effectiveness and probability of occurrence.
Not all rain is effective and part of it may be lost by surface run-off, deep percolation or evaporation. The effectiveness of rain depends on rain intensity, soil type, soil depth, cropping pattern, infiltration rates, etc.

Crop intercepted water contributes only indirectly to the soil water balance, by reducing transpiration and so lessening soil water depletion. To determine the effectiviness of the precipitation within a certain interval, local information has to be gathered on the above mentioned effectivity factors. Detailed information can be found in literature (FAO 1975, Vink 1978).
In places were rainfall is variable probability analyses are inevitable. In this paper, the probability of meeting the crop water requirements (E = P + I) is analysed, (section 2.3.3.) since the features, evaporation, precipitation and irrigation (i.e. here windspeed) are not independent variables. Higher windspeed means higher evapotranspiration; high precipitation means low evapotranspiration (overcast). Details about probability analysis of rainfall can be found in literature (Ven te Chow 1964, WHO 1965).

2.2. Water lifting with wind energy

With the help of windmills, wind energy can be converted into mechanical or electric power.
The power characteristic of a windmill is given by:

$$P_o = Cp\ \eta_t \tfrac{1}{2}\ \rho_a\ AV^3\ \ (W)$$

in which
- P_o = power (Watt)
- Cp = power coefficient of rotor (-)
- η_t = efficiency of transmission (-)
- ρ_a = density of the air (kg/m^3)
- A = area of rotor (m^2)
- V = wind velocity (m/s)

Since the power relates cubic with the windspeed, it is very important to obtain reliable windspeed data. Hourly average windspeed, measured over a great number of years (10-20) at an open representative place near or in the project area are required for a sound analysis.

Generally the height above ground surface at which observations are made is not the same as the height of the windmill rotor. Since windspeed increases with height, adjustments have to be made.
The adjustment can be made with the following empirical formula:

$$\frac{\overline{Vh}}{\overline{VH}} = \left(\frac{h}{H}\right)^a$$

where: $\overline{Vh}$ = average wind velocity at height h (m/s)
$\overline{VH}$ = average wind velocity at height H (m/s)
h = height of windmill rotor axis(m)
H = height of windspeed measuring device (m)
a = surface roughness exponent

The exponent, a, depends on the roughness of the surface. (Fig. 2.1.)

Measurements in Sudan for instance, showed a = 0.20 over the first 15 m above ground level, where the surface consisted of sand or short crops (grasses).
In open areas on land, a, will in general be between 0.2 and 0.25.

If no wind observations have been made in the project area, a rough impression can be obtained by correlating a short period of measurements in the project area with measurements of the same period from a nearby station (Beurskens 1978). It will be clear that the meteo station should be situated in the same geographical and climatic area, as the planned project.

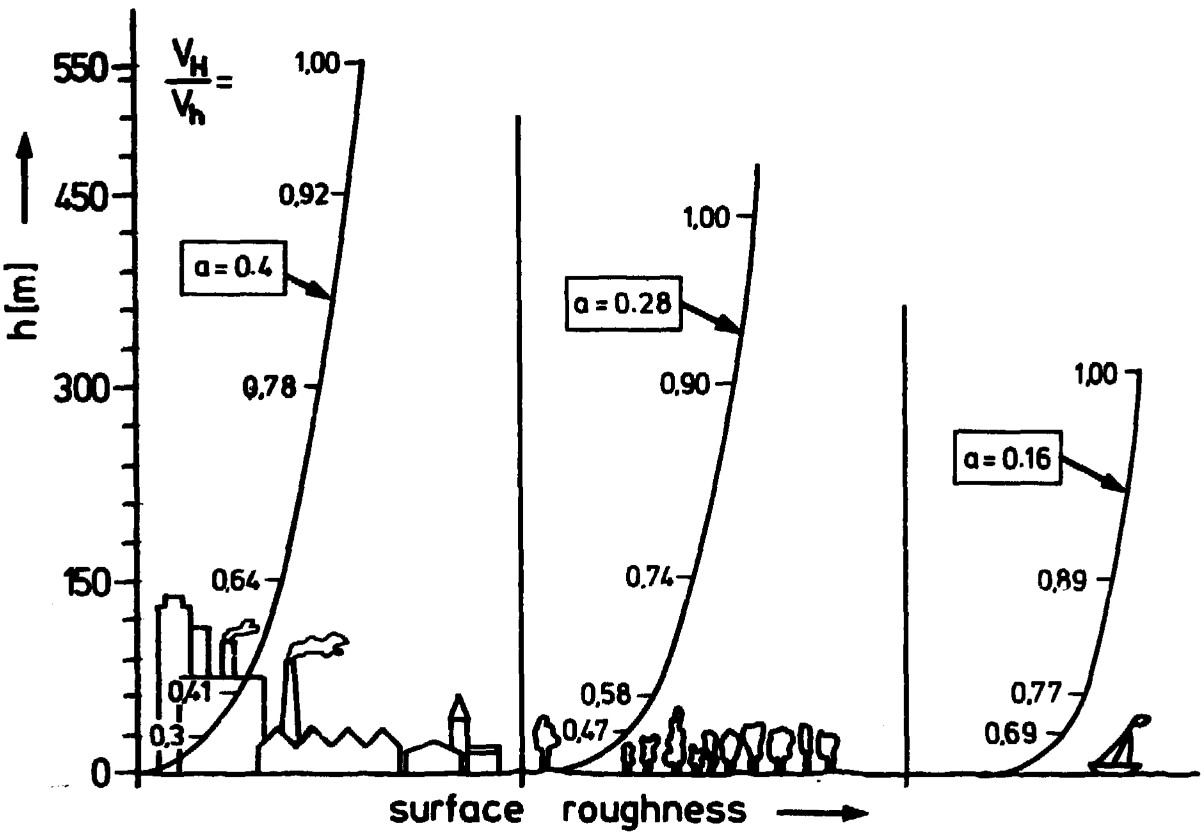


fig. 2.1. V_H/V_h as a function of surface roughness

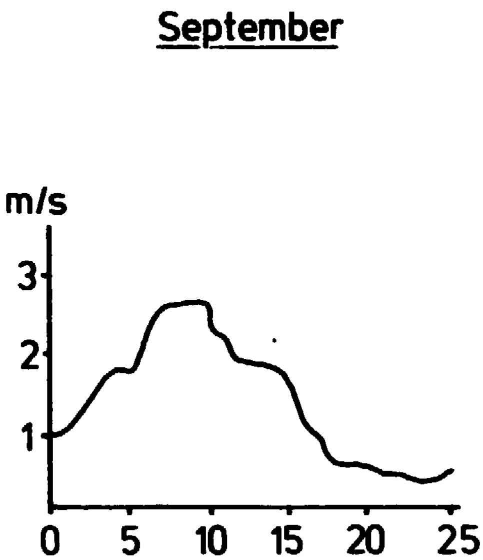
2.2.1. Wind characteristics

The following analyses of windspeed pattern are important:

a. daily wind pattern
b. annual wind pattern
c. maximum windspeeds
d. windspeeds frequency distribution

a. daily wind pattern

The average distribution of windspeed during the day for each month of the year (or for the irrigation season) will indicate at what time irrigation water will probably become available and, if this is inconvenient for the farmer (at night or during the hot midday hours), facilities have to be provided for storage. At meteorological stations windspeeds are often measured in detail during daytime only. If the 24 hour windpattern is known, the contribution of the night hours with regard to the windmill output can also be estimated.



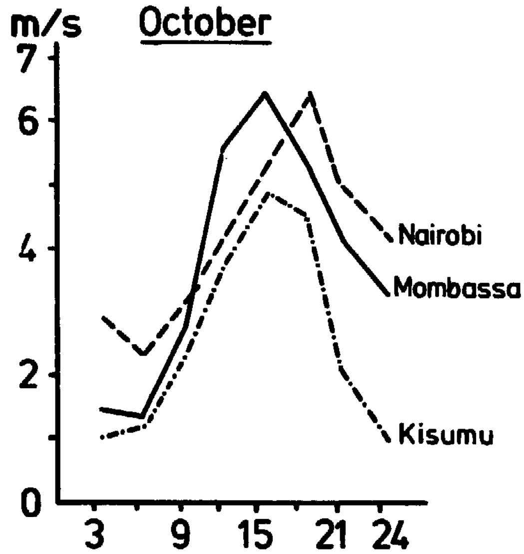


Fig. 2.2.

Daily wind pattern Jakarta, Indonesia (average 1944, 1952, 1955).
In this month the windmill output may be expected during the morning hours. In general the windmill will not run at night.

Fig. 2.3.

Daily wind pattern at 3 places in Kenya (average 1954 - 1959). In this month the windmill output may be expected during day time with a peak in the afternoon. At Nairobi and Mombassa a windmill will also run during the evening hours.

b. Annual windpattern

The annual distribution will give a first indication whether windmills will be able to supply irrigation water when it is needed, and which months will be critical in regard to sufficient water supply.

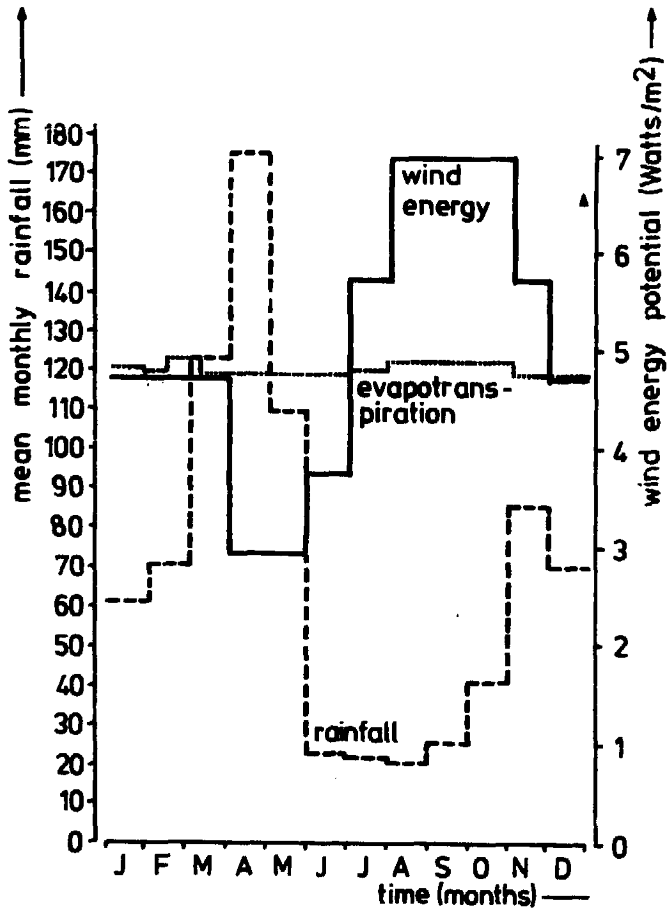


Fig. 2.4. Mean monthly rainfall, evaporation and wind energy potential at Musoma Airport, Tanzania. (Beurskens, 1978)
Note that the available windenergy is proportional to the amount of pumped water (for a given evaluation head).

c. Maximum windspeeds

A good impression of peak windspeeds (gusts) can only be obtained at places where constant windspeed recordings are made. These speeds are important for the design of the windmill (strength calculations) and the governing mechanism.
At places with regular low windspeeds and no gusts, a semi-automatic governing mechanism may be appropriate whereas a fully automatic governing mechanism will be required at places with strongly varying windspeeds.

d. Windspeed frequency distribution

This wind characteristic is an important one: the total amount of energy which can be extracted from the wind can be calculated from the windspeed frequency distribution and the mill characteristics.

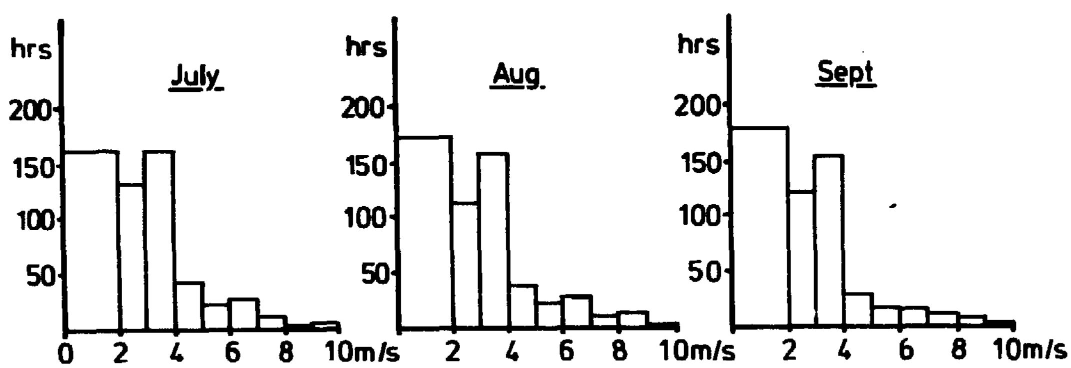


Fig. 2.5. Windspeed frequency distribution of Varanasi Airport (India) Average of 1975 - 1978

Montly intervals are usually chosen. For detailed analyses it is better to use the irrigation interval as the interval for analyses. However, in general the wind pattern does not vary much within a month, except sometimes in one in which the weather pattern changes (monsoon starts, rainy season ends etc.).
Very detailed analyses are often not realistic, due to the limited reliability of the data and the number of varying parameters.

Often hourly wind data are not available. However, with the help of average windspeed data over longer periods, (day, month) an impression can be obtained of wind energy potentials, using the following formula:

$$P = \frac{Vd}{\bar{V}} \; 0.1 \; V^3 \; A \; (W)$$

where P = power (W)
Vd = design windspeed of the selected windmill (m/s)
$\bar{V}$ = average windspeed over a certain period (m/s)
A = area swept by the rotor (m)

The coefficient 0.1 is in fact derived from $\frac{1}{2}.Cp.\eta_t.\rho_a.$, as presented in the formula on page 24.

The design windspeed is defined as the windspeed at which the energy conversion efficiency reaches its maximum.
For water-pumping windmills the design windspeed is generally around 3-4 m/sec. For more details about these technical aspects see references (van de Ven 1979, Lysen, 1980).

2.2.2. Windmill pump performance

The windmill pump performance presents the output of the windmill unit for different windspeeds at a given total elevation head.
The wind energy conversion formula was stated in the previous section as:

$$Po = Cp.(\eta_t.)\tfrac{1}{2}\rho_a .A.V^3 \ (W)$$

The general formula for the power requirements for water lifting is:

$$Po = \frac{\rho_w.g.H.Q \ (W)}{\eta_p}$$

Where: Po = Power (W)
η_p = efficiency of the pump
ρ_w = density of water (kg/m³)
g = gravitational constant (m/sec²)
H = total elavation head (m)
Q = discharge (m³/sec)

From both fomulae it can be concluded that the performance is related linearly with the square root of the windmill rotor diameter and reciprocally proportional to the total elevation head.

The total output over a certain period can be predicted from the windspeed frequency distribution over that period, provided that the windmill pump performance as well as the cut-in and cut-out windspeed are known
The cut-in windspeed, or starting windspeed, is in general around 3 m/s for water pumping mills, depending on load and starting torque.
The cut-out windspeed, or maximum windspeed (due to aspects of safety) is around 10 m/s. At this speed most water pumping mills are governed out of the wind.
It is obvious that only the windspeed frequency distribution figures between these 2 limits should be used for the performance calculations.

The windmill performance is difficult to assess accurately under field conditions and without complex measuring equipment. Moreover the figures presented in manufacturers manuals are often difficult to adjust to a local situation and sometimes are rather optimistic.
However, when the mill and the pump are well designed and well keyed to one another, there should not be much difference between the performances of the various makes, and these should all correlate with figures derived directly from the theoretical formulae.

Table 2.2. gives an indication of windmill performance for a windmill driving a piston pump with the following characteristics:
Cut-in: 3m/s, Vdesign: 3m/s; Cut-out. 10m/s. Those figures are derived from the theoretical formula, in which low efficiency factors based on the field test are used.

	Discharge, m^3/hr											
Total elevation head (m)	5			10			15			20		
Rotor diameter (m)	3.5	5.0	7.0	3.5	5.0	7.0	3.5	5.0	7.0	3.5	5.0	7.0
W 3-4	3.2	6.5	13.0	1.6	3.2	6.5	1.1	2.2	4.4	0.8	1.6	3.2
I 4-5	4.2	8.5	17.0	2.1	4.2	8.5	1.4	2.8	5.6	1.0	2.1	4.2
N 5-6	6.5	13.0	26.0	3.5	6.5	13.0	2.2	4.4	8.8	1.7	3.5	6.5
D 6-7	8.5	17.0	34.0	4.2	8.5	17.0	2.8	5.6	11.2	2.1	4.2	8.5
S 7-8	10.7	21.5	43.0	5.4	10.7	21.5	3.6	7.2	14.4	2.7	5.4	10.7
P 8-9	13.0	26.0	52.0	6.5	13.0	26.0	4.3	8.6	15.2	3.2	6.5	13.0
E 9-10	16.5	31.0	62.0	7.7	15.5	31.0	5.2	10.3	21.0	3.8	7.8	16.5
E												
D (m/s)												

Table 2.2. General windmill-pistonpump performance figures for different rotor diameters and different elavation heads. (Cut-in windspeed: 3m/s; Vdesign: 3m/s; Cut-out: 10 m/s).

2.2.3. Working efficiency

The theoretical output of a specific windmill-pump combination in a specific wind regime can be calculated as described in section 2.2.2. However, no machine will run for all the hours it can do in theory. Therefore a working-efficiency factor (η_w) has been introduced.

$$P_{max} = \eta_w . P_{theor}.$$

This efficiency depends on many factors but the main ones are management and time required for repairs and maintenance.
For the semi-automatic governed types of windmills, one additional factor has to be mentioned: the number of hours a windmill will be in secured position after the peak windspeeds ($\geq V_{max}$) have occurred. This depends on the wind regime (gustiness) and the accuracy of the operator. Such a loss has been estimated at 10%, based on practical data in a low wind regime (van Vilsteren 1979). The loss of working hours due to repair and maintenance will probably vary from 10-20%, depending upon the reliability of the windmill and the organization of the repair and maintenance service.

Note: The breakdown of the windmill pump system will generally occur at higher windspeeds, so that if 2-3 days lapses between breakdown and repair, the loss in total water output will then be considerable. If the service is centrally organized the delay is likely to be even greater as many windmills may need repair in periods of high windspeeds or storms.

To summarize, the value for working efficiency (η_w) can be estimated at 70-80%, with somewhat higher values for the fully automatic windmill systems.

If irrigation is not practiced on religious or public holidays and storage facilities are limited, the actual use made of the water pumped by the windmills will further be reduced.

2.3. Command area

The command area per windmill can be calculated by means of a water balance, the main elements of which have been discussed in the previous sections. Fig. 2.6. gives a graphical presentation of such a water balance; all figures are expressed in mm/ha.

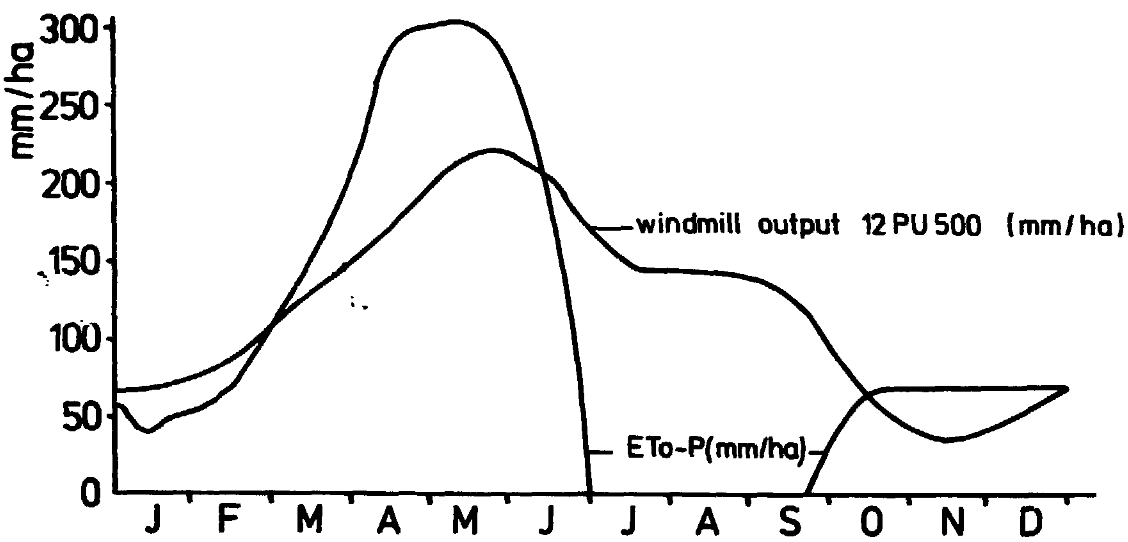


Fig. 2.6. Water balance of the Area around Ghazipur (North India) Expressed in mm/ha (1mm/ha = $10m^3$)

It can be seen that in this situation there was no need for irrigation in the period July-September (rainy season). From March till July and in November the windmill output was insufficient to meet the requirements of 1 ha.
In such a location it is still possible, by proper crop selection and crop plan adjustment, to supply sufficient water for 1 ha all year round. This is elaborated in section 2.3.1.
Not all the water pumped by the windmill unit will contribute to the water balance of the rootzone. Water will be lost in the canals and the field. Therefore an irrigation efficiency factor has to be introduced. This factor is considered in section 2.3.2.

As stated earlier, evapotranspiration, rainfall and windspeed are inter-correlated and are variable over the years. Therefore a simple probability analysis is introduced in section 2.3.3. to calculate the windmill command area.

2.3.1. Crop selection and crop plan adjustment

Crop selection is the selection of type of crops to be grown under irrigation.
Crop plan adjustment is the adjustment of the dates of sowing to allow that the crop water requirements during the growing period can be met by the windmill water output. Both are important, since they determine irrigation requirements.
The kc value in ETcrop = kc.ETo varies from crop to crop and depends on the growing phase of the crop (see table 2.1.).
e.g. Rice in the crop development stage: kc = 1.1. - 1.5.
Groundnut in the crop development stage: kc = 0.7 - 0.8.
Ripening wheat: kc = 0.2 - 0.25.
Germinating cotton: kc = 0.4 - 0.5.

The selection of crops for a windmill irrigation scheme is not unlimited. The following aspects have to be considered with regard to crop selection and crop plan adjustments.

a. wishes of the participating farmer(s)
b. ecological aspects
c. inputs and outputs
d. socio-ecnomic aspects.

a. Wishes of the participating farmers

The farmers certainly have ideas about what to grow when irrigation becomes available. Whether it is foodcrops for themselves and their cattle, or crops for the market, farmers' involvement is essential for the success of the project!
In Chapter 4 this will be discussed in more detail.

b. Ecological aspects

The climate and the soil type determine in general which crops can be grown in a certain area.
Many books about tropical crops give the ecological conditions for optimal growth as well as the soil type in which the crop flourishes best (Pursglove 1969).
The main ecological factors are: minimum and maximum temperatures, daylength, light intensity, humidity.
Main aspects of the soil type are: depth of the topsoil, texture and structure of the soil, salinity and natural fertility.

In many places more than one crop can be found in the same field. If several crops are grown in the same field without any specific order (e.g. mustard and wheat, maize with soja or groundnut), this is called mixed cropping.
With this cropping system optimal use can be made of the comparative advantages of each crop: shading, windbreak, difference in rooting depth and intensity.
In areas with a high light intensity and an adequate water supply, mixed cropping may be more advantageous than single cropping. Risk minimization is another important aspect for small and marginal farmers.

If one crop is planted in between the rows of another crop it is called intercropping (onions or black grain between young sugar cane, cotton sown between the ripening corns, etc.)
Intercropping is done to optimize the use of the land, make optimal use of the rainy period or to let one crop protect the other (shading, windbreak, winderosion).
Both mixed cropping and intercropping have their specific irrigation requirements in regard to interval, depth and efficiency.

The soil fertility and the soil structure should remain constant or be improved by the intended crop plan, by cultural practices and/or by fertilizers and manure.
Soil health can be influenced by crop sequence and crop rotation.
e.g.
- some pulse crops fixate nitrogen in the soil
- deep rooting crops will improve soil permeability and drainage capacity
- green manure crops and crops with large crop residues will improve the organic matter content of the topsoil and consequently, the infiltration rate and water-holding capacity of the topsoil.

If the project area contains slightly saline or alkanine soils or if the irrigation water is slightly saline or alkaline, crop species which are tolerant to these phenomena have to be selected. In addition, attention has to be given to drainage and leaching, to improve the soil condition. (Unesco/FAO 1973).
A table with figures about the relative tolerance of crops to salt is given in Annex II.

c. Inputs and outputs

Once a certain crop plan has been designed, strict attention should be given to the availability of all the required inputs. Good quality seed, fertilizers, and, if required pesticides should be available in time in the project area, as well as sprayers, dusters and threshers if necessary. The availability of labour for land preparation, planting, tillage and harvesting is a particularly important aspect of crop plan designing, since labour availability is difficult to forecast and lack of it may seriously influence the adoption of the new crop plan and its ecnomic results.

e.g. - labour shortage can occur due to: an existing crop plan in the region (paddy cultivation, cotton picking); migration to towns; social and cultural activities (marriage season, religious restrictions, etc.); the climate (during the hot period of the year there is often a high leisure preference).

These aspects also have to be investigated with regard to the outputs: the main products and the by-products.
Are marketing facilities as well as processing facilities available either at the farm or centrally?

e.g. - fresh fruits and vegetables have to be transported to the market directly after harvesting
- is sufficient transport available and what is the condition of the roads. Are there proper packing facilities so that fruit will not be damaged during transportation?

If a crop plan is to succeed, other facilities will be necessary in addition to the physical ones.
Apart from subsidy and credit facilities for financing the windmill pump system, small farmers may need crop loans to finance the inputs. If new crops or different cropping systems and tillage methods are introduced, a well organized agricultural extension service will be needed.
Cooperation among farmers may be needed to make full use of the windmill pumpsystem or the other farm implements such as ploughs, sprayers, dusters, harvesting and processing machines.
Cooperatives may have to be set up to organize the supply of inputs or the selling and/or processing of outputs.

d. Socio-economic aspects

The important socio-economic aspects of crop selection and crop plan adjustments are discussed in Chapter 4.

Local information can be obtained by surveying the project area and visiting local agricultural institutions (extension services, agricultural research stations and testing and demonstration farms). In general it is recommended only to introduce a few new crops at a time, while continuing to use the crops known to the target group. Introducing too many new items at a time may lead to slow adoption or failure of the project.

2.3.2. Irrigation efficiency

Not all the water pumped by a windmill will be come available to the plants in the field. Firstly seepage and evaporation losses will occur in the storage tank and the conveyance system. Special attention should be given to the seepage of the tank back to the watersource. Since the tank usually lies close to the well stream or lake, pollution and erosion may occur, damaging both the watersource and the foundation of the windmill. Seepage losses from unlined tanks and channels vary with the soil type and the means of construction (degree of compaction) and may range from 5 to 50% of the total amount pumped by the irrigation device.
Secondly, irrigation water can be lost due to run-off from the field, specially when border and furrow irrigation methods are applied. These losses can be minimized by training and motivating the operators.
Thirdly incorrect levelling and dishomogeneity of the soil may cause irrigation water to percolate beyond the reach of the plant roots. Deep percolation can partly be avoided by cultural activities (e.g. levelling). Losses can also be avoided by applying less water at a time: scarcity irrigation, deficit irrigation (see fig. 2.7).

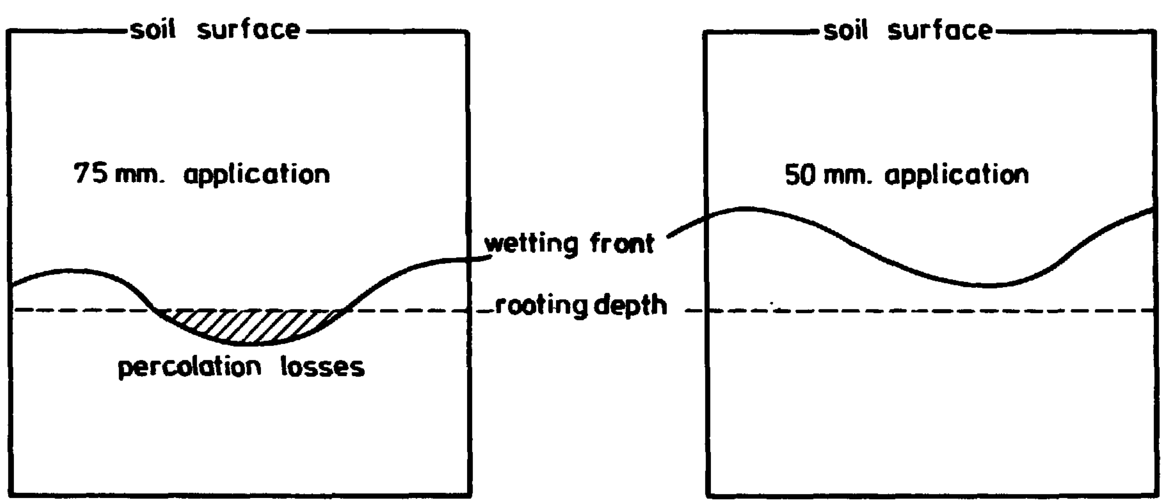


Fig. 2.7. Complete recharge of soil- moisture (left) compared with partial recharge (right) (= deficit irrigation)

Advantages of this deficit irrigation are an increased irrigation efficiency and rainfall just after the irrigation will not be lost. Disadvantages, are: shortening of the irrigation interval, probably lesser root development and slightly higher average evapotranspiration.

High losses will not only endanger the viability of the irrigation but will lead to a rise of the groundwater table and increased risk of salinization or alkaninization. In the later case, a drainage system will be needed, which again increases the cost of the system.

Windmill irrigation, with its relatively low output, is especially sensitive to irrigation efficiency. Therefore, strict attention should be given to tank and channel design, as well as to the choice of irrigation method, land preparation and training of operators.
Aspects which have a negative influence on the windmill irrigation efficiency are the relatively small discharge rates and the fact that the cost of the water pumped by the windmill is nil in the eyes of the operator (Windmills deliver water free of (variable) costs). This may affect the degree of attention that is given to irrigation.
The total irrigation efficiency will depend on many of the factors described above and will therefore vary from place to place between approximately 75-30%. This means that where the net irrigation requirement is 100 mm, the gross water requirement vary from 100/0.75 = 133 mm to 100/0.30 = 333 mm.
It will be clear that improving the irrigation efficiency may be more effective and economical than increasing the pumping capacity.

Small windmill irrigation systems with direct farmers involvement, will lead to higher irrigation efficiencies than those quoted in literature (Hagen, Nugteren, Stern).
Especially if farmers already have some experience in water management, soils are relatively heavy and the proper irrigation method is chosen, irrigation efficiencies between 60-70% are realistic.

2.3.3. Probability analyses

Probability analyses of meteo data provide indications of the chance of occurrence of wind phenomena.
In agricultural engineering, a probability of 75% or 80% is often considered to be sufficient for planning purposes.
If an irrigation system is designed with 75% probability, it means that in 3 out of 4 years the capacity will be sufficient to meet the irrigation requirements.

A simple probability analysis is as follows:
- Arrange the data in ascending sequence.
- Give each data a rank number.
- The probability of occurrence can be calculated with the following formula.

$$f_i = \left(\frac{i}{n+1}\right) \times 100\ (\%)$$

where: f_i = probability of occurence (%)
i = rank no. in ascending sequence of the data
n = total number of data

example: 15 data in ascending sequence: (e.g. evaporation in the month January for 15 years)
63, 69, 71, 71, 73, 76, 78, 78, 82, 86, 93, 93, 96, 96, 99 mm/month

rank no: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Applying the formula gives:

$$f_1 = \frac{1}{15 + 1} \cdot 100 = 6.25\%$$

$$f_4 = \frac{4}{15 + 1} \cdot 100 = 25\%$$

In this case rank no. 4 represents the data (71 mm) which will be surpassed in 100-25 = 75% of the years.
In other words: in 3 out of 4 years the monthly evaporation will exceed 71 mm/month.

It will be clear that these calculation can only be made if reliable date are available from a number of years (at least 10).
If data of more years are available the accuracy of the probability analyses will increase.
For windmill irrigation, there are three important variables (rain, evapotranspiration and wind) which are not independent of each other. Therefore the probability of each of them is not discussed, but their combination as expressed in the water balance of the rootzone (Stol 1973).

In Annex III a calculation example is presented for a growing season (March-June), using meteo data of 15 years, in which:

- Only the effective precipitation is taken into account (Pe) (see section 2.1.2).
- The wind data are converted into water output per month (see section 2.2.2.).
- An irrigation efficiency factor is introduced to estimate the effective irrigation (Ie) (see section 2.3.2.).
- The evapotranspiration is introduced in 2 steps:
  - firstly using ETo, to find the critical periods with regard to the irrigation needs
  - secondly using ETcrop, (=kc.ETo) after selection of crops and sowing dates.

  If required, part of the irrigation water should be made available for leaching, ponding of paddy fields, pre-irrigation etc.

The command area for each month can be found by using the following formula:

$$\text{Command area} = \frac{\text{ETcrop-Pe}}{\text{Ie}} \quad \text{(ha)}$$

Where: ETcrop = crop evapotranspiration (mm/month)
Pe = effective precipitation (mm/month)
Ie = effective irrigation (mm/month/ha)

If, after the introduction of a crop plan, the calculations show another criticical period, a third round of calculations may be needed, with a modified crop plan, etc.

If the area which can be irrigated by a specific windmill, does not meet expectations, the diameter of the windmill can be altered.
By changing the rotor diameter by $\sqrt{2}$ D, the power output will be doubled and consequently also the (theoretical) command area. Of course all aspects have now to be reconsidered (technical, capacity of the water source, economics, etc..)
It should be noted that predictions are made for the future on the basis of meteorological data from the past (these predictions will only be valid for the future if the climate can be considered stable).
An increase in the period of analysis increases the reliability of these predictions.

2.4. Water resources

In Chapter 1, water resources are discussed with regard to their suitability for windmill irrigation (openness, etc.).
Here it is again emphasised that the water quality (salinity, alkanlinity) is also a decisive factor in irrigation (Unesco, FAO, 1973).
Accurate water analyses are most essential in any irrigation study (see table 2.3.).

Quality of water	crops suited	conductivity micromhos/cm	TDS * mg/l	Boron ppm
good	all crops	50- 500	0- 600	0 -0,5
moderate	injurious to sensitive crops	500-2200	600-2000	0,5-2
poor to unsuitable	harmful to most crops	over 2200	over 2200	over 2

*) TDS = Total dissolved solids

Table 2.3: Standards of irrigation water (Stern, 1979)

Existing water rights are another important aspect. It should be investigated whether additional water withdrawal can be allowed and will be justified and accepted by the other users.

e.g.
- A small spring in Southern Java, Indonesia can be used for lift irrigation by a windmill near the spring. However, downstream this water is already being used for gravitational irrigation.
- Small wells in Northern India are used by all the surrounding farmers for bullock irrigation. In one farmer wants to install a windmill, sufficient place and capacity should be left for the other farmers to supply their fields with water by other means from the same well.

The capacity of the water source must be taken into consideration. Especially during the peak irrigation period, sufficient water should be available. A lake and a river might only change their waterlevels during the year, but their capacity will often not be a limiting factor. Attention must be given to the waterlevel fluctuation for the output calculations as well as for the depth of installation of the pump.
Careful attention should also be paid to the foundation of the windmill near the shore of a lake or river.
Small streams may need a small storage (dam) to meet the peak pump capacity of the windmill during the day.
If dams are needed to store the water for longer periods (some months) it is questionable whether this can be organized and financed by small or marginal farmers. However, dams that are only meant for storing a small amount of water to meet the fluctuating demand of a windmill pump system per day do not have to be large or costly. Nevertheless, the main potential for windmills are the areas where shallow groundwater can be tapped for irrigation. Of course, here too the capacity of the aquifers and the recharge of the groundwater have to be investigated as well as water rights, etc.

With groundwater irrigation, windmills can be placed at the point where the water is required, so costs for conveyance systems and conveyance water losses can be limited. In many areas wells exist already, so the total investment for the farmer will be lower. If the capacity of the open well is insufficient, a tube well may be needed to tap deep aquifers.

At places with deep water tables the pump can be placed either at the bottom of the open well or in the tube-well itself. The water table should not drop more than 6 to 7 metres below the bottom of the pump during pumping. The capacity of the well at that depth has to be sufficient to meet the capacity of the windmill pump-system.
For output predictions it is important to know how far the water table will drop during pumping. It is difficult however, to give a general rule for this, since the amount by which the water table drops at certain discharges rates can only be determined by pump tests.

The windmill pump system will work at different efficiencies in accordance with variations in elevation head and windspeed.
If the windspeed increases, the output increases and consequently the waterlevel in the well may drop. Due to this lowering of the watertable (i.e. increase in windmill-load) the output will fall and finally equilibrium will be reached. In general the performance efficiency of a windmill diminishes at increasing windspeeds and constant workload. In this case however (increasing workload at increasing windspeed) the overall efficiency will diminish less or not at all.
So far preliminary windmill output predictions, it may be a sound assumption to use the elevation head which corresponds with Vd (design windspeed) for all windspeed intervals, since the decrease in water table (linear) will be easily compensated by the increase in available power (cubic) at increasing windspeeds. If windmill and well characteristics are known in detail, more accurate output predictions are possible.

3. IRRIGATION PRACTICE

Windmill irrigation is very small scale irrigation with command areas up to 5 ha per unit. Therefore no attention is paid to irrigation methods, or irrigation organization and management. These activities take place at farm level and can be managed by the farmer, or group of farmers, if properly advised. (For references see: Stern, Hagen and F.A.O.).
The only recommendation that is again stressed here is not to introduce too many new items at a time. If possible, windmill irrigation should fit in with irrigation practices that are already known in the area.

In this chapter the aspects of irrigation with a variable power source (wind) are discussed. The effects of delayed irrigation due to windless periods are summarized and methods are given to limit the vulnerability of the farming system due to this variability.

A method is presented for the calculation of the irrigation interval and ways of extending this interval are described. The relation between crop water use and crop production is discussed as well as the influence of other inputs on the crop production.
Pre-irrigation and the introduction of drought resistant crops can also improve the application of the wind pumped water. The function of a small storage tank is also dealt with. A summary concludes the chapter.

In this chapter we use two different symbols for ETcrop:

1. ETm: maximum crop evapotranspiration without limits in regard to water and other inputs.
2. ETa: actual crop evapotranspiration under the given conditions ($ETa \leq ETm$).

3.1. Irrigation interval

The irrigation interval (IN) is defined as the period between two successive irrigations. The length of this period depends on:

- Available moisture in the soil : A.M. (mm/m)
- Rooting depth of the crop : D(m)
- The evapotranspiration rate : ETm (mm/day)

The amount of available moisture in the soil depends strongly on the type of soil, as can be seen in Table 3.1.

Available Moisture at Field Capacity*			
Soil type	Dry density (gr/cm^3)	Available water	
		%	mm/m
Fine sand	1.60 - 1.76	2 - 3	30 - 50
Sandy loam	1.28 - 1.68	3 - 6	40 - 100
Silt loam	1.10 - 1.50	6 - 8	60 - 120
Clay loam	1.10 - 1.50	8 - 14	90 - 210
Clay	1.44 - 1.54	13 - 20	190 - 300

* Field capacity: situation, 2-3 days after abundant irrigation or rainfall.

Table 3.1: Available moisture of different soil types (Stern, 1979, page 85).

The rooting depth differs for different types of plants. Roots develop from zero at the moment of sowing until the typical final depth at full growth, provided the soil and moisture conditions are not restricting. Table 3.2. provides a guideline for rooting depth under optimal soil and water conditions.

Rooting depths at full growth (m)					
Shallow		Medium		Deep	
Beans	0.5-0.7	Grains	0.9-1.5	Alfalfa	1.0-2.0
Cabbage	0.4-0.5	Clover	0.6-0.9	Cotton	1.0-1.7
Grass	0.4-0.6	Eggplant	0.9-1.2	Orchards	1.0-2.0
Onions	0.3-0.5	Peas	0.6-1.0	Maize	1.0-2.0
Potatoes	0.4-0.6	Tomatoes	1.0-1.5	Sorghum	1.0-2.0
Rice	0.5-0.7	Watermelons	1.0-1.5	Sugarcane	1.0-2.0

Table 3.2: Guidelines for rooting depths under optimal conditions (FAO, no. 24, table 39).

Note: It is recommended to inquire about the soil characteristics and crop rooting depths at a Agricultural Research Station in the region.

If the crop evapotranspiration is also known (ETm = kc.ETo, see section 2.1.1) the irrigation interval can be calculated with the following formula:

$$IN = \frac{AM \times D}{ETm} \text{ (days)}$$

example: beans in the crop development stage at a clay loam soil, with:

AM = 120 mm/m (table 3.1)
D = 0.6 m (table 3.2)
ETo = 8 mm/day
ETm = kc.ETo: kc=0.8 (table 2.1) ETm = 6.4 mm/day.

thus: $$IN = \frac{120 \times 0.6}{6.4} = 11 \text{ days}$$

Different crops have different rooting intensities and different capacities to withdraw water from the soil, which holds the water with increasing tenacity during depletion. So not all the available water in the soil will be easily available to the plants. The part of the available moisture which can be depleted without causing reduction in the crop evapotranspiration is represented by the fraction p.
This p-fraction depends on the following variables:

1. type of plant
2. magnitude of ETm
3. type of soil.

Based on physical characteristics of plants with regard to rooting intensities and resistance values for waterflow in the plants, four different crop groups are distinguished. These are presented in Table 3.3. The crops have an increasing capacity (starting from crop group 1) to withdraw water from the soil; so the p-fraction of instantly available moisture increases from crop group 1 upwards to 4.

Group	Crops
1	onion, pepper, potato
2	banana, cabbage, grape, pea, tomato
3	alfalfa, bean, citrus, groundnut, pineapple, sunflower, watermelon, wheat
4	cotton, maize, olive, safflower, sorghum, soybean, sugarbeet, sugarcane, tobacco

Table 3.3: Division of crops in four groups with increasing capacity to withdraw water from the soil (FAO, 1979).

The magnitude of ETm also influences the fraction p.
This is caused by the resistance for waterflow to the roots and through the plant. The higher ETm the larger the flow and the higher the resistance and so the earlier the point will be reached at which the ETa will fall below ETm.
So even with a relatively wet soil, evapotranspiration may be below potentional evapotranspiration (e.g. sugarbeets wilt in the middle of the day due to high ETm. In the evening, the wilting is over due to decrease of ETm).

The fraction p of instantly available soil water, in which ETa is equal to ETm, varies with the level of ETm as is shown by table 3.4 (FAO, 1979).

Crop Group	ETm mm/day								
	2	3	4	5	6	7	8	9	10
1	0.50	0.425	0.35	0.30	0.25	0.225	0.20	0.20	0.175
2	0.675	0.575	0.475	0.40	0.35	0.325	0.275	0.25	0.225
3	0.80	0.70	0.60	0.50	0.45	0.425	0.375	0.35	0.30
4	0.875	0.80	0.70	0.60	0.55	0.50	0.45	0.425	0.40

table 3.4: The instantly availably moisture fraction (p) for four different crop groups at different levels of ETm (FAO, 1979).

Soil water is more easily transmitted to and taken up by the plant roots in light textured soils than in heavy ones. Somewhat higher values of p would seem to apply to light textured soils than to heavy textured soils. Consideration of soil texture would add little to the accuracy and therefore is not given further attention here.

The irrigation interval in which ETa = ETm can be determined according to:

$$IN = \frac{AM \times D \times p}{ETm}$$

where:
- IN = irrigation interval (days)
- AM = available moisture (mm/m)
- D = rooting depth (m)
- p = instantly available moisture fraction
- ETm = crop evapotranspiration (mm/day)

Example: The same beans as in the previous example in this section:
- AM = 120 mm/m; D = 0.6 m;
- ETo = 8 mm/day; kc = 0.8 ETm = 6.4 mm/day
- p = 0.44 (beans belong to crop group 3 (table 3.3/3.4)
- IN = $\frac{120 \times 0.6 \times 0.44}{6.4}$ = 5 days

3.2 Variability of irrigation interval

The determination of the irrigation interval as presented in the previous section is based on average meteorological data. However ETo and consequently the p-fraction vary from day to day.
Here consideration is given to the influence of decreasing windspeed on the length of the irrigation interval.

In practice, the question is how many days can irrigation be delayed at periods of low windmill output, without seriously hampering crop development.

As mentioned in section 2.1.1, windspeed influences the reference evapotranspiration (ETo). In Annex I-A this effect has been calculated for three different temperatures, windspeeds and relative humidities, keeping all other factors constant. Fig. 3.1 is derived from that calculation and shows the influence of the relative windspeed ($V/\overline{V}$) on relative evapotranspiration ($ETo/\overline{ETo}$).

e.g. If the windspeed decreases by 50% ($V/\overline{V}$ = 0.5), evapotranspiration decreases to 82% of $\overline{ETo}$ ($ETo/\overline{ETo}$ = 0.82), if the relative humidity is 30%.

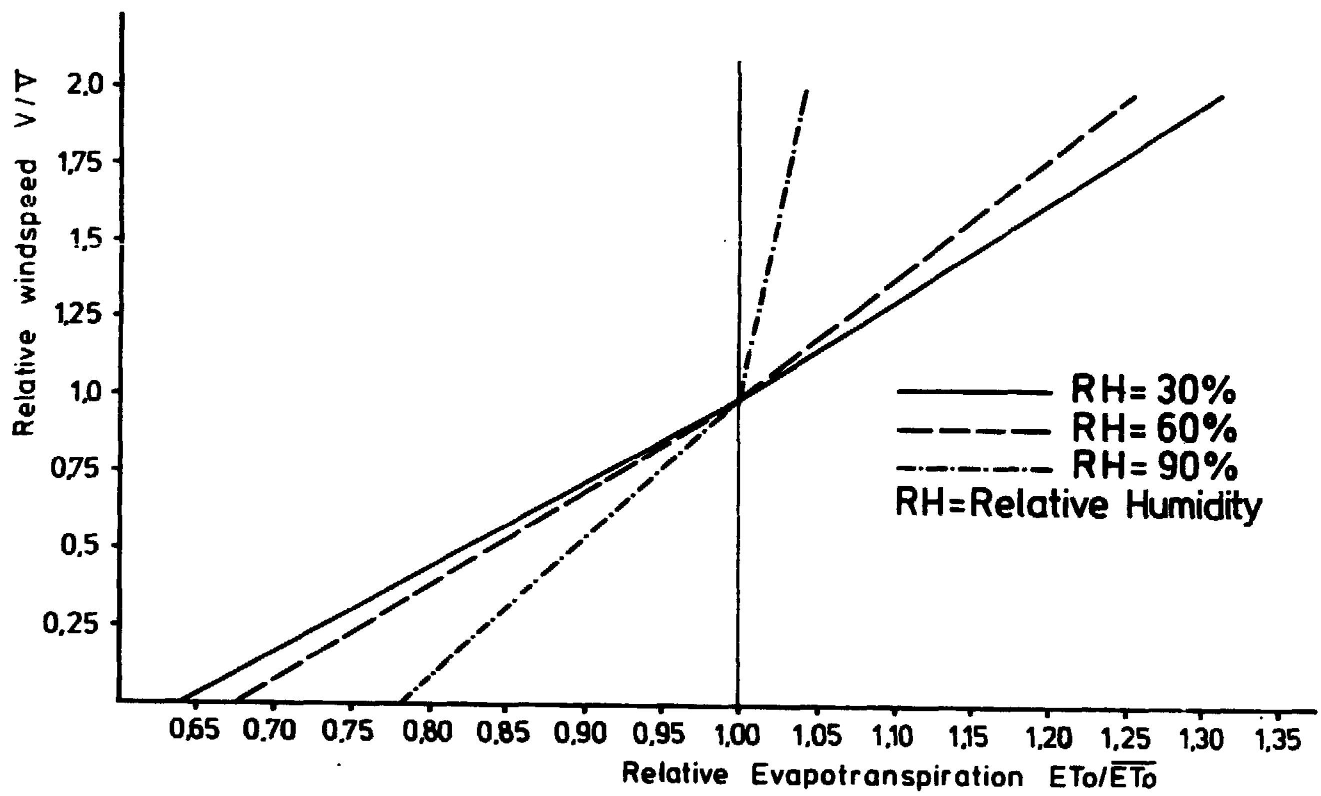


Fig. 3.1. Influence of relative windspeed on relative evapotranspiration (derived from the penman formula, with a lineair function for the aerodynamic component)

From figure 3.1 it can also be seen that windspeeds above $\bar{V}$ have less influence on the ETo than do windspeeds below $\bar{V}$. This, combined with the fact (section 2.2.1), that the windmill output increases more than linearly with increasing windspeeds, may lead us to the conclusion that high windspeeds during the irrigation interval will not shorten the length of that interval.

Since the main interest is on the number of days (d) that irrigation can be delayed the aspects considered here are the decrease of ETo in such a situation and consequently the increase in irrigation interval IN.
The procentual decrease in average daily windspeed before the daily windmill output fall to zero, depends on the daily windspeed distribution (see section 2.2.1). In general a decrease in the average daily windspeed will lead to a more than proportional decrease in windmill output, or even no output at all.

example: 24hr average windspeed: 3 m/s

			Windmill output*
Windspeed distribution:	night:	12 hr x 2m/s	-----
	morning:	6 hr x 3m/s	6 x 3.2 m^3
	afternoon:	6 hr x 5m/s	6 x 6.5 m^3

24hr average windspeed: 1.5 m/sec (reduction 50%)

Wind speed distribution I:			
	night:	12 hr x 0.5m/s	----
	morning:	6 hr x 2 m/s	----
	afternoon:	6 hr x 3 m/s	6 x 3.2 m^3

Output reduction: ± 70%

Windspeed distribution II:	night	12 hr x 1m/s	----
	day	12 hr x 2m/s	----

Output reduction: no output at all.

With a decrease of 50% in 24hr average windspeed, ETo will decrease to ± 83% of ETo (RH between 30 and 60%; RH of 90% is not realistic for areas in need of irrigation).

*) Windmill output: see Table 2.2 (Rotordia 5 m, elevation head 10 m).

The kc-factor is also influenced by wind and humidity, as can be seen in Table 2.1. In general it can be concluded that the kc-values decrease by ± 10% if the windspeed decreases to 50% of the 24hr average windspeed. Since ETm = kc.ETo, ETm will reduce up to 90% of ± 83% or ± 75% of $\overline{ETm}$. For further calculation examples we will use the figure of 75% of $\overline{ETm}$.

The soil moisture fraction (p) which can be depleted before irrigation will be required, is closely related to ET_m as can be seen in Table 3.4.

Crop Group	ET_m mm/day								
	2	3	4	5	6	7	8	9	10
1	0.50	0.425	0.35	0.30	0.25	0.225	0.20	0.20	0.175
2	0.675	0.575	0.475	0.40	0.35	0.325	0.275	0.25	0.225
3	0.80	0.70	0.60	0.50	0.45	0.425	0.375	0.35	0.30
4	0.875	0.80	0.70	0.60	0.55	0.50	0.45	0.425	0.40

Table 3.4: The instantly available moisture fraction p, at different ETm levels for four different crop groups (FAO, 1979).

So a decreasing ET_m due to lower windspeeds will result in an increasing soil moisture fraction p, which will be instantly available for evapotranspiration. Filling in these new data in the formula for the irrigation interval, will give an indication about the possible delay (d) which can be allowed before ETa will fall below its optimal value (ETm).

Example:
Continuation of the previous example with the beans. Given:
AM = 120 mm/m; D = 0.6 m; ETm = 6.4 mm; p = 0.44; I = 5 days.
Suppose the 5th day is a windless day, so there will be no irrigation water available for plot p1, which was scheduled for the end of that day.
Due to this windless day, ETm will decrease to, say 75% of $\overline{ETm}$ or 4.8 mm and consequently p will become 0.52 (see Table 3.4). The additional amount of available moisture will be: 120 x 0.6 x (0.52 - 0.44) = 5.8 mm. From the 5th day another 6.4 mm is still available. So the <u>extension</u> of the irrigation interval (d) will be now:

$$\left(\frac{(1 \times 6.4) + 5.8}{4.8}\right) - 1 = 1.5 \text{ day}$$

This means that even another 1½ windless day will not cause a decrease of ETa below its optimal level ETm.
However, before this plot p1 can be irrigated it will have to be a windy day so that the windmill runs. At that time ETm will increase and then the cropwater requirements cannot be met for 100%. Still this need not be very harmful for crop development and crop production, if it is a short period (see section 3.3).
For plots p2 and p3 which are scheduled for irrigation on days d1 and d2 respectively an even longer delay of the irrigation is possible, due to the reduction of the ETm value.

Example: continuation of previous example with the beans.

Plot p2: $$\left(\frac{(2 \times 6.4) + 5.8}{4.8}\right) - 2 = 1.9 \text{ days delay allowable}$$

Plot p4: $$\left(\frac{(4 \times 6.4) + 5.8}{4.8}\right) - 4 = 2.5 \text{ days delay allowable}$$

Plot p5: $$\left(\frac{(5 \times 6.9) + 5.8}{4.8}\right) - 5 = 2.9 \text{ days delay allowable}$$

Table 3.5 gives the possible delay period in days (d) which can be allowed during a windless period without hampering crop production. The same method of calculation has been applied as in the previous example, using Table 3.4 and a crop evapotranspiration reduction of 25%. The general formula is as follows:

$$d = \frac{\overline{ETm}.t + TAM\ (p1 - p2)}{x\ \overline{ETm}} - t$$

rewritten: $d = \left(\frac{P1-P2}{x\ \overline{ETm}}\right).TA; + t\ \left(\frac{1}{x} - 1\right)$

where:

d	:	possible delay of irrigation (days)
$\overline{ETm}$	:	average daily crop evapotranspiration (mm/day)
TAM	:	Total Available Moisture in the soil (A.M. x D) (mm)
p1	:	p-value corresponding to $\overline{ETm}$ (see table 3.4)
p2	:	p-value corresponding to $\overline{ETm}$ (see table 3.4)
t	:	number of days before the end of the planned irrigation interval (d)
x	:	reduction factor of $\overline{ETm}$, depending on the magnitude of the windfunction in the evapotranspiration formula and the reduction in the kc value due to declined wind speed.

crop group	$\overline{ET_m}$ expressed in mm/day																				
		4 mm/day				5 mm/day				6 mm/day				7 mm/day				8 mm/day			
	TAM (mm)	50	100	200	400	50	100	200	400	50	100	200	400	50	100	200	400	50	100	200	400
	1	2	3	5	10	2	3	6	12	1	2	4	7	1	1	3	5	1	1	2	4
	2	2	4	7	14	2	3	6	12	1	2	4	8	1	1	3	5	1	1	3	5
	3	2	4	7	14	2	4	7	14	1	2	5	9	1	1	3	5	1	1	3	5
	4	2	4	7	14	2	4	7	14	1	2	5	9	1	2	4	7	1	2	4	7

Table 3.5: The number of days irrigation can be delayed, depending on the average level of crop evapotranspiration ($\overline{ETm}$) and the soil moisture storage capacity (TAM) for the four groups of crops, if 24hr average windspeed decreases by 50% (x = 0.75).

Without taking the figures of Table 3.5 as absolute figures, it can be concluded from this table that increasing the soil moisture storage capacity (TAM) will lead to an increase in possible delay of irrigation. The same can be said with regard to the crop groups. Crop group 4 will be less hampered by windless periods than crop group 1.
The TAM can be influenced by choosing deep rooting crops. A derived advantage of a deep rooting zone is a long irrigation interval and consequently the increased manipulation possibilities with regard to the moment of irrigation: optimalization of the storage function of the soil.

The figures given above can be used in the crop selection in order to realize optimal water use even under highly variable wind conditions.

3.3. Relation between evapotranspiration and crop production

Until now all efforts have been made to ensure that the actual evapotranspiration of a crop (ETa) equals the potential crop evapotranspiration (ETm), because it is known that under limited evapotranspiration, (partial) closure of stomata will take place. This not only reduces the waterlosses but also limits the uptake of carbondioxide (CO_2) and consequently the ultimate production (Vink, 1980, FAO 1979).
The effect of reduced evapotranspiration on total yield is considered and the yield response factor k_y introduced in this section.
High k_y-values mean: high sensitivity to water shortage, low k_y-values mean: low sensitivity to water shortage.
The yiels response factor k_y quantifies the relation between relative yield decrease and relative evapotranspiration deficit as follows:

$$(1 - \frac{Ya}{Yp}) = k_y \, (1 \; \frac{ETa}{ETm})$$

Ya = actual production (kg/ha)
Yp = potential production (kg/ha)

This effect may either occur over the total growing period or over one of the different growth phases. For irrigation practice it is essential to know at what periods high k_y-factors occur, so that in cases of scarcity, priority can be given on the basis of this factor. It should be kept in mind, however, that the above mentioned linear relation only holds for water deficits up to 50%. Attention should therefore be given to the question whether supplying all the water to the crop with the highest k_y-value will produce optimal results, or if some of it must go to the other crops.

For irrigation planning it is essential to know which crops will have high k_y-values and which low ones.
By introducing crops with high- and low k_y-values together in the crop plan, more margin is provided in varying the irrigation interval.
Introducing only crops with low k_y-values may be optimal in regard to risk minimization in crop production, but will not automatically lead to the optimal economic solution. In general there will be a relation between crop sensitivity to production risks (water shortage, pests, soil quality etc.) and market prices.

In irrigation planning it is essential to avoid two or more crops reaching their k_y-sensitive period at the same time. Especially in windmill irrigation planning with its variable daily output, and the possibility of shortage of irrigation water during a number of consecutive days, this aspect deserves attention.

It will be clear that, if possible, none of the crops grown should reach the k_y-sensitive stage during the critical month for windmill irrigation. Or that only one of that type of crops covers only a relative small area, so priority can be given to that crop during shortage.
Table 3.6 gives the k_y-values for different crops during different growing phases.

Crop	Vegetative periode (1)			Flowering period (2)	Yield formation (3)	Ripening (4)	Total growing period
	early (1a)	late (1b)	total				
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.4	1.5	0.5	0.2	1.25
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1
Potato	0.45	0.8			0.7	0.2	1.1
Safflower		0.3		0.55	0.6		0.8
Sorghum			0.2	0.55	0.45	0.2	0.9
Soybean			0.2	0.8	1.0		0.85
Sugarbeet							
beet							0.6-1.0
sugar							0.7-1.1
Sugarcane			0.75		0.5	0.1	1.2
Sunflower	0.25	0.5		1.0	0.8		0.95
Tobacco	0.2	1.0			0.5		0.9
Tomato			0.4	1.1	0.8	0.4	1.05
Water melon	0.45	0.7		0.8	0.8	0.3	1.1
Wheat							
winter			0.2	0.6	0.5		1.0
spring			0.2	0.65	0.55		1.15

Table 3.6: k_y values for different crops in different growing phases (FAO 1979).

Calculation example:
Three crops occupying equal areas and in the following growing phases, see table 3.6.

	Maize gr. phase 2.	Soyabean gr. phase 1.	Tomato gr. phase 3.
k_y factors	1.5	0.2	0.8
ETm mm/month (arbitrary)	250	150	200

Total net required amount of irrigation water: 250 + 150 + 200 = 600 mm.
Suppose available: 500 mm and same economic values for all 3 products (yield in kg x price per kg is equal), so average yield reduction will be the decisive factor. Thus ETa will be ETm - 33 mm for each crop.
Equal distribution of the deficit will give the following yield reduction:

Maize	Soya	Tomato
$1 - Ya/Yp = 1.5(1 - \frac{217}{250})$	$1 - Ya/Yp = 0.2(1 - \frac{117}{150})$	$1 - Ya/Yp = 0.8(1 - \frac{167}{200})$
Ya = 80% Yp	Ya = 96% Yp	Ya = 87% Yp

Ya average over the 3 crops is: $\frac{80 + 96 + 87}{3}$ = 88% of Yp

Due to the low k_y value of soya, it is preferable for the soya to bear the main part of the deficit. This can be done only upto 50 mm (arbitrary) otherwise the soya will be damaged too much. The rest of the deficit will be borne by the tomato crop (lower k_y than maize).

Maize	Soya	Tomato
	$1 - Ya/Yp = 0.2(1 - \frac{150}{100})$	$1 - Ya/Yp = 0.8(1 - \frac{150}{200})$
Ya = 100% Yp	Ya = 91% Yp	Ya = 80% Yp

Ya average is now: $\frac{100 + 91 + 80}{3}$ = 91% of Yp

However, in the case than the economic value of tomato is 3x the economic value of maize and soya, production loss will be more severe if incurred on tomatoes instead of maize, despite the maize high k_y-value. Then the deficit should be divided between maize and soya:

Maize	Soya	Tomato
$1 - Ya/Yp = 1.5(1 - \frac{200}{250})$	$1 - Ya/Yp = 0.2(1 - \frac{100}{150})$	
70%	93%	100%

Now the production in money terms will be:
$\frac{70\% + 93\% + 3.100\%}{5}$ = 93% of the potential production.

In other cases the safeguarding of the farmer's own food production may be the decisive criterion.

For more complicated situations optimalization techniques are needed to find the optimal solution. In practice the choice will be limited (few crops, clear difference in production level and prizes) so that by a simple trial and error method the optimal solution can be found.

3.4. Other limiting input levels

Upto now, irrigation water availability has been used as the only limiting factor for crop production. (See also definitions of ETo and ETcrop in section 2.1.1.). This, however, will seldom occur. As soon as one limiting factor has been removed, another will come up (soil fertility, plant-variety, plant-density, pests, diseases, cultural practices etc.). Potential production levels will be reached only at research stations. Especially small holding agriculture in third world countries, on which this report is focused, will not reach these potential production levels. (e.g. although potential paddy production can be 10 ton/ha, an actual production of 2-3 ton/ha is common.)

Fig. 3.2 shows the relation between yield and evaporation for two different nitrogen levels.

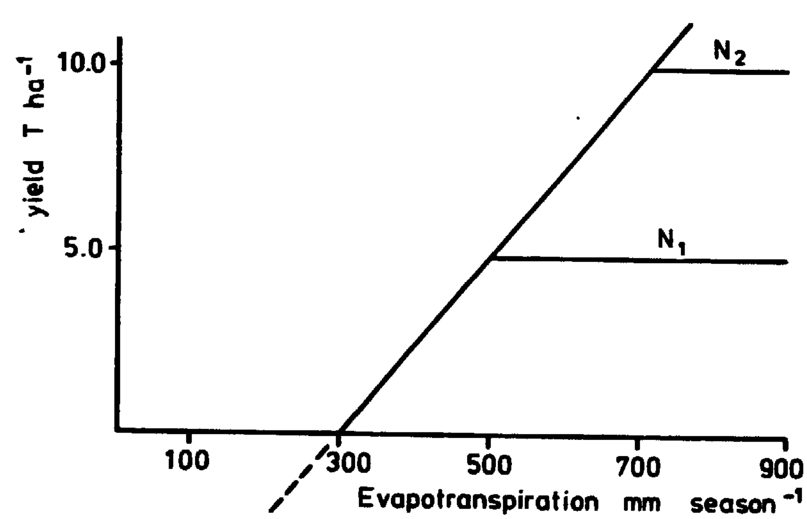


Fig. 3.2. Relation between yield and evapotranspiration for two different nitrogen levels (Vink, 1980)

So it will be clear that under practical field conditions with numerous limiting production factors, the ultimate production level will probably not be influenced significantly if ETm is not always reached during the growing season.
This gives additional freedom to the irrigation planner. On the other hand it places an additional burden on the irrigation operator and his supervisor to see that all possible obstacles to optimal production are removed. (i.e. optimize the effect of irrigation). This means in general that the extension service should not only give attention to optimal irrigation practices, but to all aspects with regard to crop production (see also section 2.3.1.).

3.5. Pre-irrigation and drought resistant crops

Besides the previously mentioned possibilities of adjusting the irrigation interval, the useful application of the variable windmill output can also be increased by pre-irrigation and by including drought resistant crops in the crop plan.

Pre-irrigation.

Pre-irrigation means, filling the rootzone with moisture before sowing the crop. Often minor pre-irrigation will be required to make soil preparation possible. The soil can also be refilled with water, say up to 1 meter. Some of the moisture will be lost by evaporation from the bare soil and some will percolate to deep soil layers, but the main part will remain in the rooting zone.
Crops can make use of this moisture at a later stage.
Evaporation of the bare soil can be limited by shallow ploughing or harrowing and by prevention of weed growth.
This pre-irrigation system makes optimal use of the capacity of the soil to store water thus reducing the difference between monthly windmill output and monthly cropwater requirement.

Drought resistant crops.

Some crops, like barley, sorghum and peas, are able to make use of the remaining soil moisture by their intensive and deep rooting system. With irrigation their yield would be higher, but they are also productive to some extent without irrigation. By including such crops in the crop plan, excess windmill output can be used for these crops, thus optimizing the windmill irrigation system. Green manure crops and/or foddercrops are also suitable for this purpose.

3.6. Need for a storage tank

In general a storage tank of sufficient capacity to meet short windless periods (100 - 500 m^3) is not feasible due to its costs and the space it requires.
In the sections 3.2 to 3.4 it is shown that with sound crop selection and irrigation management, windless periods of several days can be overcome without any significant loss in final crop production.
Storage tanks of even larger capacities to overcome months with low windspeed will only be feasible if they can be constructed at low cost, do not occupy arable land (specific topographical situations) and the seepage can be limited (rocky formations or heavy clay soils). These conditions will only be met in specific situations. Moreover such a tank may give problems to unskilled operators: over-irrigation as long as water is available and a shortage later.
In general it will be more economical to adjust the crop plan and command area to the monthly water output of the windmill and to make use of pre-irrigation, fallow and growing drought resistant crops during low wind months.
In conclusion it can be said that the variable windmill output per month can be used quite effectively by proper crop selection and crop sequence and good water management, making all possible use of the storage capacity of the rootzone. No large storage tanks are needed for this purpose. The situation is different for the windmill output variation during a day.
The possibility of a small storage tank with a capacity of about 50-100% of the average daily windmill output to collect the water pumped during the night or parts of the day needs careful consideration in regard to:

- increased irrigation efficiency with larger flows (upto 20 l/s)
- freedom of the operator with regard to moment of irrigation
- windspeed distribution over the day
- costs of the tank and space requirements
- multipurpose function of tank
- cost-comparison between increased windmill diameter and cost for tank construction.

Increased irrigation efficiency.

If a windmill pumps continuously with a capacity of 2 - 3 l/s and the water flows directly through the channels into the fields, evaporation, and deep percolation losses occur continuously as well.

Freedom of operator to decide when to irrigate.

Continuous irrigation will require continuous attention. Without this, irrigation efficiency will be reduced further, also because the flow will vary constantly due to varying windspeeds. Constant attention for a small flow is very inefficient and expensive. The farmer has other things to do besides irrigation and irrigation at night as well as during the hot midday hours is unattractive. In practice all these factors will lead to unattended irrigation and consequently low irrigation efficiency. A small storage tank may (partly) solve the problem.

Windspeed distribution

Certain areas have a very specific daily windspeed pattern, with a few hours of good wind and hardly any wind during the rest of the day (e.g. around big lakes in Africa). In general the windspeed distribution is less favorable, although there is mostly a peak during day time hours and low windspeeds during the night.

Multipurpose function of tank

Windmill water will also often be used for drinking, bathing and washing. The tank is often a swimming pool for children. This may lead to pollution of the water and development of diseases like bilharzia. The shallow tank with standing water can also become a source for malaria mosquitoes and other pathogens. If the tank is emptied daily and refilled with fresh water these problems will not easily arise.
The tank can also be used for fish breeding or growing blue-green algea.

Cost aspects

As has been discussed earlier in this chapter, the cost of tank construction depends mainly on the soil type, which determines whether lining is required or not. The space requirements for a small tank will not be too great a barrier. (50 - 100 m^2 for a tank of 50 - 100 m^3).
If the costs of a tank are high (lining) it should be considered whether a windmill with a larger capacity, to compensate the irrigation losses, would provide a better solution. Depending on the daily windspeed distribution and the number of hours the farmer is willing or able to attend the irrigation flow, an estimation can be made of the irrigation water losses without a tank and thus the required increase in capacity of the windmill or decrease of the command area per windmill.
A special case when no tank will be required occurs when paddy is continuously part of the crop plan. The standing water of the paddy field can function as a storage tank. Other crops can be irrigated from this field if the topography allows this. The windmill can pump the water continuously into the paddy field. Or to the other crops at hours with high discharge and during the rest of the day into the paddy field.

3.7. Summary

In the planning and the management of a windmill for an irrigation scheme, the following aspects should be considered:
- The crop evapotranspiration will decrease significantly (10-30%) if the windspeed decreases considerably (40-60%).
- If the crop evapotranspiration decreases the fraction of instantly available soil moisture increases and irrigation can be delayed by one or more days.

- The reduction of the evapotranspiration to below the optimal value, does not necessarily have severe effects on the crop development and crop production; this will depend on the growth phase of the crop.
- Often the availability of water is not the only impediment to crop production in small holder agriculture in the developing countries. Therefore making a goal of optimal water availability to the crop in all growth phases is not practical.
- By practising pre-irrigation and including drought-resistant crops in the crop-plan, the variable windmill output can be further optimized.
- Large storage tanks are generally not economical. Small storage tanks are often essential in order, to increase irrigation efficiency and to free the farmer for other duties besides irrigation.

On the basis of these considerations the following guidelines can be given for the design of crop plans that will minimize the reduction of crop production due to the day to day variable windmill output.

- The crop plan should consist of different crops known to the farmers. These crops should preferably differ in the depth and intensity of rooting and in sensitivity to water shortage.
- The sowing dates of different crops should be planned in such a way, that the growth phases with maximum sensitivity to water shortage do not coincide.
- As few crops as possible should reach their critical growth phase in the month(s) when the average windmill output is at its lowest value.

4. SOCIAL AND ECONOMIC ASPECTS

Windmill irrigation is not a goal in itself. The ultimate aim will be the improvement of the socio-economic situation of the project target group (small- and marginal farmers).
Furthermore is a windmill not automatically the only and optimal device to achieve this aim. Therefore intensive socio-economic feasibility studies are essential before windmills are introduced on a large scale.
Such feasibility studies are difficult to carry out because windmills (and often small scale irrigation itself) are unknown in the project area.
So it is hard to collect opinions on and to estimate all kinds of socio-economic effects connected with their introduction. Therefore it is strongly recommended to start with small pilot projects. Besides providing all kind of technical information, the socio-economic aspects can also be studied, especially if a few windmills are placed at the farms of the target group. If successful, these windmills will demonstrate their possibilities and may be accepted as an alternative waterlifting device in the area.

It is also recommended not to reserve this technology only for the target group. This might have all kind of negative effects. The new device should be available for everybody who wants one, but the feasibility study and the project activities should be concentrated on the target group, including agricultural extension, credit, subsidies, etc.

Windmill introduction should be incorporated as far as possible with other development programmes in the area. Close cooperation with government organizations in the same field is essential as well (e.g. Irrigation Department, Extension Service, governmental credit and subsidy agencies).
The social aspects that need consideration during the planning and execution are mentioned in this chapter. Special attention being given to the social aspects of crop selection and crop plan adjustment. Hardly any research on these aspects has been done up to now. In this study we can not do more than present a number of broad guidelines, drawn from the literature and from experience in India, Sri Lanka, Indonesia and Kenya.

In the second part of this chapter, the economic aspects are discussed. The cost-element of windmills and other waterlifting devices is mentioned and calculation methods are given for the economic comparison of the devices. The cost-benefit calculation from the farmers' point of view is often an important criterion for project feasibility and acceptability of the new device by the target group.
Calculating the repayment capacity will also be considered.

4.1. Social aspects

If the improvement of the living conditions of the target group is the ultimate goal of the project, it is implicit that the project will cause social changes. The project participants will earn more money or get more food when the project is successful. This will change their social status and their relations with other groups in the community. It should be investigated whether these changes will not weaken the position of the even less privileged sections of the community (e.g. landless people). Clearly landless people cannot benefit direct from this technology, so that windmills per se may not be considered a medium for improving the living conditions of the weakest sections of the community.

Very small landholders might benefit from windmill irrigation by cooperation and joint ownership of a windmill. However, joint ownership of a windmill may cause even more problems than joint ownership of other small irrigation devices, because:
- a windmill cannot be moved from one place to another
- a windmill requires a high initial investment
- division of the unpredictable daily output is difficult.

A group of marginal farmers with fields at different places can still own and operate a mobil petrol pumpset together. A windmill cannot be moved from field to field.
A high investment means that security is needed for the loan. Often marginal farmers cannot meet the security criteria of the banks. Moreover the repayment capacity of a group of marginal farmers is low if there are no other sources of income. Before a family can be expected to repay the annual installment of a loan, its minimal living requirements have to be met.
example: Suppose the net annual benefit of a windmill irrigation unit is Rs. 6000, the minimal annual living costs of an average family is Rs. 1500 and the annual loan repayment is Rs. 2000.
If 4 families own the windmill together, each will get Rs. 1500 to meet living costs and nothing is left for loan repayment.
If 2 families share the windmill, each will get Rs. 2000 and Rs. 2000 will be left for repayment.
Note: 8 Indian Rupies ≅ 1$U.S. (1980)
Only if the windmill is given free of cost, or with a high subsidy, this problem can be overcome. (see also section 4.2.3.).

In section 1.2. the problems with regard to the distribution of the irrigation water of a waterlifting device with a variable daily output were briefly discussed. After studying Chapters 2 and 3, it will be clear that modification of the irrigation interval as well as efficient crop selection and crop plan adjustment are much more difficult with a group of farmers, each with his own ideas and priorities.

4.1.1. Social aspects with regard to crop selection and crop plan adjustment

Crop selection and crop plan adjustment are important to optimize the windmill irrigation system and to decrease its vulnerability, as discussed in Chapters 2 and 3. The selection of the crops to be grown under windmill irrigation, the sequence of the different crops and of the sowing dates may also be restricted by social factors.
Often a large number of social factors and customs determine agricultural practices and vice versa. This influences the crop selection (main food crops and vegetable crops as well as traditional cash crops) but also the crop sequence and the sowing dates. Especially in regard to sowing dates and harvesting periods, many customs have developed, often based on a tradition of experience with climate, rainy seasons etc. In most cases it is not simple to change these customs even if circumstances change due to the artificial water supply.
Demonstration and extension may lead to changing of these patterns, especially if social or religious leaders have agreed to it.
It may also be very important to investigate the women's role in the existing agriculture and what will alter for them if traditional patterns are changed. The women should be involved in the demonstration and extension programme and in the final decision making.

Here some of these social factors in agriculture will be mentioned. They should be considered when a crop plan is designed. However, every situation will differ from others, so no specific rules can be given.

- Function of agriculture

It is important to know what the current function of the local agriculture is. Five possible types can be distinguished:

a. provides food and cash income for the nuclear family
b. provides food for the extended family only; other family members provide cash
c. provides food for animal husbandry which is the source of cash
d. production for the market only
e. mixtures of above mentioned functions.

The crop plan that is developed should fit in with the existing function of the agriculture in that area. Additional activities can only be successfull if the primary function has been fulfilled: sufficient food for the family and/or the cattle.

- Risk minimization is another socio-economic factor.

Often the traditional systems have a balanced crop plan aimed at risk minimization in securing food production for the family and for the livestock. Mixed cropping and delayed sowing practices are examples of this as are traditional drought resistant varieties etc....

- Religious, cultural and social activities can have their influence on the existing agriculture and vice versa.

Special functions during particular seasons may require the availability of harvested products or

cash at a certain moment (marriage parties, house or road construction etc.). Religious customs about animals may mean that a part of the arable land has to be used for fodder crops all year.
In some places it is not allowed to kill animals which can destroy standing crops. Some crops are traditionally not grown because of their attractiveness for certain animals (birds, insects, rats). Other crops may not be raised continuously in a certain area to prevent the survival of certain animals which migrate from one field to another.

- Labour requirements of certain crops, and labour availability over the year (and for the peak periods)

Paddy is a traditional example. Proper attention should be given to this aspect in new crop plan designing and establishment of new growing periods. Data about both the availability of labour and the labour costs are important. In some periods these charges will increase due to high demand for labour and also because the work has to be done in the fields during the hot period (leisure preference is high during such periods and labour productivity low). If field work is not allowed on religious or public holidays, this should be incorporated in the calculation of labour availability and the irrigation intervals. If water storage facilities are insufficient, water pumped by the windmill on these days will be lost thus reducing the total amount available for irrigation.

- Labour differentiation between male and female is often traditionally based and difficult to change. The same holds for labour differentiation between different social groups. Care should be taken not to help only one group to improve its living conditions while depriving other groups from their income, or a part of it.

- The chance of theft of the fruits standing in the field should not be underestimated. The farmers often live in villages situated far from the fields. Introduction of vegetable crops can be difficult because they can so easlily be stolen from the fields at night.
The same can happen with the fish bred in the shallow windmill storage tanks. It may be socially unacceptable that members of the farmer's family stay night after night guarding the fields far from home.

In conclusion it can be said that the crop plan designed for windmill irrigation should not differ too much from the traditional pattern. Proper attention should be given to the above mentioned aspects and sufficient information on the aspects mentioned should be gathered by all means to eliminate the chances of failure or unwanted developments.

If "modern" agriculture has not yet been introduced in a certain area, it is doubtful whether windmills for irrigation will form the most suitable introduction. Other, more simple, improvements might then be more appropriate.

4.2. Economic aspects

In this section economic aspects of windmill irrigation are discussed with special attention to those of importance from the farmer's point of view:

- Which waterlifting device is the most economical?
- What are the financial benefits of irrigation?
- Can the loan repayments be met?

Methods and examples are given for the estimation of costs and benefits "with" windmills, with other devices and "without" irrigation.

The questions whether windmills will from a sound economic alternative for the economy as a whole (macro-economy against opportunity costs; important for a national windmill subsidy programma) or whether a choice must be made between a windmill project and other projects are not discussed here.

4.2.1. Cost comparison

Costs can be divided into fixed costs and variable costs. Fixed costs are those which do not change, whether the device is used or not. Variable costs depend on the use of the device.

e.g.
- For diesel pumpsets, the fuel is a variable cost.
- For electric pumpsets, the charge for electricity is often a fixed cost, since it is usually a fixed amount per month independent of the use of the pump set.
- For bullock irrigation, only additional food given to the bullock, above the normal quantity, is a variable cost. The other costs of bullocks are more or less fixed costs (except when they have to be hired).

Where applicable, insurances and taxes also have to be added to the fixed costs. Maintenance will often be partly variable and partly fixed. Painting of a windmill will be required, whether the windmill is working or not and thus a fixed cost.
Table 4.1. presents the main elements of fixed and variable costs of four different irrigation devices.

	Bullock	Windmill	Diesel	Electricity
F	bullocks	windmill	pumpset	pumpset
I	structure	installation	installation	installation
X	bucket/rope	tank	shed	shed
E				powerline
D				electricity charges
	well	well	well	well
		tubewell	tubewell	tubewell
	canals	canals	canals	canals
V	add. food	rep./maint.	fuel	repair/maintenance
A	2 operators		oil	
R	rep./maint.		rep./maint.	
I				
A				
B				
L				
E				

Table 4.1:Main elements of fixed and variable costs of four different irrigation devices.

Although here we compare the costs to the farmer including existing subsidies on fuels or investments, it is recommended to investigate if the different cost-elements are subsidized and if so, to see whether the new device (the windmill) can be subsidized on the same principles. This will increase the reliability of the comparison. Since all investments will last for several years it is also advised to investigate whether price rises, additional to inflation, of the variable costs (e.g. fuel) are expected in the near future. If so, these price rises should be included in the calculation (see Annex IV for a calculation method).

If part of the installation is used for other purposes, (engines used for grinding, threshing, fodder cutting, sugarcane crushing, etc.) the costs have to be divided proportionally over the different activities. (Also: Bullocks are used for irrigation, ploushing, levelling, transport, etc.).

A first indication of whether windmills will be economically attractive, can be found by comparing the annual cost of the different devices at different output levels. If this comparison is to be valid, the value of the water pumped by each device should be equal. Water pumped by a windmill during a rainy season has no value!.
Whether the value of the water pumped during the irrigation season will be of equal value for the different devices depends mainly on their reliability.
Windmills have always had a low reliability and electric and diesel pumpsets a higher one. However, irregular availability of electricity and diesel is becoming more and more rule instead of the exception in rural areas of many third world countries.

Fig. 4.1. shows an example of the annual costs of windmills and diesel-pumpsets each with different assumptions, at different annual output rates over an elevation head of 5 m.
For the calculation the capital recovery factor is used, which is explained in detail in Annex IV. Cost elements which are equal for both devices are omitted (e.g. canals, bunds).

For the viability of windmills, lifespan and the annual repair and maintenance costs are important as well as the costs for the storage tank. For internal combustion engines, lifespan and expected fuel price rises are especially important.
By making different assumptions for these important variables, the influence of the assumptions on the final results can be estimated.
Inclusion of the variable cost lines of the diesel pumpset alternatives, (parallel to the existing costlines, but now through point 0,0) shows at what annual output levels it is economically attractive to install a windmill beside a diesel pumpset plant, to take over a part of the pumping and save variable cost (fuel, oil).
The difference between the annual costs of the two devices at a certain annual output level also indicates the sensitivity to the main assumption made here: the value of the water (the benefits) pumped by each device is equal. If the difference in annual costs is considerable, the benefits may vary as well without affecting the conclusion based on the costs only. The next section deals with cost benefit analyses in more detail.
In Annex IV some rules of thumb with regard to output, lifspan and repair and maintenance costs are given, als well as the basic calculation methods used for Fig. 4.1.

4.2.2. Cost-Benefit analysis

In general matters are not as simple as in the case presented in the previous section. The different devices have different functions and the economic value of the water pumped is not always equal.
By comparing costs and benefits of each device, a better indication can be obtained of the advantages of the different alternatives for the farmer. Also the "with" irrigation situation has to be compared with the "without" situation (actual agricultural practice of the targetgroup farmers).

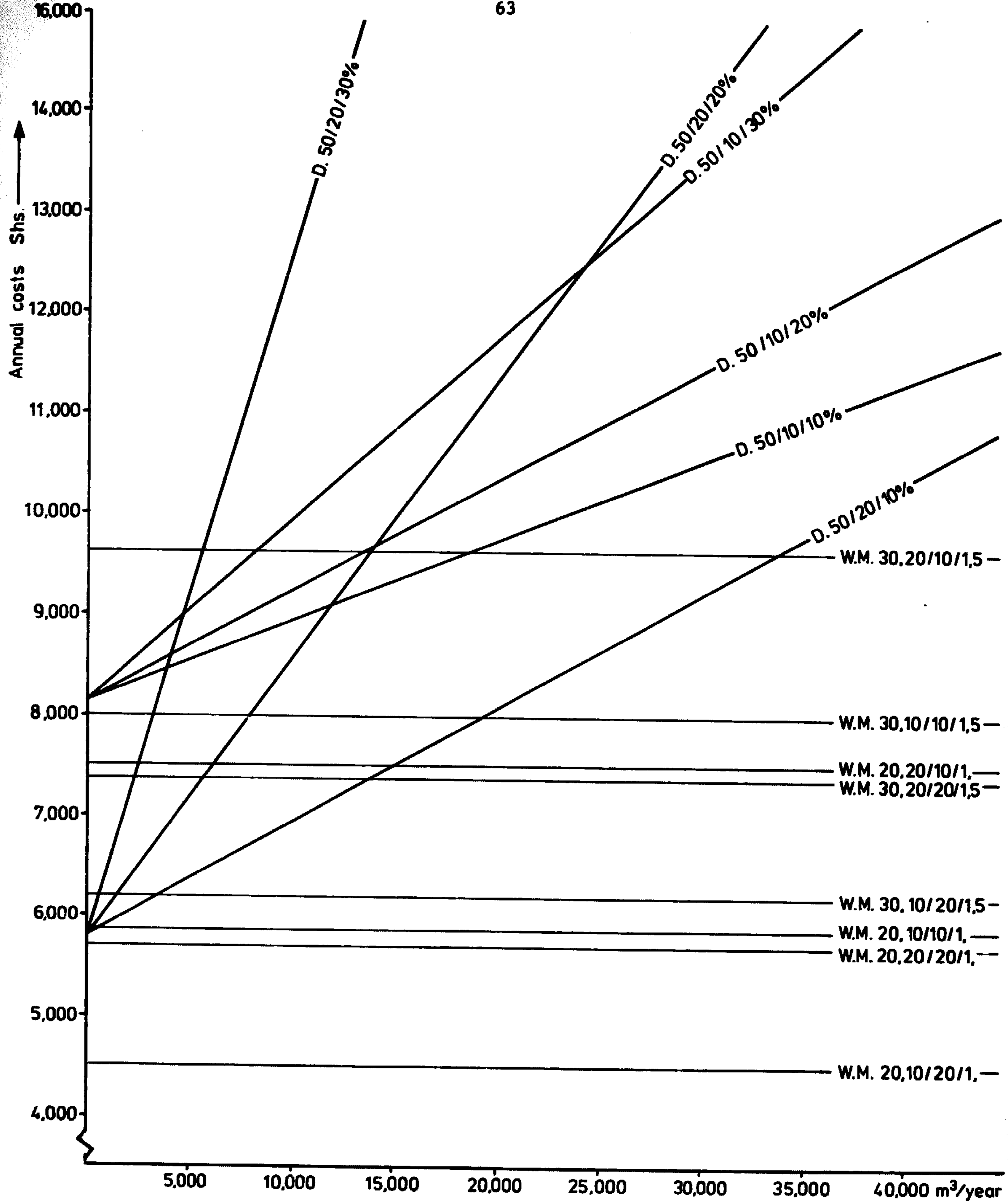


Fig. 4.1. Comparison of annual costs of windmills and 5 H.P. diesel pump sets, for different options with regard to total investments, lifespan and annual fuel price rises in Kenya (elevation head 5m). (Vilsteren 1980)

W.M. 20, 10/20/1. means: Windmill Shs 20,000; Tank Shs 10,000/ Lifespan 20 years/Repair + maintenance Shs 1,000 p.a.

D.50/20/10% means: 5 H.P. Dieselpumpset + pumphouse: Shs 50,000/

Since there will be a learning process in the new "with" situation and there will be developments in the inputs, outputs and their price levels in both situations, the costs and benefits over a large number of years have to be estimated e.g. over the whole lifespan of the investment. Therefore the Internal Rate of Return (I.R.R.) will be introduced here. The I.R.R. is that discount rate (or interest rate) for which the sum of the annual costs is equal to the sum of the annual benefits. In formula:

$$\sum_{1}^{t} \frac{bt}{(1+i)^{t}} = \sum_{1}^{t} \frac{ct}{(1+1)^{t}}$$

where:
- bt = benefits of year t*
- ct = costs of year t
- t = number of years included in the comparison 1, 2, 3,.....t
- i = Internal Rate of return

The I.R.R. can be found by a "trial and error" procedure in order to solve to the former equation.
Comparing the I.R.R. with the actual interest rate indicates the profitability of the device; comparing it with the I.R.R. of the other alternatives gives an indication for the most economical alternative for the farmer.

An example:

Suppose the following data are found.

Year	0	1	2	3
Costs	6,000	300	300	300
Benefits	--	2,500	3,000	3,500

Trial and error procedure:
Suppose i = 15% thus (1+i) = 1.15
The sum of the (discounted) costs is then:

$$6000 + \frac{300}{1.15^1} + \frac{300}{1.15^2} + \frac{300}{1.15^3} = 6000 + 261 + 227 + 197 = 6685$$

The sum of the (discounted) benefits is:

$$0 + \frac{2500}{1.15^1} + \frac{3000}{1.15^2} + \frac{3500}{1.15^3} = 0 + 2174 + 2268 + 2301 = 6743$$

The sum of the discounted benefits is slightly higher than the sum of the discounted costs, so the I.R.R. will be slightly higher than 15 %.

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*) Using "constant" prices i.e. inflation which will affect both costs and benefits is eliminated. Generally current prices are taken. Price rises additional to the inflation rate are accounted for. (e.g. fuel price rises)

In annex IV, an example is presented of the I.R.R. calculation with respect to four different devices and the "without" situation (rainfed farming).

Some points are now considered for the case when the data for costs and benefits needed for this calculation are collected from different sources.
Except for the selling of irrigation water, the benefits of a pumping device can only be calculated indirectly, on the basis of increased agricultural production due to irrigation. So again proper attention has to be paid to the costs and the benefits of agriculture "with" and "without" irrigation. Then the net benefits due to the application of the irrigation device can be estimated.
Soil quality and levels of inputs (seed, manure, fertilizer, pesticides, manpower and bullockpower) often vary considerably over an area, as do the level of outputs (main product, by products, quality of products). Prices of inputs as well as outputs also differ over the year and from year to year. The capability of the farmers is another varying factor.

Nevertheless, data have to be collected (either by holding a survey among the farmers, or making use of existing surveys) and knowledge gathered at demonstration farms and agricultural research stations. Data from the latter often show results that are far above those of actual farming practice in the area.

Besides the current data something should be known about the growth rate of the production and/or expected price rises. We have to know the input and output levels for a large number of years to perform projections for the future.
It is to be expected that optimal results will not be achieved immediately after the introduction of a new device.
The farmer will go through a learning process which can take several years. Production rises may occur with any irrigation device.This is even so without irrigation, supposing a better yielding variety is introduced and more fertilizer becomes available etc.
With the help of local agricultural research stations, estimations can be made about the expected percentages of growth for the "with" and the "without" case.

In calculations of the net benefits of different crops, the amount used for home consumption should not be neglected, but added to the total benefits.
It is often difficult to estimate the contribution of bullock power, or farmyard manure, or the value of the by-products which are often fed to cattle. If the contributions are relatively small, they may compensate each other. Contribution of bullock power for ploughing and levelling and the contribution of the farmyard manure can be compensated by the supply of by-producys or by the production of a small field of fodder.

Another difficult item in calculating the net benefits is the labour supply by the farmer and his family.
Generally it is only hired labour that is regarded as a cost factor. The net benefits of the crop plan are often regarded as the farmers income, but the introduction of irrigation always almost implies increased labour requirements. To see what part of the additional benefits are due to the irrigation device, all labour has to be included as costs.
e.g. Suppose the additional benefit of 1 ha irrigated crop will be Rs. 1.000,--but also requires 100 additional mandays at Rs. 5 per day. The additional benefit due to the irrigation device will be only Rs. 1.000-(100 x Rs. 5) = Rs. 500,--.
It is not only difficult to estimate the additional labour requirements but also its value. If there are no off-farm employment opportunities, the opportunity cost of labour is even zero. Often these off-farm employment opportunities also vary during the year in rural areas and so their opportunity cost.
Usually the minimum wages for farm labour are used in the calculations.

From the suggestions given above, it will be clear that the results of the calculation largely depend on the assumptions made. Therefore here again it is recommended to make several calculations, each with different assumptions for the main aspects (e.g. fuel price rises, production level, etc.). In this way the influence of the assumptions on the final outcome can be investigated. In case of a large uncertainty economists can be asked for advice.

4.2.3. Farmers repayment capacity

In general it can be stated that the I.R.R. also indicates whether the investment will repay itself. If the I.R.R. is higher than the current interest rate, this will usually be the case. But even then it is not automatically implied that the farmer will also be able to repay the loan for the the required investment in windmill, the well and tubewell, tank etc. The repayment capacity of the farmer is a very critical factor in adopting windmills.

One reason for such a limited repayment capacity can be the loan conditions of the bank or other loan agencies. These institutions often demand security in the form of owned land. This is often difficult for the small farmer (property rights not always being officially registered or more persons own the property) and impossible for the tenant or share cropper.
Another aspect is formed by the repayment conditions of the loan: interest rate and repayment period. Real interest rates are sometime above the official rates (add. charges, bribes) and the repayment period is often shorter than the lifespan of the investment. Furthermore it starts immediately in the first year after the investment is made.

Yet the farmer is not getting optimal benefits out of his investment in that period, since he is still in the learning process.

A calculation example:
Investment: Rs. 10,000; Interest rate: 12%; Repayment period: 5 years.
With the capital recovery factor (discussed in Annex IV) the annual repayment can be calculated as:

$$A = 10{,}000 \times \frac{0.12 \times (1.12)^5}{(1.12)^5 - 1} = \text{Rs. } 2{,}774$$

This is about twice the actual annual costs based on the total lifetime of the windmill of 15 years (see Annex IV).
It will be clear that the additional benefits from windmill irrigation may be insufficient to meet the obligations to the loan agency.
Other sources of family income or saving deposits are then required to meet these obligations. Alternative loan conditions or subsidies can also partly solve this problem.

Another reason for the limited repayment capacity of the farmer may be the low family income.
If this income is insufficient to meet the primary living costs (poverty line), the farmer will not be able to meet the loan repayment requirements.
This problem will increase if the windmill and thus its benefits are to be shared by a group of farmers; each farmer will first have to meet the minimum living expenditures. All these problems occur when there are no opportunities for off-farm employment.

Another calculation example:
(based on data from Ghazipur, India)

See previous example: loan repayment annually Rs. 2774
Suppose net benefit from 1 ha irrigated by the windmill Rs 3500
Suppose minimum living expenditures of a family Rs. 1500
Amount left for repayment: Rs. 3500 - 1.500 = Rs. 2000
Suppose 2 families have to live from this 1 ha irrigated land
Repayment capacity Rs. 3500 - 2 x Rs. 1.500 = Rs. 500

Before windmill irrigation was introduced these families probably lived below the poverty line, but that will not mean that they will continue doing so, if they receive more money.
Meeting minimum living costs is much more important to them than the bank loan repayment. Banks know this as well and therefore will not give them a loan at all.
What is to be taken as the poverty line is arbitrary and will vary from area to area.

If the repayment of the loan can just be met, this is still a risky affair for the bank and the farmer. The moment something happens (sickness of farmer or someone in his family, a dying bullock or a failing crop), the repayment duties cannot be fulfilled.

The farmer employing a windmill is sometimes part of a larger family, called extended family. It maybe possible that other members of this unit will assist in repaying the loan.
Sometimes, it is even possible to pay the investment out of previous savings or by selling piece of land or other valuable goods. All these possibilities can occur in one and the same area.
Therefore a sound knowledge of the socio-economic aspects of the project area and a flexible organization will be required to deal with all these aspects in such a way that the introduction of windmills will ultimately benefit the selected target group. If the repayment problems above described are expected, proper arrangements with subsidies and possibilities for delayed loan repayment should be made. This is a very difficult task and it is even harder to collect the repayment fees, even when these are low due to all kind of arrangements. Sanctions such as removing the device are very costly, especially for windmills, and do not solve the problems. Farmers know this very well and will act accordingly.

An effective method to examine whether the farmer will be able to meet the repayment duties is a projection of the cash flows during the repayment period of the loan.
Fig. 4.2. presents 2 examples of these cashflow projections per holding of 1 acre in a 4 ha irrigation scheme in Kenya applying a windmill or a diesel pump set. Adding the minimum living costs (e.g. Shs. 2,000 p.a.) to the costs for irrigation will complete the picture and then conclusions can be drawn with regard to the repayment capacity of the farmer.

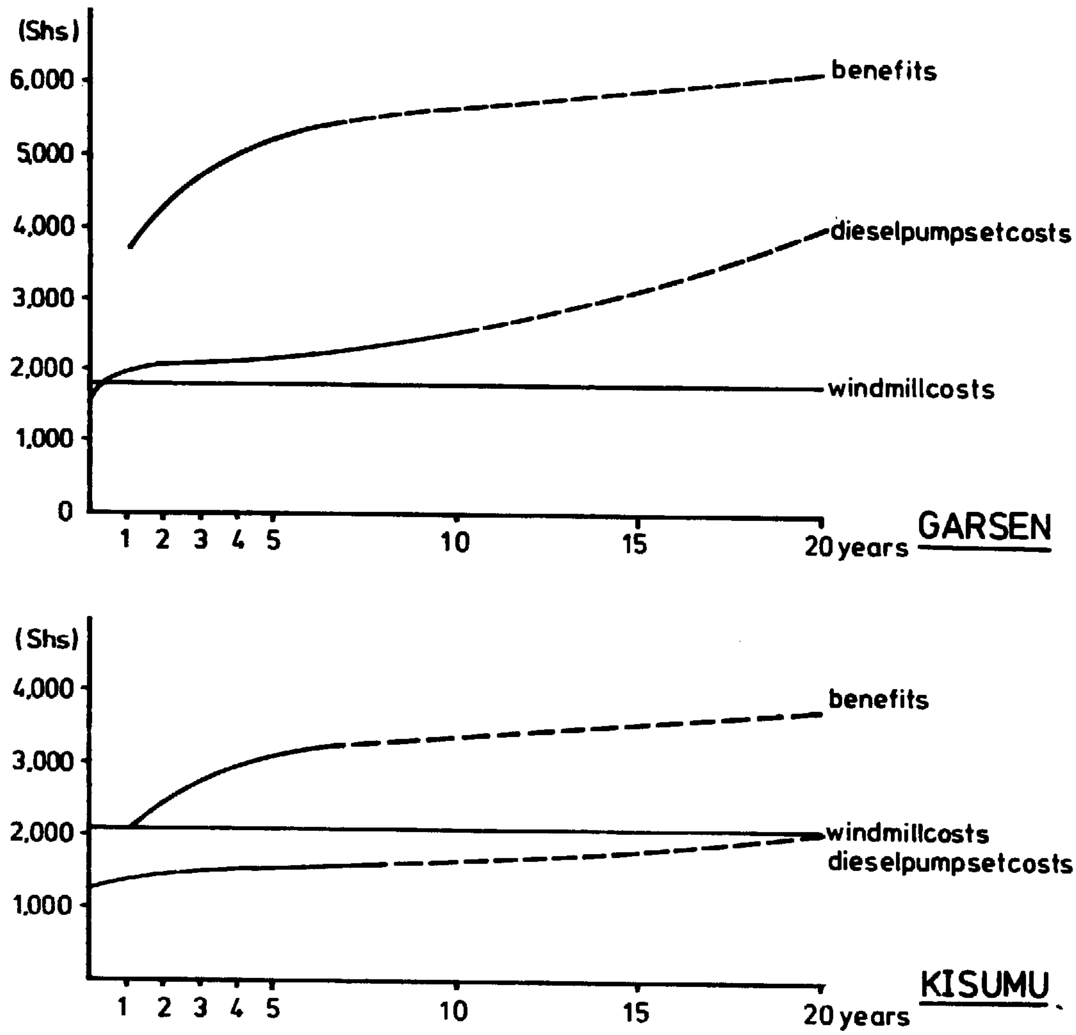

Fig. 4.2. Cashflows per acre for 4 ha. irrigationschemes with Windmills
or Dieselpumpset in two places in Kenya.
Repayment in 20 years.
(Vilsteren, 1980)

The government will have to provide aid if it wants to promote windmill irrigation by small farmers but the repayment capacity is insufficient and also if the risks, seen from the small farmer's point of view, are too high.
Subsidizing windmills is simple, since there is only one main cost factor, the initial investment.

5. CONCLUDING REMARKS

In this chapter brief attention is given to the skills required by the farmers to deal with windmill-irrigation and to the combination of windmills with other pumping devices.

5.1. Farmer training

On the basis of Chapter 3, the reader might question whether the rules for windmill irrigation can be learned by small and marginal farmers with a low level of education.
A distinction should be made between farmers who already have some experience with irrigation (controlled flooding, bullock irrigation, bought water, etc) and farmers with only rainfed farming experience. Farmers with irrigation experience already know how to irrigate and often know by experience how crops respond to water and the economic effects of timely irrigation. So there is no much need to teach the farmer how to use his limited water to optimize the final economic results and to minimize the risk of crop failure.

To facilitate adoption of windmill irrigation it is essential to show the farmers the effect of windless days on crop water needs. So they will understand that delayed irrigation due to windless days will not seriously harm crop development and crop production.
Another essential point be tought is the differing capacities of the windmill system in each season. Often farmers become enthousiastic during the windy season and want to cultivate the same area in the next season, which is less windy.
A third point is to teach the farmer to grow at one time crops with different irrigation requirements and to supplement the command area with a low input crop (fodder, green manure) or a drought resistant crop, so little will be lost if it proves to be a poor season with regard to windspeed. If sufficient irrigation water becomes available, this remaining area will also benefit. The water will be used effectively and ultimately the farmer will benefit from it. Another matter to be made clear is that irrigation alone will not result in good crops (see para 3.4.).
Finally, delayed sowing of traditional crops, to correspond with irrigation water requirement and wind pattern may meet resistance, because tradition has learned, that the existing sowing date is the optimal one to obtain good yields as well as to minimize risks.

In conclusion it can be said that proper in-field training and demonstration will be essential for the introduction of windmill irrigation. After a few years of intensive guidance of the windmill farmers experience will be available in the area and these windmill farmers will become demonstrators for others, if they belong to the same socio-economic group.

This transfer of technology should be executed by an extension service, which is trained and activated by the windmill project. Just as with other new agricultural techniques this extension will be essential. The scope of the service may include loans and subsidies, training in windmill maintenance and minor repair and other agricultural or socio-economic aspects.

It will be clear from previous remarks that introduction of windmill irrigation to farmers with no experience in irrigation will require more training and attention. The design and layout of the field irrigation system has to be made and farmers have to be taught how to handle water efficiently. The crop plan should be kept very simple and much less critical (safety factors at all moments), the number of crops should be limited etc.
It will be clear that the extension service has a lot more to do in such situations, but this applies for any irrigation device.
In some cases it can be questioned whether irrigation will be the most appropriate step in further development (see also section 1.1.).

5.2. Windmills combined with other irrigation devices.

In discussions about windmills, often one of the first questions of the layman is whether windmills can be combined with other devices, espicially manual ones.
From previous chapters it will be clear that short windless periods can be coped with by other means. Moreover, manual power is too limited to deliver a quantity that can supplement windmill irrigation. Power output of a man will be about 75 Watt when working for a few hours continuously; this implies less than 3 m^3/hour when elevation head is 10 meter. In addition, suggesting handpumps may give rise to problems of dignity, status etc.
The difference in power levels also makes it almost impossible to use the windmill pump for hand pumping, so a lower capacity pump would have to be installed additionally for this purpose.
If irrigation with animals is known in the area, this can easily be combined with windmill irrigation, if there is sufficient space around the water source and if the water source is an open one, thus not a tubewell.
On windmill installation, attention should be given to this space aspect.
An example:

> In the Ganga-plain of North-India, bullock irrigation from open wells has been practiced for centuries.
> Windmill irrigation has been introduced to replace this bullock irrigation during the windy hot summer season (April-June).
> Due to the low water tables and the hot weather, bullock irrigation is a tedious job in that period for men and animals and the output was low (0.1 - 0.2 ha per unit/day).
> During this period windmills can supply sufficient water for about 1 - 1.5 ha.

However during the low wind winterperiod, bullock irrigation can supplement windmill irrigation, so the same acreage can be irrigated as during summer season.

The additional investment costs for bullock irrigation are low, provided bullocks are already available for other agriculatural practices (land-preparation, transport).
However, here again, farmers may think that it is below their dignity to continue with bullock irrigation once they have installed a modern new irrigation device.

Combining windmills with electric or diesel pumping sets will be not economical in most cases.
The initial investment for the two devices are often above the financial capacity of the small farmer. Since both devices are only used below their optimum capacity the total annual cost (thus also the cost per m^3 water) will be quite high.
Only if both bevices can be used to a nearly optimal degree or if very high quality cash crops, which are sensitive to water shortage, are grown, may this combination be a good solution. Often the capacity of the pumpset is so high that it can easily pump the windmill output in addition to its own output and so reduce the cost per m^3 water, except if the variable costs of the pumpset are far above the costs per m^3 of the windmill (high fuel prices). In general however the small farmer will prefer a low initial cost to low annual costs.
This aspect of high costs and low annual output of the pumpset could be solved if a number of windmill farmers together were to operate one mobile pumping set. However this will lead to the following problems:

- a windless period will lead to a peak demand for the pumpset, since all farmers are hit by the same windless period at the same time;
- joint ownership of a device which needs proper maintenance and operation often gives rise to difficulties;
- the capacity of the water source may be sufficient with respect to the (low) windmill output, but insufficient for the pumpset capacity;
- if the elevation head exceeds 5 -7 m., arrangements have to be made to install the pumpsets below groundlevel, which is complicated and needs additional facilities.

These points indicate that combined irrigation is not a simple matter since all its aspects need carefull consideration.
Often a windmill with a rather larger capacity can solve the problems just as well, but at lower costs.

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ANNEX I

PAN EVAPORATION METHOD AND PENMAN METHOD, INCLUDING TABLES AND CALCULATION EXAMPLES.

1. PAN EVAPORATION

Evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from a specific open water surface. Plants reponds to the same climatic variables in a similar fashion, but several factors may produce a significant difference in water loss. However with proper siting, evaporation pans can be used to predict crop water requirements for periods of 10 days or longer.

To relate pan evaporation (Epan) to the reference crop evapotranspiration (ETo) empirically derived coefficients (Kp) are given, which take climate and pan environment into account.
Reference crop evapotranspiration (ETo) can be obtained from the following formula:

$$ETo = Kp \times Epan.$$

where: Epan = pan evaporation in mm/day and represents the mean daily value of the period considered.
Kp = pan coefficient

Values for Kp are given in table 1 for the class-A pan and in table 2 for the sunken Colorado pan, for different humidity and wind conditions and pan environments. The Kp-values relate to pans located in an open field with no crops taller than 1 m. within some 50 m. of the pan. The immediate surroundings, within 10 m. of the pan, are covered by a green frequently mowed, grasscover or by bare soil. The pan is unscreend.

Evaporation pans can be manufactured locally.
Descriptions and installations conditions are given below.

CLASS-A PAN.

The class-A evaporation pan is circular, 121 cm. (46 inches) in diameter and 25.5 cm. (10 inches) deep. It is made of galvanized iron (22 gauge) or Monel metal (0.8 mm.). The pan is mounted on a wooden open frame platform with its bottom 15 cm above groundlevel. The soil is built up within 5 cm of the bottom of the pan. The pan must be level. It is filled with water 5 cm. below the rim, and water level should not drop to more than 7.5 cm below the rim. Water is regularly renewed to eliminate extreme turbidity. If galvanized, the pan is painted annually with aluminium paint.

SUNKEN COLORADO PAN.

Sunken Colorado pans are sometimes preferred in crop water requirement studies, since these pans have a water level 5 cm. below the rim at soil level height and give a better direct prediciton of potential evapotranspiration of grass than does the Class-A pan. The pan is 92 cm (36 inches) square and 46 cm (18 inches) deep. It is made of galvanized iron, set in the ground with the rim 5 cm. (2 inches) above groundlevel. The water level inside the pan is maintained at or slightly below groundlevel. (Reference is made to Irrigation and Drainage Paper No. 27 Agrometeorological field stations. FAO Rome, Italy 1976).

EXAMPLE:

Given:	Cairo, July. Epan= 11.1 mm/day from Class-A pan. RHmean = Medium; Wind = Moderate. Pan station is located within a cropped area of several hectares; The pan is not screened.
Calculation:	See table 1 of this annex. Since the pan station is covered by grass and is surrounded by some 100 m. of cropped area, case A applies. From table 1 for moderate wind and medium humidity conditions the Kp value is estimated at 0.75 ETo = Kp x Epan = 0.75 x 11.1 = 8.3 mm/day.

Table 1 Pan Coefficient (Kp) for Class A Pan for Different Groundcover and Levels of Mean Relative Humidity and 24 hour Wind (FAO, 1977)

Class A pan	Case A: Pan placed in short green cropped area				Case B[1]: Pan placed in dry fallow area			
RH mean %		low <40	medium 40-70	high >70		low <40	medium 40-70	high >70
Wind km/day	Windward side distance of green crop m				Windward side distance of dry fallow m			
Light <175	1	.55	.65	.75	1	.7	.8	.85
	10	.65	.75	.85	10	.6	.7	.8
	100	.7	.8	.85	100	.55	.65	.75
	1000	.75	.85	.85	1000	.5	.6	.7
Moderate 175-425	1	.5	.6	.65	1	.65	.75	.8
	10	.6	.7	.75	10	.55	.65	.7
	100	.65	.75*	.8	100	.5	.6	.65
	1000	.7	.8	.8	1000	.45	.55	.6
Strong 425-700	1	.45	.5	.6	1	.6	.65	.7
	10	.55	.6	.65	10	.5	.55	.65
	100	.6	.65	.7	100	.45	.5	.6
	1000	.65	.7	.75	1000	.4	.45	.55
Very strong >700	1	.4	.45	.5	1	.5	.6	.65
	10	.45	.55	.6	10	.45	.5	.55
	100	.5	.6	.65	100	.4	.45	.5
	1000	.55	.6	.65	1000	.35	.4	.45

[1]) For extensive areas of bare-fallow soils and no agricultural development, reduce Kpan by 20% under hot, windy conditions; by 5-10% for moderate wind, temperature and humidity conditions.

Table 2 Pan Coefficient (Kp) for Colorado Sunken Pan for Different Groundcover and Levels of Mean Relative Humidity and 24 hour Wind (FAO, 1977)

Sunken Colorado	Case A: Pan placed in short green cropped area				Case B[1]: Pan placed in dry fallow area			
RH mean %		low <40	medium 40-70	high >70		low <40	medium 40-70	high >70
Wind km/day	Windward side distance of green crop m				Windward side distance of dry fallow m			
Light <175	1	.75	.75	.8	1	1.1	1.1	1.1
	10	1.0	1.0	1.0	10	.85	.85	.85
	≥100	1.1	1.1	1.1	100	.75	.75	.8
					1000	.7	.7	.75
Moderate 175-425	1	.65	.7	.7	1	.95	.95	.95
	10	.85	.85	.9	10	.75	.75	.75
	≥100	.95	.95	.95	100	.65	.65	.7
					1000	.6	.6	.65
Strong 425-700	1	.55	.6	.65	1	.8	.8	.8
	10	.75	.75	.75	10	.65	.65	.65
	≥100	.8	.8	.8	100	.55	.6	.65
					1000	.5	.55	.6
Very strong >700	1	.5	.55	.6	1	.7	.75	.75
	10	.65	.7	.7	10	.55	.6	.65
	≥100	.7	.75	.75	100	.5	.55	.6
					1000	.45	.5	.55

1) For extensive areas of bare-fallow soils and no agricultural development, reduce Kpan by 20% under hot, windy conditions; by 5-10% for moderate wind, temperature and humidity conditions.

<u>Penman Method</u> (FAO, 1977)

Climatic data required are: mean temperature (T in °C), mean relative humidity (RH in %), total windrun (U in km/day at 2 m height) and mean actual sunshine duration (n in hour/day) or mean radiation (Rs or Rn equivalent evaporation in mm/day). Also measured or estimated data on mean maximum relative humidity (RHmax in %) and mean daytime windspeed (Uday in m/sec at 2 m height) must be available. Reference evapotranspiration (ETo) representing the mean value in mm/day, over the period considered, is obtained by:

$$ETo = [W. Rn + (1-W) . f(U) . (ea-ed)].c$$

where:

(ea-ed)	=	vapour pressure deficit i.e. the difference between saturation vapour pressure (ea) at Tmean in mbar (Table 3) and actual vapour pressure (ed) in mbar where: ed = ea . RH/100
f(U)	=	wind function of f(U) = 0.27 (1 + U/100) with U in km/day measured at 2 m height
Rn	=	total net radiation in mm/day or Rn = 0.75 Rs - Rnl where Rs is incoming shortwave radiation in mm/day either measured or obtained from Rs = (0.25 + 0.50 n/N)Ra. Ra is extraterrestrial radiation in mm/day (Table 4), n is the mean actual sunshine duration in hour/day and N is maximum possible sunshine duration in hour/day (Table 5). Rnl is net longwave radiation in mm/day and is a function of temperature, f(T), of actual vapour pressure, f(ed) and sunshine duration f(n/N), or Rnl = f(T).f(n/N).f(ed) (Tables 6, 7 and 8)
W	=	temperature and altitude dependent weighting factor (Table 9)
c	=	adjustment factor for ratio Uday/Unight, for RHmax and for Rs (Table 10).

EXAMPLE

<u>Given</u>: Location 30°N; altitude 95 m; July; Tmean 28.5°C; RHmean 55%; Umean 232 km/day; n mean 11.5 hour/day; (RHmax 80%, Uday 3 m/sec, Uday/Unight 1.5).

Calculation:

ea	T = 28.5°C	Table 3	38.9 mbar
ed	ea.RH/100	calc	21.4 mbar
ea-ed		calc	17.5 mbar
f(U)	0.27(1 + U/100); U = 232 km/day	calc	0.9
Ra	30°N, July	Table 4	16.8 mm/day
N	30°N, July	Table 5	13.9 hour/day
Rs	(0.25 + 0.50 n/N)Ra	calc	11.2 mm/day
Rnl	f(T).f(ed).f(n/N)	Tables 6,7,8	1.8 mm/day
Rn	0.75 Rs - Rnl	calc	6.6 mm/day
W	T = 28.5°C; 95 m	Table 9	0.77
c	RHmax 80%; Rs11.2; Uday/Unight 1.5	Table 10	1.01
ETo	c [W.Rn + (1-W).f(u).(ea-ed)]	calc	8.8 mm/day

Table 3 Saturation Vapour Pressure (ea) in mbar as Function of Mean Air Temperature (T) in °C 1/

Temperature °C	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ea mbar	6.1	6.6	7.1	7.6	8.1	8.7	9.3	10.0	10.7	11.5	12.3	13.1	14.0	15.0	16.1	17.0	18.2	19.4	20.6	22.0
Temperature °C	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
ea mbar	23.4	24.9	26.4	28.1	29.8	31.7	33.6	35.7*	37.8*	40.1*	42.4	44.9	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9

1/ Also actual vapour pressure (ed) can be obtained from this table using available Tdewpoint data. (Example: Tdewpoint is 18°C; ed is 20.6 mbar.

Table 4 Extra-terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day

Northern Hemisphere													Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40°	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8*	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Table 5 **Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes**

Northern Latitudes	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Southern Latitudes	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9*	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Table 6 **Effect of Temperature f(T) on Longwave Radiation (Rnl)**

T^oC	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
$f(T) = \delta Tk^4$	11.0	11.4	11.7	12.0	12.4	12.7	13.1	13.5	13.8	14.2	14.6	15.0	15.4	15.9	16.3*	16.7	17.2	17.7	18.1

Table 7 **Effect of Vapour Pressure f(ed) on Longwave Radiation (Rnl)**

ed mbar	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
$f(ed) = 0.34 - 0.044\sqrt{ed}$	0.23	.22	.20	.19	.18	.16	.15	.14	.13*	.12	.12	.11	.10	.09	.08	.08	.07	.06

Table 8 **Effect of the Ratio Actual and Maximum Bright Sunshine Hours f(n/N) on Longwave Radiation (Rnl)**

n/N	0	.05	.1	.15	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85	.9	.95	1.0
$f(n/N) = 0.1 + 0.9n/N$	0.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.64	.69	.73	.78	.82*	.87	.91	.96	1.0

Table 9 **Values of Weighting Factor (W) for the Effect of Radiation on ETo at Different Temperatures and Altitudes**

Temperature °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
W at altitude m																				
0	0.43	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77*	.78	.80	.82	.83	.84	.85
500	.45	.48	.51	.54	.57	.60	.62	.65	.67	.70	.72	.74	.76	.78	.79	.81	.82	.84	.85	.86
1000	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.80	.82	.83	.85	.86	.87
2000	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88
3000	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.88	.88	.89

Table 10 **Adjustment Factor (c) in Presented Penman Equation**

	RHmax = 30%				RHmax = 60%				RHmax = 90%			
Rs mm/day	3	6	9	12	3	6	9	12	3	6	9	12
Uday m/sec	Uday/Unight = 4.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.79	.84	.92	.97	.92	1.00	1.11	1.19	.99	1.10	1.27	1.32
6	.68	.77	.87	.93	.85	.96	1.11	1.19	.94	1.10	1.26	1.33
9	.55	.65	.78	.90	.76	.88	1.02	1.14	.88	1.01	1.16	1.27
	Uday/Unight = 3.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.76	.81	.88	.94	.87	.96	1.06	1.12	.94	1.04	1.18	1.28
6	.61	.68	.81	.88	.77	.88	1.02	1.10	.86	1.01	1.15	1.22
9	.46	.56	.72	.82	.67	.79	.88	1.05	.78	.92	1.06	1.18
	Uday/Unight = 2.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.69	.76	.85	.92	.83	.91	.99*	1.05*	.89	.98	1.10*	1.14*
6	.53	.61	.74	.84	.70	.80	.94	1.02	.79	.92	1.05	1.12
9	.37	.48	.65	.76	.59	.70	.84	.95	.71	.81	.96	1.06
	Uday/Unight = 1.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.64	.71	.82	.89	.78	.86	.94*	.99*	.85	.92	1.01*	1.05*
6	.43	.53	.68	.79	.62	.70	.84	.93	.72	.82	.95	1.00
9	.27	.41	.59	.70	.50	.60	.75	.87	.62	.72	.87	.96

Annex I-A

Determination of the relative influence of windspeed on ETo, derived according to Penman.
For formula and tables see ANNEX I. The results of these calculations are discussed in section 3.2 and are graphically presented in fig. 3.1.

Assumptions:

Altitude = 0	Altitude will have no influence on relative difference (see table 9).
$RH_{max} = RH_{mean}$	No variation in RH during day and night. This influences c-factor (table 10). No influences on relative differences.
n/N = 1, Ra = 17 mm/day	See table 4, 30° North, month June. This influences only radiation part of formula.
Uday/Unight = 3	This influences only c-factor (table 10). No influence on relative differences.
α=0.25	α=is reflection coefficient; 0.25 for full covering green crop.

Variables:

Temp.	(20, 30, 40°C)
RH	(30, 60, 90 %)
Wind	(0, 3, 6 m/sec. = 0, 260, 520 km/day)

Explanation of columns of table on next page:

column 4	: table 9
column 5, 7, 8, 10, 12, 14	: calculations
column 6	: table 3
column 9	: table 4
column 11	: table 6, 7, 8
column 13	: A = WxRN (Radiation component)
column 15	: B = (1-W).fu.(ea-ed) Aerodynamic component
column 16	: table 10
column 17	: ETo = (A+B)xC (= column (13+15)x16)
column 18	: Relative evaporation (V = 3m/sec. = 100%)

The last column on the next page shows the relative influence of the windspeed on the evaporation. This column is the basis of fig. 3.1 in section 3.2.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
T°C	RH %	Vkm/day	W	(1-W)	ea	ed	(ea-ed)	Rs	Rns	Rnl	Rn	A	fu	B	C	ETo	%
20	30	0	.68	.32	23.4	7.0	16.4	12.75	9.5	3.3	6.2	4.2	0.27	1.4	1.0	5.6	64 %
20	30	260	.68	.32	23.4	7.0	16.4			3.3	6.2	4.2	0.97	5.1	.94	8.7	100%
20	30	520	.68	.32	23.4	7.0	16.4			3.3	6.2	4.2	1.67	8.8	.88	11.4	131%
20	60	0	.68	.32	23.4	14.0	9.4			2.6	6.9	4.7	0.27	0.8	1.05	5.8	68 %
20	60	260	.68	.32	23.4	14.0	9.4			2.6	6.9	4.7	0.97	2.9	1.12	8.5	100%
20	60	520	.68	.32	23.4	14.0	9.4			2.6	6.9	4.7	1.67	5.0	1.10	10.7	126%
20	90	0	.68	.32	23.4	21.1	2.3			2.0	7.5	5.1	0.27	0.2	1.10	5.8	78 %
20	90	260	.68	.32	23.4	21.1	2.3			2.0	7.5	5.1	0.97	0.7	1.28	7.4	100%
20	90	520	.68	.32	23.4	21.1	2.3			2.0	7.5	5.1	1.67	1.2	1.22	7.7	104%
30	30	0	.78	.22	42.4	12.7	29.7			3.1	6.4	5.0	0.27	1.8	1.0	6.8	63 %
30	30	260	.78	.22	42.4	12.7	29.7			3.1	6.4	5.0	0.97	6.4	.94	10.7	100%
30	30	520	.78	.22	42.4	12.7	29.7			3.1	6.4	5.0	1.67	10.9	.88	14.0	131%
30	60	0	.78	.22	42.4	25.4	17.0			2.0	7.5	5.9	0.27	1.0	1.05	7.2	68 %
30	60	260	.78	.22	42.4	25.4	17.0			2.0	7.5	5.9	0.97	3.6	1.12	10.6	100%
30	60	520	.78	.22	42.4	25.4	17.0			2.0	7.5	5.9	1.67	6.2	1.10	13.3	125%
30	90	0	.78	.22	42.4	38.1	4.2			1.2	8.3	6.5	0.27	0.2	1.10	7.3	77 %
30	90	260	.78	.22	42.4	38.2	4.2			1.2	8.3	6.5	0.97	0.9	1.28	9.5	100%
30	90	620	.78	.22	42.4	38.2	4.2			1.2	8.3	6.5	1.67	1.5	1.22	9.8	103%
40	30	0	.85	.15	73.5	22.1	51.4			1.3	8.2	7.0	0.27	2.1	1.0	9.1	65 %
40	30	260	.85	.15	73.5	22.1	51.4			1.3	8.2	7.0	0.97	7.5	0.94	14.0	100%
40	30	520	.85	.15	73.5	22.1	51.4			1.3	8.2	7.0	1.67	12.9	.88	18.4	131%
40	60	0	.85	.15	73.5	44.1	29.4			0.9	8.6	7.3	0.27	1.2	1.05	8.9	68 %
40	60	260	.85	.15	73.5	44.1	29.4			0.9	8.6	7.3	0.97	4.3	1.12	13.0	100%
40	60	520	.85	.15	73.5	44.1	29.4			0.9	8.6	7.3	1.67	7.4	1.10	16.2	125%
40	90	0	.85	.15	73.5	66.1	7.4			0.3	9.2	7.8	0.27	0.3	1.10	8.9	78 %
40	90	260	.85	.15	73.5	66.1	7.4			0.3	9.2	7.8	0.97	1.1	1.28	11.4	100%
40	90	520	.85	.15	73.5	66.1	7.4	12.75	9.5	0.3	9.2	7.8	1.67	1.9	1.22	11.8	104%

Annex II

RELATIVE TOLERANCE OF CROPS TO SALT

FRUIT CROPS		
High salt tolerance	Medium salt tolerance	Low salt tolerance
Date palm	Pomegranate Fig Olive Grape Cantaloup	Pear Apple Orange Grapefruit Prune Plum Almond Apricot Peach Strawberry Lemon Avocado
VEGETABLE CROPS		
EC_{dw} = 12 mmhos/cm Garden beets Kale Asparagus Spinach	EC_{dw} = 10 mmhos/cm Tomato Broccoli Cabbage Bell pepper Cauliflower Lettuce Sweet corn Potatoes (White rose) Carrot Onion Peas Squash Cucumber	EC_{dw} = 4 mmhos/cm Radish Celery Green beans
EC_{dw} = 10 mmhos/cm	EC_{dw} = 4 mmhos/cm	ED_{dw} = 3 mmhos/cm

FORAGE CROPS		
High salt tolerance	Medium salt tolerance	Low salt tolerance
EC_{dw} = 18 mmhos/cm	EC_{dw} = 12 mmhos/cm	EC_{dw} = 4 mmhos/cm
Alkali sacaton	White sweetclover	White Dutch
Saltgrass	Yellow sweetclover	Clover
Nuttall Alkali grass	Perennial ryegrass	Meadow foxtail
Bermuda grass	Mountain brome	Alsike clover
Rhode grass	Strawberry clover	Red clover
Rescue grass	Dallis grass	Ladino clover
Canada wildrye	Sudan grass	Burnet
Western wheatgrass	Hubam clover	
Barley (hay)	Alfalfa (California common)	
Bridsfoot trefoil	Tall fescue	
	Rye (hay)	
	Wheat (hay)	
	Oats (hay)	
	Orchard grass	
	Blue grama	
	Meadow fescue	
	Reed canary	
	Big trefoil	
	Smooth brome	
	Tall meadow oatgrass	
	Cicer milkvetch	
	Sourclover	
	Sickle milkvetch	
EC_{dw} = 12 mmhos/cm	EC_{dw} = 4 mmhos/cm	EC_{dw} = 2 mmhos/cm

FIELD CROPS

High salt tolerance	Medium salt tolerance	Low salt tolerance
EC_{dw} = 16 mmhos/cm	EC_{dw} = 10 mmhos/cm	EC_{dw} = 4 mmhos/cm
Barley (grain)	Rye (grain)	Field beans
Sugar beet	Wheat (grain)	
Rape	Oats (grain)	
Cotton	Rice	
	Sorghum (grain)	
	Corn (Field)	
	Flax	
	Sunflower	
	Castor beans	
EC_{dw} = 10 mmhos/cm	EC_{dw} = 6 mmhos/cm	

ED_{dw} = electric conductivity of drainage water (= EC_e)

<u>Reference</u>: Agriculture Handbook no. 60 Diagnosis and Improvement Saline and Alkali Soils. February 1954

Annex III

CALCULATION EXAMPLE OF THE PROBABILITY ANALYSIS OF THE AREA WHICH CAN BE IRRIGATED BY A SPECIFIC WINDMILL WITH A CERTAIN ROTOR DIAMETER AND CONNECTED WITH A SUITABLE PISTON PUMP. (See section 2.3.3.)

Suppose meteorological data of 15 years are available for 4 months of the year which have a rainfall deficit. These data are adjusted for their real contribution to the soil moisture content, thus:

Pe = effective precipitation (mm/month)
ETo = reference cropwater use of a full covering, healthy crop (mm/month)
Ie = effective irrigation (monthly windmill output minus irrigation losses (mm/month)
Z = the change in soil moisture content (mm)

ETo-Pe represents the net irrigation requirement.

$\frac{Ie}{ETo-Pe}$ represents the acreage which can be irrigated by one windmill.

Calculation of the 75% probability, that a certain area can be irrigated by the windmill is done as follows:

$$fi = \frac{i \times 100\%}{n + 1}$$

where fi = probability of occurrence (%)
i = rank number in the climbing sequence of the data
n = no. of data available.

In this calculation: n = 15

$$f1 = \frac{1 \times 100}{16} = 6.25\ \%$$

$$f2 = \frac{2 \times 100}{16} = 12.50\ \%$$

$$f4 = \frac{4 \times 100}{16} = 25.00\ \%$$

In this case rank no. 4 represents the command area of the windmill, which can be irrigated at least 3 out of 4 years. This will be surpassed in 100% - 25% = 75% of the years. So the 4th-lowest data represents the 75% probability level in this case.

In the first round, the reference crop evapotranspiration (ETo) is used, to find the critical-month with regard to the command area of the windmill pump unit.

MARCH						APRIL				
n (years)	Pe (mm)	ETo (mm)	ETo-Pe (mm)	Ie (mm/ha)	Ie / ETo-Pe (ha)	Pe (mm)	ETo (mm)	ETo-Pe (mm)	Ie (mm)	Ie / Eto-Pe (ha)
1	100	100	0	90	***	102	128	26	83	3.2
2	206	86	-120	76	***	89	131	42	110	2.6
3	102	90	- 12	103	***	109	120	11	120	10.9
4	84	133	49	93	1.9(3)*	63	148	85	76	0.9(1)
5	104	120	16	99	6.1	78	110	32	99	3.0
6	34	141	127	106	0.8(1)	100	113	13	111	8.5
7	102	118	16	105	6.6	39	129	90	94	1.0(2)
8	143	125	- 17	83	***	68	140	72	115	1.6
9	101	105	4	92	23	112	99	- 13	143	***
10	73	131	58	66	1.1(2)	131	155	24	95	3.9
11	113	127	14	83	5.9	63	143	80	123	1.5(4)
12	111	113	2	98	4.9	112	119	7	118	16.8
13	103	133	30	104	3.5	118	138	20	131	6.6
14	89	118	29	58	2.0(4)**	83	164	81	93	1.1(3)
15	110	123	13	68	5.2	111	123	12	75	6.2

MAY						JUNE				
1	23	133	110	168	1.5	13	148	135	93	0.7
2	18	118	100	183	1.8	28	153	125	73	0.6
3	0	174	174	124	0.7(1)	0	123	123	100	0.8
4	43	108	65	133	2.0	0	175	175	115	0.7
5	17	133	116	188	1.6	14	168	154	83	0.5(2)
6	15	145	130	201	1.5	3	183	180	125	0.7
7	33	99	66	133	2.0	11	145	134	99	0.7
8	8	125	117	199	1.7	33	123	90	110	1.2
9	61	138	77	211	2.7	0	188	188	78	0.4(1)
10	0	143	143	179	1.2(3)	0	193	193	95	0.5(3)
11	0	164	164	148	0.9(2)	7	146	139	88	0.6(4)
12	14	141	137	215	1.6	13	139	126	93	0.7
13	37	108	71	175	2.3	5	173	168	105	0.6
14	19	133	114	193	1.7	33	168	135	113	0.8
15	10	121	111	161	1.5(4)	0	160	160	108	0.7

* Figures between brackets are the first 4 rank numbers of the ascending sequence in that column.

** Figures in the squares are the areas which can be irrigated by the windmill in (100-25) 75% of the years.

*** No need for irrigation; ETo-Pe ≤0.

Explanation: The 4th rank of the ascending sequence presents the command area which will be realized in at least 25% of the years. So a larger command area will be realized in (100-25) 75% of the years.

Here: in March 2.0 ha; April 1.5 ha; May 1.5 ha; June 0.6 ha. The month of June is the critical month with regard to the size of command area.

Knowing now that the month of June is critical and on the ground of all kinds of other considerations (chapter 2), it is assumed that the following crops can be grown:

Vegetables:	March - May 25% of the area
Sugar cane:	February - January 50% of the area
Cotton:	January - May 25% of the area
Maize:	June - September 50% of the area

This will give the following crop plan and average kc value (see tabel 2.1 in section 2.1.1.):

		March	April	May	June
A	25%	vegetables			Maize
R	25%	cotton			
E A	50%	sugar cane			
kc veg/maize		0.7	1.0	1.0	0.3
kc cot/maize		1.0	0.8	0.6	0.3
kc sugar c.		0.5	0.7	0.9	1.0
kc sugar c.		0.5.	0.7	0.9	1.0
kc average		0.67	0.80	0.85	0.65

Furthermore, it is assumed that leaching is not required, due to abundant rainfall after June and since the month of June is cirtical, a soil water depletion (Δz) of 50 mm at the end of that month will be allowed for sugar cane (deep rooting crop, abundant rainfall in next month). Since sugar cane covers 50% of the area, Δz will be 50% of 50 mm = 25 mm.

Again, it is stressed here that these are only assumptions for this calculation model. What is actually possible under the given circumstances in a specific area, has to be thoroughly investigated.

With these modifications a new probability analysis can be made with:

ETcrop = kc.ETo, and

ETcrop - Pe-ΔZ now representing the net irrigation requirement (ΔZ only in the month of June.)

MARCH

n (years)	Pe (mm)	ETcrop (mm)	ETcrop-Pe (mm)	Ie (mm/ha)	Ie / ETcrop-Pe (ha)
1	100	67	- 33	90	---
2	206	58	-148	76	---
3	102	60	- 42	103	---
4	84	89	5	93	18.6(3)
5	104	80	- 24	99	---
6	34	94	60	106	1.8(1)
7	102	79	- 23	105	---
8	143	84	- 59	83	---
9	101	70	- 31	92	---
10	73	88	15	66	4.4(2)
11	113	85	- 28	83	---
12	111	76	- 35	98	---
13	103	89	- 14	104	---
14	89	79	- 10	58	---
15	110	82	- 28	68	---

APRIL

Pe (mm)	ETcrop (mm)	ETcrop-Pe (mm)	Ie (mm/ha)	Ie / Etcrop-Pe (ha)
102	102	0	83	---
89	105	16	110	7.0
109	96	- 13	120	---
63	118	55	76	1.4(2)
78	88	10	99	9.9
100	90	- 10	111	---
39	103	64	94	1.5(2)
68	112	44	115	2.6
112	79	- 33	143	---
131	124	- 7	95	---
63	114	51	123	2.4(4)
112	95	- 17	118	---
118	110	- 8	131	---
83	131	48	93	1.9(3)
111	98	- 13	75	---

MAY

n (years)	Pe (mm)	ETcrop (mm)	ETcrop-Pe (mm)	Ie (mm/ha)	Ie / ETcrop-Pe (ha)
1	23	113	90	168	1.9
2	18	100	82	183	2.2
3	0	148	148	124	0.8(1)
4	43	92	49	133	2.7
5	17	113	96	188	2.0
6	15	123	98	201	1.9
7	33	84	51	133	2.6
8	8	106	98	199	2.0
9	61	117	56	211	3.7
10	0	122	122	179	1.5(3)
11	0	131	131	148	1.1(2)
12	14	120	106	215	2.0
13	37	92	55	175	3.2
14	19	113	95	193	2.1
15	10	102	92	161	1.8(4)

JUNE						
n	Pe	ETcrop	ΔZ	ETcrop-Pe Δz	Ie	Ie / Etcrop-Pe-Δz
(years)	(mm)	(mm)	(mm)	(mm)	(mm/ha)	(ha)
1	13	96	25	58	93	1.6
2	28	99	25	46	73	1.6
3	0	80	25	55	110	2.0
4	0	114	25	89	115	1.3(4)
5	14	109	25	70	83	1.2(3)
6	3	119	25	91	125	1.4
7	11	94	25	58	99	1.7
8	33	80	25	22	110	5.0
9	0	122	25	97	78	0.8(1)
10	0	125	25	100	95	0.9(2)
11	7	94	25	62	88	1.4
12	13	90	25	52	93	1.8
13	5	112	25	82	105	1.3
14	33	109	25	57	113	2.2
15	0	104	25	79	108	1.4

From these calculations it can be concluded that the command area of the windmill, with this crop plan and soil moisture depletion, can be 1.3 ha in the critical month of June. This area can be irrigated in 75% of the years.
It is obvious that when land is in abundance the command area can be expanded during the other months. During the month of March there will be no need for irrigation in 3 out of 4 years.

If there are possibilities to reduce the irrigation requirements further during the month June, the windmill command area can be increased even more. (c.q. planning of a harvest in June, or 1 month delayed sowing of maize.) This can only be considered in the perspective of the crop plan for a whole year. A new calculation round will show the effect of the modification in the command area.

Annex IV

FORMULAE AND CALCULATION EXAMPLES FOR ECONOMIC ANALYSES OF WINDMILL IRRIGATION

DISCOUNTING

Discounting is the process of reducing future costs and benefits to present values.
Since costs and benefits are mostly unevenly spread over a number of years, discounting to the present value is required for proper comparison of both.
Present costs and benefits are valued higher than future costs and benefits.
The discount rate used is about equal to the interest rate of bank loans.
e.g. An income in next year of Rs.* 1000 is at present valued lower than Rs. 1000 in this year, since the same amount can be obtained also by putting now Rs. 909 in a saving account with 10% interest (Rs. 909 x (1+0.1) = Rs. 1000).
The same applies for costs. A cost outlay of Rs. 1000 next year has a present value of Rs. $\frac{1000}{(1+i)}$ this year (i = discount rate).
A cost outlay of Rs. 1000 after 2 years will have a present value of Rs. $\frac{1000}{(1.1)^2}$ = Rs. 826 this year. (i = 10%).

ANNUAL PRICE RISE

Suppose the price of diesel will rise annually by 10% in real terms (i.e. in excess of the inflation). Suppose the present price is Ksh.**3.50 per litre. Next year it will be: 3.50 x (1.+0.1) = 3.85.
After 2 years it will be: 3.50 x (1+0.1) x (1+0.1) = 4.23.

In formula:

Year	1	2	3...........	n
Price	$a(1+r)^1$	$a(1+r)^2$	$a(1+r)^3$	$a(1+r)^n$

where:

a = present price of diesel
r = annual price rise
n = number of years.

If all these costs have to be discounted to the present value, the formula will be:

$$\text{Present value, } P = \frac{a(1+r)^1}{(1+i)^1} + \frac{a(1+r)^2}{(1+i)^2} + \frac{a(1+r)^3}{(1+i)^3} + \ldots\ldots\ldots\ldots + \frac{a(1+r)^n}{(1+i)^n}$$

*) Rs. = Indian Rupies; 8Rs. ≅ 1 $US (1980)
**) Ksh. = Kenyan Shilling; 8Khs. ≅ 1 $US (1980)

Calculation example:
Suppose the diesel pumpset in the cost comparison calculation uses 1000 l. of diesel per annum and the annual price rise is 15%. The present price is Ksh. 3.50/l. So the cash outlay is now: (1000 x 3.50) = Ksh. 3500. A discount rate of 10% will be used.
The present costs of the 1000 l/year over a period of 4 years is:

$$P = 3500 \times \frac{1.15^1}{1.10^1} + 3500 \times \frac{1.15^2}{1.10^2} + 3500 \times \frac{1.15^3}{1.10^3} + 3500 \times \frac{1.15^4}{1.10^4} = \text{Ksh. } 15,665$$

So, if the farmer wants to be sure that he will be able to buy the required 1000 liter of fuel, he has to put now (theoretically) Ksh. 15.655 in a saving deposit with an interest rate of 10%. During the 4 years he can withdraw the required amount for buying the fuel. Of course this is not the way the farmer will act, but these kinds of calculations are carried out in order to obtain a real economic comparison.

Thus with the discounted costs and benefits, a comparison between the different alternatives can be made. This is also the essential point in the calculation of the Internal Rate of Return I.R.R., as discussed in section 4.2.2.
Often it may also be important to know the annual costs of the devices for different annual output levels. Therefore the capital recovery factor is introduced.

CAPITAL RECOVERY FACTOR
The capital recovery factor gives the fraction of the present value which has to be paid in annual instalments to repay the initial amount and the compounded interest.
In formula: $x = \dfrac{i.(1+i)^n}{(1+i)^n-1}$

where: x = the capital recovery factor
i = the discount rate (or interest rate)
n = number of years of calculation, or repayment.

Example.
Suppose a windmill unit costs: Rs. 10,000 and will work for 15 years (n = 15). The interest rate will be 12%.
The capital recovery factor is $\dfrac{0.12 \times (1+0.12)^{15}}{(1+0.12)^{15}-1} = 0.147$
So the annual costs over a period of 15 years are: Rs. 10,000 x 0.147 = Rs. 1470 per annum. (Compare this figure with the calculation of the farmers loan repayment in section 4.2.3.)

CALCULATION EXAMPLE OF ANNUAL COSTS

Here a presentation is made of the basic cost calculations needed for the comparison of different devices, at different output levels.

Firstly some estimates with regard to output levels, lifespan and repair- and maintenance costs for small waterlifting devices are given:

	Diesel pumpset	Petrol pumpset	Electric pumpset	Windmill pumpset
Energy/l.fuel	3KWH	2.3KWH	----	----
Total Efficiency	30-50%	30-50%	50-70%	20-5%
Output/l. fuel over 10m. el.head.	30-55 m^3	25-40 m^3	15-25 m^3/KWH	----
Lifespan	5,000-10,000 hours	1,000-3,000 hours	± 10,000-15,000 hours	10-20 years
Rep.+Maint.	20-50% of fuel cost	20-50% of fuel cost	10-20% of energy cost	5-10% of investement

Lifespan depends mainly on proper repair and maintenance and both depend again on the working conditions and on the quality of the used materials. Therefore local information should be collected with regard to these aspects, instead of using only these estimates.

After verifying the required variables, the calculations can be performed for the calculation of the prize per m^3, as presented in fig. 4.1. of section 4.2.1.

The windmill, pump unit.
The annual cost of four different options of a windmill pump are given in the following table, using a discount rate of 10% and the capital recovery formula.

The different options are:

- costs for windmill : Ksh 30,000
- costs for tank : Ksh 10,000-20,000
- lifespan : 10-20 years
- cost for maintenance: Ksh 1500 per year

	OPTIONS			
	1	2	3	4
Windmill (Shs)	30,000	30,000	30,000	30,000
Tank (Shs)	10,000	20,000	10,000	20,000
Lifespan (Years)	10	10	20	20
Cap. rec. factor	0.1627	0.1627	0.1175	0.1175
An. fixed cost (Shs)	6,508	8,135	4,700	5,875
An. repair cost (Shs)	1,500	1,500	1,500	1,500
Total an. cost (Shs)	8,008	9,635	6,200	7,375

The annual costs for four different options, at different output levels, of a windmill pump unit.

The diesel pump unit.
The different options are here: Lifespan: 10-20 years
Ann. fuel price rise: 10-20%
The actual fuel cost per m^3 water pumped over a head of 5 m. is:
1 litre fuel to 110 m^3. Price per litre diesel: Ksh. 3.75. So the actual cost per m^3 is Ksh. 0.0341.
Lubrication costs are estimated at 10% of the fuel cost.
So the total costs are: (0.0341x1.1)=Ksh 0.0375 per m^3 water pumped by the unit. Since prices for lubrication-oil are closely linked with the fuel prices, this latter figure will be used for the further calculations with regard to the annual fuel price rise.
The calculation of the annual fuel costs for the two different price increase rates and lifespans are calculated in the table given below.
The capital recovery formula is used here again, using a discount rate of 10%.

	OPTIONS			
	1	2	3	4
Ann. fuel price inc.	10%	10%	20%	20%
Lifespan (years)	10	20	10	20
Present value (Shs)	0.3750	0.7500	0.6242	2.1144
Capital recovery factor	0.1627	0.1175	0.1627	0.1175
Annual fuel cost/m^3 (Shs)	0.06	0.09	0.10	0.25

With these figures and the investment costs for the pumpset and pumphouse, the total annual costs for the four options can be calculated for different output levels, as presented in the following table. For annual repair and maintenance costs a fixed amount of 5% of the investment costs has been assumed here, recalculated to cost per m^3.

		OPTIONS			
		1	2	3	4
Diesel pumpset	(Shs)	30,000	30,000	30,000	30,00
Pumphouse	(Shs)	20,000	20,000	20,000	20,000
Lifespan	(Years)	10	20	10	20
Capital rec. factor		0.1627	0.1175	0.1627	0.1175
Annual fixed costs	(Shs)	8.135	5.875	8.135	5.875
Annual fuel price rise		10%	10%	20%	20%
Fuel costs/m^3	(Shs)	0.06	0.09	0.10	0.25
Rep.+Maint. cost/m^3	(Shs)	0.01	0.02	0.01	0.02
Total ann. costs	(Shs)				
at 20,000 m^3/year		9,535	8,075	10,335	11,275
40,000 m^3/year		10,935	10,275	12,535	16,675

The same procedure can be followed for petrol pumpsets and electrical ones.

COST-BENEFIT CALCULATION FOR FOUR DIFFERENT WATERLIFTING DEVICES AND RAINFED AGRICULTURE

Before such a calculation can be started, all kind of data have to be collected on costs and benefits and on the expected trends in both in the future. Crop plans have to be developed and the net benefits calculated, including a learning period etc.

There is no need to go into much detail, which will not increase the accuracy due to many possible unpredictable developments.

e.g. If the real benefits after 10 years differ Rs. 500 with your estimation, the effect on the actual value is $\frac{500}{1.1^{10}} = 200$ at a discount rate of 10%.

We will give a simple calculation example based on fictive date, to illustrate the calculation process. The Internal Rate of Return will be calculated here for the total investment in agricultural equipment and not only for the irrigation device.

Assumptions:
- We want to start with agriculture on 1 ha. of good soil in North India.
- Required farm equipment: 1 pair of bullocks with plough, mouldboard etc.. Investment Rs. 2000, lifetime 5 years. So additional investment of Rs. 2000 in the 6th year.
- Irrigation with bullocks requires a well (Rs. 2000).

- Irrigation with windmills, diesel or electric pumpsets requires a tubewell in addition to the well: (Rs. 2000).
- Windmills + tank: Rs. 10,000; Diesel pumpsets + shed: Rs. 8000; Electrical pumpset + farm power line + shed: Rs. 10,000. All irrigation devices will last 10 years.
- Engines and pumpsets are only used for irrigation of this 1 ha.

Investment costs and annual costs of the farm equipment and the irrigation device:

Year	0	1	2	3	4	5	6	7	8	9	10
Rainfed	2000	-	-	-	-	-	2000	-	-	-	-
Bullock	4500	100	100	100	100	100	2100	100	100	100	100
Windmill	16000	300	300	300	300	300	2300	300	300	300	300
Diesel	14000	850	900	950	1050	1100	3200	1250	1350	1500	1600
Electric	16000	800	850	875	900	950	3000	1000	1050	1100	1200

Notes: 1) annual costs of bullock and windmill: only repair and maintenance costs

2) annual costs of diesel and electric pumpset include repair and maintenance costs and fuel costs.
An annual rise in fuel costs is assumed to be ± 10% for diesel and ± 5% for the electricity charges.
This is in addition to inflation, which is not included in this type of calculation.

Net benefits of 1 ha of agriculture (Rs) over 10 years.

Year	0	1	2	3	4	5	6	7	8	9	10
Rainfed	-	500	505	510	515	520	525	530	535	540	550
Bullock	-	1000	1010	1020	1030	1040	1050	1060	1070	1080	1090
Windmill	-	2000	2200	2400	2650	2900	2950	2990	3020	3050	3080
Diesel	-	2500	2750	3000	3300	3650	3700	3740	3770	3810	3850
Electric	-	2500	2750	3000	3300	3650	3700	3740	3770	3810	3850

Notes : 1) rainfed and bullock irrigation are known practices for the small farmer. There will be no learning process. Only an annual production increase of ± 1% is assumed here

2) windmill, diesel and electrical irrigation is new and a learning process of 5 years is assumed, with an annual increase of ± 10%. After the 5th year it will be ± 1%.

Calculations of the internal rate of return can be started now, following the process of trial and error as demonstrated in section 4.2.2.

The results of this calculation process are:

	Rainfed	Charsa	Windmill	Diesel	Electric
I.R.R.	8-9%	9-10%	5-6%	7-8%	6-7%

Let us suppose now that we have a 2 ha plot which can be irrigated with the same irrigation devices, without additional investments.
Investment costs and annual costs for the windmill and the diesel- and electrical pumpset per ha, if the command area is 2 ha.

	0	1	2	3	4	5	6	7	8	9	10
Windmill	8000	150	150	150	150	150	2150	150	150	150	150
Diesel	7000	850	900	950	1050	1100	3200	1250	1350	1500	1600
Electric	8000	400	425	450	475	500	2500	525	550	575	600

Note: Electricity charge is a fixed charge per month, so the annual cost per ha for an electrical pumpset will decrease.

The benefits per ha will remain the same.
The calculations of the Internal Rate of Return give the following results:

	Windmill	Diesel	Electric
I.R.R.	20-22%	23-24%	25-26%

So depending on the local conditions, the I.R.R. will change. Thus it is important to obtain the most reliable data possible.
Other examples: The use of engines for both purposes besides irrigation.
Change in net benefits, or the possibility of.
Off-farm employment of men and/or bullocks.

By introducing other crop plans or price rises of inputs (fuel) or outputs (selling prices), and performing the calculations again, the sensitivity of these assumptions can be studied.

SWD

STEERING COMMITTEE
WINDENERGY
DEVELOPING COUNTRIES

P.O. BOX 85
3800 AB AMERSFOORT
THE NETHERLANDS

A brief introduction to the Netherlands program for assistance to developing countries in the utilization of wind energy.

August 1982

The basis for a sound economic development of many countries in the Third World is the development of agriculture. The oil crisis in 1973 once again stressed the vital role of energy in this development process and thus caused a world-wide revival of the interest in the utilization of renewable energy sources. In the Netherlands wind energy still appeals to many people and in 1974 a study was made to analyse the possibilities of utilizing wind energy in developing countries. It appeared that in many countries wind energy could play an important role in satisfying the energy need for water pumping, particularly for irrigation purposes.

In July 1975 the Steering Committee Wind Energy Developing Countries (SWD) was established by the Netherlands Minister for Development Co-operation. SWD promotes the interest for wind energy in developing countries and aims to help governments, institutions and private parties in the Third World with their efforts to utilize wind energy.

The SWD pursues this aim in three ways:

1. provision of assistance to wind energy projects in developing countries
2. wind energy research, mainly undertaken in the Netherlands
3. transfer of knowledge on wind energy use.

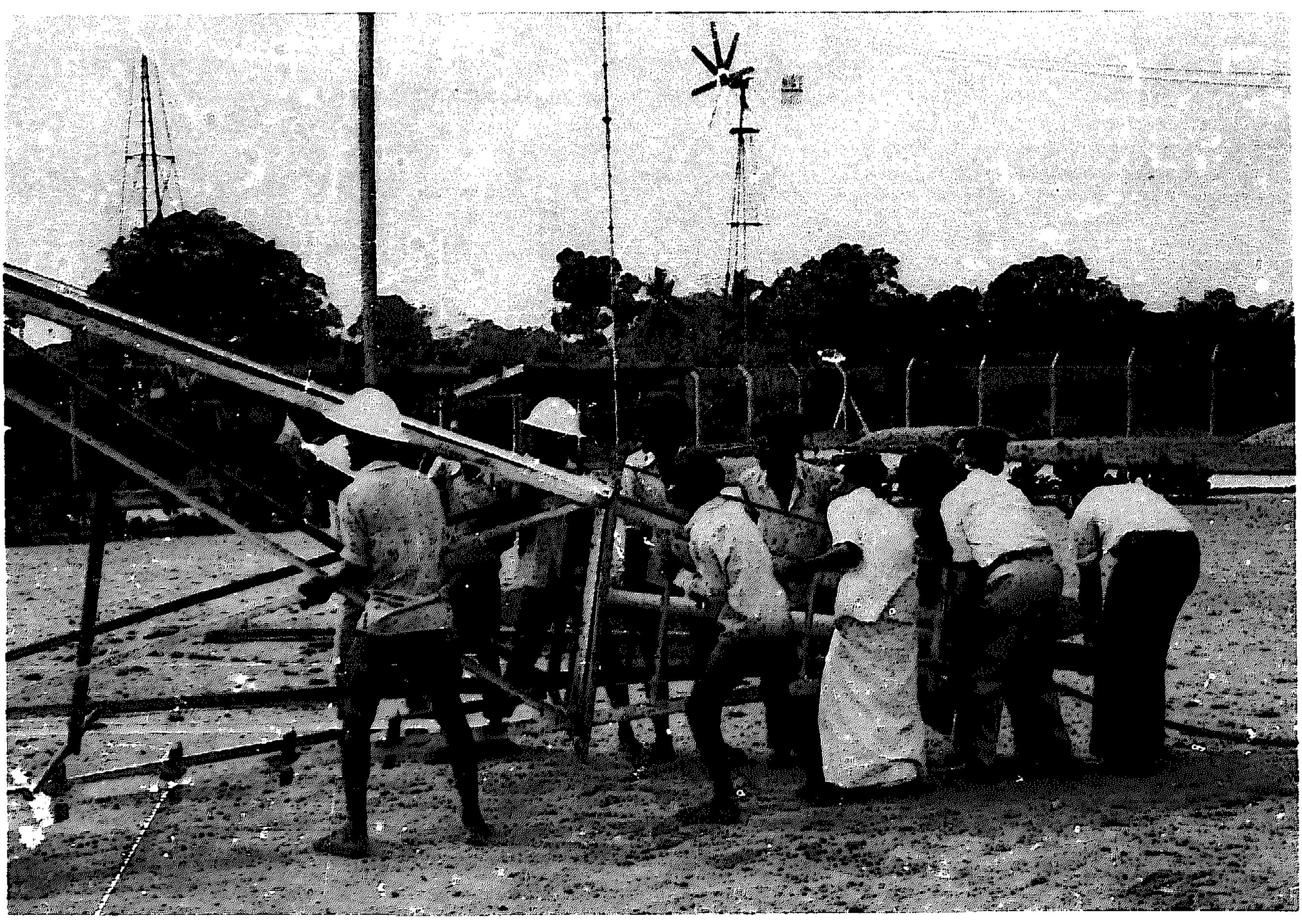
The parties that currently participate in SWD are:

Eindhoven University of Technology (Wind Energy Group)
Twente University of Technology (Windmill Group)
DHV Consulting Engineers.

Each participant has its own, more or less well defined, field of research and the co-ordination is in the hands of DHV Consulting Engineers.

In the field of agriculture SWD closely collaborates with the Institute of Land Reclamation and Improvement (ILRI).

SWD has regular contacts with the Working Group on Development Technology (WOT) at Twente University. Also contacts exist with the Dutch national wind energy research program, co-ordinated by the Energy Research Centre (ECN).



The installation of a Ø 5 m windmill in Colombo, Sri Lanka; in the background the Ø 2 m WEU I windmill

RESEARCH ACTIVITIES

The research activities are undertaken with the following purposes:

- to develop windmill components as well as complete prototypes
- to support the country projects
- to train future experts for country projects

Rotors

A large number of rotors have been designed and tested, both at open air test stands and in a large windtunnel. Good results have been achieved with horizontal axis curved metal plate rotors, as predicted by theory. For low Reynolds numbers (< 100,000) curved plate profiles turn out to be better than airfoils.
Designing with higher tip speed ratios (λ>1) results in lighter rotors and thus lighter and cheaper windmills.

Pumps

The optimum matching of a pump to the quadratic torque-speed characteristic of a wind rotor has been pursued by the development of variable torque reciprocating pumps and the application of centrifugal pumps. This optimum matching results in much higher overall outputs than with the traditional (constant torque) piston pumps. The closing of valves and the operation of air chambers has been analyzed.

Generators

For deep wells electrically driven pumps are considered as a serious alternative to direct mechanically driven pumps. Two types of generators have been tested to drive these pumps:

- a self exciting induction generator
- an induction generator equipped with a permanent magnet rotor

Also two control systems for alternators have been developed.

Safety Systems

A reliable safety system has been developed and tested for wind speeds up to 30 m/s. The system operates by means of a small auxiliary vane that pushes the rotor out of the wind against the normal directional vane that is hinged on a leaning axis. A complete theoretical model is being studied.

Wind measurement

An electric counter with extremely low energy consumption has been developed for contact-anemometers.

Theory

Theoretical models have been developed or refined on:

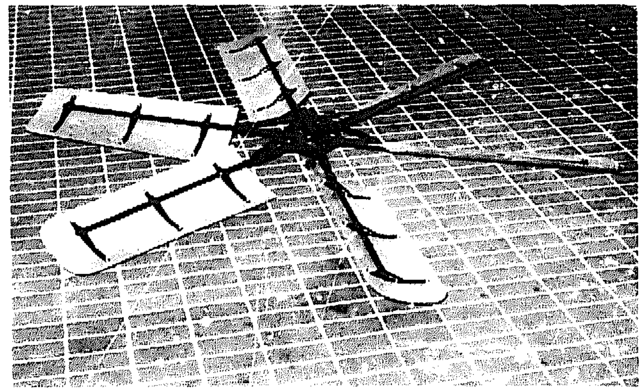
- rotor performance
- forces on rotor blades
- output in different wind regimes
- matching of rotor with generator or pump
- dynamic behaviour of pumps.

Windmill prototypes

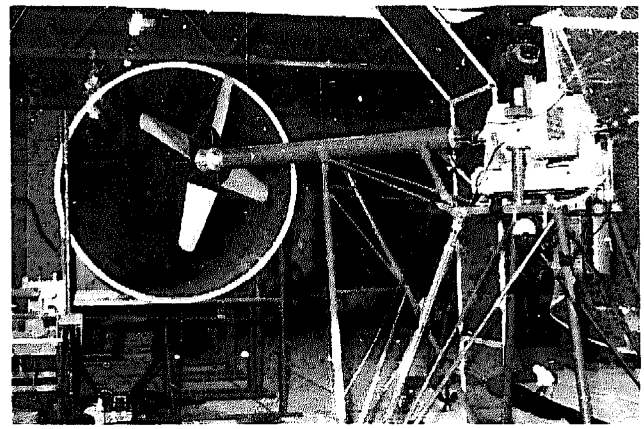
The following prototypes have been developed:

	diameter	number of blades	tip speed ratio	remarks
SWD 2740	2.74 m	6	2	piston pump
SWD 4000	4.00 m	8	2	piston pump
SWD 5000 RS[1]	5.00 m	4	5	centrifugal pump. Rotating Shaft
WEU I	3.00 m	6	2	piston pump
WEU II[2]	5.00 m	8	2	piston pump
Cretan[3]	6.00 m	8	1	piston pump
Under development				
SWD 5000 HW	5.00 m	8	2	piston pump, for High Wind regime
SWD 5000 LW	5.00 m	8	2	piston pump, for Low Wind regime
SWD 2000	2.00 m	6	2	piston pump
SWD 1000 EL	1.00 m	2	4	Electricity generation

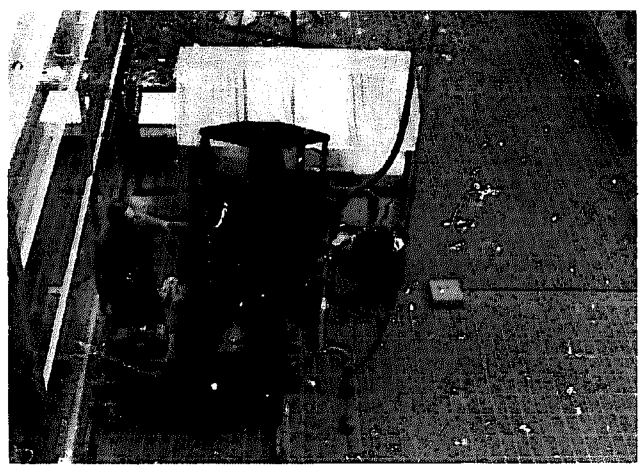
[1] developed as testmodel only
[2] partially based on WOT-designed 12 PU 500



Rotor of SWD 2740 prototype



Windtunnel (Ø 2.2 m) at Delft University of Technology for testing rotor models



Pump test stand at Eindhoven University of Technology

Project for rural watersupply and irrigation on the Cape

Prototype installed in Hammamet, Tunisia, irrigating an orchard.

COUNTRY PROJECTS

SWD gives assistance in the execution of wind energy programmes in close co-operation with interested ministries, institutions or private parties. The country projects encompass assistance in a number of fields:

— measurement and analysis of wind data
— selection of favourable areas
— selection and construction of prototype windmills
— training and education in the field of wind energy
— selection of application purposes
— organisation of pilot projects.
— maintenance
— agricultural application analysis
— production engineering assistance
— economic programming and
— credit systems

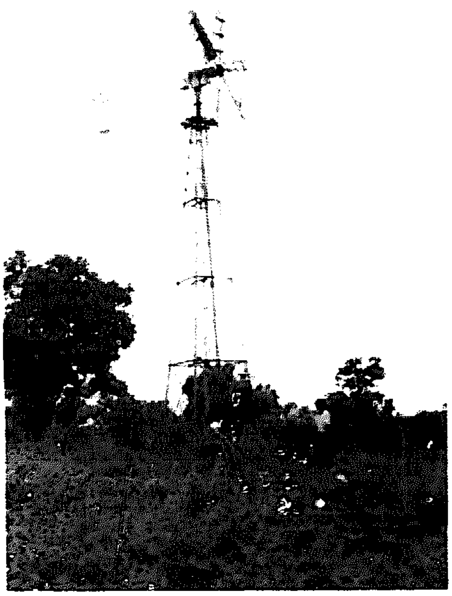
The guiding principles for the country projects are:

— water pumping has the highest priority
— local production of as many components as possible
— construction methods and materials must be appropriate to the local technical level.

SWD is involved in projects in the following countries:

Sri Lanka

In March 1977 the Wind Energy Utilization Project was started with financial support from the governments of Sri Lanka and the Netherlands. The execution is in the hands of the Wind Energy Unit of the Water Resources Board.
The project is staffed by Sri Lankan engineers, technicians, workers and two SWD experts (wind energy and agriculture). In 1981 50 WEU-I prototypes were installed in pilot projects and private farms. In 1982 this program has been extended with another 180 windmills, to be produced by small and medium scale workshops. Subsidies have been arranged for this program.



WEU-I prototype irrigating in Sri Lanka

Republic of Cape Verde

Since 1981 SWD supplies two wind experts in a large renewable energy project with emphasis on wind power, executed by the Ministry of Rural Development. The project focusses on training of staff in installation, repair and maintenance of windmills.
A high-wind-prototype for waterlifting of 5 m diameter is under development.

Pakistan

Stimulating contacts with Merin Ltd. in Karachi led to SWD's consultancy to start production of windmills. The WEU-I prototype developed in Sri Lanka was selected and in 1980 a SWD expert paid a three-month visit for technical assistance.

Tanzania

The Ujuzi Leo Industries in Arusha have been supported in improving their windmill design via a two-month course in the Netherlands and short-term expert visits.

Tunisia

In support of the ASDEAR (Association pour le développement et l'animation rurale) SWD supervised in 1980 the construction of three SWD 4000 prototypes as a start of production in series by a local entrepreneur.

Peru

As a part of an agricultural project, supported by the Netherlands Ministry of Development Co-operation, a SWD 2740 prototype has been built. Since 1981 technical backstopping has been given to a Dutch expert in a bilateral co-operation program.

Feasibility Studies

SWD has carried out feasibility studies on the use of wind energy in the following countries or areas:
Sri Lanka (1976), Cape Verde (1980), Tanzania (1977), The Sahel (1976), Djibouti (for GTZ, 1981), Yemen Arab Republic (1980), Sudan (1980), Maldives (for ADB, 1980), Kenya (1982), Netherlands Antilles (1982).

Explaining the particulars of windmill

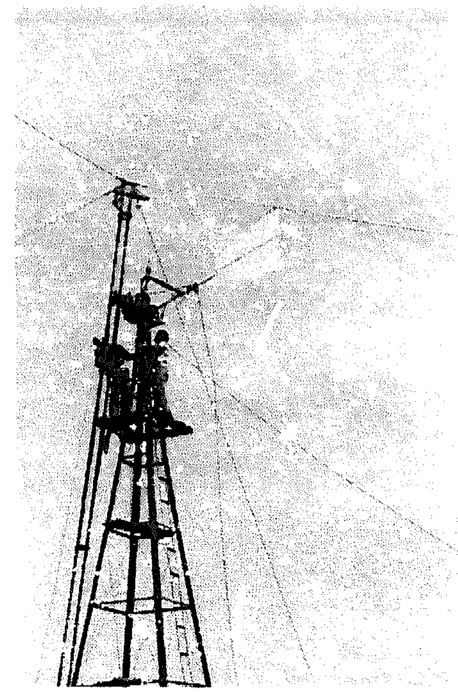
TRANSFER OF KNOWLEDGE

Local knowledge is gathered in country projects and during visits of experts from abroad. Particularly the failures of windmill projects in the past deserve great attention. A first analysis of the causes for failure resulted in the following list:
- import restrictions on spare parts
- lack of funds
- lack of local know-how and of care for maintenance
- introduction of (subsidized) electric and diesel pumps
- drop of ground water table
- reduction on the number of windmills, making repair a non profitable job
- fear for repairs on top of a high tower
- termination of production and of supply of parts by manufacturers.

Knowledge in wind energy technology and related fields is transferred by SWD to developing countries by:
- publications
- drawings and construction manuals of prototypes
- visits and consultancies
- education and training

SWD also functions as a clearing-house for information and experience with wind energy systems: the experience with the WEU 1/3 windmill in Sri Lanka has been transferred to Pakistan for example.

Another facet is the supply of experts for lecturing purposes such as for the six-month UN-ESCAP Roving Seminar on Rural Energy Development in 1977. In the summer of 1980 and 1981 SWD sent an expert to the Asian Institute of Technology, Bangkok, to give introductory and advanced courses on wind energy and to coach MSc students.



Installation of windmills on Cape Verde.

PUBLICATIONS

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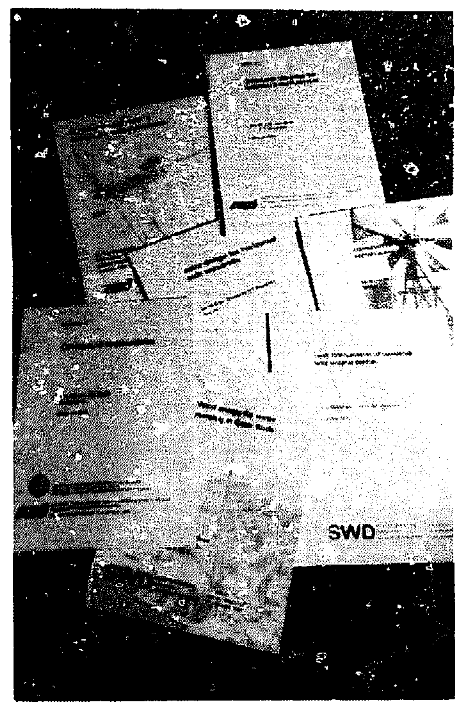

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ADDRESSES

General address SWD:

DHV Consulting Engineers	P.O. Box 85, 3800 AB Amersfoort	The Netherlands, Tel.: 033 - 68 91 11/ 68 23 66 Telex 79348 dhv nl

Addresses of the other participants:

Eindhoven University of Technology Wind Energy Group	Department of Physics, Building W & S P.O. Box 513, 5600 MB Eindhoven	The Netherlands, Tel.: 040 - 47 2160
Twente University of Technology Windmill Group	Department of Mechanical Engineering P.O. Box 217, 7500 AE Enschede	The Netherlands, Tel.: 053 - 89 40 98

Address of ILRI:

International Institute for Land Reclamation and Improvement	P.O. Box 45, 6700 AA Wageningen	The Netherlands, Tel.: 08370 - 19100

Address of WOT:

Working Group on Development Technology (WOT)	Twente University of Technology Vrijhof 152, P.O. Box 217, 7500 AE Enschede	The Netherlands, Tel.: 053 - 89 38 70

Address of ECN:

National Energy Research Centre (ECN)	P.O. Box 1, 1755 ZG Petten	The Netherlands, Tel.: 02246 - 62 62

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SWD 79-1	**Catalogue of Windmachines. By L.E.R. van der Stelt & H. Wanders, 44 p., September 1979 (WOT/SWD)** Inventory of commercially available windmills for water pumping and electrically generation based on data of manufacturers; with addresses.	4.-	9,-
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SWD 81-2	**Wind energy in Sudan. By Dr. Yahia H. Hamid & W.A.M. Jansen, 71 p., July 1980.** Report on the windmill potential in Sudan detailing energy situation, wind and water situation and cost aspects, as well as a proposal for a wind energy centre in Sudan.	6.-	15,-

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SWD-81-3	**Energia eólica para a bombagem de água em Cabo Verde (versao portuguesa de SWD 81-1).** **Por H.J.M. Beurskens, 162 p., Fevereiro de 1981.** Estudo de actividades actuais de energia eõlica em Cabo Verde, recursos de agua freãtica, utilização e aspectos econõmicos de energia eõlica. E elaborado uma proposta de projecto.	14.-	34,-
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ADDITIONAL INFORMATION ON THE PUBLICATION CWD 81-4

'ASPECTS OF IRRIGATION WITH WINDMILLS'

1. INTRODUCTION

The publication 'Aspects of irrigation with windmills' has been written in 1980. At that time only limited experience was gained in the field of irrigation with windmills.
From 1981 onwards C.W.D. started to cooperate closely with the Institute for Land Reclamation and Improvement (ILRI) Wageningen, The Netherlands. Research on windmill-irrigation carried out by this Institute, as well as further experiences in windmillprojects, showed that some aspects of the publication 'Aspects of irrigation with windmills' nowadays are considered to be out-dated.
Since still a lot of valuable information is given it was decided to add a short note to the publication to inform the reader on the latest information with respect to irrigation with windmills.
The remarks given below mainly deal with the relationship between wind and irrigation requirements and with the economic aspects of windmills.
For the information of the reader the ILRI reprint no. 32 'Windmills for small scale irrigation' is also added.

2. REMARKS ON THE INFORMATION GIVEN IN THE PUBLICATION

2.1. Possibility to delay the irrigation during periods of low wind

paragraph	page	alnea
Summary	4	4
2.1.1 Evapotranspiration	20	2 + 3
3.2 Variability of irrigation interval	43-48	
3.7 Summary	54	statement one and two
Annex 1-A	85-86	

In the above mentioned paragraphs of the publication it is stated that during periods of low windvelocities (resulting in a low output of the windmill) the irrigation of the crops can be delayed for several days without many problems. This is because the evapotranspiration of the crop should decrease with decreasing wind velocity. As a consequence the amount of instantly available moisture in the soil increases. Thus, the waterbalance changes in such a way that a delay of irrigation of 2-3 days is acceptable. One of the main aspects of windmill-irrigation (the variable output pattern, including days without any output) is thus reduced to a minor problem.

The above mentioned statement is proved by the influence of the wind velocity on the theoretical calculation (formula of Penman) of the evapotranspiration. By keeping all other factors constant it is found that a reduction of the wind speed with 50% reduces the evapotranspiration with 25%.
In reality, however, the evapotranspiration depends on a set of intercorrelated as well as independently varying determinants. Since wind only influences the areodynamic determinant, which varies in comparison to the radiation determinant, the influence of the wind on the evapotranspiration varies from place to place. In many places the influence of a decreasing velocity of the wind therefore will not result in a significant decreasing change in the evapotranspiration.
Even the reverse can take place, by which a decrease in the velocity of wind results in an increase of the evapotranspiration and viceversa.
In 'Plant Response to Wind', by I. Grace it is stated on page 62 that 'Under many conditions an increase in windspeed leads to reduction in transpiration rate of the crop.'
Wind can also affect the roughnes factor of the crops and thus the evapotranspiration. Wheat for instance bends during strong winds which results in a lower evapotranspiration of the crop.

The possible delay of irrigation is also based on the fact that due to

the reduction of the evapotranpiration the available moisture fraction in the soil increases. This is based on the FAO Irrigation and Drainage Paper No. 34, 1979. The possible relationship between the evapotranspiration and the 'available moisture fraction', however, still is a matter of discussion among scientists and the data presented in the FAO paper only indicate an order of magnitude. According to scientists the exact relationship is still unclear.
At this moment it should not be used in detailed calculations on possible delay of small gifts of irrigation water.

Given the fact that a reduction in windvelocity not automatically leads to a reduction in evapotranspiration and certainly not to a reduction up to 75% and also given the fact that the relationship between a reduced evapotranspiration and the instantly available moisture fraction in the soil is still under discussion, it must be concluded that the irrigation gift can not be delayed with 2-3 days just because of a period of low wind. The irregular output pattern of the wind - including days without output - surely has to be considered as one of the major problems to be solved (see also par. 2.3 of this note).

2.2 The use of a probability-analysis for the calculation of the command-area of the windmill

Paragraph	Page	Alinea/line
1.2 Selection of irrigation device	9	5-8
Agro-economical		
2.1.2 Precipitation	23	4
2.3.1 Crop selection and cropplan	32	3
2.3.3 Probability Analysis	36-38	

In the report a probability-analysis is used to calculate the command-area of the windmill, based on the assumption that wind, precipitation and evapotranspiration are closely related.

Although in very specific circumstances some relationship might be there it must be said that in general these factors are not closely related.
In using a probability-analysis wind, precipitation and evapotranspiration therefore must be looked upon as independent factors.

Besides this, the used method of a 75% probability-analysis - a standard in irrigation engineering - is much under discussion presently. The main issue is the fact that the level of probability should not be chosen beforehand but made dependable on a cost-benefit analysis (extra profit in years of high winds versus extra losses in years of low wind). A probability model which can be used for windmill-irrigation is being developed by C.W.D.

2.3 Need for a storagetank

Paragraph	Page
3.6 Need for a storagetank	53-54

The report states that a storagetank can be used to overcome windless periods of several days. This, however, is based on the assumptions as discussed in par. 2.1 of this note. Recent research has shown that storagetanks with a capacity to overcome windless periods of several days in general are too large to be economical attractive.
Computerized model study's have shown that with a tank volume of 50% of the daily output in the peak irrigation period the major problems can be solved. For Sri Lanka this resulted in a storagetank with a capacity of 50 m^3. With such a tank only during short periods the irrigation by windmills was sub-optimal.

2.4 Determination of the economic attractiveness of the use of the windmill

The report uses three criteria by which from a farmers point of view the attractiveness of a windmill can be determined:
- cost-comparison
- internal rate of return
- repayment period

These criteria, however, cannot be commonly used, especially not if one wants to determine the attractiveness from a farmers point of view. In fact, only a cost-comparison can be used in the specific case when irrigation already is a common and proved profitable enterprise among farmers and when the output pattern of the windmill is equal to that of the other irrigation devices used by the farmers. The internal rate of return as well as the repayment period better should not be used at all. If one wants to determine whether or not windmill are attractive for farmers the methodology to be used should be the cost-benefit analysis. A clear and handy publication on this is C.W.D. publication No.84-1, 'Farm economics of waterlifting windmills' by A.M. Mueller.

2.5 Conclusions

Due to continuous research and ongoing experiences with windmillprojects some aspects of the publication 'Aspects of irrigation with windmills' had to be 'renewed'. It is the intention of the C.W.D. to publish in 1985 a complete new publication, called 'Small scale irrigation with windmills'.

Literature consulted for this note.

1. I. Grace 'Plant Response to Wind'.
2. FAO Irrigation and Drainage Paper No. 24: Crop water requirements.

3. L.R. van Veldhuizen: The choice of the design windspeed and storagetank capacity influencing water availability via windmill irrigation system. Interim report.
4. A.M. Mueller, Farmeconomics of waterpumping windmills. Draft report