Policy Analysis
of Water Management
for the Netherlands

Vol. XIII, Models for Sprinkler
Irrigation System Design,
Cost, and Operation

R. L. Petruschell, T. Repnau, G. Baarse

March 1982

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PREFACE

For some time the Netherlands has had a problem with water quality, particularly salinity, eutrophication, and thermal pollution. Moreover, the future demand for fresh water is expected to exceed the supply. The growing demand for the limited supply of groundwater is leading to increased competition among its users: agriculture, industry, nature preserves, and companies that supply drinking water. The supply of surface water is sufficient except in dry years, when there is competition not only among such users as agriculture, power plants, and shipping, but also among different regions.

Facing such water management problems, the Dutch government wanted an analysis to help draft the first national water management law and to select the overall water management policy for the Netherlands. It established the Policy Analysis for the Water Management of the Netherlands (PAWN) Project in August 1976 as a joint research project of Rand (a nonprofit corporation),\(^1\) the Rijkswaterstaat (the government agency responsible for water control and public works),\(^2\) and the Delft Hydraulics Laboratory (a leading Dutch research organization).\(^3\)

The primary tasks of the PAWN project were to:

1. Develop a methodology for assessing the multiple consequences of water management policies.
2. Apply it to develop alternative water management policies\(^4\) for the Netherlands and to assess and compare their consequences.
3. Create a Dutch capability for further such analyses by training Dutch analysts and by documenting and transferring methodology developed at Rand to the Netherlands.

The methodology and results of the PAWN project are described in a series of publications entitled Policy Analysis of Water Management for the Netherlands. The series contains the following volumes:

- Volume I, Summary Report (Rand R-2500/1)
- Volume II, Screening of Technical and Managerial Tactics (Rand N-1500/2)
- Volume III, Screening of Eutrophication Control Tactics (Rand N-1500/3)
- Volume IV, Design of Long-Run Pricing and Regulation Strategies (Rand N-1500/4)
- Volume V, Design of Managerial Strategies (Rand N-1500/5)
- Volume VA, Methodological Appendixes to Vol. V (Rand N-1500/5A)
- Volume VI, Design of Eutrophication Control Strategies (Rand N-1500/6)
Volume VII, Assessment of Impacts on Drinking-Water Companies and Their Customers (Rand N-1500/7)
Volume VIII, Assessment of Impacts on Industrial Firms (Rand N-1500/8)
Volume IX, Assessment of Impacts on Shipping and Lock Operation (Rand N-1500/9)
Volume X, Distribution of Monetary Benefits and Costs (Rand N-1500/10)
Volume XI, Water Distribution Model (Rand N-1500/11)
Volume XII, Model for Regional Hydrology, Agricultural Water Demands and Damages from Drought and Salinity (Rand N-1500/12)
Volume XIII, Models for Sprinkler Irrigation System Design, Cost, and Operation (Rand N-1500/13)
Volume XIV, Optimal Distribution of Agricultural Irrigation Systems (Rand N-1500/14)
Volume XV, Electric Power Reallocation and Cost Model (Rand N-1500/15)
Volume XVI, Costs for Infrastructure Tactics (Rand N-1500/16)
Volume XVII, Flood Safety Model for the IJssel Lakes (Rand N-1500/17)
Volume XVIII, Sedimentation and Dredging Cost Models (Rand N-1500/18)
Volume XIX, Models for Salt Intrusion in the Rhine Delta (Rand N-1500/19)
Volume XX, Industry Response Simulation Model (Rand N-1500/20)

Four comments about this series of publications seem appropriate. First, the series represents a joint Rand/Rijkswaterstaat/Delft Hydraulics Laboratory research effort. Whereas only some of the volumes list Dutch coauthors, all have Dutch contributors, as can be seen from the acknowledgments pages.

Second, except where noted, these publications describe the methodology and results presented at the final PAWN briefing at Delft on December 11 and 12, 1979. For Rand, this briefing marked the beginning of the documentation phase of the project and the end of the analysis phase. Rand and the Rijkswaterstaat (RWS) considered the results to be tentative because (1) some of the methodology had not become available until late in the analysis phase, and (2) the RWS planned to do additional analysis.

Third, the RWS is preparing its Nota Waterhuishouding, the new policy document on water management scheduled for publication in 1982, by combining some of the PAWN results from December 1979 with the results of considerable additional analysis done in the Netherlands with the PAWN methodology. Because the understanding gained in the original analysis led to improvements in the data--and, in some instances, the models--used to represent the water management system in the additional analysis, the reader is hereby cautioned that the numerical results and conclusions presented in the PAWN volumes will not always agree with those presented in the Nota Waterhuishouding or its companion reports. (It has not been possible to indicate such differences in the volumes
since they are being written before the Nota is published.) Thus, the present series of publications puts primary emphasis on documenting the methodology rather than on describing the policy results.

Fourth, Vols. II through XX are not intended to stand alone, and should be read in conjunction with the Summary Report (Vol. I), which contains most of the contextual and evaluative material.

The primary audience for this volume is the Dutch engineers and policy analysts who use the PAWN methodology and need to understand it. However, both in the Netherlands and elsewhere, the study should be of considerable interest to farmers and agricultural engineers who are concerned with agricultural irrigation systems, and to policy analysts and policymakers who are concerned with assessing the costs and benefits of water management policies.

NOTES

1. Rand had had extensive experience with similar kinds of analysis and had been working with the Rijkswaterstaat for several years on other problems.
2. The Rand contract was officially with the Rijkswaterstaat, Directie Waterhuishouding en Waterbeweging (Directorate for Water Management and Water Movement), but numerous other parts of the Rijkswaterstaat contributed to the analysis.
3. Delft Hydraulics Laboratory research was performed under project number R1230, sponsored by the Netherlands Rijkswaterstaat.
4. Each water management policy involved a mix of tactics, each a particular action to affect water management, such as building a particular canal or taxing a particular use. Four kinds of tactics were considered: building new water management facilities (infrastructure) or applying various treatments to the water (called technical tactics); using managerial measures (called managerial tactics) to change the distribution of water among competing regions and users; and imposing taxes or quotas to affect the quantity or quality of water extracted or discharged by different users (called price and regulation tactics, respectively). A mix of tactics of the same kind is called a strategy. Thus, the overall policy could be conceived as a combination of technical, managerial, pricing, and regulation strategies.
SUMMARY

In the dry summer of 1976, Dutch farmers increased their use of sprinkler systems considerably. The amount of installed sprinkling capacity was roughly doubled. However, even with this large increase, only a small fraction of the total planted area was being sprinkled. Considerable future growth seems possible. Whether or not this growth takes place and how large it will be depends to a considerable extent on the relative costs and benefits of sprinkling. The demands for fresh water will, of course, depend on the amount of water actually sprinkled.

In this volume we describe a methodology for estimating the cost of sprinkling farms in the Netherlands and for calculating the amount of water sprinkled. The methodology that was developed includes five basic analytical models—sprinkler system design, sprinkler system cost, daily sprinkler system operations simulation, decade sprinkler system operations simulation, the sprinkler system allocation and cost—and a procedure for using them.

The major PAWN models used to analyze agriculture are the Distribution Model¹ (DM), the District Hydrologic and Agriculture Model² (DISTAG), the Plot Water Model³ (PLOTWAT, included in DISTAG), and the Managerial Strategy Design Model⁴ (MSDM). The methodology described here has three objectives: (1) to produce sprinkling cost factors for use by the DM and the DISTAG; (2) to produce optimal sprinkler operating policies for use in the PLOTWAT; and (3) to develop a method for calculating sprinkling in the PLOTWAT. All of these objectives also serve the MSDM.

To obtain sprinkling cost factors, we first produced sprinkler system designs for a representative sample of sprinkling equipment and field sizes using the design model. We then estimated the cost of these sprinkler systems using the cost model. Next, we selected least-cost sprinkler systems from among the alternatives in the representative sample. Finally, we assigned the least-cost sprinkler systems to farm types, and calculated weighted average cost factors across field size using the sprinkler system allocation and cost model. The weighted average operating cost factors are used by the DISTAG and the MSDM to calculate sprinkler operating costs. The investment cost factors are used by the DM to calculate sprinkler investment cost.

To select optimal sprinkler operating policies, we first assigned sprinkler systems to crop/soil type combinations. Then, we used the sprinkler system characteristics from the design model and simulated sprinkling operations with the daily sprinkler operations simulation model under a set of alternative operating policies and a range of weather scenarios. We used the estimates of sprinkler operating cost and crop damage to select optimal sprinkler operating policies for each crop and soil type combination. These optimal policies, which consist of a statement about how much to sprinkle and when, are used to control sprinkling in the PLOTWAT.
The last part of the methodology consists of an algorithm, which we
developed, for calculating the amount of water sprinkled given the
optimal sprinkler operating policy and decade weather data. This
algorithm is embedded in the PLOTWAT.

The Buis (portable pipe) and the Haspel (portable hose reel) systems
were considered representative of the systems used in the
Netherlands. A design and a cost model were built for each. These
models reflect the technical characteristics and cost of commercially
available sprinkling equipment.

The inputs to the design model fall into three categories: system
parameters, the setting for the system, and selected cost trade-off
variables. System parameters include pumping efficiencies, length of
available pipes, allowable pressure drops in pipes, etc. The setting
is described by specifying the field size and one of eight system
configurations. A configuration is a qualitative description of the
components that will be used in a sprinkler system. The different
configurations distinguish between Buis and Haspel and among different
sources of water and pumping power. The model designs a feasible
sprinkler system (if possible), sizes the components, and calculates
the labor and energy requirements.

The cost model takes the specifications produced by the design model,
together with financial inputs, and applies generalized cost
estimating relationships to estimate the investment and operating
cost of the sprinkler system. It uses the financial inputs--annual
interest rate and useful lives of components--to calculate annualized
investment cost. Annualized investment cost is combined with annual
operating cost to obtain total annualized cost.

The sprinkler system design and cost models provided estimates that
are useful for choosing among alternative sprinkler systems but not
for estimating the resources required to operate the systems in the
real world, where farmers make sprinkling decisions on a day-to-day
basis, taking rain and soil moisture into account. The Daily
Sprinkler Operations Simulation Model (DSM) treats this latter
problem.

The DSM simulates a Dutch farmer's daily operation of his sprinkler
system throughout the entire six months of the growing season. The
growing season extends from the beginning of April to the end of
September. Sprinkler system characteristics, daily rainfall, daily
evapotranspiration, and a sprinkling policy are inputs to the model.
A sprinkling policy stipulates the rules for deciding when to start
and when to stop sprinkling. The model simulates the farmer's
sprinkling activities and calculates the number of times he moves his
equipment and the amount of water sprinkled. These two quantities
determine the variable cost of operating the sprinkler system. The
DSM also calculates the drought damage incurred by the crop.
The DSM was used to evaluate alternative sprinkling policies and to investigate the effect of policies on the efficiency of water use. However, it was too detailed for use in other PAWN analyses. For this purpose, the Decade Sprinkling Algorithm was developed. This algorithm accepts a sprinkling policy and uses the total rainfall and evapotranspiration during a decade (10 days) and the average soil moisture level at the beginning of that time period to estimate the amount of water that a farmer would sprinkle during that decade. The Decade Sprinkling Algorithm was calibrated to output from the DSM. The algorithm was used in the Plot Water Model and in the Managerial Strategy Design Model to estimate the demand for sprinkling water.

The models described thus far treat sprinkler systems and their operation independent of where they are used. The remainder of this volume describes how we selected sprinkler systems and policies for use in PAWN analyses.

First, we selected optimal sprinkler systems based on their performance and cost under average weather conditions. We identified a least-cost sprinkler system design for each combination of the eight sprinkler system configurations, three different amounts of water applied per irrigation, and fields ranging in size up to 40 hectares.

Either the Buis or the Haspel may be used in the highlands where groundwater is available. The annualized total cost of each system increases with field size but more rapidly for the Buis than for the Haspel. The Buis is cheaper for small fields and the Haspel is cheaper for large fields. The costs of the two are equal when the field size is about 18 ha. The Buis systems show slight dis-economies of scale. The cost per hectare at 10 ha is 540 Dfl and at 40 ha the cost is 590 Dfl. On the other hand, the Haspel indicates significant economies of scale. At 10 ha, the cost per hectare is about 700 Dfl while at 40 ha it drops to about 470 Dfl.

For surface water configurations in the lowlands, the Buis is still cheaper for small fields and more expensive for large fields but the difference between it and the Haspel is less pronounced than it was for the highlands configurations. Furthermore, both systems exhibit significant economies of scale. The Buis has a cost of roughly 400 Dfl/ha at 10 ha and less than 300 Dfl/ha at 40 ha. The Haspel shows even stronger economies of scale costing about 450 Dfl/ha at 10 ha and only 225 Dfl/ha at 40 ha. The two systems have equal cost when the field size is about 12 ha.

Having identified the least-cost systems, we prepared four cost functions: total investment, annualized investment, labor cost per move, and energy cost per millimeter of water sprinkled, all as a function of field size, configuration, and amount of water applied per irrigation. These cost functions are input to the Sprinkler System Allocation and Cost Model (SSACM).
The SSACM estimates weighted average cost factors for 11 crop types in each of 14 agricultural regions, given the sprinkled area in the region. The model distributes the sprinkled area to fields, assigns sprinkler systems to each field, and computes weighted average cost factors.

For installed sprinkling capacity comparable to that of 1976, the weighted average annualized fixed cost is on the order of 175 to 250 Dfl/ha for grass and arable crops, and somewhat higher for horticulture crops. Energy cost ranges from 0.35 to 0.80 Dfl/mm-ha (equivalent to 0.035 to 0.08 per Dfl/m³, since 1 mm on a hectare equals 10 m³). Labor cost varies from less than 0.50 Dfl/mm-ha to over 2.00 Dfl/mm-ha. The annualized fixed cost is generally higher for horticulture crops because the sprinkled areas are smaller and the cost per ha is higher for smaller fields. However, the differences are not very great since, for the bigger fields on arable and cattle farms, the relatively more expensive Haspel system is frequently used.

The average annualized total cost for the horticulture crops varies between 300 and 700 Dfl/ha. The lower cost is for fruit farms in North Holland and the IJsselmeer Polders where the average field size is 14.6 ha. The higher cost is for ornamental trees in the Western Pasture Area where the average field size is only 1.2 ha. For other crops, average field sizes range from 7 to 20 ha and the annualized total cost of sprinkling ranges from 400 down to about 300 Dfl/ha.

In 1976 some crops in some regions were not sprinkled. Under more optimistic assumptions about the amount of installed sprinkling capacity (see Vol. XIV), many of these crop-region combinations were provided with sprinklers. The costs for these fall within the ranges described above. In crop-region combinations with installed capacity in 1976, the increased capacity means an increase in sprinkled area, whence more smaller fields will be sprinkled, the overall average sprinkled field size will be smaller and the cost per hectare will increase. Indeed, the annualized total costs per hectare increase by up to 70 Dfl/ha.

The SSACM cost factors are used by the DISTAG to calculate the variable cost of sprinkling and by the DM to calculate the total cost. The cost factors were also used to determine optimal sprinkler intensities for different sprinkler scenarios.

The final section of this volume presents the sprinkling policies that were used with the Decade Sprinkling Algorithm in other PAWN models and some insights into how they were selected. Sprinkling policies were selected to minimize the sum of sprinkling cost and crop damage, taking into account how the policies did in each of three years—a very wet year, a normal year, and an extremely dry year.

The optimum value of GIFT, i.e., the amount of water to apply per irrigation, was relatively insensitive to the weather scenario. The values of GIFT that we considered—20 mm, 25 mm, and 30 mm—were
typical of the amounts generally applied in the Netherlands. The horticulture crops with root zones that hold a reasonable amount of water appeared to do marginally better (under all scenarios) with a larger GIFT and so we selected the 30 mm GIFT for them. We chose a GIFT of 25 mm for all other crop/soil group combinations.

The optimum value for \textit{START} (the soil moisture to begin sprinkling) differs with the weather scenario. A high \textit{START} value will ensure against the drought damage that would come in a rare dry year, while to ensure against the expected damage in a normal or wet year, a lower \textit{START} value would be selected. The \textit{START} value that does well in a dry year will result in excess sprinkling and unnecessary cost in a wet year. Conversely, an optimum \textit{START} value for a wet year will result in insufficient sprinkling and high crop damage in a dry year.

We selected two \textit{START} values for each combination of crop type and soil group, one for a dry year and the other for a wet year. Both do a reasonable job in a normal year. When combined with the GIFT, above, these form the dry year and the wet year policies. The dry year policy is characterized by a \textit{START} value that causes sprinkling to begin before the soil has a chance to dry out very much. On the other hand, the wet year policy has a \textit{START} value that allows the soil to dry out well into the damage zone before sprinkling is started. The dry year policy attempts to minimize drought damage, while the wet year policy attempts to minimize sprinkling cost.

Our dry year is very rare and it is not likely that a farmer will base his daily operations on such a low probability event. Since the actions required for sprinkling interfere with his normal tasks, he will probably not sprinkle until he really sees the need for it. Moreover, sprinkling too soon increases the risk of root zone saturation and damage from excess water in wet periods. This damage was not taken into account, but would have made the dry year policy less favorable from a cost point of view. Based on these considerations, we decided to use the wet year policies in PAWN analyses.

\textbf{NOTES}

1. The Distribution Model is the central model in PAWN's analysis methodology. It simulates the water distribution system in the Netherlands to calculate water demands and allocate water resources. It is described fully in Vol. XI.

2. The District Hydrologic and Agriculture Model was used by the DM to calculate the demand for agricultural water, the cost of sprinkling, and crop damage. This model is described in Vol. XII.
3. The Plot Water Model is invoked by DISTAG to calculate water flows and agricultural sprinkling requirements. It is described fully in Vol. XII.

4. The Managerial Strategy Design Model is another of the set of PAWN models. Given a fixed set of infrastructure and facilities, the MSDM determines a managerial strategy that yields the lowest possible total cost to all users of water. This model is described fully in Vols. V and VA.
ACKNOWLEDGMENTS

The work reported in this volume has benefited immeasurably from the many contributions of our Rand and Dutch colleagues.

T. F. Kirkwood of Rand helped formulate and later implemented significant parts of the sprinkler system design models, and supervised the production runs made with the Haspel system design and cost models. J. H. Bigelow of Rand developed and programmed the first version of the Daily Sprinkler System Operations Simulation Model. He also provided invaluable insights and suggestions throughout the course of the study. He helped us solve many difficult problems. K. E. Phillips of Rand worked with us in the early days of the study. He participated in the initial data collection both in the U.S. and in the Netherlands and helped with the formulation of the Sprinkler System Design and Cost models. David Jaquette programmed an early version of the sprinkler system design and cost models and Stan Abraham prepared the first documentation for these models. The assistance of all of these people is greatly appreciated.

Many people in the Netherlands provided us with valuable insights about irrigation in that country. Their inputs, usually informal and scattered throughout the life of the study, did much to clarify many important problems faced by Dutch farmers with regards to crop irrigation. In particular, we thank H. Ton of the Dutch Ministry of Agriculture and Fisheries for coming to the United States to review our overall research plan and preliminary versions of several of our models.

A first draft of this volume was reviewed by Sorrel Wildhorn, of Rand, and by several people from the Dutch Ministry of Agriculture and Fisheries. Their suggestions did much to improve the clarity of presentation and the accuracy of the information presented. We thank them for their valuable contributions.

B. F. Goeller, project leader of PAWN at Rand, provided broad guidance throughout the project, as well as very helpful administrative support. Our sincere thanks go to E. T. Gernert, managing editor of PAWN at Rand, and her colleagues in the Publications Department for their care in guiding our study to press; and to M. P. Dobson for proofreading and painstakingly incorporating the corrections.

While we have relied extensively on inputs from many people, the authors assume the sole responsibility for any and all errors that may have found their way into this volume.
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GLOSSARY

Buis                    Dutch word for pipe. Refers to a sprinkler system consisting of one or more movable lateral pipes equipped with multiple sprinkler heads.
BTW                     Belasting over de toegevoerde waarde (value-added tax).
CER                     Cost estimating relationship.
CRF                     Capital recovery factor.
Decade                  Used by the Dutch to refer to one-third of a month. The first two decades in any month have ten days each, and the third has the number of days remaining in the month.
Dfl                     Dutch florin (guilder).
Dflm                    Millions of Dutch florins (millions of guilders).
DSM                     Acronym for Daily Sprinkler Operations Simulation Model.
Gift                    The amount of sprinkling water applied per irrigation--measured in millimeters. Sometimes referred to as WA.
ha                      The hectare, a measure of area. One hectare = 10,000 square meters.
Haspel                  Dutch word for hose. Refers to a sprinkler system consisting of a large reel and hose. The hose, with sprinkler on one end, is wound onto the reel to move the sprinkler across the field.
hp                      Horsepower.
hr                      Hour.
KEMA                    Dutch Union of Electricity Producers.
km                      Kilometer.
kW                      Kilowatt.
kWh                     Kilowatt-hour.
l                       Liters.
m                       Meters
mm                      Millimeters.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>m²</td>
<td>Square meters.</td>
</tr>
<tr>
<td>m³</td>
<td>Cubic meters</td>
</tr>
<tr>
<td>mwk</td>
<td>Meters water column, a measure of pressure. Ten mwk is approximately 1 atmosphere.</td>
</tr>
<tr>
<td>WA</td>
<td>The amount of sprinkling water applied per irrigation—measured in millimeters. Sometimes referred to as Gift.</td>
</tr>
<tr>
<td>yr</td>
<td>Year.</td>
</tr>
</tbody>
</table>
INTRODUCTION

1.1. OVERVIEW

The number of sprinkler systems in use by Dutch farmers was small prior to 1976 but grew rapidly during the very dry summer of that year. The demand for new systems was so high that some farmers were unable to get delivery of new systems and many of these farmers were assisted by the military, who loaned portable pumps and pipes to bring water to crops.

If growth in the use of sprinkler irrigation systems were to continue at the 1976 rate, the demands for water, during dry periods, might soon exceed the capability of the infrastructure to supply this water. The possibility of a large future demand was considered a serious enough problem that several Dutch organizations had made projections of the demand for water through the year 2000. They were generally based on historical data and, as there was very little experience with sprinkling prior to 1976, the data to establish a meaningful trend were just not available. Thus, all projections typically reflected different peoples' guesses about whether or not the 1976 experience would continue. Some thought it would, while others thought not. As might be expected, the excercise did little more than alert people to the fact that there might be a problem.

In PAWN, we developed and applied a comprehensive methodology for investigating a wide range of water management issues, of which the potential agricultural demand for water was one. We were also concerned with the subsidiary questions of whether or not farmers might make more efficient use of available water, the extent to which agriculture competes with other economic sectors for water, and whether or not providing farmers with irrigation water would result in a net benefit or a net cost. How we estimated the benefits from sprinkling is described in several other PAWN volumes. This volume describes the methods we developed and used to estimate the cost of sprinkling and the amount of water used.

Sprinkling cost consists of sprinkler system investment, maintenance, and other operating cost. Investment and maintenance costs are fixed once the system is purchased, while other operating costs vary with the amount of water sprinkled. The amount of water sprinkled, of course, depends on the uncontrollable weather and the farmer's judgment about how much water his field needs. The amount sprinkled affects soil moisture levels and thence the amount of drought damage to crops. More sprinkling means less drought damage and less drought damage increases benefits to farmers. These two aspects are thus central to any analysis of the costs and benefits of sprinkling.
1.1.1. Approach

We developed sprinkler system design models to design sprinkler systems and sprinkler system cost models to estimate the investment and operating costs and variable operating cost factors for these same systems. At the outset, we found that no such models were readily available, that little relevant literature or studies could be found, that existing rules of thumb were often misleading, and that useful cost-estimating relationships did not exist.

We built a simulation model to investigate the effects of different sprinkler operating policies. The model simulates the day-to-day operation of a sprinkler system, in the face of uncertain weather, and was used to determine possibilities for more efficient use of water and to select sprinkler system operating policies for use in other PAWN models.

We also built another model that assigned sprinkler systems to crops and fields by geographic location and crop type and then calculated weighted average cost factors that reflected the particular assignment. We considered many different assignments involving different numbers of hectares being sprinkled. The alternative assignments followed from different assumptions about the availability of sprinkling water (infrastructure tactics) and about the locations and the crops that might be sprinkled in the future.

1.1.2. Applications

Sprinkler system investment and operating costs were used, with estimates of the benefits from sprinkling, in the screening of proposed infrastructure tactics. Sprinkler system variable operating cost factors and sprinkling policies were used (see Vol. XII) to estimate the variable costs of sprinkling and the amount of water used under a wide range of weather conditions and for several different scenarios describing the amount of future sprinkling (see Vol. XIV). These same factors and sprinkling policies were used in the Managerial Strategy Design Model (see Vol. V) to design strategies for managing the national infrastructure in times of drought.

1.2. SPRINKLER SYSTEMS

Many different kinds of sprinkler systems are in use today. They include permanently installed complete coverage systems, portable hose-pull systems, drip irrigation systems, portable pipe-based systems, portable hose-reel systems, etc. There is almost an infinite variety of sprinkler system components available for use in tailoring sprinkler systems to the special conditions found on individual farms and each farm is bound to be special in some way. We could not possibly consider all of the variations, so we chose two representative sprinkler systems and eight representative system configurations.
1.2.1. Representative Sprinkler Systems

As the portable pipe or Buis system and the hose-reel or Haspel system are the two most widely used in the Netherlands, we used them exclusively in our sprinkling analyses.

Buis is the Dutch word for pipe. The Buis system is a semi-portable agricultural sprinkling system consisting of one or more movable pipes with multiple sprinkler heads spaced along them. These pipes are called "lateral" and are used to supply water to the sprinklers. All of the sprinklers along a lateral operate simultaneously. The laterals are usually connected at different points along the length of a main distribution pipe that runs through a field and supplies water to the laterals. The system requires a water pump, which may be driven either by an electric motor or by the farmer's diesel tractor. To irrigate a field, the laterals are moved manually from one location to another.

Haspel is the Dutch word for reel. A Haspel system consists of a long flexible hose with a sled-mounted sprinkler at one end, a large take-up reel onto which the hose is wound during sprinkling, a motor for winding the reel, and a tractor-driven pump to deliver water through the hose to the sprinkler. Like the Buis, a main distribution pipe is sometimes used to supply water to the Haspel. In this case, the pump would supply water to the main distribution pipe and there would be provision for attaching the Haspel to the main distribution pipe at various locations. In principle, more than one Haspel may be included in a Haspel system. The Haspel(s) must be moved from place to place to irrigate the entire field. Because the Haspel is so heavy, a tractor is required to move it.

We have considered three representative types of Haspels, each available from the Dutch distributor Cebeco-Handelsraad: the Junior, C-75, and C-90; they differ in hose diameter, nominal hose length, nozzle operating pressure, and in the water discharge rate for which they are designed.

The Haspel differs from the Buis in many respects. One of the most important is that the Haspel has only one sprinkler head while the Buis usually has many operating simultaneously. The Buis, with its multiple sprinkler heads, can apply water much more quickly than the Haspel, which has only one head and must be pulled the length of the sprinkled area.

1.2.2. System Configurations

Before a detailed sprinkler system design can be prepared, the kind of sprinkler system and the basic components must be identified and how the components relate to each other and to sprinkling a field must be specified. After the kind of system--Buis or Haspel--has
been determined, one must decide what pumping power source (tractor pump or electric motor) to use, whether or not a main distribution pipe is required, and if a well will be required. We represented the menu of possible system configurations with five different Buis and three different Haspel configurations. Each of these is illustrated in Fig. 1.1.

Buis configuration B2 is used in the low-lying parts of the Netherlands. It consists of a single lateral pipe and a tractor driven pump. Water is obtained from a ditch that runs along one side of the field. No main distribution pipe is required as water is taken directly from the ditch. When the lateral pipe is moved to a new position, the pump must also be moved with it. We have chosen a tractor pump, mounted on a tractor, for use in this configuration because it is easy to move and has the tractor as a power source. This is the cheapest of the five Buis configurations but can only be used where there is an irrigation ditch (the cost of the tractor is not charged to the sprinkler system).

The remaining Buis configurations are typically for use in the highlands. These configurations may access either surface water or groundwater, but all require a main distribution pipe. Each uses one or more lateral pipes. Configurations B1 and B3 take water from a ditch, river, or canal at a point in or around the field. The important distinction is that the ditch, river, or canal does not run along one entire side of the field as the ditch does in the lowlands. With the point source of water, a main distribution pipe is required for these configurations. Configuration B1 uses an electric motor-driven pump while configuration B3 uses a tractor-driven pump. Configuration B4 and B5 use groundwater and hence have a well as the point water source. Configuration B4 uses an electric motor for pumping power and configuration B5 uses a tractor for pumping power.

Haspel configuration H1 is similar to Buis configuration B2. It is used in the lowlands where ditches are alongside the fields. It consists of a single Haspel unit. Pumping power is provided by a tractor-driven pump. Unlike the Buis, a tractor is required to move the Haspel unit. Also, the field dimensions are constrained so that the dimension normal to the ditch is always equal to the nominal length of the Haspel hose.

Haspel configurations H2 and H3 are for use in the highlands. Both have a point source of water—H2 uses a well and H3 a ditch, river, or canal—and so require a main distribution pipe. Pumping power is provided by the tractor which is also used to power the hose-reel and to move the Haspel unit.

The distinction between lowland and highland configurations was made because ditches are usually found along fields in the lowlands and not in the highlands. Of course, any of the highlands systems can also be used in the lowlands. Furthermore, if source of water runs along an entire side of a highlands field, the lowlands system may also be used there.
1.3. CROPS AND SOILS

We were able to identify roughly 100 different crops and 150 different soil types in the Netherlands. This was just too many to consider in detail. Consequently, we aggregated similar crops and soils to obtain 11 open-air crops and 4 soil groups. We did distinguish among these in selecting sprinkling policies and assigning sprinkler systems.

1.3.1. Crops Sprinkled

The Dutch Central Bureau of Statistics distinguishes more than 100 different crop types. These have been aggregated into 13 crop groups, eleven open-air and two glass house crops (see Vol. XII). Here we are interested in only the open-air crops because all of the crops grown under glass are irrigated as a matter of course and we are concerned here with possible new sprinkling. Tables 1.1 and 1.2 show crops together with the area planted, the total value, and the value per hectare for an average year and a dry year. Note that grass is planted on roughly 60 percent of the cultivated area. Furthermore, it is the single largest contributor to the total agricultural product of the country. Of course, this grass provides the primary input to the production of cattle and cattle-related products--milk, butter, cheese, meat, etc.

Crop type was not considered explicitly in designing sprinkler systems. Rather, we designed a wide enough range of candidate systems to accommodate the requirements of all of the crops. Crop type was considered explicitly in assigning sprinkler systems to fields and it dictated the choice of sprinkler operating policies.

1.3.2. Soil Type

Different soils may have very different geo-hydrological characteristics. Most important, from the point of view of sprinkling, are the soil moisture retention properties, i.e. the amount of water the soil can hold and the part that is available to the plant before any yield reduction occurs. The soils that have a low moisture retention capacity will require sprinkling more frequently.

As many as 156 different soil types may be found in the Netherlands. For PAWN purposes, nine representative soil types were used. These nine were further aggregated into four soil groups--loam, clay, sand, and peat--for the selection of sprinkling policies.
1.4. COST CONCEPTS

Several cost analysis concepts are employed extensively in this volume. Each of them, and the reasons why we used them, are discussed briefly below. All costs and benefits in PAWN are assumed to be in 1976 price levels.

1.4.1. Incremental Cost

We are concerned with a farmer's decision to purchase and operate a sprinkler system, and, for that purpose, only the incremental costs of owning and operating such a system are relevant. These are the costs that would be added to the normal farm costs if a sprinkler system were purchased and used. Clearly, the cost of buying the sprinkler system components would be included. If the farmer purchased the system with borrowed funds, the interest would also be included. Operating costs--energy for pumping sprinkling water and the regular maintenance of the sprinkler system--must also be included. Agricultural water is now and we assume will continue to be available to Dutch farmers at zero cost. There has been some discussion, in the Netherlands, of possible charges for groundwater. In PAWN, we did consider the implications of such a charge but the costs to the farmers were calculated outside the Sprinkler System models.

When we look only at the incremental cost of sprinkling, the cost of the tractor to drive the pump for sprinkling is not included, as the tractor is assumed to be part of normal farm equipment. The cost of maintaining the tractor is also not included for the same reason. The extra maintenance cost associated with sprinkling should be included but, as we had no simple way of estimating it and it was in all likelihood small, we excluded it. However, we do include the cost of the diesel fuel consumed by the tractor when operating the pump because it can be attributed to the sprinkling activity.

At least one Dutch study of sprinkling assumed that the farmer's labor was free [1.1]. Finding the labor to operate a sprinkler system on a small single-family farm may be difficult. At best, these farmers have their immediate family to help them and are unable to contract sprinkling labor. Farmers typically work long days during the growing season just to keep up with normal farming activities and operating a sprinkling system, in addition, might be an unacceptable burden. As the opportunity cost of this labor seems high, we wanted to include a reasonable estimate for it in our analyses. We recognize that there is considerable uncertainty about the value of labor in the private sector but have used 18.50 Dfl/hr, the typical wage rate for farm labor in 1977-1978, as a reasonable estimate.
Nonsprinkling farm costs may also be affected by a farmer’s decision to sprinkle. For example, if yield increases significantly, harvesting and marketing costs may also increase. However, it appears that changes in nonsprinkling farm costs are small enough to be neglected. In actuality, some of the sprinkling costs included here will be absorbed by the Dutch government through investment tax credits and income tax deductions. These were taken into account in the final cost-benefit analyses (see Vol. I) where a distinction between cost to the farmer and to the nation was made explicit.

1.4.2. Fixed vs. Variable Cost

Fixed costs are those which cannot be varied in the short run, where short run is a day or a decade (ten days) and long run is a year or years. The annualized investment in a sprinkler system is considered a fixed annual cost. Annual maintenance of the sprinkler system is also considered a fixed cost.

Variable costs are those costs that can change in the short run. The cost of energy for pumping sprinkling water is a variable cost, which changes with the amount of water sprinkled. Sprinkling labor cost is also a variable cost. Variable costs are partly under the control of the farmer, but mostly depend on the weather, i.e., the amount of rainfall and hence the amount of sprinkling required.

A cost factor is a constant of proportionality that expresses the relationship beteen a cost and the activity rate that generates that cost. In this volume we will use the following cost factors: investment cost per ha, annualized investment cost per ha, energy cost per mm of water sprinkled per ha, and labor cost per mm of water sprinkled per ha. While the variable costs change in the short run, the variable cost factors are assumed to remain constant. It is the activity rates that cause the costs to change.

1.4.3. Investment vs. Operating Costs

Investment costs are those costs incurred to purchase a sprinkler system. They include the cost of the system components themselves but not the cost of operating and maintaining them. All investment costs are fixed costs. Investment costs do not include an allowance for contingencies because they are estimated using prices of off-the-shelf equipment and there is little uncertainty about what should be included in the cost of a sprinkling system. Value-added tax (BTW) is included or not, depending on how the costs are to be used. The rate is 4 percent of the investment cost for completely assembled systems and 18 percent for individual components. Because we have designed and estimated the cost of complete systems, we have always used the 4 percent rate.
Operating costs are those costs that are necessary to operate and maintain the sprinkler system. The cost of labor to move the system from set to set, and the cost of energy to pump the sprinkling water are variable costs, while normal system maintenance is a fixed cost.

1.4.4. Annualized Investment Cost

Sprinkling costs must be compared with the benefits (annual value of crop damage prevented by sprinkling). In PAWN, the benefits are estimated for four selected years so we need annual sprinkling costs that can be compared with these annual benefits. Annualized investment cost is added to the fixed annual operating costs to obtain such a number.

An interpretation of the annualized investment is that the investment is financed with borrowed funds and the loan is paid off with equal annual payments, including principal and interest, over the life of the item. The annualized investment cost is the annual payment on the loan. The final payment on the loan coincides with the end of the useful life of the investment item.

The annualized investment is obtained by applying a capital recovery factor to the investment. A capital recovery factor is a device for converting a lump-sum payment made now into an equivalent stream of equal annual payments to be made in the future. Of course, the size of the annual payments depends not only on the lump sum, but on the useful life of the equipment and the interest rate selected. The formula for the capital-recovery factor is

\[ CRF = \frac{i \times (1+i)^n}{(1+i)^n - 1} \]  \hspace{1cm} (1.1)

where \( CRF \) = the capital recovery factor,
\( i \) = annual interest rate (decimal),
\( n \) = useful life (yrs).

There are different capital recovery factors for the different system components because the components have different useful lives. Recognizing that the value of capital is very uncertain, we have used a nominal interest rate of 10 percent to reflect the cost of capital to Dutch farmers. In using this approach, we assume that each investment item is replaced at its initial cost as soon as it ends its useful life.
1.5. OUTLINE OF REPORT

Chapter 2 describes the sprinkler system design models for the Buis and the Haspel systems. The problem is one of assembling commercially available components to form a system that will allow a farmer to irrigate his field so as to maintain the moisture in the soil within predetermined bounds and thus prevent crop damage. Fundamental design equations that apply generally are discussed first and then the detailed models for each of the two systems are presented.

The Buis and Haspel system cost models are described in Chap. 3. The cost models use the output from the design models and cost estimating relationships to estimate the investment and operating costs of the sprinkler systems. The derivation of the investment cost estimating relationships is discussed and then the detailed cost models are presented. There are separate models for the Buis and the Haspel.

In Chap. 4 we describe the daily sprinkler operations simulation model which we used to investigate the effect of many different operating policies on the efficiency of water use, sprinkling costs, and crop damage. This model simulates a farmer's daily operation of his sprinkler system during the growing season. It uses data on daily rainfall and evapotranspiration and calculates the number of times the farmer moves his equipment and the amount of water sprinkled. This model was used to select sprinkling policies that were used in other PAWN analyses.

The decade sprinkling algorithm described in Chap. 5 estimates the demand for sprinkling water in response to decade rain and evapotranspiration given a sprinkling policy. This algorithm was incorporated into the Plot Model (see Vol. XII) and the Managerial Strategy Design Model (see Vol. V), both of which were too large and complex to use the daily simulation model directly. This algorithm was calibrated to the results of the daily sprinkler operations simulation model.

The models described in Chaps. 2 through 5 deal with sprinkler systems and their operation independent of where they are used. The remaining three chapters describe how we selected systems and policies for use in PAWN analyses.

Chapter 6 describes how we selected least-cost sprinkler system. We ran the design and cost models to generate detailed cost estimates for each configuration, considering a variety of fields of different sizes. For each field size, the number of laterals and moving interval for Buis systems and the type of Haspel for Haspel systems are chosen so as to minimize total annualized sprinkling cost. We identified a least-cost system for each configuration, field size, and amount of water applied per irrigation.

Chapter 7 presents the sprinkler system allocation and cost model (SSACM), which was used to assign sprinkler systems to fields and to
calculate weighted average costs and cost factors based on this assignment. The costs and cost factors are used to estimate sprinkling cost under many different weather scenarios in other PAWN models. An extensive data base was prepared to support the development of this model. How these data were obtained and organized is described first. Then the model itself is presented. The chapter concludes with a discussion of the model results.

Chapter 8 describes how we selected sprinkler operating policies and presents the policies. Policies were selected for 40 crop, soil group, and root zone combinations. The selections were chosen to maximize farmers' expected profit. We did not deal with profit directly, but instead selected policies that minimized the sum of variable sprinkler operating cost and crop damage.

The reader should note that figures and tables are located at the end of chapters.

NOTES

1. If a Haspel system uses a distribution pipe (which is often underground) then a fixed electric or diesel engine may be used. We have not included this variation because we assumed that a tractor was needed to move the Haspel and that it would also be readily available for pumping. The configuration with the fixed engine was inadvertently omitted. However, the difference in cost between the two configurations is small (see Chap. 6.).

2. Multiple Haspel units are not usually used on farms in the Netherlands and hence have not been considered in PAWN analyses.

3. Current developments are to replace the single sprinkler head on a Haspel by several smaller ones in order to avoid unfavorable effects on soil properties (caused by high flow rates). As we had no detailed information on these systems, we were unable to include them in our analysis.

REFERENCE

Buis system: Lowlands

<table>
<thead>
<tr>
<th>CONFIG type</th>
<th>Water source</th>
<th>Pumping power</th>
<th>Dimension,</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 (s)</td>
<td>Ditch, river, canal</td>
<td>Electric</td>
<td>WF</td>
</tr>
<tr>
<td>B3</td>
<td>Ditch, river, canal</td>
<td>Tractor</td>
<td>WF</td>
</tr>
<tr>
<td>B4 (b)</td>
<td>Well</td>
<td>Electric</td>
<td>WF</td>
</tr>
<tr>
<td>B5</td>
<td>Well</td>
<td>Tractor</td>
<td>WF</td>
</tr>
</tbody>
</table>

[a] Can also be used in the Lowlands.
[b] Can also be used in the Lowlands when groundwater is available.

Buis system: Highlands

<table>
<thead>
<tr>
<th>CONFIG type</th>
<th>Water source</th>
<th>Pumping power</th>
<th>Dimension,</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 (s)</td>
<td>Well</td>
<td>Tractor</td>
<td>300 m for C-75/90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200 m for Junior</td>
</tr>
<tr>
<td>H2 (a)</td>
<td>Ditch, river, canal</td>
<td>Tractor</td>
<td>200 m for C-75/90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200 m for Junior</td>
</tr>
</tbody>
</table>

[a] Can also be used in the Lowlands when groundwater is available.

Haspel system: Lowlands

<table>
<thead>
<tr>
<th>CONFIG type</th>
<th>Water source</th>
<th>Pumping power</th>
<th>Dimension,</th>
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<tr>
<td>H1</td>
<td>Haspel</td>
<td>Tractor</td>
<td>300 m for C-75/90</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>200 m for Junior</td>
</tr>
</tbody>
</table>

 NOTES: AF = area of field (ha)
WF = dimension of field normal to lateral pipe or haspel hose (meters)
FD = dimension of field parallel to lateral pipe or haspel hose (meters). FD = WF means that the field is square.

Fig. 1.1--Sprinkler system configurations
Table 1.1

AGGREGATE CROP TYPES, AREAS, AND VALUES: AVERAGE YEAR

<table>
<thead>
<tr>
<th>Crop Number</th>
<th>Crop Type</th>
<th>Area Planted (ha)</th>
<th>Crop Value Total (Dflm)</th>
<th>Average (Dfl/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Nature</td>
<td>928,704</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Grass</td>
<td>1,254,497</td>
<td>3757</td>
<td>3,000</td>
</tr>
<tr>
<td>2</td>
<td>Consumption potatoes</td>
<td>59,204</td>
<td>592</td>
<td>10,000</td>
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<tr>
<td>3</td>
<td>Milling potatoes</td>
<td>71,625</td>
<td>274</td>
<td>3,383</td>
</tr>
<tr>
<td>4</td>
<td>Seed potatoes</td>
<td>27,493</td>
<td>371</td>
<td>13,500</td>
</tr>
<tr>
<td>5</td>
<td>Sugar beets</td>
<td>127,507</td>
<td>663</td>
<td>5,200</td>
</tr>
<tr>
<td>6</td>
<td>Cereals (and others)</td>
<td>269,986</td>
<td>850</td>
<td>3,150</td>
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<tr>
<td>7</td>
<td>Cut corn</td>
<td>89,305</td>
<td>321</td>
<td>3,600</td>
</tr>
<tr>
<td>8</td>
<td>Bulbs</td>
<td>13,228</td>
<td>362</td>
<td>27,400</td>
</tr>
<tr>
<td>9</td>
<td>Vegetables in open air</td>
<td>55,657</td>
<td>868</td>
<td>15,600</td>
</tr>
<tr>
<td>10</td>
<td>Pit and stone fruits</td>
<td>30,331</td>
<td>315</td>
<td>10,400</td>
</tr>
<tr>
<td>11</td>
<td>Trees</td>
<td>4,945</td>
<td>212</td>
<td>42,800</td>
</tr>
<tr>
<td>12</td>
<td>Vegetables under glass</td>
<td>4,596</td>
<td>1066</td>
<td>232,000</td>
</tr>
<tr>
<td>13</td>
<td>Flowers under glass</td>
<td>3,266</td>
<td>1584</td>
<td>485,000</td>
</tr>
</tbody>
</table>

SOURCE: Volume XII.
NOTE: Nature, crop type 0, includes everything except cash or marketable crops.

Table 1.2

AGGREGATE CROP TYPES, AREAS, AND VALUES: DRY YEAR (1976)

<table>
<thead>
<tr>
<th>Crop Number</th>
<th>Crop Type</th>
<th>Area Planted (ha)</th>
<th>Crop Value Total (Dflm)</th>
<th>Average (Dfl/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Nature</td>
<td>928,704</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Grass</td>
<td>1,254,497</td>
<td>6262</td>
<td>5,000</td>
</tr>
<tr>
<td>2</td>
<td>Consumption potatoes</td>
<td>59,204</td>
<td>962</td>
<td>16,250</td>
</tr>
<tr>
<td>3</td>
<td>Milling potatoes</td>
<td>71,625</td>
<td>418</td>
<td>5,830</td>
</tr>
<tr>
<td>4</td>
<td>Seed potatoes</td>
<td>27,493</td>
<td>558</td>
<td>20,300</td>
</tr>
<tr>
<td>5</td>
<td>Sugar beets</td>
<td>127,507</td>
<td>663</td>
<td>5,200</td>
</tr>
<tr>
<td>6</td>
<td>Cereals (and others)</td>
<td>269,986</td>
<td>850</td>
<td>3,150</td>
</tr>
<tr>
<td>7</td>
<td>Cut corn</td>
<td>89,305</td>
<td>536</td>
<td>6,000</td>
</tr>
<tr>
<td>8</td>
<td>Bulbs</td>
<td>13,228</td>
<td>399</td>
<td>30,140</td>
</tr>
<tr>
<td>9</td>
<td>Vegetables in open air</td>
<td>55,657</td>
<td>1129</td>
<td>20,280</td>
</tr>
<tr>
<td>11</td>
<td>Pit and stone fruits</td>
<td>30,331</td>
<td>315</td>
<td>10,400</td>
</tr>
<tr>
<td>11</td>
<td>Trees</td>
<td>4,945</td>
<td>212</td>
<td>42,800</td>
</tr>
<tr>
<td>12</td>
<td>Vegetables under glass</td>
<td>4,596</td>
<td>1280</td>
<td>278,400</td>
</tr>
<tr>
<td>13</td>
<td>Flowers under glass</td>
<td>3,266</td>
<td>1346</td>
<td>412,250</td>
</tr>
</tbody>
</table>

SOURCE: Volume XII.
NOTE: Nature, crop type 0, includes everything except cash or marketable crops.
Chapter 2
SPRINKLER SYSTEM DESIGN MODELS

2.1. THE GENERAL DESIGN PROBLEM

2.1.1. The Problem

The sprinkler system design problem is one of assembling commercially available sprinklers, pipes, pumps, controls and other components to form a sprinkler system that will allow a farmer to irrigate his field so as to maintain the moisture in the soil within predetermined bounds. This is done within the context of a weather scenario—no rain and a constant evapotranspiration rate.

2.1.2. Sprinkler System Characteristics

The system design procedure is influenced by certain inherent characteristics of the sprinkler system. Two important ones are (1) whether or not the system is a single or multiple sprinkler head system and (2) whether or not the sprinkler heads are stationary or travel while sprinkling. We define a Buis unit as a lateral pipe of length LL with NS sprinkler heads. A Haspel unit is a single sprinkler head on a movable sled pulled by a hose of length HL. The Buis is a multiple sprinkler head stationary system while the Haspel is a single sprinkler head traveling system.

Both systems use impact sprinklers which sprinkle a full or partial circular pattern. The size—measured in terms of delivery rate, operating pressure, and spray diameter—can vary considerably. Manufacturers of sprinkling equipment provide these sprinkler heads in great variety, and choosing the appropriate sprinkler head or heads is part of the system design process.

Figure 2.1 shows a typical Buis unit, consisting of a single lateral pipe with five sprinkler heads. The lateral pipe is connected to a main pipe, which supplies water to the lateral. While each sprinkler head covers a circular area, the effective area sprinkled by a sprinkler head is a rectangle. The dimensions of the rectangle relative to the spray diameter are selected at the discretion of the system designer, based on such things as prevailing winds, slope of the land, etc.

A typical Haspel unit is shown in Fig. 2.2. The hose is fully extended and the sprinkler is sprinkling a half circle. Water is supplied from a main distribution pipe, through the hose to the sprinkler. As the hose is wound on the reel, the sled carrying the sprinkler travels to the left at a constant velocity. When the hose is completely wound up, the entire rectangular area indicated will have been sprinkled. Based on manufacturers' information, the width
of the sprinkled rectangle is 85 percent of the spray diameter. It follows that the length of the sprinkled rectangle exceeds the length of the hose by 31 percent of the spray diameter.

The Buis and Haspel design models are formulated so as to take advantage of the inherent capabilities of these systems. The Buis can apply water quickly, and so the model allows the moving interval to be specified as an input, and designs the system so that it is convenient for the farmer. The Haspel applies water very slowly and has only a limited range of nozzle discharge rates, whence the moving interval cannot be input and the model is constructed to design systems that lie within the nozzle discharge rate constraints and to calculate the moving interval.

2.1.3. Inputs and Outputs

All of the design model input and output variables are summarized in Tables 2.1 and 2.2.

The inputs to the design model are general enough to permit the user to specify a sprinkler system without knowing minute details about the particular system and the field on which the system will be used. The model was tailored for use in PAWN, where we treated typical, rather than specific, systems and fields. At the same time, the inputs are sufficiently numerous that the user may specify systems with quite different characteristics if he desires.

The inputs to the design model fall into three categories. The first category consists of parameters that describe the setting for the sprinkler system. These include the dimensions of the field to be sprinkled, the system configuration, the amount of water to be applied per irrigation, the design evapotranspiration rate, etc. The second category consists of parameters that describe the physical and performance characteristics of the sprinkler system components and include such things as pumping and sprinkling efficiencies, tractor specific fuel consumption, the length of a lateral pipe segment for the Buis, minimum and maximum nozzle discharge rates for the Haspel, etc. The third category consists of cost trade-off variables--the moving interval and the number of laterals for the Buis and the type of Haspel unit for the Haspel. These variables are used to determine least-cost sprinkler systems, as described in Chap.6.

Design model outputs are descriptors of the system that are needed to estimate the sprinkler system cost and to define the system operating characteristics. Those outputs required to estimate the system cost are dictated by the form of the cost estimating relationships (CERs) used in the cost models, which will be described in Chap. 3. For example, the cost of pipe is a function of the length and diameter of the pipe so the design model must provide values for each of these. The system operating characteristics--such as number of sets, the sprinkling rate, time to move the equipment, and the moving interval--are all needed by the daily sprinkler operations simulation model, which is described in Chap 4.
2.2. FUNDAMENTAL DESIGN EQUATIONS

2.2.1. Introduction

The design process determines the appropriate nozzle discharge rate and from that the size and number of system components required so that the system can irrigate the entire field and replace the water lost through evapotranspiration.

The area sprinkled by a unit is a function of the lateral (Buis) or hose (Haspel) length and the spray diameter. As will be shown below, the spray diameter depends on the nozzle discharge rate and pressure. A single unit generally cannot sprinkle the entire field in one placement, but rather must be moved from one placement to the next until the whole field is irrigated. The number of placements required depends on the area covered in one placement.

The sprinkler systems here are designed to apply a specified amount of water at each placement. It takes time to apply the water and to move the equipment from one placement to the next. Moreover, while the system is applying water at one placement, the remainder of the field is drying out. This means that, having sprinkled the area at a given placement, the equipment must return to sprinkle at this placement again before the moisture loss in the soil there exceeds the amount that the system applies.

2.2.2. Area Coverage Requirement

All sprinkler system units considered sprinkle a rectangular area, AU (m²), in a given placement (see Fig. 2.3). This area depends on the dimensions of the field and the sprinkling system characteristics. Moreover, for a given system, the width of this rectangle can vary considerably, depending on the nozzle discharge rate, QN (m³/hr). One of the design considerations is to determine QN. More than one sprinkling unit can be used simultaneously so the total area sprinkled in one placement (one set) is

\[ AS(QN) = N \times AU(QN) \]  \hspace{1cm} (2.1)

where \( AS(QN) \) = area sprinkled per set (m²),
\( N \) = number of units used simultaneously,
\( AU(QN) \) = area sprinkled with one unit (m²).

To irrigate an entire field requires successive relocations of the sprinkling units. The number of relocations (or sets) required to sprinkle a field with an area AF hectares is

\[ NSET(QN) = \frac{10,000 \times AF}{AS(QN)} \]  \hspace{1cm} (2.2)
where \( NSET(QN) \) = number of sets, \\
\( AF = \) area of field (ha).

This is the area coverage requirement. It says that when each set has been sprinkled once, the whole field has been irrigated.

2.2.3. Soil Moisture Cycle

The soil moisture cycle is shown in Fig. 2.4. We assume that the farmer is willing to allow the soil moisture level in the root zone to vary between two levels. We define the difference between these two levels as the amount of water, \( WA \) (mm), to be applied per irrigation.

Water leaves the root zone through the plants according to a process known as evapotranspiration, a combination of evaporation and of transpiration from the plants growing in the soil. The rate at which this process occurs is defined as the evapotranspiration rate, \( RE \) (mm/day). For design purposes, we assume that \( RE \) is constant and that there is no water input from rain. We further assume that evapotranspiration takes place continuously, even while irrigation water is being applied.

The soil moisture cycle begins with the soil moisture at its minimum desirable level. An amount of water \( WA \) is applied to a set at a rate \( RU \) (mm/hr) in a time \( TU \) (hr). The rate \( RU \) depends on the nozzle discharge rate \( QN \) and the time \( TU \) depends on both \( QN \) and \( RE \). We define the net application rate, \( R \), as the rate at which water actually accumulates in the soil:

\[
R(QN) = RU(QN) - \frac{RE}{24}. 
\]  
(2.3)

The time \( TU \) that it takes to accumulate an amount of water \( WA \) in the soil is then

\[
TU(QN) = \frac{WA}{R(QN)}. 
\]  
(2.4)

At the end of \( TU \) hours, the soil moisture has been raised by the amount \( WA \). At an evapotranspiration rate \( RE \), it will take \( TD \) hours for the soil moisture to dry out to the minimum desirable level:

\[
TD = 24 \frac{WA}{RE}. 
\]  
(2.5)
The length of the soil moisture cycle is TS hours:

\[
TS(QN) = TU(QN) + TD. \tag{2.6}
\]

In order to maintain the soil moisture above the minimum desired level, sprinkling on a set must begin every TS hours. This means that the sprinkling units must progress through all sets in TS hours. Thus the maximum time that the sprinkling units can remain in one location is

\[
M(QN) = \frac{TS(QN)}{NSET(QN)}. \tag{2.7}
\]

We define M(QN) as the moving interval (hr). During the time M, a set must be sprinkled and the equipment must be moved to the next set. If these activities require less than M hours, there will be idle time. A major design constraint is that this idle time TI must be nonnegative.

The soil moisture cycle requirement says that the sprinkling units must successively sprinkle all sets in the soil moisture cycle time TS.

2.2.4. Spray Width Estimating Equation: Haspel System

Cebeco-Handelsraad has provided us with data on the three Haspel systems. The data include values for nozzle diameter, nozzle pressure, nozzle flow rate, and width of sprinkled area, for each Haspel system.

Data for the C-75 and C-90 systems were used to develop an empirical equation for describing the sprinkled-area width, WS, as a function of the nozzle discharge rate, QN, and pressure at the nozzle, PN. In Fig. 2.5, WS is plotted against QN for each system and for each of three nozzle pressures. We regressed WS on QN using a power function and holding PN constant; the regression equation took the form \( WS = a^{*}QN^{b} \). The following results, applicable only to the C-75 and C-90 systems, were obtained:

<table>
<thead>
<tr>
<th>PN (mwm)</th>
<th>a</th>
<th>b</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>49</td>
<td>30.5235</td>
<td>0.2581</td>
<td>0.9992</td>
</tr>
<tr>
<td>56</td>
<td>30.9211</td>
<td>0.2597</td>
<td>0.9992</td>
</tr>
<tr>
<td>63</td>
<td>31.4029</td>
<td>0.2595</td>
<td>1.0000</td>
</tr>
</tbody>
</table>
The regression-equation constant "a" was itself regressed on PN (again using a power function), with the following result ($R^{2} = 0.9924$):

$$a = 19.6753 \times PN^{0.1127}$$

As the exponent "b" was so nearly the same for each value of PN, we assumed an average value for it of 0.2591 in the following combined result ($R^{2} > 0.95$):

$$WS = 19.6753 \times (PN^{0.1127}) \times (QN^{0.2591})$$

where $WS =$ width of sprinkled area (m),
$PN =$ pressure at the nozzle (mwk),
$QN =$ nozzle discharge rate (m$^3$/hr).

The above equation holds only for the C-75 and C-90 Haspel systems, and only for variable values within the following ranges:

$$49 \leq PN \text{ mwk} \leq 63$$

$$25 \leq QN \text{ m}^3/\text{hr} \leq 40 \quad \text{for the C-75 system}$$

$$30 \leq QN \text{ m}^3/\text{hr} \leq 60 \quad \text{for the C-90 system}$$

To ensure that the nozzle-performance equation is satisfied for the C-75 and C-90 systems, we consider only nozzle discharges within the allowable range and use the above equation to determine the resulting spray width. Since Fig. 2.5 shows that pressure has only a modest effect on the effective spray width $WS$, we have elected to use an average value of 56 mwk in our analysis.

The Junior Haspel system appears to have quite different characteristics. Data from the manufacturer indicate that the system is used with combinations of nozzle pressure and flow such that the spray width $WS$ is approximately constant (nominally 62 m). The Junior system has a maximum hose length of 200 m and operates in the following flow range:

$$30 \leq QN \text{ m}^3/\text{hr} \leq 42.$$
The nozzle-performance equation is satisfied for the Junior system by considering only nozzle discharges within the above range and using a spray width of 62 m.

The spray width estimating equation for the Haspel systems is summarized below. For the C-75 and C-90 systems, we have substituted the average value of 56 mwk for the nozzle pressure, PN, in the regression equation above. For the Junior systems, we use a constant spray width.

\[
\begin{align*}
WS &= 30.9701*QN^{.2591} & \text{For C-75 and C-90} \\
WS &= 62.0 & \text{For Junior}
\end{align*}
\]  
(2.8)

2.2.5. Spray Diameter Estimating Equation: Buis System

Using data on commercially available nozzles, we developed an empirical equation describing the nozzle spray diameter as a function of nozzle discharge, shown plotted in Fig. 2.6 and given below:

\[
DS = 25.6*QN^{.35}
\]  
(2.9)

where DS = nozzle spray diameter (m),
QN = nozzle discharge (m³/hr).

2.2.6. Nozzle Pressure Estimating Equation: Buis System

Although any particular nozzle can be operated over a range of pressures, we found that both Rainbird and Dutch data indicate a gradual increase of design nozzle pressure with increasing nozzle discharge. We represent this by the following equation:

\[
PN = 31.44*QN^{.132}
\]  
(2.10)

where PN = pressure at the sprinkler nozzle (mwk),
QN = nozzle discharge (m³/hr).

2.2.7. Pipe Diameter Estimating Equation

Data showing the head drop in aluminum pipe as a function of flow rate and pipe diameter were obtained from Ref. 2.1. The head drop was given in feet per hundred feet, the flow rate in gallons per minute,
and the pipe diameter in inches. Reference 2.1 stated that the head drops were calculated using Scobey’s formula and a friction factor appropriate for aluminum pipe. These data were given in tabular form and in English units. We needed to express these same data in functional form and in metric units.

We plotted the head drop vs. flow rate for different pipe diameters on logarithmic coordinate paper (see Fig. 2.7) and found a series of parallel lines each describing head drop as a function of flow rate. We calculated the slope of these lines using selected data points from one of these curves. All of the lines have the functional form

\[ h = a \cdot Q^b \]

where \( h \) = the head drop (feet of water) per hundred feet of pipe, 
\( Q \) = flow through the pipe (gallons per minute).

The slope that we calculated is actually the exponent \( b \) in the expression for \( h \) above. We knew that the parameter \( a \) was dependent on the inside diameter, \( D \), of the pipe and observed that the relationship seemed to be log-linear. We had one curve for each of seven pipe diameters. All we needed was one point from each curve to determine the value of the parameter \( a \) for that curve. We regressed these values of \( a \) on the pipe diameter \( D \) using a function of the form:

\[ a = c \cdot D^g. \]

The fit was extremely good (\( R^2 = 0.9999 \)). Having determined values for all the parameters \((b, c, \text{ and } g)\), we converted the estimating equation from giving the head drop in feet per hundred feet to feet per foot and from English to metric units. Multiplying the result by the pipe length, \( L \), gives the total pressure drop in the pipe:

\[
\begin{align*}
P &= L \cdot \left( Q^{1.9} \right) \\
&= \frac{1000 \cdot (D/44.62)^{5.5}}{}
\end{align*}
\]

Where \( P \) = total pressure drop in pipe (m\( \text{w} \)), 
\( L \) = length of pipe (m), 
\( Q \) = flow through pipe (m\(^3\)/hr), 
\( D \) = inside diameter of pipe (mm).

By definition, the pressure drop in the pipe is the difference between the inlet and the outlet pressure. Thus, if the inside
diameter and outlet pressure are specified and the pipe length and flow are known, we can use Eq. 2.11 to estimate the pipe inlet pressure.

We also use Eq. 2.11 to estimate the pipe diameter required to accommodate the allowable head drop in the pipe. The allowable head drop is stated as a fraction of the pipe inlet pressure:

\[
\text{PI} - \text{PO} \quad \Delta = \frac{\text{PI}}{\text{PO}}
\]

where PI = pressure at inlet, PO = pressure at outlet.

The pressure drop in the pipe, i.e., the difference between the inlet and the outlet pressures, can be expressed as \(\text{DELTA} \times \text{PI}\):

\[
\frac{\text{L} \times Q^{1.9}}{1000 \times (D/44.62)^{5.5}}
\]

We rewrite this equation to express the diameter as a function of the other variables:

\[
D = 44.62 \times \left(\frac{L 	imes Q^{1.9}}{1000 \times \text{DELTA}}\right)^{0.2}
\]  (2.12)

where \(D\) = inside diameter of pipe (mm),
\(L\) = length of pipe (m),
\(\text{DELTA}\) = pressure drop as a fraction of inlet pressure,
\(Q\) = flow through pipe (m\(^3\)/hr),
\(\text{PI}\) = pressure at the inlet (mwh).

We recognize that \(Q\) might well decrease as the distance from the inlet point increases. For example, for a Buis lateral with five sprinklers, the part of the lateral pipe near the sprinkler farthest from the inlet would need to carry only enough water for one sprinkler. On the other hand, the part of the pipe nearest to the inlet would need to carry enough water to supply all five sprinklers. For simplicity, and also because it is conservative, we have assumed that the maximum \(Q\) flows through the entire length of the pipe.
2.3. BUIS SPRINKLER SYSTEM DESIGN MODEL

2.3.1. Approach to Designing a Buis System

In designing a Buis system, we take advantage of the system's capability to apply irrigation water quickly and allow moving intervals that are convenient to the farmer to be input. For example, a 24-hour moving interval means that the system need be moved at most once a day (also the same time every day). Moving intervals ranging from 12 to 144 hours are generally possible.

We rewrite Eq. 2.7 as

\[ NSET = \frac{TS}{M} \]  \hspace{1cm} (2.13)

and observe that we now have two equations for NSET: Eq. 2.13, which gives NSET as a function of the soil moisture cycle, and Eq. 2.2, which gives NSET as a function of the area covered per set. We require that the right hand sides of these two equations yield the same value for NSET. Thus

\[ 10^{4}A\times AF = TS \]
\[ \frac{--------}{AS} \hspace{1cm} \frac{--}{M} \]  \hspace{1cm} (2.14)

The soil moisture cycle, TS, and the area per set, AS, can be expressed as functions of input variables and RU, which when substituted into Eq. 2.14 yields an expression for RU in terms of known input variables. Once we have determined the value of RU, the values for the remaining design variables can be calculated directly.

Using Eqs. 2.3 through 2.6, we express TS as a function of RU:

\[ TS = \begin{bmatrix}
- & -
\end{bmatrix} \begin{bmatrix}
24 \times WA \\
RE
\end{bmatrix} \begin{bmatrix}
- & -
\end{bmatrix} \begin{bmatrix}
1
\end{bmatrix} + \begin{bmatrix}
- & -
\end{bmatrix} \begin{bmatrix}
24 \times RU/RE - 1
\end{bmatrix} \]  \hspace{1cm} (2.15)

In order to derive the expression for AS as a function of RU, we need to introduce some definitions and then use Eq. 2.9 to express the spray diameter, DS, as a function of RU.
The water application rate, RU (mm/hr), is defined as

\[ RU = \frac{ES \times QN \times 10^{+3}}{AN} \]  

(2.16)

where \( ES \) = sprinkling efficiency, 
\( QN \) = nozzle discharge (m\(^3\)/hr), 
\( AN \) = area considered to be sprinkled by one nozzle (m\(^2\)).

The sprinkling efficiency, \( ES \), is the ratio of the sprinkled water actually impacting the soil to the total discharged from the sprinkler nozzle. The factor of 1000 converts from meters per hour to millimeters per hour. The effective area, \( AN \), sprinkled by a nozzle is assumed to be rectangular with sides of length \( CA \times DS \) and \( CB \times DS \) (see Fig. 2.1). Values for \( CA \) and \( CB \) are chosen to ensure a uniform distribution of coverage given prevailing wind conditions and the general slope of the land.

\[ AN = CA \times CB \times DS \times 2 \]  

(2.17)

where \( CA \) = fraction of nozzle spray diameter effective parallel to the lateral,  
\( CB \) = fraction of nozzle spray diameter effective normal to the lateral,  
\( DS \) = nozzle spray diameter (m).

We obtain the desired relationship between RU and \( DS \) by rewriting Eq. 2.9 to express \( QN \) as a function of \( DS \) and substituting this for \( QN \) in Eq. 2.16. We also substitute for \( AN \) from Eq. 2.17, combine terms and reorder to obtain \( DS \) as a function of RU:

\[ DS = \frac{RU \times CA \times CB}{94.7 \times 10^{+3} \times (-3) \times ES} \]  

(2.18)

We are now in a position to express \( AL \), the area per set, as a function of RU. By definition (see Figs. 1.1 and 2.1), the area, \( AL \), sprinkled by one lateral in one location is

\[ AL = KM \times FD \times CB \times DS \]  

(2.19)
where \( KM \) = a constant depending on the sprinkler-system configuration (0.5 for \( CONFIG = 1, 3, 4, \) and 5; 1 for \( CONFIG = 2 \)), 
\( FD \) = length of field parallel to laterals (m).

Multiplying \( AL \) by the number of laterals, \( NL \), gives the area sprinkled per set (see Eq. 2.1, with \( N = NL \) and \( AU = AL \)). Substituting for \( AL \) from Eq. 2.19 and for \( DS \) from Eq. 2.18 gives \( AS \) as a function of \( RU \):

\[
\begin{align*}
\text{AS} &= \frac{NL \times KM \times FD \times CB \times 1.1667}{0.0947 \times ES} \\
&= \frac{NL \times KM \times FD \times CB \times 1.1667}{0.0947 \times ES} \\
&= \frac{26.64 	imes AF \times M \times ES \times 1.1667}{KM \times NL \times FD \times CB \times 2.1667 \times CA \times 1.1667 	imes WA \times RE \times 0.1667} \\
&= \frac{1}{1 + \frac{24 \times RU \times RE - 1}{RE}} \times 1.1667 \\
&= \frac{1}{1 + \frac{24 \times RU \times RE - 1}{RE}} \times 1.1667
\end{align*}
\]

(2.20)

We can now solve Eq. 2.14 in terms of known input quantities. Substituting for \( TS \) from Eq. 2.15 and for \( AS \) from Eq. 2.20, we combine terms and collect the known input variables in the left-hand side:

\[
\frac{26.64 \times AF \times M \times ES \times 1.1667}{KM \times NL \times FD \times CB \times 2.1667 \times CA \times 1.1667 \times WA \times RE \times 0.1667} \\
= \frac{1}{1 + \frac{24 \times RU \times RE - 1}{RE}} \times 1.1667
\]

(2.21)

Note that "\( K \)," the left-hand side of Eq. 2.21, is completely determined by the values of the design input variables.

Unfortunately, Eq. 2.21 cannot be solved directly for \( RU \) in terms of \( K \). However, we can describe a relationship between \( K \) and \( RU/RE \) as follows. We assign an arbitrary value to the ratio \( RU/RE \) and evaluate the right-hand side of Eq. 2.21, assigning the result to \( K \). We repeat this, letting \( RU/RE \) vary over a range of values. We then fit a log-linear curve to the variable \( RU/RE \) as a function of \( K \) using the data points generated in the above manner. We were able to fit the points very well (\( R^2 = 0.9999 \)) with the following expression:

\[
RU = 0.9567 \times RE \times K^{0.8805}
\]

(2.22)
In determining the range of values for RU/RE, we made use of manufacturers' data on nozzle flow rates and spray diameters to assess minimum and maximum attainable water application rates. We divided these minimum and maximum values of RU by the design evapotranspiration rate value of 2.5 mm/day; values of RE much lower than this would imply such moist weather that sprinkling would not be needed, and values much higher would only reduce the upper bound on the range we specified. We also included a few points just outside the range to ensure reasonable fits at either end of the range.

2.3.2. Designing Feasible Systems

The major requirement for a system to be feasible is that the idle time be non-negative. Specifically, the system must be capable of sprinkling and being moved within the prescribed moving interval. In the Buis design model, this translates into the constraint that the sprinkling time must be shorter than the moving interval because the model allows men to be added until the system can be moved in the time available. A secondary requirement is that the length of the lateral pipe must be greater than zero. If it were zero, there would be a single sprinkler head with no way to supply water to it. Further, if the length of the lateral were negative, the design is meaningless.

Although it is not dealt with explicitly in the model, a further constraint that should be observed is that the application rate lie within the range indicated by the rates for commercially available nozzles. This can only be observed by looking at the model output and checking it against available nozzle data. In the absence of data the range 5 to 15 mm per hour should be acceptable.

In this section, we present the steps in the design procedure through the point where either a feasible system has been determined or the design process has been halted. Descriptive material is held to a minimum because either the equations have been discussed in their general form earlier, or they are definitional.

Calculate water application rate, RU, using Eq. 2.21 for K and Eq. 2.22 for RU as a function of K.

\[
K = \frac{26.64 \times AF \times M \times ES \times 1.1667}{KM \times FD \times NL \times CB \times 2.1667 \times CA \times 1.1667 \times WA \times RE \times 0.1667}
\]  (2.23)

\[
RU = 0.9567 \times RE \times K^{0.8805}
\]  (2.24)
Calculate nozzle spray diameter, DS, using Eq. 2.18, nozzle discharge, QN, using Eq. 2.9, spray width, WS, area per lateral, AL, from Eq. 2.19, number of sets, NSET, from Eqs. 2.1 and 2.2.

\[
DS = \frac{RU*CA*CB}{(0.09467*ES)}^{**1.1667} \tag{2.25}
\]

\[
QN = 9.467*(10**(-5.0))*DS^{**2.8571} \tag{2.26}
\]

\[
WS = CB*DS \tag{2.27}
\]

\[
AL = WS*KM*FD \tag{2.28}
\]

\[
NSET = AF*10000.0/(NL*AL) \tag{2.29}
\]

\[
WF = AF*10000.0/FD \tag{2.30}
\]

Calculate times: sprinkling time, TU, from Eq. 2.4; drying time, TD, from Eq. 2.5; soil moisture cycle time, TS, from Eq. 2.6.

\[
TU = WA/(RU-RE/24.0) \tag{2.31}
\]

\[
TD = 24.0*WA/RE \tag{2.32}
\]

\[
TS = TU + TD \tag{2.33}
\]

Check for a feasible system. The sprinkling time, TU, must be less than the moving interval, M.

Determine values for sprinkler head variables: number of sprinklers per lateral, NS; total number of sprinklers in system, NST; and pressure at sprinkler head, PN (Eq. 2.10, repeated below).

\[
NS = KM*FD/(CA*DS) \tag{2.34}
\]

\[
NST = NL*NS \tag{2.35}
\]

\[
PN = 31.44*QN^{**0.132} \tag{2.36}
\]
The value of KM in Eq. 2.34 is 1 for Buis configuration B2 and 0.5 for all other configurations. In configuration 2 the length of the area sprinkled with a single lateral extends the full length of the field, FD, while in other configurations, which have a main distribution pipe running down the center of the field, the length of the sprinkled area is just half of FD (see Fig. 1.1).

Check for a feasible system. The number of sprinkler heads must be greater than 0.5. This is equivalent to requiring that the length of the lateral pipe on which the sprinkler head is to be mounted must be greater than zero.

2.3.3. Sizing System Components

Sizing system components involves calculating component specifications such as length, diameter, flows, and inlet pressure for the lateral pipe and for the main pipe (where it is used). This and subsequent parts of the model are used for feasible systems only. The necessary equations are presented first and followed by explanatory information.

2.3.3.1. Determine Values for Lateral Pipe Variables: Length of a lateral pipe, LL in meters; flow through lateral, QL in m³/hr; pressure at lateral inlet, PL (m w k); and the inside diameter of the lateral pipe, DL in mm.

\[
LL = (NS-0.5) \times CA \times DS \quad (2.37)
\]

\[
QL = NS \times QN \quad (2.38)
\]

\[
PL = PN/(1.0-DELTAL) \quad (2.39)
\]

\[
DL = 44.62 \times (LL \times QL \times 1.9/(1000 \times PL \times DELTAL))^{0.2} \quad (2.40)
\]

A lateral pipe must be long enough to accommodate NS sprinkler heads spaced every CA*DS meters along its length. However, it need not project beyond the center of the spray pattern of the outermost sprinkler head, which is accounted for by subtracting 0.5 from NS in Eq. 2.37.

Equation 2.40 is Eq. 2.12 using variable names appropriate to lateral pipes.

2.3.3.2. Determine Values for Main Pipe Variables: Length of main pipe, LM in meters; flow through main pipe, QM in m³/hr; pressure at main pipe inlet, HM in m w k; inside diameter of main pipe, DM in mm (Eq. 2.12, repeated below); number of tees, NT; and the number of end
plugs, NP. The first five variables shown below are set to zero for Buis configuration 2 because there is no main pipe (see Fig. 1.1).

\[ \text{LM} = \text{WF} - 0.5 \times \text{WS} \quad (2.41) \]

\[ \text{QM} = \text{QL} \times \text{NL} \quad (2.42) \]

\[ \text{HM} = \text{PL}/(1-\text{DELTAM}) \quad (2.43) \]

\[ \text{DM} = 44.62 \times (\text{LM} \times \text{QM} \times 1.9/(1000 \times \text{HM} \times \text{DELTAM}))^{0.2} \quad (2.44) \]

\[ \text{NT} = \text{NL} \times \text{NSET} \quad (2.45) \]

\[ \text{NP} = \text{NT} + \text{NL} \quad (2.46) \]

The main pipe, when it is used, is assumed to run down the center of the field and is long enough for the spray pattern of the sprinkler heads on the outermost lateral to reach the far edge of the field. One-half of the spray width, WS, is subtracted from WF, the dimension of the field parallel to the main pipe, to adjust the length of the main pipe accordingly in Eq. 2.41.

Two types of fittings are used: tees and end-plugs. Tees are used to join the laterals to the main pipe, and end-plugs are used to close one end of the laterals and one end of the tees. The couplings that connect the lateral pipe segments together are not considered here as a "fitting" because they are an integral part of the lateral-pipe segments and hence included in the cost estimates for the lateral pipe.

For configuration 2 (which does not require a main pipe), only one end-plug per lateral is needed. For all other configurations, we assume that a tee must be provided for each position of every lateral, and that there must be enough end-plugs to plug every tee and one end of every lateral.

In calculating the pressure at the main pipe inlet, we have not accounted for any drop through tees or around bends. Given that we have sized the pipes for a pressure drop of 10 percent, the velocities through the pipes are small enough that pressure drops in tees and curves are negligible.
2.3.4. Estimating Labor, Power, and Energy Requirements

2.3.4.1. Determine Labor Requirements and System Idle Time:
Distance walked in moving one lateral, DW in meters; time for one man to move one lateral, TM1 in hours; number of men required to move lateral from one set to next in the available time, NMEN; time to move lateral with NMEN men, TM in hours; system idle time, TI in hours; and moving man-hours per man per irrigation, TMOVE.

\[
DW = ((LL/LP)+0.5)*LP + WS*(LL/LP) \\
+ ((LL/LP)-2.0)*((2.0*LP)**2 + WS**2)**0.5 \\
+ ((1.5*LP)**2 + WS**2)**0.5
\]  
(2.47)

\[
\begin{array}{c}
\text{DW} \\
2*LL*UM \\
\text{CM}^*1000.0 \\
\text{LP}
\end{array} + \begin{array}{c}
\text{DW} \\
2*LL*UM \\
\text{CM}^*1000.0 \\
\text{LP}
\end{array} \\
\text{for CONFIG = 1,3,4,5}
\]

\[
TM1 = \begin{array}{c}
\text{DW} \\
2*LL*UM \\
\text{CM}^*1000.0 \\
\text{LP}
\end{array} \\
\text{for CONFIG = 2}
\]

\[
NMEN = \text{MAX}(1,\text{INT}(TM1/(M-TU) + 0.99))
\]  
(2.49)

\[
TM = TM1/NMEN
\]  
(2.50)

\[
TI = M - TU - TM
\]  
(2.51)

\[
TMOVE = NSET*(NL*TM + TKM)
\]  
(2.52)

The time it takes one man to move a lateral includes the man's walking time and the time needed to couple and uncouple the lateral pipe segments. For configuration 2, where there is no main pipe, the moving time is increased by ten minutes to allow the man to move his tractor and pump.

Lateral pipes are made by connecting short pipes together. The individual sections are assumed to be of equal length. In moving a lateral, the man must uncouple, move, and couple each section until the entire lateral has been moved to its new position. The man moves a lateral by carrying it, one section at a time, along the path shown in Fig. 2.8. Although this is one of many possible variations, we took it to be sufficiently representative for modeling purposes. It assumes that the walking path is independent of the number of men and that each man carries only one pipe segment at a time.
The path starts when the man reaches the lateral at the point where it joins the main pipe (or the pump for configuration 2). He uncouples the first pipe section from the main pipe, walks to the other end of the first section and uncouples it from the second section. He then walks back to the center of the first section, picks it up and carries it to its new location. He puts it down, walks over to the main pipe and couples the section to the main pipe. Next he walks to the far end of the second section (still in its original location), uncouples it from the third section, walks back to the center of the second section, picks it up, carries it to its new location, puts it down, walks to the end nearest the first section, and couples the sections. He repeats this process until he has moved all but the last pipe section. The last pipe section does not need to be uncoupled so he walks directly to the middle of that section, moves it to its new location and couples it. The total distance, DW, the man walks following a path like this is given by Eq. 2.47.

The time it takes a man to move the lateral depends on the total distance he has to walk, his average walking speed, the number of couplings and uncouplings he has to make, and the time he takes for each coupling or uncoupling. The total distance walked, DW, is measured in meters. The average walking speed, CM, is specified in kilometers per hour and converted to meters per hour. There will be LL/LP uncouplings and equal number of couplings. The time in hours to accomplish either, UM, is assumed to be the same. The total time for one man to move a lateral is given by Eq. 2.48.

In cases where one man cannot complete the move quickly enough, the model is programmed to keep adding men in an attempt to reduce the moving time until both sprinkling and moving can be accomplished within the moving interval. Even when additional men are added, however, some system designs may still be infeasible because the sprinkling time alone may be greater than the moving interval. In such cases, the model calculates and displays a negative idle time, letting the user decide whether or not the case should be rejected.

Note that we have assumed the number of manhours (which determines labor cost) is independent of the number of men used for the moving process (i.e., two men can move the system in half the time that one can, 3 men in a third the time, etc.). Thus, whereas increasing the number of men can reduce the moving time so as to make a particular system design feasible, it does not affect the cost of its operation.

We require that the number of men be an integer, equal to or greater than one. In Eq. 2.50 we divided the time required for one man to move a lateral by the time available to move the lateral. This quotient may be less than one and it will probably have both an integer and a fractional part. We add 0.99 to the quotient and use only the integer part of the result. This, in effect, will add a man when the fractional part of the quotient is 0.01 or larger. We then use the maximum of this number and 1 as our estimate of the number of men required to move the lateral in the available time.
In calculating the total hours per man per irrigation (Eq. 2.52), spent moving the Buis units, we allow for additional time to be spent traveling to and from the field via the input variable TKM.

2.3.4.2. Calculate Pumping Power and Energy Requirements: Pump shaft horsepower, SHP (metric); electrical energy consumed per irrigation, KWH (kilowatt-hours); and diesel fuel consumed per irrigation, DFUEL (liters).

\[
\begin{align*}
\text{SHP} &= \begin{cases} 
\frac{Q_M \cdot HM}{(270.0 \cdot EP)} & \text{for } \text{CONFIG} = 1,3,4,5 \\
\frac{Q_L \cdot PL}{(270.0 \cdot EP)} & \text{for } \text{CONFIG} = 2.
\end{cases} \\
\text{KWH} &= \begin{cases} 
0.736 \cdot \text{SHP} \cdot \text{TU} \cdot \text{NSET} / \text{EM} & \text{for } \text{CONFIG} = 1,4 \\
0 & \text{for } \text{CONFIG} = 2,3,5.
\end{cases} \\
\text{DFUEL} &= \begin{cases} 
\frac{\text{SFC} \cdot \text{SHP} \cdot \text{TU} \cdot \text{NSET}}{} & \text{for } \text{CONFIG} = 2,3,5 \\
0 & \text{for } \text{CONFIG} = 1,4.
\end{cases}
\end{align*}
\]

The power required by the pump is determined by the flow rate through the pump and the pressure rise across it. When the pump supplies water through a main distribution pipe, pump shaft horsepower is calculated from the inlet pressure and flow in the main pipe. For Buis configuration 2, where there is no main pipe, pump shaft horsepower is calculated from the lateral flow and inlet pressure. Equation 2.53 gives the power required by the pump in metric horsepower.

The energy required to complete one irrigation is estimated using either Eq. 2.54 or Eq. 2.55, depending on the power source for driving the pump. Buis configurations B1 and B4 use an electric motor and hence the pumping energy requirement is measured in kilowatt-hours. In estimating the electrical energy, we take into account the efficiency, EM, of the electric motor. There are 0.736 kilowatts per metric horsepower. All other Buis configurations use tractor-driven pumps so the energy requirement is the diesel fuel consumed by the tractor. The tractor specific fuel consumption, SFC, converts the horsepower-hours of power needed to the liters of diesel fuel consumed.
2.4. HASPEL SPRINKLER SYSTEM DESIGN MODEL

2.4.1. Approach to Designing a Haspel System

In designing a Haspel system, we constrain the utilization rate, UTIL, to be less than or equal to 75 percent of the moving interval. We select the smallest nozzle discharge rate, QN, from the range of permissible discharge rates that will yield a utilization rate less than or equal to 0.75. The system is then designed to provide this QN.

The choice of 75 percent results from a desire both to hold the cost down and to build in a reasonable degree of flexibility. Furthermore, we observe that 75 percent is the maximum utilization rate currently being achieved by Dutch farmers.

In reality, the choice of QN and the nozzel pressure, PN, will influence the waterdrop size and hence the kind of crops and soils that can be sprinkled with a Haspel system. The relationship among QN, PN, nozzel design, and waterdrop size was considered too complex to include in the design model. However, to the extent that the systems designed with the design model have flexibility to adjust QN and PN, some accommodation is possible.

The evapotranspiration rate RE, the area of the field AF, the sprinkling efficiency ES, and the allowable range of nozzle discharge rates (QMIN, QMAX) are all inputs. Once these are specified, a utilization rate, corresponding to each permissible value of QN, can be calculated directly. We can choose any discharge rate within the allowable range to design a Haspel system.

The maximum allowable discharge rate, QMAX, will yield a lower utilization rate than any lower discharge rate—the higher the discharge rate, the less time required for sprinkling. Low utilization rates are good because they allow more flexibility. For example, during periods when the actual RE is greater than the design RE a system designed to have a low utilization rate would be able to keep up with the demand while one designed with a higher utilization rate might not. However, systems designed to operate at QMAX would require bigger main pipes (where used) and bigger pumps, which cost more to buy, than systems designed to provide lower nozzle discharge rates and still do the same job.

Haspel systems designed with QMIN may in fact have quite low utilization rates (for small fields). However, for large fields, the utilization rate for QMIN may reach or exceed 100 percent. When 100 percent is exceeded, the system is clearly infeasible and QN must be increased. The design model insists that QN be in the allowable range and that the utilization rate be no greater than 75 percent.

In order to hold the cost down, we use the smallest nozzle discharge rate possible. We design the system to operate at the minimum nozzle discharge rate, QMIN, provided that the utilization does not exceed
0.75. When the utilization rate associated with QMIN exceeds 0.75, we calculate the QN required to give a utilization rate of 0.75. Should the QN required to meet the constraint on UTIL exceed the maximum allowable discharge rate, QMAX, no feasible system can be designed as the field size exceeds the maximum area that the Haspel type can irrigate.

Below, we derive the expression for UTIL as a function of input variables and QN. We begin by defining the utilization rate, UTIL, as the proportion of the moving interval taken up by sprinkling:

\[ UTIL = \frac{TU}{M}. \]  

(2.56)

The sprinkling time, TU, and the moving interval, M, can be expressed as functions of input variables and the nozzle discharge rate QN, which when substituted into Eq. 2.56 yields an expression for UTIL in terms of known input variables and QN.

From Eqs. 2.6 and 2.7, the moving interval can be expressed as

\[ M = \frac{TU + TD}{NSET}, \]  

(2.57)

which, when substituted into Eq. 2.56, gives

\[ UTIL = \frac{NSET}{1 + TD/TU}. \]  

(2.58)

Using Eqs. 2.3 through 2.5, we relate the ratio TD/TU to known input variables and the water application rate RU:

\[ \frac{24*WA/RE}{WA/(RU - RE/24)} = \frac{24*RU}{RU - 1} \]  

(2.59)

and substitute this into Eq. 2.58. Thus

\[ UTIL = \frac{NSET}{(24/RE)*RU}. \]  

(2.60)
The water application rate, RU, is defined as

\[ RU = \frac{1000^*QN^*ES}{AH} \]  \hspace{1cm} (2.61)

where \( ES \) = sprinkling efficiency,
\( AH \) = area covered by Haspel unit in one placement,

and the factor of 1000 converts from meters per hour to millimeters per hour.

Using Eqs. 2.2 and 2.1, we can express NSET as

\[ NSET = \frac{10000^*AF}{AH} \]  \hspace{1cm} (2.62)

where \( AF \) = area of field (hectares),

and \( AH \) was defined above. Inasmuch as the model allows only one Haspel unit, the variable \( N \) in Eq. 2.1 drops out. Substituting Eqs. 2.61 and 2.62 into Eq. 2.60, we obtain the desired expression for UTIL as a function of input variables and QN.

\[ UTIL = \frac{10000^*AF/AH}{(24/RE)^*(1000^*QN^*ES)/AH} \]
\[ = \frac{10^*(RE/24)^*AF}{QN^*ES} \]  \hspace{1cm} (2.63)

2.4.2. Designing Feasible Systems

A feasible Haspel system has a nozzle flow rate within the range QMIN to QMAX (inclusive), a utilization rate equal to or less than 75 percent, and a nonnegative idle time.

Check for feasible system: the Haspel type operating at its maximum nozzle discharge rate must be able to sprinkle the field without exceeding a 75-percent utilization rate. The maximum field size that the Haspel can accommodate operating at maximum nozzle discharge is defined as AFMAX.
AF\text{MAX} = 0.75*Q\text{MAX}^*\text{ES}/[(\text{RE}/24)^*10] \hspace{1cm} (2.64)

If the field size input, AF, is equal to or less than AF\text{MAX}, a feasible system can be designed.

Determine nozzle discharge rate, QN, and the constrained utilization rate UTIL. Initially the model sets QN equal to the minimum nozzle discharge rate, QMIN, and calculates the utilization rate UTIL. If the utilization rate, UTIL, calculated this way is less than or equal to 75 percent, the system is designed at the minimum nozzle discharge rate, QMIN.

\[ QN = QMIN \]

\[ UTIL = \frac{(\text{RE}/24)^*10*AF/(QN^*\text{ES})}{\text{for UTIL} < 0.75} \]

Should the value of UTIL calculated above exceed 75 percent, the model constrains UTIL to 75 percent and determines the required nozzle discharge rate. Because the model has already verified that the system can cover the entire field, operating at the maximum nozzle discharge rate, QMAX, ON will be within the prescribed range.

\[ UTIL = 0.75 \]

\[ QN = \frac{(\text{RE}/24)^*10*AF/UTIL/\text{ES}}{\text{for QMIN} < \text{QN} < \text{QMAX}} \]

Calculate the effective width of spray, WS, using Eq. 2.8.

\[ WS = \begin{cases} - & 30.9701*\text{QN}^{*0.2591} \quad \text{for C-75 and C-90} \\ - & 62.0 \quad \text{for Junior} \end{cases} \hspace{1cm} (2.65) \]

Determine the area sprinkled by one Haspel unit in one placement.

\[ AH = FDA^*WS \hspace{1cm} (2.66) \]

Calculate the length of hose, HL, required for the Haspel unit. Note that the hose need not extend all the way from the reel to the far
edge of the field (see Fig. 2.2). The spray will reach beyond the end of the hose.

\[ HL = FD - 0.31^*WS \]  
\[ (2.67) \]

Calculate the net application rate, \( R \), in millimeters per hour. The net application rate is the total supplied by the Haspel less that amount of water which is lost from the soil during sprinkling. The sprinkling efficiency, \( ES \), is the ratio of the sprinkled water actually impacting the soil to the total discharged from the sprinkler nozzle. The factor of 1000 converts from meters per hour to millimeters per hour and the 24 is to convert from millimeters per day to millimeters per hour.

\[ R = 1000.0^*QN^*ES/AH-(RE/24) \]  
\[ (2.68) \]

Calculate the number of sets, \( NSET \), the field width, \( WF \), the sprinkling time, \( TU \), the drying time, \( TD \), the soil moisture cycle time, \( TS \), and the moving interval, \( M \).

\[ NSET = AF^*10000./AH \]  
\[ (2.69) \]

\[ WF = AF^*10000./FD \]  
\[ (2.70) \]

\[ TU = WA/R \]  
\[ (2.71) \]

\[ TD = 24^*WA/RE \]  
\[ (2.72) \]

\[ TS = TU+TD \]  
\[ (2.73) \]

\[ M = TS/NSET \]  
\[ (2.74) \]

Time to move a Haspel unit: The tractor, which drives the pump, is also used to move the Haspel unit from one location to the next and it is assumed to travel at an average speed of 4.5 km (4500 m) per hour. The Haspel unit is moved first, then the tractor is attached to the sled and the sled is pulled out until the hose is fully extended. Finally, the tractor returns to the point where the tractor pump (mounted on the tractor) will be used and the pump is connected to either the Haspel reel or the main distribution pipe as appropriate for the configuration.
\[ \text{TM} = \frac{2 \times (\text{WS+HL})}{4500} + \frac{10}{60}. \]  

(2.75)

In configuration 1, the tractor pump is collocated with the Haspel reel. Thus, the distance traveled by the tractor is one WS to move the sled and reel to the next position, one HL to extend the hose, and another HL to return the tractor (and pump) to the reel. An extra distance equal to WS has been included to account for miscellaneous other travel. Further, an extra ten minutes is provided to place the pump intake hose in the ditch, to connect and disconnect the pump inlet and outlet hoses, to prime the pump, to perform minor maintenance tasks, to fuel the tractor, etc. This sounds like a lot to do in ten minutes, but the fact is that many of these tasks will not be performed very often and the ten-minute allowance is an average.

In configurations H2 and H3 the tractor follows the same path as it does in configuration H1 when moving the hose and reel. However, the tractor pump and the tractor will be located at the main pipe inlet point so the tractor must start from and return to that point. This distance varies depending on the location of the Haspel unit (from set to set) and rather than trying to determine the exact distance, we have assumed that the time spent traveling this extra distance is included in the extra ten minutes (added for all configurations) along with the other items mentioned above. When simply coming from and returning to its pumping location, the tractor would probably be able to travel considerably faster than indicated by the average speed above.

The idle time is the time that the Haspel unit spends neither sprinkling nor moving.

\[ \text{TI} = \text{M-TU-TM} \]  

(2.76)

Check for feasibility. The idle time, as calculated above, must be nonnegative. This check is made for completeness, as it will almost never be violated. The constraint on the utilization rate ensures that the sprinkling time will never exceed 75 percent of the moving interval, which almost always leaves more than enough time for moving the Haspel unit.

Calculate the sled velocity, VS (m/hr).

\[ \text{VS} = \frac{\text{HL}}{\text{TU}} \]  

(2.77)

Although the technical specifications state minimum and maximum sled velocities, the model does not make a feasibility check on
VS. Rather, it displays the calculated value and lets the user decide whether or not the velocity--and thence the sprinkling system--is feasible.

2.4.3. Sizing System Components

Calculate hose inlet pressure, $PH$ (mwk). The nozzle discharge rate, $QN$, gives the required flow through the hose. The inside diameter ($DH$) of the hose is input. The pressure ($PN$) at the sprinkler head, also input, is the same as the hose outlet pressure. We assume that the pressure drop estimating equation for a pipe (Eq. 2.11) applies to the Haspel hose as well.

$$PH = PN \times (1 + H/L \times QN^{**1.9} / 1000 \times PN / (DH/44.62)^{**5}) \quad (2.78)$$

Determine values for main pipe variables: length of main pipe, $LM$ in meters; flow through main pipe, $QM$ in $m^3/hr$; pressure at main pipe inlet, $HM$ in $mwk$; inside diameter of main pipe, $DM$ in mm; and number of tees, $NT$.

$$LM = \begin{cases} 
0.0 & \text{for configuration H1} \\
0.0 & \text{for configurations H2, H3 and NSET} \leq \text{1.4} \quad (2.79) \\
WF - WS & \text{for configurations H2, H3 and NSET} > \text{1.4} 
\end{cases}$$

$$QM = \begin{cases} 
0 & \text{for } LM = 0 \\
QN & \text{for } LM > 0 
\end{cases} \quad (2.80)$$

$$HM = \begin{cases} 
0 & \text{for } LM = 0 \\
PH / (1.0 - DELTAM) & \text{for } LM > 0 
\end{cases} \quad (2.81)$$
\[
\begin{align*}
&DM = \begin{cases} 
0.00 & \text{for } LM = 0 \\
0.2 & \text{for } LM > 0 \\
44.62 \cdot 1000 \cdot HM \cdot \text{DELTAM} & \text{for } LM > 0
\end{cases} \\
&\text{(2.82)}
\end{align*}
\]

\[
\begin{align*}
&NT = \begin{cases} 
0.0 & \text{for } LM = 0 \\
\text{NSET} & \text{for } LM > 0
\end{cases} \\
&\text{(2.83)}
\end{align*}
\]

The main pipe, when it is used, is assumed to run down one side of the field, normal to the Haspel, and is long enough for the spray pattern of the Haspel to reach the edge of the field when attached at either end of the main pipe (see Fig. 1.1). The Haspel can reach half a spray width, WS, beyond the end of the pipe. A full spray width (half at either end of the main pipe) is subtracted from WF, the dimension of the field parallel to the main pipe, to adjust the length of the main pipe accordingly.

In calculating the pressure at the main pipe inlet, we have not accounted for any drop through tees or around bends. Given that we have sized the pipes for a pressure drop of 10 percent, the velocities through the pipes are small enough that pressure drops in tees and curves are negligible.

Haspel configurations 2 and 3, which use a point water source, require a main pipe to distribute the water along the length of the field (perpendicular to the hose). However, when the field is so narrow that it can be sprinkled adequately in one set, no pipe is needed. We assume that, without a pipe, sprinkling is "adequate" if the field can be covered in 1.4 sets or less. A main pipe is not used in Haspel configuration 1.

2.4.4. Estimating Labor, Power, and Pumping Energy Requirements

The total hours per man per irrigation spent moving the Haspel unit are

\[
T_{\text{MOVE}} = \text{NSET} \cdot (TM + TKM) \\
\text{(2.84)}
\]
We allow for additional time to be spent traveling to and from the field via the input variable TKM.

Calculate pumping power and energy requirements: pump shaft horsepower, SHP (metric), and diesel fuel consumed per irrigation, DFUEL (liters).

\[
\text{SHP} = \begin{cases} 
\frac{\text{QN} \times \text{PH} / 0.9 / 270}{\text{EP}} & \text{for } \text{LM} = 0 \\
\frac{\text{QM} \times \text{HM} / 0.9 / 270}{\text{EP}} & \text{for } \text{LM} > 0
\end{cases}
\] (2.85)

\[
\text{DFUEL} = \text{SFC} \times \text{SHP} \times \text{TU} \times \text{NSET}
\] (2.86)

The power required by the pump is determined by the flow rate through the pump and the pressure rise across it. When the pump supplies water through a main distribution pipe, pump shaft horsepower is calculated from the inlet pressure and flow in the main pipe. When there is no main pipe, pump shaft horsepower is calculated from the hose flow and inlet pressure. In Eq. 2.85, which gives the power required by the pump in metric horsepower, the factor 0.9 is to allow for a ten-percent power diversion to drive the Haspel reel and 270 takes into account the mass of the water and converts to metric horsepower.

The pumping energy required to complete one irrigation is estimated by the amount of diesel fuel consumed by the tractor while pumping. The tractor specific fuel consumption, SFC, converts the horsepower-hours of power needed to the liters of diesel fuel consumed. The diesel fuel consumed by the tractor while moving the Haspel unit is so small as to be considered negligible.

NOTES

1. This follows the practice of Rainbird. See Ref. 2.1.

2. For example, in moving lightweight aluminum pipe, several pipe sections may be moved at the same time. If more than one man is involved, the path of each man may differ from the path that would be followed by one man working alone.

REFERENCE

Fig. 2.1—Typical Buis lateral
Number of sets = \frac{\text{Area of field}}{\text{Area of set}}

Fig. 2.3—Sets and the area coverage requirement
Fig. 2.5—Haspel spray width vs. nozzle discharge rate and pressure

The equation for the relationship is:

\[ WS = 19.6753PN^{0.1127}QN^{0.2591} \]

with a coefficient of determination \( R^2 > 0.95 \).
Fig. 2.6--Nozzle spray diameter vs. nozzle discharge rate

\[ DS = 25.6QN^{0.35} \]
Fig. 2.7--Pressure drop in pipe vs. flow rate and inside diameter

\[ P = 10^{-1}D^{-5}Q^{1.9} \]

where:
- \( P \) = pressure drop per ft. (feet of water)
- \( D \) = pipe inside diameter (inches)
- \( Q \) = flow rate (gallons per minute)

SOURCE: Rainbird Sprinkler Irrigation Handbook, Aluminum pipe
Fig. 2.8--Path walked to move one lateral pipe
Table 2.1
INPUTS TO SPRINKLER SYSTEM DESIGN MODEL

<table>
<thead>
<tr>
<th>Input Description</th>
<th>Variable Name</th>
<th>Buis</th>
<th>Haspel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design evapotranspiration rate (mm/day)</td>
<td>RE</td>
<td>RE</td>
<td></td>
</tr>
<tr>
<td>System parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkling efficiency</td>
<td>ES</td>
<td>ES</td>
<td></td>
</tr>
<tr>
<td>Fraction of nozzle spray diameter effective along the lateral</td>
<td>CA</td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>Fraction of nozzle spray diameter effective normal to the lateral</td>
<td>CB</td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>Minimum flow rate through nozzle (m$^3$/hr)</td>
<td>QMIN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum flow rate through nozzle (m$^3$/hr)</td>
<td>QMAX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nozzle pressure (mhw)</td>
<td>PN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric motor driven pump efficiency</td>
<td>EP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tractor driven pump efficiency</td>
<td>EP</td>
<td>EP</td>
<td></td>
</tr>
<tr>
<td>Electric motor efficiency</td>
<td>EM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tractor specific fuel consumption (1/hp-hr)</td>
<td>SFC</td>
<td>SFC</td>
<td></td>
</tr>
<tr>
<td>Length of lateral pipe segment (m)</td>
<td>LP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowable pressure drop in lateral as a fraction of lateral inlet pressure</td>
<td>DELTAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hose inside diameter (mm)</td>
<td>DH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowable pressure drop in main pipe as a fraction of inlet pressure</td>
<td>DELTAM</td>
<td>DELTAM</td>
<td></td>
</tr>
<tr>
<td>Walking speed when moving laterals (km/hr)</td>
<td>CM</td>
<td>(b)</td>
<td></td>
</tr>
<tr>
<td>Time to couple (uncouple) a pipe joint (hr)</td>
<td>UM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Setting for sprinkling system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System configuration</td>
<td>CONFIG</td>
<td>ICON</td>
<td></td>
</tr>
<tr>
<td>Area of field (ha)</td>
<td>AF</td>
<td>AF</td>
<td></td>
</tr>
<tr>
<td>Field dimension parallel to lateral pipe or Haspel hose (m)</td>
<td>FD</td>
<td>FD</td>
<td></td>
</tr>
<tr>
<td>Amount of water to be applied per irrigation (mm)</td>
<td>WA</td>
<td>WA</td>
<td></td>
</tr>
<tr>
<td>Transit time to and from field (hr)</td>
<td>TKM</td>
<td>TKM</td>
<td></td>
</tr>
<tr>
<td>Cost trade-off variables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moving interval (hr)</td>
<td>M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of laterals (c)</td>
<td>NL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of Haspel unit</td>
<td>I</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) The corresponding variables for the Haspel are built into the model by specifying that the effective spray width is equal to 0.85 times the spray diameter.
(b) The tractor speed, when moving the Haspel, is built into the model at 4.5 km/hr.
(c) Only one lateral is allowed in configuration 2.
Table 2.2
OUTPUTS FROM SPRINKLER SYSTEM DESIGN MODEL

<table>
<thead>
<tr>
<th>Output Description</th>
<th>Variable Name</th>
<th>Buis</th>
<th>Haspel</th>
</tr>
</thead>
<tbody>
<tr>
<td>From design of feasible systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water application rate (mm/hr) (net for Haspel)</td>
<td>RU</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Nozzle discharge rate (m³/hr)</td>
<td>QN</td>
<td>QN</td>
<td></td>
</tr>
<tr>
<td>Nozzle spray diameter (m)</td>
<td>DS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective spray width or width</td>
<td>WS</td>
<td>WS</td>
<td></td>
</tr>
<tr>
<td>of sprinkled swath (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of sprinkler heads per lateral</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of sprinkler heads in system</td>
<td>NST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure at sprinkler head (mwwk)</td>
<td>PN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area covered by one lateral or Haspel (m²)</td>
<td>AL</td>
<td>AH</td>
<td></td>
</tr>
<tr>
<td>Number of sets required</td>
<td>NSET</td>
<td>NSET</td>
<td></td>
</tr>
<tr>
<td>Sprinkling time per set (hr)</td>
<td>TU</td>
<td>TU</td>
<td></td>
</tr>
<tr>
<td>Drying time (hr)</td>
<td>TD</td>
<td>TD</td>
<td></td>
</tr>
<tr>
<td>Soil moisture cycle time (hr)</td>
<td>TS</td>
<td>TS</td>
<td></td>
</tr>
<tr>
<td>Moving interval (hr)</td>
<td>M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to move one Haspel unit (hr)</td>
<td>TM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System idle time per set (hr)</td>
<td>TI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hose length (m)</td>
<td>HL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hose travel velocity (m/hr)</td>
<td>VS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of field normal to hose (m)</td>
<td>WF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>From sizing system components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of a lateral pipe (m)</td>
<td>LL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow through lateral pipe (m³/hr)</td>
<td>QL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inside diameter of lateral pipe (mm)</td>
<td>DL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure at inlet to lateral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pipe or Haspel hose (mwwk)</td>
<td>PL</td>
<td>PH</td>
<td></td>
</tr>
<tr>
<td>Length of main pipe (m)</td>
<td>LM</td>
<td>LM</td>
<td></td>
</tr>
<tr>
<td>Flow through main pipe (m³/hr)</td>
<td>QM</td>
<td>QM</td>
<td></td>
</tr>
<tr>
<td>Inside diameter of main pipe (mm)</td>
<td>DM</td>
<td>DM</td>
<td></td>
</tr>
<tr>
<td>Pressure at inlet to main</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pipe (mwwk)</td>
<td>HM</td>
<td>PH</td>
<td></td>
</tr>
<tr>
<td>Number of tees</td>
<td>NT</td>
<td>NT</td>
<td></td>
</tr>
<tr>
<td>Number of end plugs</td>
<td>NP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>From calculating labor, power, and energy requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time for one man to move lateral (hr)</td>
<td>TM1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of men required to move one lateral in the available time</td>
<td>NMEN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to move one lateral (hr)</td>
<td>TM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System idle time (hr)</td>
<td>TI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time moving equip. per man per irrig. (hr)</td>
<td>TMOVE</td>
<td>TMOVE</td>
<td></td>
</tr>
<tr>
<td>Pump or motor horsepower (metric)</td>
<td>SHP</td>
<td>SHP</td>
<td></td>
</tr>
<tr>
<td>Electricity per irrigation (kWh)</td>
<td>KWH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel fuel per irrigation (l)</td>
<td>DFUEL</td>
<td>DFUEL</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3
SPRINKLER SYSTEM COST MODELS

3.1. INTRODUCTION

Although they have much in common, there are two sprinkler system cost models; one for Buis systems and the other for Haspel systems. Each model consists of a number of generalized cost estimating relationships (CERs) and a logical structure that selects the CERs appropriate to a specified system and configuration.

Complete lists of cost model input and output variables are provided in Tables 3.1 and 3.2. A glance at the tables indicates the high degree of commonality between the models for the two systems. Some of the inputs and outputs are not appropriate for both systems so blanks appear in the tables. The cost models obtain most of the inputs directly from the design models and the only additional inputs that must be specified are the total amount of water sprinkled per year, the annual interest rate, and the useful lives of the system components.

The primary outputs are investment cost, annual operating cost, annualized investment cost, annualized cost, and annual operating cost factors. Investment cost reflects the size of the one-time outlay or commitment that a farmer must make to purchase a sprinkler system. Annual operating costs, on the other hand, are recurring and thus reflect an ongoing commitment. Annualized investment cost is calculated and added to annual operating cost so that a single annualized cost is available for comparing alternative sprinkler systems. The annual operating cost coefficients are provided for use in other PAWN models where it is necessary to estimate the cost of a sprinkler system operated under assumptions reflecting different weather scenarios than those used in the cost model.

Investment and operating costs are calculated and presented by cost element (system component for the most part) to make it easy to see why one system costs more or less than another. Further, cost elements are closely related to resource requirements such as labor, material, energy, etc., and demands for particular kinds of resources can often be more important than money cost when deciding among sprinkler systems. For example, labor cost is a cost element to bring the demand for a potentially scarce resource--the farmer's time--clearly into focus.

Working at the cost element level has at least three other advantages. First, it is easier to develop CERs to estimate the cost of pumps, pipes, sprinkler heads, etc., than to estimate total system cost directly. Second, even though more inputs are required, the user of the model is allowed to specify the system he wants costed at a meaningful level of detail and to see the effect of variations in
system specification on cost. Third, with CERs at the component level, the model is easy to validate and change.

In the remainder of this chapter, we first present a brief discussion of the development of each investment CER. Next, the factors used to estimate annual operating cost are presented with an explanation of how they are applied. The logical structures for the Buis and the Haspel cost models are then presented to show how the CERs and operating cost factors are used with other inputs to estimate sprinkler system costs.

3.2. INVESTMENT COST ESTIMATING RELATIONSHIPS

Investment CERs for the Buis and the Haspel cost models are discussed together in this section. All investment CERs exclude value added tax (BTW) and are assumed to be in 1976 price levels. CERs are required for nine investment cost elements. These cost elements and the independent variables used to estimate their costs are summarized in Table 3.3.

3.2.1. Sprinkler Heads

Rotating sprinkler heads, frequently called impact sprinklers, are considered as they are most commonly used for agricultural irrigation. These sprinklers eject a stream of water under pressure and are constructed so that the force created by the water leaving through the nozzle causes the sprinkler head to rotate. If left alone, these sprinklers will continue to turn in the same direction as long as water is being forced out the nozzle. However, most are constructed with adjustable stops that, when contacted by a trigger on the rotating part of the head, cause the sprinkler to reverse the direction of rotation. There are usually two of these stops and by presetting them, the sprinkler can be caused to sprinkle any fraction of the entire circle. Only full circle sprinkling is considered in the Buis sprinkler system design model.

The diameter of the circle sprinkled by a particular sprinkler head varies considerably with the angle of elevation of the nozzle, the pressure at the nozzle, the rate of flow through the nozzle, and the diameter of the hole in the nozzle. Further, most of these parameters can be varied over a wide range (some parameters can be varied only during manufacture) without affecting the cost of the sprinkler head.

For example, one sprinkler head (typical of the smaller ones considered) can be made to sprinkle circles ranging from approximately 25 to 35 meters in diameter. In the first instance, the nozzle pressure is 27 mwk, the nozzle diameter is 3.6 mm, and the flow through the nozzle is 0.8 m³/hr. To achieve the larger spray diameter, the pressure is increased to 50 mwk, the nozzle diameter to 5.6 mm, and the flow rate to 2.7 m³/hr. This illustrates the fact that there is no simple way to relate sprinkler head cost and performance.
Sprinkler head cost and technical data were obtained from one U.S. manufacturer and two Dutch distributors [3.1, 3.2, and 3.3] on several hundred sprinkler heads like the ones described above. Dutch price lists were used for the cost of the U.S. manufacturers' sprinkler heads. Many of the sprinkler heads fell into classes, with each member of the class only a minor variation of the other members, and in many instances each manufacturer provided identical sprinkler heads. This commonality allowed us to represent the relevant range of sprinkler heads with a sample of less than 20.

Figure 3.1 is a graph showing the cost of these sprinkler heads as a function of the range of spray diameters achievable with each. The exponential function, also shown in Fig. 3.1, more or less reflects the cost of a sprinkler head as a function of its nominal or average spray diameter:

\[
\text{SHCOST} = 24.39 \times \text{EXP}(0.0394 \times \text{DS})
\]  

(3.1)

where SHCOST = investment in sprinkler heads (Dfl),
DS = nozzle spray diameter (m).

This sprinkler head CER is only used for Buis systems as the cost of the sprinkler head for Haspels is included in the cost of the Haspel units.

3.2.2. Haspel Units

The CERS for Haspel units are based on cost and technical data obtained from CEBECO [3.4]. Costs are in 1977 price levels and exclude value-added tax (BTW). A Haspel unit includes a reel, hose, sled, and sprinkler head. There are other suppliers of Haspel systems and most of them provide systems that cost substantially more than those supplied by CEBECO. Inasmuch as CEBECO is big Dutch national cooperative for buying and selling farming equipment, we have assumed their data is representative and used it to develop our Haspel CERs.

CEBECO supplies three basic Haspel units: the Junior, the C-75, and the C-90. The Junior is a minimum system, while the C-75 and the C-90 are progressively larger and more elaborate. The Junior comes with a standard hose 200 m long and 75 mm in diameter (outside diameter). The C-75 comes with 300 m of 75-mm hose and the C-90 with 300 m of 90-mm hose. The costs of the Junior, C-75, and C-90 are 18,100 Dfl, 22,300 Dfl, and 25,900 Dfl, respectively. Hose can be purchased for the Junior and the C-75 at 11 Dfl/m and for the C-90 at 15 Dfl/m.

Because of reel capacity, the longest hoses that can be accommodated are 200 m for the Junior, 370 m for the C-75, and 350 m for the C-90. We assumed that each unit could be purchased with more or less than the
normal amount of hose. The CERs shown below were obtained by subtracting the cost of the nominal hose length from the total Haspel cost and then expressing the cost of each Haspel unit as a constant plus a cost per meter of hose purchased (see Fig. 3.2).

\[
\text{HSCOST} = \begin{cases} 
15900 + 11 \times \text{HL} & \text{for Junior system} \\
19000 + 11 \times \text{HL} & \text{for C-75 system} \\
21400 + 15 \times \text{HL} & \text{for C-90 system}
\end{cases}
\quad (3.2)
\]

where HSCOST = investment in Haspel unit (Dfl),
HL = length of hose (m).

3.2.3. Pipe

Buis systems require both lateral and main distribution pipes while the Haspel systems need only a main distribution pipe. We gathered information on the cost of irrigation system pipe from several manufacturers who market this kind of pipe in the Netherlands [3.2, 3.3, 3.4]: Mannesmann-Rohrbau, Perrot, and Cebeco-Handelsraad (CEBECO). These pipes are made of either aluminum or hot dip galvanized steel, range in diameter from 50 to 160 mm, and come in standard lengths.

From each we selected a sample of pipes (range of diameters) that together spanned the requirements of the sprinkler systems being considered and made a plot of pipe cost per meter vs. pipe diameter (see Fig. 3.3). We observed that pipe cost per meter varies among suppliers, but in general seems to increase exponentially with pipe diameter. The cost of pipes supplied by CEBECO were always lowest, and inasmuch as CEBECO is the major supplier of sprinkling equipment in the Netherlands, we based our CER on their data.

\[
\text{PCOST} = 3.8 \times \text{EXP} (0.0161 \times \text{D})
\quad (3.3)
\]

where PCOST = investment cost of pipe per meter (Dfl),
D = diameter of pipe (mm).

The pipe CER was developed using pipe outside diameter. The design model, on the other hand, estimates the inside diameter. In the cost model, we use the inside diameter to estimate pipe cost, on the grounds that the error caused by this is much less than the error inherent in the CER itself.
3.2.4. Pipe Fittings

Two kinds of pipe fittings are considered: Tees, which are used to join lateral pipes and Haspels to the main distribution pipe, and end plugs, which are used to close the ends of the lateral pipes and the tees (when nothing is connected to them). Cost and technical data from Refs. 3.2 and 3.4 were used to develop the CERs shown in Figs. 3.4 (end plugs) and 3.5 (tees).

\[
\text{PLUG} = 0.2120D^{1.0439} \quad (3.4)
\]

\[
\text{TEE} = 0.4107D^{1.2424} \quad (3.5)
\]

where PLUG = the cost of one end plug (Dfl),
TEE = the cost of one tee (Dfl),
D = the appropriate pipe diameter (mm).

In each case, power functions were used to describe the unit costs of end plugs and tees as a function of the diameter of the pipe they are used with. The function fits the data for end plugs quite well. The tees supplied by Ref. 3.4 cost less than those in Ref. 3.2 and are said to be more widely used in the Netherlands. Therefore, the CER for tees has been intentionally biased toward these data.

The diameters of the fittings used to develop the CERs are consistent with the following rules for choosing the appropriate pipe diameter, D.

Tees join sections of the main distribution pipe at the points where either lateral pipes or Haspels can be connected. As the diameter of the main part of the tee is determined by the diameter of the main pipe, the main pipe diameter is used to estimate the cost of tees.

The cost of end plugs, for Buis systems, is always estimated using the lateral pipe diameter. One end of each lateral is closed with an end plug and the branch of the tee where the lateral connects is also closed with an end plug when the lateral is not present. Further, the diameter of that part of the tee which connects the lateral to the main distribution pipe has the same diameter as the lateral.

With Haspel systems, end plugs are used only to close tees and their costs are estimated using the diameter of the main pipe. This probably overstates the cost as in reality, the diameter of that part of the tee that connects to the Haspel might be less than that of the main pipe.
3.2.5. Tractor-Driven Pump

Tractor pumps attach directly to the farmer's tractor and are powered by the tractor's engine. We obtained cost and performance data on 13 different size pumps from Ref. 3.4. These pumps vary in capacity from about 20 to 550 m³/hr, operate at head pressures from less than 6 to more than 100 m³/hr, and range in price from 950 to 2675 Dfl (1976 prices excluding BTW). Each pump has a single price but can operate at many different combinations of flow rate and pressure. For example, the data for one pump consist of: capacity from 72 to 144 m³/hr, pumping head from 75 to 57 m³/hr, cost 1700 Dfl.

These pumps are driven by the tractor engine, and larger or smaller tractors can supply more or less power to the pump, so it seems reasonable that a single pump can be operated at a relatively wide range of horsepowers.

The data indicated that cost increased with both flow rate and head pressure even though a single pump can be operated at different combinations of these two variables. In the cost model, we need to estimate the cost of a pump that will operate at the single combination of flow rate and head pressure specified by the design model. Therefore, averaging the flow rates and head pressures for each of the 13 pumps in the data seemed justified.

We plotted cost vs. average head pressure and wrote the corresponding average flow rate next to each point. We noted that for points with roughly equal flow rates the cost increased with head pressure and that for points with roughly equal head pressure the cost increased with flow rate. We drew equal flow rate contours guided by the data points. A parabola was chosen to describe the shape of these contours because it was the simplest mathematical function that had the appropriate properties.

All of the equal flow contours were parallel so that the coefficients of head pressure will not vary with the flow rate. The constant term will, of course, vary with the flow rate. The general form of the CER is thus

\[ \text{PUMPT} = f(Q) + a\times P + b\times P^2 \]  \hspace{1cm} (3.6)

where PUMPT = the cost of the tractor pump,
\[ P = \text{the head pressure}. \]

To investigate the functional relationship between cost and flow rate, we made a plot of cost vs. flow rate using each of the 13 data points and wrote the head pressure on the graph with each point as it was plotted. Here we anticipated that the result would be nonlinear and so made the plot on logarithmic coordinate paper. We drew a straight line located where we thought it should be for head pressure equal to zero. This straight line is the function \( f(Q) \)
\[ f(Q) = 140Q^{0.51} \]

where \( Q \) = flow rate (m\(^3\)/hr).

We fit a parabola to one of the equal flow rate contours to obtain values for the coefficients of head pressure (\( a \), and \( b \)) and substituted these, together with the expression for \( f(Q) \) into Eq. 3.6 to obtain the following result

\[ \text{PUMPT} = 140Q^{0.51} - 10.02P + 0.18P^{0.52} \quad (3.7) \]

which is the CER used to estimate the investment cost of tractor pumps as a function of both flow rate and head pressure. Figure 3.6 shows how well this expression reproduces the costs in the original data when they are estimated using the average head pressures and flow rates. Eleven of the thirteen estimates are within plus or minus 10 percent of the costs in the original data. The maximum difference is 14 percent.

3.2.6. Electric Motor-Driven Pump

Pumps driven by electric motors are mounted permanently together with the motor, usually on a concrete slab. We obtained cost and performance data on nine different size pumps from Ref. 3.5. These pumps, which constitute the Centrinorm series built by the Dutch manufacturer Stork Pompen, are typical of agricultural irrigation pumps used in the Netherlands. Therefore, these pumps were taken as representative of all sprinkling pumps for the analyses discussed here. They vary in flow rate from 10 to 80 m\(^3\)/hr, operate at head pressures from 10 to 120 mwk, and cost from 760 to 1275 Dfl (1978 price levels, excluding BTW). Each pump can operate under various combinations of flow rate and head pressure. For example, one pump will operate with flow rates from 35 to 90 m\(^3\)/hr and head pressures of 120 to 30 mwk.

The CER for the electric motor-driven pump is a modification of the one for tractor-driven pumps. We calculated an average flow rate and head pressure for each of the nine pumps and used these values in the tractor pump CER to obtain a first approximation of the cost for electric motor-driven pumps. We then plotted the actual cost vs. these approximations and observed that the relationship could be described closely with the linear equation

\[ \text{PUMPE} = 585 + 0.3297 \times \text{PUMPT} \quad (3.8) \]
where \( PUMPE = \) cost of electric motor-driven pump, \\
\( PUMPT = \) first approximation using tractor pump CER.

Substituting for \( PUMPT \) from Eq. 3.7, we obtain the CER for electric motor-driven pumps:

\[
PUMPE = 585 + 46.16Q^{*0.51} - 3.304P + 0.059P^{*2} \quad (3.9)
\]

Figure 3.7 shows how well this CER reproduces the actual costs. Eight of the nine estimates differ from the actual cost by less than 10 percent. The maximum difference is less than 12 percent.

3.2.7. Electric Motor and Control Equipment

The CER for electric motors is based on the cost and horsepower rating of the motors that Stork Pompen suggested using with their Centrinorm series of pumps [3.5]. The motors range from 4 to 30 horsepower and cost from 870 to 2845 Dfl (1978 price levels, excluding BTW). The cost includes the motor, couplings to the pump, a foundation for the pump and motor, and connecting the pump and motor. We plotted cost vs. horsepower in Fig. 3.8 and described the relationship with the piecewise linear function:

\[
\text{MOTOR} = \begin{cases} 
400 + 103\times\text{SHP} & \text{SHP} < 6.6 \\
523 + 84.4\times\text{SHP} & 6.6 < \text{SHP} < 17.5 \\
1034 + 55.2\times\text{SHP} & 17.5 < \text{SHP} 
\end{cases} \quad (3.10)
\]

where \( \text{MOTOR} = \) investment in electric motor (Dfl), \\
\( \text{SHP} = \) motor or pump horsepower (metric).

Control equipment, which consists primarily of the electrical hookup and switches, is required only when an electric motor is used. We obtained estimates of the cost of control equipment and of associated electric motor-driven pumps from Ref. 3.6. The costs are in 1977 price levels and exclude BTW. These data are plotted (control equipment cost vs. pump cost) in Fig. 3.9. There are only 5 points with the two higher ones reflecting use with Haspel systems and the three lower ones use with Buis systems. The graph indicates that two straight lines (one for the Haspel and another for the Buis) would fit the data better than the single straight line that we picked. However, the data are so sparse, we decided to use the single
straight line shown as our CER. It was located by eye so that it
would pass through the origin and be biased slightly towards the
higher cost Haspel data points. The magnitude of the costs for this
cost element are small relative to other investment costs so no
further refinement was attempted. The CER is simply:

\[ \text{CONTEQ} = 0.46 \times \text{PUMPE} \] (3.11)

where CONTEQ = investment in control equipment (Dfl),
PUMPE = investment in electric motor-driven
pump (Dfl).

3.2.8. Well

A well is used as the source of irrigation water in several of our
sprinkling system configurations and is a relatively expensive item.
The cost of wells varies widely with the location of the well, the
type of construction used, the depth and capacity of the well, the
intended use of the well, and other factors too numerous to be
considered explicitly in this model. Further, no data specific to
agricultural wells in the Netherlands were available. We did obtain
five estimates of the cost of wells (including BTW at 4 percent) used
with sprinkling systems in the Netherlands [3.6]. As the area of
the field sprinkled by each well was the only explanatory variable
available from this source, we were forced to use it in our CER. This
relationship is shown by the straight line and the data plotted in
Fig. 3.10. The CER, excluding BTW, is

\[ \text{WELL} = 1250 + 216 \times \text{AF} \] (3.12)

where WELL = investment in well (Dfl),
AF = area of sprinkled field (ha).

3.3. OPERATING COST FACTORS

Annual operating costs include the labor cost associated with moving
the sprinkler system, the energy cost for pumping and the labor and
materials required to maintain the system. Labor and energy costs
are estimated using operating cost factors-- labor cost per manhour,
diesel fuel cost per liter, and electricity cost per kilowatt-hour.
Although the information from which they were obtained may sometimes
reflect more recent experience and because they are gross averages,
all operating cost factors are assumed to be in 1976 price levels.

The operating cost factors are used to calculate coefficients that
can be applied in a detailed simulation of sprinkling operations and
weather to obtain estimates of operating cost (see Chaps. 4 and 8).
The factors are also used to estimate sprinkler system operating cost, which, together with investment cost, will be used to compare different systems doing the same job (see Chap. 6). In this latter application, we insist that each system apply the same amount of water, WSPRIK, per year. In the design models we calculated labor and pumping energy requirements per irrigation. Furthermore, the number of irrigations is simply the total amount of water applied divided by the amount per irrigation, or WSPRIK/WA.

Annual labor cost is estimated by applying 18.50 Dfl per man-hour to the annual man-hours spent moving the sprinkler system. The design model estimates the man-hours required per man per irrigation and the number of men required. These are inputs to the cost model, where they are used together with the number of irrigations to obtain the annual man-hours. The hourly rate of 18.50 Dfl is an estimate of the value of the farmer’s labor, based on reported labor rates for hired farm labor for the period 1977 through 1978 (see also Sec. 1.4.1).

Annual energy cost reflects the cost of purchased electricity or diesel fuel, depending on whether an electric motor or a tractor is used to pump sprinkling water. The design model estimates the pumping energy required per irrigation in either kilowatt-hours of electricity or liters of diesel fuel. Energy used for purposes other than pumping, such as the diesel fuel consumed by the tractor while moving a Haspel unit, is not included. The cost model multiplies the energy required per irrigation by the number of irrigations to obtain the estimated annual energy consumption. Electricity cost is estimated at .08 Dfl per kilowatt-hour—the average for commercial users in the Netherlands reported by KEMA in 1977. Diesel fuel is estimated at a nominal 0.40 Dfl per liter based on information reported informally from the Netherlands.

We estimate the annual maintenance cost at 3.5 percent of the initial investment cost excluding BTW. We assume that annual maintenance includes not only a substantial amount of labor for repair work but also that required to bring the entire sprinkler system out to the field at the beginning of the season and put it away again at the end of the season. No data were available on the actual cost of maintaining sprinkler systems. The figure of 3.5 percent was selected by the authors based on knowledge of the maintenance cost of similar kinds of equipment (heating, ventilating and air conditioning equipment).

3.4. BUIS COST MODEL

In this section we present the logical structure of the Buis system cost model and indicate the CERs that are used to estimate the cost of each system component. Investment costs are treated first followed by annual operating costs, annualized investment costs, and then operating cost factors that can be used to estimate annual operating costs for any sprinkling schedule.
In Sec. 3.2, the CERs were presented in their general but complete form. To make the logic of the cost model stand out, the same CERs are shown here using functional notation. The name of the function can be distinguished from the name of the CER because it carries an F prefix. For example, the well CER was expressed in Sec. 3.2.8 as WELL = 1250 + 216*AF while in this section it will be expressed as WELL = FWELL(AF). It is understood that FWELL denotes the CER function in general and that the argument, AF, takes on the value relevant to the system whose cost is being estimated. Similarly, the CER for estimating the cost of a tractor pump (see Sec. 3.2.5) is expressed here as PUMPT = FPUMPT(Q,P) where the arguments Q and P may take on the values of the variables QN and PH or QM and HM. To help the reader, a summary of the investment CERs is presented in Table 3.4.

3.4.1. Investment Costs

Calculate: investment in sprinkler heads, SHCOST; investment cost of lateral pipes, LPCOST; investment cost of main pipe, MPCOST; investment in fittings, FITNG; investment in tractor-driven pump, PUMPT; investment in electric motor-driven pump, PUMPE; investment in electric motor, MOTOR; investment in control equipment, CONTEQ; investment in well, WELL; total investment cost excluding BTW, TOTINV; total investment cost including BTW, TOTINV.

\[
SHCOST = FSHCOST(DS)\times NST \\
LPCOST = FPCLCOST(DL)\times LL\times NL \\
MPCOST = FPCLCOST(DM)\times LM \\
FITNG = FTEE(DM)\times NT + FPUG(DL)\times NP
\]

\[
PUMPT = \begin{cases} 
0.0 & \text{for CONFIG = 1,4} \\
FPUMPT(QL,PL) & \text{for CONFIG = 2} \\
FPUMPT(QM,HM) & \text{for CONFIG = 3,5} 
\end{cases}
\]

\[
PUMPE = \begin{cases} 
0.0 & \text{for CONFIG = 2,3,5} \\
FPUMPE(QM,HM) & \text{for CONFIG = 1,4} 
\end{cases}
\]
\[
\begin{align*}
\text{MOTOR} &= 0.0 \quad \text{for CONFIG} = 2, 3, 5 \\
&= \text{FMOTOR(SHP)} \quad \text{for CONFIG} = 1, 4 \\
\text{CONTEQ} &= 0.0 \quad \text{for CONFIG} = 2, 3, 5 \\
&= 0.46\times \text{PUMPE} \quad \text{for CONFIG} = 1, 4 \\
\text{WELL} &= 0.0 \quad \text{for CONFIG} = 1, 2, 3 \\
&= \text{FWELL(AF)} \quad \text{for CONFIG} = 4, 5 \\
\text{TOTINV} &= \text{SHCOST} + \text{LPCOST} + \text{MPCOST} + \text{PUMPE} + \text{PUMPT} + \text{MOTOR} \\
&\quad + \text{WELL} + \text{CONTEQ} + \text{FITNG} \\
\text{TOTINB} &= 1.04\times \text{TOTINV}
\end{align*}
\]

3.4.2. Annual Operating Costs

Estimate annual cost of labor, LABOR; annual electric energy cost, ENCSTE; annual diesel fuel cost, ENCSTD; annual system maintenance cost, MAINT; total annual operating cost, TOTOC. Labor and energy costs are based on an average number of irrigations per year, NIRG.

\[
\begin{align*}
\text{NIRG} &= \text{WSPRIK/WA} \\
\text{LABOR} &= 18.5\times \text{TMOVE}\times \text{NMEN}\times \text{NIRG} \\
\text{ENCSTE} &= 0.08\times \text{KWH}\times \text{NIRG} \\
\text{ENCSTD} &= 0.40\times \text{DFUEL}\times \text{NIRG} \\
\text{MAINT} &= 0.035\times \text{TOTINV}
\end{align*}
\]
TOTOPC = LABOR + ENCSTE + ENCSTD + MAINT \hspace{1cm} (3.29)

3.4.3. Annualized Cost

Calculate annualized investment costs: sprinkler heads, ANSPRK; lateral pipes, ANLATP; main pipes, ANMAIN; fittings, ANFTG; tractor-driven pump, ANPumpt; electric motor-driven pump, ANPUME; electric motor, ANMOTR; control equipment, ANCTEQ; well, ANWELL; total investment excluding BTW, ANINV; total investment including BTW, ANINB.

The annualized investment cost is the product of the capital recovery factor and the investment cost excluding BTW. Thus, for each component of the Buvis system (the following equation is really nine equations in one), we have:

\[
\begin{array}{c|c}
\text{ANSPRK} & \text{SHCOST} \\
\text{ANLATP} & \text{LPCOST} \\
\text{ANMAIN} & \text{MPCOST} \\
\text{ANFTG} & \text{FITNG} \\
\text{ANPUMT}=\text{CRF} \ast & \text{PUMPT} \\
\text{ANPUME} & \text{PUMPE} \\
\text{ANMOTR} & \text{MOTOR} \\
\text{ANCTEQ} & \text{CONTEQ} \\
\text{ANWELL} & \text{WELL} \\
\end{array}
\]

The capital-recovery factor, CRF, takes on the value appropriate to the particular component and is calculated using the relevant useful life and an interest rate. The useful life varies among components but the interest rate is assumed to be the same for all components. Salvage value is assumed to be zero at end of useful life.

\[
\text{ANINV} = \text{ANSPRK} + \text{ANLATP} + \text{ANMAIN} + \text{ANFTG} + \text{ANPUMT} + \text{ANPUME} + \text{ANMOTR} + \text{ANCTEQ} + \text{ANWELL} \hspace{1cm} (3.30)
\]

\[
\text{ANINB} = 1.04^{\ast}\text{ANINV} \hspace{1cm} (3.31)
\]

Calculate annualized total cost (Dfl): annualized total investment cost (excluding BTW) plus annual operating cost, ANTOT; annualized total investment cost (including BTW) plus annual operating cost, ANTOTB.
ANTS = ANINV + TOTOPC
(3.32)

ANTOTB = ANINB + TOTOPC
(3.33)

3.4.4. Operating Cost Coefficients

Calculate: labor cost per move, CMOVE; energy cost per mm of water applied to entire field, CSPRIK; annual maintenance cost for the sprinkler system, CMAINT.

CMOVE = LABOR/NSET/NIRG
(3.34)

CSPRIK = (ENCSTD + ENCSTE)/WA/NIRG
(3.35)

CMAINT = MAINT
(3.36)

3.5. HASPEL COST MODEL

In this section we present the logical structure of the Haspel system cost model and indicate the CERs that are used to estimate the cost of each system component. Investment costs are treated first followed by annual operating costs, annualized investment costs, and then operating cost factors which can be used to estimate annual operating costs for any sprinkling schedule.

In Sec. 3.2, the CERs were presented in their general but complete form. To make the logic of the cost model stand out, the same CERs are shown here using functional notation (see Sec. 3.4). A summary of the investment CERs is presented in Table 3.5.

3.5.1. Investment Costs

Calculate: Haspel plus hose cost, HSCOST; main pipe cost, MPCOST; cost of fittings, FITNG; cost of tractor pump, PUMPT; cost of well, WELL; total investment cost excluding BTW, TOTINV; total investment cost including BTW at 4 percent, TOTINB.

HSCOST = FHSCOST(HL)
(3.37)

MPCOST = FPCOST(DM)*LM
(3.38)
FITNG = FTEE(DM)*NT + FPLUG(DM)*NT  \hspace{1cm} (3.39)

\[
PUMPT = \begin{cases} 
\text{FPUMPT(QN,PH)} & \text{for } LM = 0 \\
\text{FPUMPT(QM,HM)} & \text{for } LM > 0
\end{cases}
\hspace{1cm} (3.40)
\]

WELL = \begin{cases} 
0.0 & \text{for } ICON = 1,3 \\
\text{FWELL(AF)} & \text{for } ICON = 2
\end{cases}
\hspace{1cm} (3.41)

TOTINV = HSCOST + MPCOST + FITNG + PUMPT + WELL
\hspace{1cm} (3.42)

TOTINB = 1.04 \times TOTINV \hspace{1cm} (3.43)

3.5.2. Annual Operating Costs

Calculate: annual cost of labor, LABOR; annual diesel fuel cost, ENCSTD; annual system maintenance cost, MAINT; total annual operating cost, TOTOPC.

Labor and diesel fuel costs depend on the number of irrigations (NIRG), which in turn is controlled by the total amount of water applied per year (input as WSPRIK), and by the water applied per irrigation (WA).

Assume diesel fuel costs 0.40 Dfl/l and value a farmer's labor at 18.50 Dfl/hr.

\[
NIRG = \frac{WSPRIK}{WA} \hspace{1cm} (3.44)
\]

\[
LABOR = 18.5 \times TMOVE \times NIRG \hspace{1cm} (3.45)
\]

\[
ENCSTD = 0.40 \times DFUEL \times NIRG \hspace{1cm} (3.46)
\]

\[
MAINT = 0.035 \times TOTINV \hspace{1cm} (3.47)
\]
TOTOPC = LABOR+ENCSTD+MAINT  

(3.48)

3.5.3. Annualized Costs

Calculate annualized investment cost: annualized Haspel cost, ANHSP; annualized main pipe cost, ANMAIN; annualized fittings cost, ANFPTG; annualized tractor pump cost, ANPUMT; annualized well cost, ANWELL; total annualized investment cost excluding BTW, ANINV; total annualized investment cost including BTW at 4 percent, ANINB; annualized total cost excluding BTW, ANTOT; annualized total cost including BTW at 4 percent, ANTOTB.

The annualized investment cost is the product of the capital recovery factor and the investment cost excluding BTW. Thus, for each component of the Haspel system (the following equation is really five equations in one):

\[
\begin{align*}
\text{ANHSP} & \quad \text{HSCOST} \\
\text{ANMAIN} & \quad \text{MPCOST} \\
\text{ANFPTG} & = \text{CRF} \times \text{FITNG} \\
\text{ANPUMT} & \quad \text{PUMPT} \\
\text{ANWELL} & \quad \text{WELL}
\end{align*}
\]

The capital-recovery factor, CRF, takes on the value appropriate to the particular component and is calculated using the relevant useful life and an interest rate. The useful life varies among components but the interest rate is assumed to be the same for all components. Salvage value is assumed to be zero at end of useful life.

\[
\begin{align*}
\text{ANINV} & = \text{ANHSP}+\text{ANMAIN}+\text{ANFPTG}+\text{ANPUMT}+\text{ANWELL} \\
\text{ANINB} & = 1.04^{\times}\text{ANINV} \\
\text{ANTOT} & = \text{ANINV}+\text{TOTOPC} \\
\text{ANTOTB} & = \text{ANINB}+\text{TOTOPC}
\end{align*}
\]

(3.49)  

(3.50)  

(3.51)  

(3.52)

3.5.4. Operating Cost Coefficients

Calculate: labor cost per move, CMOVE; energy cost per mm of water applied, CSPRIK; annual system maintenance cost, CMAINT.
CMOVE = LABOR/NSET/NIRG \hspace{1cm} (3.53)

CSPRIK = ENCSTD/WA/NIRG \hspace{1cm} (3.54)

CMAINT = MAINT \hspace{1cm} (3.55)

3.6. APPLICATIONS

The design and cost models are configured to be used together—the design model designs a system and supplies the design characteristics to the cost model which then uses them to estimate the cost. While the design and cost models could be used separately, it would be very difficult to specify inputs to the cost model that describe a feasible sprinkling system without first using the design model. In fact for use in PAWN, the design and cost model were implemented in a single program—one each for the Buis and the Haspel.

The cost models can be used, with the design models, to compare alternative sprinkler system designs in terms of their cost, resource requirements, operating characteristics, etc. This can be useful in selecting the best system to do a given job and to investigate the cost of doing different jobs. Two sprinkler systems do the same job if they sprinkle the same size field, apply the same amount of water per irrigation, and the same total amount of water per year. Within PAWN, these models have been used to select preferred sprinkler systems for various crops on different field sizes in different areas of the Netherlands.

The models have also been used to generate operating cost coefficients, which are used to estimate the cost of operating the preferred systems under a wide range of weather (rainfall and evapotranspiration) scenarios. The total annual operating cost for any sprinkling schedule and quantity of water applied can be estimated using the following function:

\[ \text{ANOTC} = \text{CMOVE} \times \text{NMOVE} + \text{CSPRIK} \times \text{WSPRIK} + \text{CMAINT}, \] \hspace{1cm} (3.56)

where ANOTC = total annual operating cost (Dfl),
NMOVE = number of times system is moved per year,
WSPRIK = total amount of water applied per year (mm),

and the operating cost coefficients CMOVE, CSPRIK, and CMAINT are standard outputs from the cost models.
NOTES

1. The basic cost data from which the CERS were obtained were in the price levels of different years--1976 through 1978. We judged that the bias introduced by the different price levels was small relative to that introduced by the generalizations in the CERS and elsewhere in the models. As we did not make any adjustments for price level, we have probably slightly overestimated some of the costs.

REFERENCES

3.2. Price and technical information on sprinkling equipment, Perrot (Ede) B.V., Netherlands, January 1978.
Fig. 3.1--Sprinkler head cost estimating relationship

\[ \text{SHCOST} = 24.39 \cdot e^{0.0394 \cdot DS} \]
Fig. 3.2—Haspel unit cost estimating relationship

SOURCE: CEBECO-Hendleraad
Fig. 3.3--Pipe cost estimating relationship

Pipe cost per meter, PCOST (Df1)

Pipe diameter, D (mm)

PCOST = 3.8e^{0.0161D}
Fig. 3.4--End plug cost estimating relationship

Fig. 3.5--Tee cost estimating relationship
PUMPT = 140Q^{0.51} - 10.02P + 0.18P^2
for Q < 400 and P < 110

where: Q = Flow rate (m^3/hr)
P = Head pressure (m.wk)

Fig. 3.6—Goodness of fit for tractor pump cost estimating relationship
Fig. 3.7--Goodness of fit for electric motor driven pump CER

\[ \text{PUMPE} = 585 + 46.16Q^{0.51} \cdot 3.304P + 0.059P^2 \]

for \( 10 < Q < 80 \) and \( 10 < P < 120 \)

where:
- \( Q \) = Flow rate (m\(^3\)/hr)
- \( P \) = Head pressure (mwyk)

SOURCE: Stork Pompen
Fig. 3.8—Electric motor cost estimating relationship
CONTEQ = 0.46PUMPE

Fig. 3.9—Control equipment cost estimating relationship
WELL = 1300 + 225AF

NOTE: Includes BTW at 4 percent

Fig. 3.10—Well cost estimating relationship
### Table 3.1

**INPUTS TO SPRINKLER SYSTEM COST MODEL**

<table>
<thead>
<tr>
<th>Input Description</th>
<th>Variable Name</th>
<th>Buis</th>
<th>Haspel</th>
</tr>
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<tbody>
<tr>
<td>Sprinkler system component descriptors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Buis laterals (a)</td>
<td>NL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of Buis lateral or Haspel hose (m)</td>
<td>LL</td>
<td></td>
<td>HL</td>
</tr>
<tr>
<td>Inside diameter of Buis lateral (mm)</td>
<td>DL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nozzle discharge rate (m³/hr)</td>
<td>DS</td>
<td></td>
<td>QN</td>
</tr>
<tr>
<td>Nozzle spray diameter (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of sprinkler heads in system</td>
<td>NST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow through lateral (m³/hr)</td>
<td>QL</td>
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<td></td>
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<tr>
<td>Pressure at inlet to Buis lateral or Haspel hose (mWk)</td>
<td>PL</td>
<td></td>
<td>PH</td>
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<tr>
<td>Length of main distribution pipe (m)</td>
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<td>Size of electric motor (metric horsepower)</td>
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<td>Labor, power, and energy requirements</td>
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<td>Number of placements per irrigation</td>
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<td>Total time spent moving equipment per man per irrigation (hr)</td>
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</tr>
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<td>Number of men working simultaneously</td>
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<td>(b)</td>
</tr>
<tr>
<td>Electricity per irrigation (kWh)</td>
<td>KWH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel fuel per irrigation (l)</td>
<td>DFUEL</td>
<td></td>
<td>DFUEL</td>
</tr>
<tr>
<td>Design specifications and sprinkling schedule</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area of field (ha)</td>
<td>AF</td>
<td></td>
<td>AF</td>
</tr>
<tr>
<td>System configuration</td>
<td>CONFIG</td>
<td></td>
<td>ICON</td>
</tr>
<tr>
<td>Type of Haspel unit</td>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Amount of water applied per irrigation (mm)</td>
<td>WA</td>
<td></td>
<td>WA</td>
</tr>
<tr>
<td>Total amount of water sprinkled per year (mm)</td>
<td>WSPRIK</td>
<td></td>
<td>WSPRIK</td>
</tr>
<tr>
<td>Financial inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual interest rate (fraction)</td>
<td>INTRST</td>
<td></td>
<td>INTRST</td>
</tr>
<tr>
<td>Useful life of Haspel unit (yr)</td>
<td></td>
<td></td>
<td>HASLIF</td>
</tr>
<tr>
<td>Useful life of sprinkler heads (yr)</td>
<td>SPKLIF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Useful life of a lateral pipe (yr)</td>
<td>LPLIFE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Useful life of a main pipe (yr)</td>
<td>MPLIFE</td>
<td></td>
<td>MPLIFE</td>
</tr>
<tr>
<td>Useful life of fittings (yr)</td>
<td>FTGLIF</td>
<td></td>
<td>FTGLIF</td>
</tr>
<tr>
<td>Useful life of a pump (yr)</td>
<td>PUMLIF</td>
<td></td>
<td>PUMLIF</td>
</tr>
<tr>
<td>Useful life of a motor (yr)</td>
<td>MOTLIF</td>
<td></td>
<td>MOTLIF</td>
</tr>
<tr>
<td>Useful life of control equipment (yr)</td>
<td>CNTLIF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Useful life of a well (yr)</td>
<td>WELIF</td>
<td></td>
<td>WELIF</td>
</tr>
</tbody>
</table>

(a) Only one lateral is allowed in Buis configuration 2.
(b) Always assumed to be one man.
Table 3.2
OUTPUTS FROM SPRINKLER SYSTEM COST MODEL

<table>
<thead>
<tr>
<th>Output Description</th>
<th>Variable Name Buis</th>
<th>Variable Name Haspel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment costs (Df1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haspel unit</td>
<td>HSCOST</td>
<td></td>
</tr>
<tr>
<td>Sprinkler heads</td>
<td>SHCOST</td>
<td></td>
</tr>
<tr>
<td>Lateral pipes</td>
<td>LPCOST</td>
<td></td>
</tr>
<tr>
<td>Main distribution pipe</td>
<td>MPCOST</td>
<td>MPCOST</td>
</tr>
<tr>
<td>Fittings</td>
<td>FITNG</td>
<td>FITNG</td>
</tr>
<tr>
<td>Tractor pump</td>
<td>PUMPT</td>
<td>PUMPT</td>
</tr>
<tr>
<td>Electric motor driven pump</td>
<td>PUMPE</td>
<td></td>
</tr>
<tr>
<td>Electric motor</td>
<td>MOTOR</td>
<td></td>
</tr>
<tr>
<td>Control equipment for electric motor</td>
<td>CONTEQ</td>
<td></td>
</tr>
<tr>
<td>Well</td>
<td>WELL</td>
<td>WELL</td>
</tr>
<tr>
<td>Total investment cost (excluding BTW)</td>
<td>TOTINV</td>
<td>TOTINV</td>
</tr>
<tr>
<td>Total investment cost (including BTW)</td>
<td>TOTINB</td>
<td>TOTINB</td>
</tr>
<tr>
<td>Annual operating costs (Df1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labor</td>
<td>LABOR</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>ENCTSE</td>
<td>ENCTSD</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>ENCTD</td>
<td>ENCTD</td>
</tr>
<tr>
<td>Sprinkler system maintenance</td>
<td>MAINT</td>
<td>MAINT</td>
</tr>
<tr>
<td>Total annual operating cost</td>
<td>TOTOPC</td>
<td>TOTOPC</td>
</tr>
<tr>
<td>Annualized investment costs (Df1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haspel unit</td>
<td>ANHSP</td>
<td></td>
</tr>
<tr>
<td>Sprinkler heads</td>
<td>ANSPRK</td>
<td></td>
</tr>
<tr>
<td>Lateral pipes</td>
<td>ANLATP</td>
<td></td>
</tr>
<tr>
<td>Main distribution pipe</td>
<td>ANMAIN</td>
<td>ANMAIN</td>
</tr>
<tr>
<td>Fittings</td>
<td>ANFTG</td>
<td>ANFTG</td>
</tr>
<tr>
<td>Tractor pump</td>
<td>ANPUMT</td>
<td>ANPUMT</td>
</tr>
<tr>
<td>Electric motor-driven pump</td>
<td>ANPUME</td>
<td></td>
</tr>
<tr>
<td>Electric motor</td>
<td>ANMOTR</td>
<td></td>
</tr>
<tr>
<td>Control equipment for electric motor</td>
<td>ANCTEQ</td>
<td></td>
</tr>
<tr>
<td>Well</td>
<td>ANWELL</td>
<td>ANWELL</td>
</tr>
<tr>
<td>Total annualized investment (excluding BTW)</td>
<td>ANINV</td>
<td>ANINV</td>
</tr>
<tr>
<td>Total annualized investment (including BTW)</td>
<td>ANINB</td>
<td>ANINB</td>
</tr>
<tr>
<td>Annualized total cost (Df1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excluding BTW</td>
<td>ANTOT</td>
<td>ANTOT</td>
</tr>
<tr>
<td>Including BTW</td>
<td>ANTOTB</td>
<td>ANTOTB</td>
</tr>
<tr>
<td>Annual operating cost factors (Df1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labor cost per move</td>
<td>CMOVE</td>
<td>CMOVE</td>
</tr>
<tr>
<td>Energy cost per mm of water applied</td>
<td>CSPRIK</td>
<td>CSPRIK</td>
</tr>
<tr>
<td>Maintenance cost per year</td>
<td>CMAINT</td>
<td>CMAINT</td>
</tr>
</tbody>
</table>
Table 3.3
COST ELEMENTS FOR WHICH CERS ARE REQUIRED

<table>
<thead>
<tr>
<th>Cost element</th>
<th>Independent variables used to determine cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinkler head</td>
<td>Spray diameter (m)</td>
</tr>
<tr>
<td>Haspel unit</td>
<td>Hose length (m), Haspel type</td>
</tr>
<tr>
<td>Pipe</td>
<td>Inside diameter (mm)</td>
</tr>
<tr>
<td>Fittings</td>
<td></td>
</tr>
<tr>
<td>End plug</td>
<td>Pipe diameter (mm)</td>
</tr>
<tr>
<td>Tee</td>
<td>Pipe diameter (mm)</td>
</tr>
<tr>
<td>Tractor pump</td>
<td>Flow (m³/hr), pressure (mWk)</td>
</tr>
<tr>
<td>Electric motor pump</td>
<td>Flow (m³/hr), pressure (mWk)</td>
</tr>
<tr>
<td>Electric motor</td>
<td>Motor shaft horsepower</td>
</tr>
<tr>
<td>Well</td>
<td>Area of sprinkled field (ha)</td>
</tr>
</tbody>
</table>
Table 3.4

INVESTMENT COST ESTIMATING RELATIONSHIPS FOR BUIS SYSTEMS

<table>
<thead>
<tr>
<th>CER</th>
<th>Investment Cost Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSHCOST</td>
<td>One sprinkler head with spray diameter DS</td>
</tr>
<tr>
<td>FPCCOST</td>
<td>One meter of pipe with inside diameter D</td>
</tr>
<tr>
<td>FTEE</td>
<td>One tee for a pipe with diameter D</td>
</tr>
<tr>
<td>FPLUG</td>
<td>One end plug for a pipe with diameter D</td>
</tr>
<tr>
<td>FPUMPT</td>
<td>Tractor pump for flow rate Q and head pressure P</td>
</tr>
<tr>
<td>FPUMPE</td>
<td>Electric motor driven pump for flow rate Q and head pressure P</td>
</tr>
<tr>
<td>FMOTOR</td>
<td>Electric motor with horsepower SHP</td>
</tr>
<tr>
<td>FWELL</td>
<td>Well for sprinkling field with area AF</td>
</tr>
</tbody>
</table>

Generalized CERs:

FSHCOST(DS) = 24.39*EXP(0.039*DS)

FPCCOST(D) = 3.8*EXP(0.0161*D)

FTEE(D) = 0.4107*D**1.2424

FPLUG(D) = 0.2120*D**1.0439

FPUMPT(Q,P) = 140*Q**0.51 - 10*P + 0.18*P**2

FPUMPE(Q,P) = 585 + 46.16*Q**0.51 - 3.304*P + 0.059*P**2

FMOTOR(SHP) = |
| 400 + 103.0*SHP for SHP<6.6 |
| 523 + 84.4*SHP for 6.6<SHP<17.5 |
| 1034 + 55.2*SHP for 17.5<SHP |

FWELL(AF) = 1250 + 216.346*AF
### Table 3.5

INVESTMENT COST ESTIMATING RELATIONSHIPS FOR HASPEL SYSTEMS

<table>
<thead>
<tr>
<th>CER</th>
<th>Investment Cost Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHSCOST</td>
<td>One Haspel unit with hose length HL</td>
</tr>
<tr>
<td>FPCOST</td>
<td>One meter of pipe with inside diameter D</td>
</tr>
<tr>
<td>FTEE</td>
<td>One tee for a pipe with diameter D</td>
</tr>
<tr>
<td>FPLUG</td>
<td>One end plug for a pipe with diameter D</td>
</tr>
<tr>
<td>FPUMPT</td>
<td>Tractor pump for flow rate Q and head pressure P</td>
</tr>
<tr>
<td>FWELL</td>
<td>Well for sprinkling field with area AF</td>
</tr>
</tbody>
</table>

Generalized CERs:

\[
\begin{align*}
\text{FHSCOST}(HL) & = \begin{cases} 15900 + 11\times HL & \text{for Junior} \\ 19000 + 11\times HL & \text{for C-75} \\
21400 + 15\times HL & \text{for C-90} \end{cases} \\
\text{FPCOST}(D) & = 3.8\times \exp(0.0161\times D) \\
\text{FTEE}(D) & = 0.4107\times D^{1.2424} \\
\text{FPLUG}(D) & = 0.2120\times D^{1.0439} \\
\text{FPUMPT}(Q,P) & = 140\times Q^{0.51} - 10\times P + 0.18\times P^{2} \\
\text{FWELL}(AF) & = 1250 + 216.346\times AF
\end{align*}
\]
Chapter 4

DAILY SPRINKLER OPERATIONS SIMULATION MODEL

4.1. PURPOSE AND OVERVIEW

The sprinkler system design and cost models described in the previous two chapters provide resource estimates that are useful for choosing among alternative sprinkler systems given field size, system configuration, and the amount of water applied per irrigation. However, these models are not appropriate for estimating the resources required to operate these sprinkler systems in the real world, where farmers take advantage of water supplied by rain to reduce the amount of sprinkling required and they make decisions about whether to sprinkle or not on a day-to-day basis.

Operating a sprinkler system given a stochastic pattern of rainfall and evapotranspiration is a complex task. The farmer attempts to maintain the soil moisture within acceptable bounds to prevent crop damage. He has imperfect knowledge about future rain and evapotranspiration. Yet, he must make decisions about when to start sprinkling, and when to move his equipment from one set to the next. At the same time, he tries to minimize his labor input and to use water efficiently to hold sprinkling costs down. Within the constraints imposed on him by the technical capabilities of his sprinkler system and the other demands on his time, he continually trades off crop damage and sprinkling costs.

We built and used the Daily Sprinkling Model (DSM) to help us select sprinkling policies for use in PAWN analyses and to implement these policies in the Plot Model (see Vol. XII). We also used the DSM to investigate the effect of many different policies on the efficiency of water use, sprinkling cost, and crop damage.

The DSM simulates a Dutch farmer's daily operation of his sprinkler system throughout the entire six months of the growing season--April 1 through September 30. It accepts daily rainfall and evapotranspiration and sprinkler system characteristics as inputs and simulates the farmer's behavior, regarding sprinkling, day by day to calculate the number of times the farmer moves his sprinkling equipment and the amount of water sprinkled--data which are then used to calculate sprinkler system operating cost.

Whenever a set has been sprinkled, the sprinkling equipment is moved to the next set and the model records one move and accumulates the amount of water used. Sprinkler system operating cost factors are applied to the number of moves and the amount of water sprinkled to calculate the sprinkler system operating costs for any specified sprinkler system, field size, weather scenario, and sprinkling policy. The DSM also calculates the damage, from drought, incurred by the crops so that the total marginal cost of sprinkling (operating cost plus crop damage) can be obtained.
While we have not been able to validate the model with actual data (it was not available), we believe that the DSM captures most of the important aspects of the sprinkling problem.

The DSM is discussed fully in the remainder of this chapter.

4.2. INPUT PARAMETERS

A complete list of the inputs required by the DSM is shown in Table 4.1. Note that the variables ETDES, GIFT, and RATE are that same as RE, WA, and RU, respectively, which were used in Chaps. 2 and 3. Some general information needed by the model to keep the bookkeeping straight and to predict the soil moisture is provided first.

The DSM predicts soil moisture each looking interval--once or twice a day. The input, TLOOK, can be specified by the user as either 12 or 24 hours. If it is 12 hours, predictions will be made every 12 hours. If 24 hours is specified, predictions will be made once a day. The design evapotranspiration rate, ETDES, is used to predict the soil moisture in each set. ETDES is estimated by the user and will be applied constantly throughout the simulation. The single estimated rate is intended to capture some of the uncertainty under which the farmer must make his prediction.

The DSM looks at sprinkling on several different soil types. Each soil type is described by a soil moisture curve, which gives three types of information about the soil: the field capacity or maximum amount of water it will hold; the damage point, i.e., the soil moisture level below which damage will be incurred; and the ratio of actual to potential evapotranspiration as a function of soil moisture level below the damage point.

The DSM permits the user to select one or more weather scenarios under which the sprinkling simulation will be made. Each weather scenario consists of data on rainfall and open water evaporation for every day of a selected year. We had fourteen years of historical data recorded at the De Bilt weather station in the Netherlands, and we used data selected from this sample in our sprinkling analyses. The input, KYEAR, identifies the particular year and PREC and OVAR are the rainfall and evaporation for each day in that year.

The variables that define the sprinkling policy are GIFT and START. The farmer seeks to maintain the soil moisture level of his field above the minimum target level, START, and every time he sprinkles he applies the same amount of water, GIFT.

A sprinkler system is characterized by a specified number of sets, NSET, a sprinkling rate, RATE, a moving interval, M, the time that it takes to move the equipment from one set to the next, TMOVE, the labor cost per move, COEFM, and the energy cost per cubic meter of water applied, COEFP. These system characteristics are obtained from the sprinkler system design and cost models.
The DSM uses crop damage functions to estimate crop damage each decade as a function of the ratio of actual to potential evapotranspiration in that decade. This function consists of two piecewise linear segments and the inputs RPT, RD, and DYPT define these two segments for each of eleven different crop types. Because crops are more or less susceptible to damage at different times during the growing season, the RD varies with the decade. Further, as the growing season evolves, parts of the total crop are harvested and that part of the crop already harvested is not subject to future damage. The input REMYLD, indicates the fraction of each crop that remains to be harvested for each decade in the growing season.

4.3. OUTPUTS

The outputs from the DSM are shown in Table 4.2. The DSM, as implemented, generates an output data file containing much of the input data and the simulation results by decade. This output file is post-processed to generate a variety of additional statistics such as monthly or yearly summaries of water used, crop damage, and sprinkler operating cost.

The outputs are identified as pertaining to a decade in a month in a year by the variables, DECADE, MONTH, and YEAR. The other outputs shown make up the substance of any of the output reports generated.

Summary information about the climate and the soil moisture during the decade is presented with the outputs RAIN, EVAPD, EACT, and ENDSM. EACT and ENDSM are averages for all sets. Water used for sprinkling, water lost to drainage, and the number of moves required are given by the variables SWAT, ROFF, and MOVES.

Sprinkler operating cost, OPCOST, is the sum of labor cost and energy cost.

Crop damage is presented in monetary units (Dfl/ha) for each of the eleven different crop types and for each decade. The eleven different crop types are shown in Table 4.2.

4.4. MODEL DESCRIPTION

For simulation purposes, we had to describe a farmer's behavior in a few terms that captured the essential characteristics rather than the details of his sprinkling activities. To do this, we made the following assumptions. He predicts soil moisture using a constant evapotranspiration rate consistent with the Sprinkler System Design Model. He never moves his equipment more often than specified by the design moving interval. His minimum acceptable soil moisture level remains constant throughout the growing season. He applies the same amount of water (the gift) on each set whenever he sprinkles.
Capillary rise in sprinkled soils is so small that we left it out. Potential evapotranspiration is estimated at 80 percent of open water evaporation, which is typical for most of the agricultural area in the Netherlands. Damage estimates are based on field average rather than set specific evapotranspiration reductions.

The DSM simulates the operation of a sprinkler system by stepping through each day in the growing season and making decisions about when to start sprinkling and when to move the sprinkler equipment from one set to the next. These decisions are, of course, influenced by the weather. The field to be sprinkled is divided into sets and there is sprinkling equipment to sprinkle only one set at a time, so the equipment must be moved from set to set in order to sprinkle the entire field.

The decision to sprinkle or not is made at regular intervals (once or twice a day) and is based on a prediction of the soil moisture in each set. A decision to move the sprinkling equipment is made at the end of each looking interval after at least one moving interval has passed.

Crop damage is calculated at the end of each decade. Output data on climate and soil moisture, water used and number of moves, and crop damage are summarized and transferred to an output file at the end of each decade.

A somewhat more detailed description of the steps in the simulation is presented with the flowcharts in Figs. 4.1 and 4.2. The flow chart in Fig. 4.1 shows the organization of the simulation model and identifies the decisions the farmer must make and the information he uses to make these decisions. Although different time steps can be used, it will simplify the discussion if we use one day and examine the first part of the growing season. Thus, we begin with the first day of the growing season.

4.4.1. Steps in the Simulation

We enter box 1, where the DSM calculates the maximum daily sprinkling rate (DRATE), initializes the beginning soil moisture in each set to the field capacity (all sets are assumed to be full at the beginning of the growing season), and sets the counter for accumulating number of moves (MOVES) to zero. It also initializes the set index (ISET) to zero to indicate that the sprinkling equipment has not yet been moved onto the first set.

We intend that every time the sprinkler equipment is turned on, it will deliver the same amount of water, the GIFT. The time to deliver this water is the GIFT divided by the sprinkling rate, RATE. If it is impossible to apply the entire gift in one simulation time step (GIFT > DRATE), the amount not delivered this period is carried over for delivery in the next time step.
In box 2, the beginning of the first simulation day, the sprinkling equipment is moved onto the first set (ISET = 1) and the set timer is turned off (STIME = 0). It will be turned on when the sprinkling equipment is turned on. The sprinkler system was designed to be moved every moving interval. The DSM uses the set timer to record the amount of time that has passed since the decision to sprinkle was made and permits the equipment to be moved only after the set timer indicates that one entire moving interval has passed since the sprinkling equipment was turned on.

In diamond 3, the farmer makes the sprinkling decision, i.e., decides whether to turn the sprinkling equipment on or not. He consults his soil moisture gauge to obtain the current soil moisture level in each set. He wants to sprinkle so as to keep the moisture level of all sets above the minimum acceptable level START. Inasmuch as it may take him days to reach the farthest set with his equipment, he cannot afford to wait until the set his equipment is sitting on requires sprinkling. Rather, he must look ahead to how the other sets will fare. He is conservative as he expects there to be no rain in the future and he assumes a constant moisture loss per day—a rate he chooses independent of the year, or of recent weather.

Actually, when the sprinkling equipment is off, the model farmer consults his moisture gauge at the beginning of every look interval and estimates how long it would take each set to dry out to the minimum acceptable level. He then compares the drying out time with the time it would take for the equipment to reach that set if he started sprinkling the current set at once. When this indicates that no set will go critical before he can reach it, he leaves the sprinkling equipment off and waits until the next look period. Otherwise, he turns the sprinkler on.

While the sprinkler is on, the moisture gauge continues to record current levels, but the farmer does not consult it until he has completed sprinkling the set, and has moved his equipment onto the next one. With his sprinkler on the next set and turned off, he repeats the cycle of predicting soil moisture and determining critical times, as above.

We assume that the farmer has decided not to sprinkle today and move from box 3 to box 4. The DSM sets the amount of water sprinkled today to zero, and updates the soil moisture to account for today's rainfall and evapotranspiration. Then, at the beginning of the next day, the DSM returns to the sprinkling decision, diamond 3, and repeats the process until the farmer decides to start sprinkling.

When sprinkling starts, the DSM proceeds to box 6. It turns on the set timer and sets the GIVE meter to 1.0 (fraction of constant gift to be given). In this condition, the GIVE meter indicates that 100 percent of the gift remains to be given. If, due to system design constraints, it is impossible to apply the entire gift in this day, the give meter is adjusted downward to reflect the amount of water remaining to be applied.
In box 7, the DSM calculates the amount of water to be sprinkled this day (SPRKL). Either the entire gift is given, or, if the gift is larger than DRATE, DRATE is given and and the DSM calculates the deficit, DEFIC—the carryover sprinkling requirement. The give meter, GIVE, is adjusted to indicate the fraction of the gift that remains to be applied in subsequent time steps.

Box 8 assumes that the amount of sprinkling water just calculated has been applied, adds this to the rainfall during the day, subtracts the evapotranspiration and any drainage that might have occurred, and calculates an updated soil moisture in the set just sprinkled. The soil moisture in all the other sets is also adjusted to account for today's rain and evapotranspiration.

In box 9, the DSM adds TLOOK to the set timer and, in diamond 10, it compares the cumulative time with the moving interval to see if it is time to move the sprinkling equipment to the next set.

Assume for the moment that it is not, i.e., STIME is less than the moving interval. At the beginning of the next day, the DSM picks up at diamond 11, where it asks if the entire gift was applied yesterday. If not, the give meter shows a number between zero and one. For example, a value of 0.4, means that 40 percent of the gift remains to be applied. The DSM moves to box 7, where it calculates the amount to be sprinkled this day. If the entire gift has already been applied, GIVE = 0, and the DSM sets the amount of water to be applied this day to zero (box 12). In either case, from box 12 or box 7, the DSM proceeds to box 8 where it updates the soil moisture levels and returns to box 9.

Now, when the DSM compares STIME to the moving interval, diamond 10, suppose that it finds that the equipment has been on the set for one moving interval and can be moved to the next set. Inasmuch as all systems are designed to be able to give the entire gift within one moving interval, the sprinkler has been turned off before the equipment is moved. At the end of the day, box 2, the equipment is moved to the next set. The set index, ISET, is increased by one to indicate the new location of the equipment, and the set timer is turned off. In this way, the equipment moves from set to set, returning to the first set after the last one has been sprinkled.

At the end of each decade, information is obtained from boxes 5 and 8 and used with other input data to generate the output reports. This is indicated by the dotted lines on the flow chart.

4.4.2. Controlling the Simulation

The flow chart in Fig. 4.2 shows how the DSM actually steps through the days in the growing season, determines when to output decade results, and determines when to terminate the simulation. This procedure is invoked in conjunction with updating the soil moisture at the end of every look interval, TLOOK.
At the beginning of the simulation run, several counters are initialized including the index KDAY, which is used to access the daily weather data, and the index, K0, which is used to determine when decade results are to be output. The procedure requires, as part of the input data, an identification of each day with a decade.

When the DSM goes to box 5 or 8, in Fig. 4.1, it branches to the triangle labeled ENTER in Fig. 4.2. The index KDAY is pointing to the current day and the model looks at the input data to find out the number of the decade in which this day is included. The number of this decade is compared with the decade index, K0, and if the two are equal, i.e., the DSM is in the middle of a decade, the DSM updates the soil moisture in each set. If KDAY is not equal to K0, a new decade is being started and the DSM prepares the decade output for the decade just concluded. Having presented the decade output report, the DSM checks whether the new decade is still within the growing season. If it is not, the simulation is terminated. If the new decade is still within the growing season, the DSM sets the decade index, K0, equal to the new decade number, reinitializes the variables used to accumulate information by decade, and proceeds to updating the soil moisture levels of all sets.

Before returning to the main procedure (Fig. 4.1), the model updates the look interval counter, NLKS, so that it points to the next look interval in the day. If the counter exceeds the number of look intervals per day (NLOOK), the next look interval will be in a new day; NLKS is reset to 1 and the day index, KDAY, is incremented by one.

4.4.3. The Soil Moisture Gauge

The soil moisture gauge measures the amount of moisture (in mm) above the wilt point. It employs a simple water balance relationship between one time period and the next:

\[
SM(JSET,T) = SM(JSET,T-1) + RAIN(T) + SPRKL(JSET,T) - EA(JSET,T) - DRNG(JSET,T),
\]

where

\begin{align*}
SM(JSET,T) & = \text{the soil moisture in set JSET at the end of time period T (mm)}, \\
SM(JSET,T-1) & = \text{the soil moisture in set JSET at the end of time period T-1 (mm)}, \\
RAIN(T) & = \text{the rainfall during period T (mm)}, \\
SPRKL(JSET,T) & = \text{the amount of water sprinkled on set JSET during period T (mm)}, \\
EA(JSET,T) & = \text{the actual evapotranspiration from set JSET during period T (mm)}, \\
DRNG(JSET,T) & = \text{the drainage from set JSET during period T (mm)}. \\
\end{align*}
\[ \text{DRNG} (\text{JSET}_T) = \text{the water drained from set JSET during period } T \text{ (mm)}. \]

The time period is either 12 or 24 hours. Daily rainfall is provided externally. For 12-hr time periods, half the daily rain is assumed to fall in each period.

Potential evapotranspiration is the rate at which water will evaporate from a vegetation covered surface as long as the ability of plants to transpire water is not constrained by insufficient moisture in the root zone. The DSM assumes that potential evapotranspiration is 80 percent of open water evaporation—typical for most of the agricultural area in the Netherlands.

When the soil moisture level drops sufficiently, the amount of water actually lost through evapotranspiration falls below the potential loss. The ratio of actual to potential evapotranspiration as a function of the soil moisture level is input to the DSM. The data describe a piecewise linear curve that is specific to the soil type and root zone. In all cases, the ratio \( \text{EA/EP} \) is zero at the wilt point, i.e., the point at which plants can no longer absorb water from the soil. Between the wilt point and a soil moisture level that we call the damage level the ratio increases with soil moisture level. Between the damage level and field capacity plant transpiration is not constrained and actual evapotranspiration equals potential, whence the ratio is 1.0.

The DSM estimates the ratio \( \text{EA/EP} \) using the soil moisture level at the beginning of a time period and applies the ratio to the potential evapotranspiration during the period to obtain the actual evapotranspiration.

The maximum amount of water that a soil can hold occurs at saturation capacity. Below this lies a level referred to as field capacity. In the DSM, we have assumed that water in excess of field capacity will drain off. This provides a smaller buffer zone before drought damage will occur than if the saturation capacity were to be used.

4.4.4. Estimating Crop Damage

Crop damage can result from many causes—too much water, too little water, or water that is too saline. In the DSM we consider only drought damage, i.e., the damage that results from too little water in the root zone.

Crop damage begins to occur when the soil moisture level falls below the damage point, where actual evapotranspiration is less than the potential evapotranspiration (EA/EP). Between the damage and reduction points, \( \text{RPT} \), crop damage is moderate. The reduction damage, \( \text{RD} \), which is the fraction of crop yield that would be lost at the reduction point, is less than 10 percent for all the crop types.
considered. When the soil moisture level drops so that the ratio of actual to potential evapotranspiration falls below the reduction point, severe damage occurs. Maximum damage occurs at the dying point, DYPT. In the DSM, the entire crop is assumed to be lost when EA/EP falls below this point.

The remaining yield, REMYLD, specifies the fraction of the total yield that remains to be harvested in this and subsequent decades. The remaining yield is zero for decades that precede planting of the crop. When the crop is planted, the remaining yield is set to 1.0, where it remains while the crop is maturing. The remaining yield drops back down to zero as the crop is harvested. Harvesting may be done very quickly, as is the case for seed potatoes, or it may be a continuous process, as is the case for grass.

The reduction point, RPT, for a given crop remains constant over the length of the growing season. However, the reduction damage, RD, that occurs at this point can vary over time. Potatoes, cereals, corn, and bulbs have drought sensitive periods, during which the same degree of drought will cause more damage than at other times during their specific growing seasons.

The damage function consists of linear segments, delineated by the damage point, the reduction point, and the dying point (see Vol. XII for a full description). The reduction and dying points, together with the reduction damage and the remaining yield for each of the crop types are input to the model.

Crop damage is calculated at the end of each decade, using the ratio of actual to potential evapotranspiration, EA/EP, for the decade. At the beginning of the growing season, the DSM sets a variable that keeps track of the fraction of the crop that has survived, SURVF, to 1.0. As drought damage occurs, the survival fraction is reduced. The model first estimates the damage fraction:

\[
\text{DDFRAC} = \begin{cases} 
\frac{(1-\text{EA/EP})}{(1 - \text{RPT})} & \text{for } \text{RPT} \leq \text{EA/EP} \leq 1 \\
\frac{[1-\text{RD}(K)](\text{RPT-\text{EA/EP}})}{(\text{RPT-\text{DYPT}})} & \text{for } \text{DYPT} \leq \text{EA/EP} \leq \text{RPT} 
\end{cases}
\]

where DDFRAC = damage fraction,
K = decade number,
RD(K) = reduction damage for decade K,
EA/EP = ratio of actual to potential evapotranspiration,
RPT = reduction point,
DYPT = dying point.
Note that, when EA/EP equals one, the damage fraction is zero; and when EA/EP equals the dying point (DYPT), the damage fraction is one. The crop damage is then estimated:

\[
\text{DAMG} = \text{DDFRAC} \times \text{REMYLD}(K) \times \text{SURV} \times \text{CROPV}
\]  \hspace{1cm} (4.3)

where 
- \( \text{DAMG} \) = crop damage in decade \( K \), in Dfl/ha,
- \( \text{REMYLD}(K) \) = remaining yield in decade \( K \),
- \( \text{SURV} \) = fraction of crop that has survived through decade \( K - 1 \),
- \( \text{CROPV} \) = crop value, in Dfl/ha, assuming the total yield is realized.

Finally, the survival fraction is updated to reflect the fraction of the crop that survives at the end of decade \( K \):

\[
\text{SURV} = \text{SURV} \times (1 - \text{DDFRAC})
\]  \hspace{1cm} (4.4)

4.4.5. Estimating Variable Operating Cost

The DSM also calculates the variable sprinkler operating costs, where variable operating cost includes sprinkling labor and the cost of energy to pump the water sprinkled out of the ditch or from a the well. Annual sprinkler maintenance cost is not calculated here as it is assumed to be independent of the sprinkling activity rate.

The sprinkler cost model (see Chap. 3) provides operating cost factors that can be used to estimate system operating costs given the number of moves and the quantity of water sprinkled. The labor cost per move, \( \text{COEFM} \), is a direct output of the cost model. The cost model also provides the energy cost factor \( \text{CSPRIK} \), which is the cost of energy used to apply one millimeter of water to the entire field. \( \text{CSPRIK} \) is converted to a cost per cubic meter sprinkled to obtain the input \( \text{COEFP} \). \( \text{COEFP} \) is then multiplied by the cubic meters of water sprinkled to obtain the sprinkling energy cost.

Sprinkler operating costs are expressed in terms of Dfl per hectare so that they may be combined with the crop damage estimates. The expression for total variable operating cost is

\[
\text{OPCOST} = \text{COEFM} \times \text{MOVES/AF} + 10 \times \text{SPRKL} \times \text{COEFP}
\]  \hspace{1cm} (4.5)
where OPCOST = total variable sprinkler operating cost,
COEFM = labor cost per move,
MOVES = number of times sprinkler equipment is moved from
one set to the next,
AF = area of field sprinkled (ha),
SPRKL = amount of water sprinkled (mm) averaged over sets,
COEFFP = pumping energy cost per cubic meter of water
sprinkled.

4.5. APPLICATION

In PAWN, the DSM was used to select preferred sprinkling policies for
crops with four different root depths on four different soil types. A
sprinkling policy specifies how dry to let the soil become before
sprinkling starts and how much water to apply with each irrigation. For
example, start sprinkling when the soil holds 50 mm of moisture and
apply 30 mm of water. The preferred policies selected for use in PAWN
analyses were those that had the lowest total marginal cost of
sprinkling (sprinkling cost plus crop damage).

Once the sprinkling policies were selected, they had to be implemented
in the PAWN Plot Model (see Vol. XII). The Plot Model is large and
expensive to run. To hold the computing cost down, it operates with a
time step of a decade (ten days) rather than a day or a half-day as does the
DSM. Further, it considers plots rather than sets (plots are
aggregates of fields and fields are aggregates of sets) and so the
information that is obtained each day in the DSM is not available in
the Plot Model.

The problem was to work with the more aggregate information from the
Plot Model and still obtain results comparable to those produced by
the DSM. An algorithm requiring decade and plot data was devised and
tested. The amount of water used and the crop damage estimated with
the algorithm were compared with similar estimates made with the DSM.
The form and parameters of the algorithm were adjusted until the
outputs from the DSM and the algorithm were similar (see Chap. 5).
The DSM, which reflects as realistic an approach to sprinkling as we
could devise, thus supplied the data base to which we calibrated the
sprinkling algorithm implemented in the Plot Model.
Fig. 4.2—Simulation control flow chart
Table 4.1

INPUTS TO DAILY SPRINKLER OPERATIONS SIMULATION MODEL

<table>
<thead>
<tr>
<th>Input Description</th>
<th>Variable Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>General information</td>
<td>TITLE</td>
<td>Case title</td>
</tr>
<tr>
<td></td>
<td>CASEID</td>
<td>Case identification number</td>
</tr>
<tr>
<td></td>
<td>CCODE</td>
<td>Case code</td>
</tr>
<tr>
<td></td>
<td>CDATE</td>
<td>Date case was run</td>
</tr>
<tr>
<td></td>
<td>MODRUN</td>
<td>Number of model run</td>
</tr>
<tr>
<td>Weather prediction parameters</td>
<td>TLOOK</td>
<td>Time between weather predictions (hr)</td>
</tr>
<tr>
<td></td>
<td>ETDES (a)</td>
<td>Design evapotranspiration rate (mm/day)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Ratio of potential to open water evaporation</td>
</tr>
<tr>
<td>Weather scenario</td>
<td>KYEAR</td>
<td>Year number</td>
</tr>
<tr>
<td></td>
<td>KD</td>
<td>Decade number</td>
</tr>
<tr>
<td></td>
<td>PREC</td>
<td>Daily rainfall (mm)</td>
</tr>
<tr>
<td></td>
<td>OVAP</td>
<td>Daily open water evaporation (mm)</td>
</tr>
<tr>
<td>Soil moisture curve</td>
<td>SOIL</td>
<td>Soil type</td>
</tr>
<tr>
<td></td>
<td>EFUN</td>
<td>Evapotranspiration vs. soil moisture curve</td>
</tr>
<tr>
<td>Sprinkling policy</td>
<td>GIFT (a)</td>
<td>Water applied per irrigation (mm)</td>
</tr>
<tr>
<td></td>
<td>START</td>
<td>Target soil moisture (mm), minimum</td>
</tr>
<tr>
<td>Sprinkler system characteristics</td>
<td>SPRSYS</td>
<td>Sprinkler system identification</td>
</tr>
<tr>
<td></td>
<td>AF</td>
<td>Area of field (ha)</td>
</tr>
<tr>
<td></td>
<td>NSET</td>
<td>Number of sets for field</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>Moving interval (hr)</td>
</tr>
<tr>
<td></td>
<td>TMOVE</td>
<td>Time required to move equipment (hr)</td>
</tr>
<tr>
<td></td>
<td>RATE (a)</td>
<td>Water application rate (mm/hr)</td>
</tr>
<tr>
<td></td>
<td>EFFIC</td>
<td>Sprinkler efficiency</td>
</tr>
<tr>
<td></td>
<td>COEFM</td>
<td>Cost to move equipment (Df1/move)</td>
</tr>
<tr>
<td></td>
<td>COEFP</td>
<td>Cost to apply water (Df1/m³)</td>
</tr>
<tr>
<td>Crop damage function</td>
<td>RPT</td>
<td>Reduction point (mm)</td>
</tr>
<tr>
<td></td>
<td>RD</td>
<td>Reduction damage (fraction of yield lost at RPT)</td>
</tr>
<tr>
<td></td>
<td>DYPT</td>
<td>Death point (mm)</td>
</tr>
<tr>
<td></td>
<td>REMYLD</td>
<td>Remaining yield</td>
</tr>
<tr>
<td></td>
<td>CROPV</td>
<td>Crop values (Df1/ha)</td>
</tr>
</tbody>
</table>

(a) ETDES, GIFT, and RATE are the same as the variables RE, WA, and RU, respectively, in Chaps. 2 and 3.
Table 4.2

OUTPUTS FROM DAILY SPRINKLER OPERATIONS SIMULATION MODEL

<table>
<thead>
<tr>
<th>Output Description</th>
<th>Variable Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>General information</td>
<td></td>
</tr>
<tr>
<td>Year (last two digits)</td>
<td>YEAR</td>
</tr>
<tr>
<td>Month number (range: 4 - 9)</td>
<td>MONTH</td>
</tr>
<tr>
<td>Decade number (range: 10 - 27)</td>
<td>DECADE</td>
</tr>
<tr>
<td>Length of decade (days)</td>
<td>LENDEC</td>
</tr>
<tr>
<td>Climate and soil moisture</td>
<td></td>
</tr>
<tr>
<td>Total rain for decade (mm)</td>
<td>RAIND</td>
</tr>
<tr>
<td>Potential evapotranspiration for decade (mm)</td>
<td>EVAPD</td>
</tr>
<tr>
<td>Actual evapotranspiration for decade (mm)</td>
<td>EACT</td>
</tr>
<tr>
<td>Soil moisture at end of decade (mm)</td>
<td>ENDSM</td>
</tr>
<tr>
<td>Water use and number of moves</td>
<td></td>
</tr>
<tr>
<td>Amount of water sprinkled in decade (mm)</td>
<td>SWAT</td>
</tr>
<tr>
<td>Total drainage for decade (mm)</td>
<td>ROFF</td>
</tr>
<tr>
<td>Number of times equipment was moved in decade</td>
<td>MOVES</td>
</tr>
<tr>
<td>Sprinkling costs for decade</td>
<td></td>
</tr>
<tr>
<td>Total operating cost (Dfl/ha)</td>
<td>OPCOST</td>
</tr>
<tr>
<td>Crop damage, in Dfl/ha, for decade (a)</td>
<td></td>
</tr>
<tr>
<td>Crop type 1: Grass</td>
<td>DAMG1</td>
</tr>
<tr>
<td>Crop type 2: Consumption potatoes</td>
<td>DAMG2</td>
</tr>
<tr>
<td>Crop type 3: Milling potatoes</td>
<td>DAMG3</td>
</tr>
<tr>
<td>Crop type 4: Seed potatoes</td>
<td>DAMG4</td>
</tr>
<tr>
<td>Crop type 5: Sugar beets</td>
<td>DAMG5</td>
</tr>
<tr>
<td>Crop type 6: Cereals</td>
<td>DAMG6</td>
</tr>
<tr>
<td>Crop type 7: Cut corn</td>
<td>DAMG7</td>
</tr>
<tr>
<td>Crop type 8: Bulbs</td>
<td>DAMG8</td>
</tr>
<tr>
<td>Crop type 9: Vegetables (open air)</td>
<td>DAMG9</td>
</tr>
<tr>
<td>Crop type 10: Fruits</td>
<td>DAMG10</td>
</tr>
<tr>
<td>Crop type 11: Trees</td>
<td>DAMG11</td>
</tr>
</tbody>
</table>

NOTE: The model as implemented generates an output data file containing the input variables as well as the results of the simulation by decade. This output file can be post-processed to generate additional statistics, such as monthly or yearly summaries of water used, damage incurred, and operating cost.

(a) Although damage is computed for all crop types, not all are found on the soil.
Chapter 5

DECADE SPRINKLING ALGORITHM

5.1. INTRODUCTION AND OVERVIEW

We needed a sprinkling model suitable for use on a decade basis in the Plot Model (see Vol. XII) and in the Managerial Strategy Design model (see Vol. V). These latter models operate with decade rather than daily information on rain and evaporation and they are far too large and complex to permit carrying detailed information by set. The requirements for the decade sprinkling algorithm were that it use decade rainfall and evapotranspiration and a soil moisture level averaged over sets at the beginning of each decade and from these estimate the amount of water sprinkled. The sprinkling estimates were to replicate those that would have been made by the DSM had it been used.

The decade sprinkling algorithm estimates the demand for sprinkling water in response to decade rain and evapotranspiration given a sprinkling policy. This algorithm consists of three parts: the first imposes a daily weather pattern on the decade, the second calculates the sprinkling requirement, and the third calculates the amount of water lost to drainage. Imposing a weather pattern on a decade means dividing a decade into three periods (dry, rain, dry) and specifying the length of each period, the daily rain during the rain period and the daily evapotranspiration during the entire decade. The sprinkling and drainage calculations follow the logic used in the DSM.

Following a very brief description of the inputs and outputs, we describe each of the three parts of the algorithm in detail and conclude with an evaluation of the results by comparison with the DSM.

5.2. INPUTS AND OUTPUTS

The inputs and outputs for the decade sprinkling algorithm are shown in Table 5.1. The first three inputs describe the decade and the weather during the decade. The next two inputs specify the sprinkling policy. The next two provide information about the soil and the final input reflects the sprinkler system design to impose an upper limit on the amount of water that can be sprinkled in a decade.

There are only two outputs, the amount of water sprinkled and the amount of water lost to drainage during the decade. These outputs are generally intermediate results in the models that employ the algorithm.
5.3. INITIALIZATION AND WEATHER PATTERN

5.3.1. Initial calculations

We calculate the number of days required to complete one irrigation, DAYIRR. The assumption is that we must complete one irrigation of the entire field in the time that it takes one GIFT to dry out at the design evapotranspiration rate of 2.5 mm/day. We also calculate the average potential evapotranspiration per day, EPINC, assuming that the total is uniformly distributed over the days in the decade.

\[
\text{DAYIRR} = \frac{\text{GIFT}}{2.5} \tag{5.1}
\]

\[
\text{EPINC} = \frac{\text{EPOT}}{\text{XLDEC}} \tag{5.2}
\]

5.3.2. Imposing the Weather Pattern on the Decade

Each decade is assumed to consist of three periods—a beginning dry period followed by a rainy period, followed by an ending dry period. Here we calculate the lengths of each of these periods in days. A dryness index is calculated first and then used in specifying the length of the initial dry period and the maximum daily rainfall.

The dryness index, DI, is taken as EPINC divided by the maximum potential evapotranspiration, 5.28 mm/day, observed at the De Bilt weather station in the years 1930 through 1976. We set the index to 1.0 when the maximum is exceeded. The maximum at De Bilt occurred in decade 19 of 1976 when the recorded open water evaporation averaged 6.6 mm per day. In the DSM, we assumed that potential evapotranspiration was equal to 80 percent of open water evaporation and have used the same percent to obtain 5.28 mm/day, which is our estimate of the maximum daily potential evapotranspiration.

\[
\text{DI} = \min(1.0, \frac{\text{EPINC}}{5.28}) \tag{5.3}
\]

The calculation of the daily rainfall, RMAX, is best described by looking at the two components. Looking first at the average of EPOT and RAIN, we see that the daily rain will be high when either the period is very wet or when the potential evapotranspiration is high. Typically, EPOT is high during dry periods and low during wet periods. Observations indicate that when there is a significant amount of rain during dry periods, it occurs in a short period of time—the daily rainfall is high. The other component is the dryness index, DI. When the dryness index is high, the daily rain will be high and conversely so. This index has the effect of concentrating the rain during dry decades and spreading it out during wet decades.
\[ RMAX = \frac{DI \times (EPOT + RAIN)}{2.0} \] (5.4)

Having determined the daily rainfall, we now calculate the number of days of rain assuming that the same amount falls every day in the rain period. Moreover, the number of days of rain cannot exceed the number of days in the decade, so when this does occur, we set the days of rain equal to the length of the decade and recalculate the daily rainfall as \( RAIN/RDAYS \).

\[ RDAYS = \min(XLDEC, RAIN/RMAX) \] (5.5)

\[ \text{IF (RDAYS.EQ.XLDEC) RMAX=RAIN/RDAYS} \] (5.6)

The length of the initial dry period is calculated considering both the dryness index and the number of rainy days. We assume that the length of the initial dry period is proportional to the dryness index. The drier the decade, the longer the initial dry period. This pushes the onset of rain toward the end of the decade and increases the amount of water that will be sprinkled. In the limit, all the rain will come at the end of the decade and sprinkling will be a maximum. The wetter the decade, the shorter the initial dry period, which pushes the onset of rain toward the beginning of the decade and decreases the amount of sprinkling required. In the limit, rain will be uniform over the days in the decade and sprinkling will be minimum. The initial dry period cannot exceed the number of days in the decade minus the days of rain. If this should occur, we set the initial dry period equal to the difference.

\[ PDRY = \min(DI \times XLDEC, XLDEC - RDAYS) \] (5.7)

Finally, we calculate the number of days in the ending dry period as the days remaining in the decade.

\[ DRYDAY = XLDEC - PDRY - RDAYS \] (5.8)

### 5.4. SPRINKLING REQUIREMENT

Sprinkling is assumed to take place only in the beginning and ending dry periods. There is never any sprinkling during the rain period. Sprinkling days need not be integer. We calculate the number of days during which sprinkling would take place and assume that the sprinkled amount is 2.5 mm per day times the number of days. This is the average amount sprinkled on the entire field. All sets are assumed
to be at the average soil moisture level, SMOIST, at the beginning of the period. We assume a 24-hour moving interval.

5.4.1. Sprinkling Before Rain

We begin by calculating STOP0, the soil moisture target level, which will tell us when to start sprinkling the first set. The presumption is that if we start sprinkling set 1 at this time, we will be able to get to the last set before it dries out to the minimum desirable soil moisture, START. The target is reduced by 1.25 mm (one-half the design evapotranspiration rate) to reflect the 12-hour look interval, TLOOK, used in the DSM for generating the sprinkling policies.

\[ \text{STOP0} = \text{START} + \text{GIFT} - 1.25 \]  

(5.9)

The number of days, DO, that it would take the soil to dry out to STOP0 is zero if the beginning soil moisture is already below STOP0. Otherwise, it equals the difference between SMOIST and STOP0 divided by the daily evapotranspiration rate.

\[ \text{DO} = \text{MAX}(0.0, (\text{SMOIST} - \text{STOP0}) / \text{EPINC}) \]  

(5.10)

At this point, we calculate the number of days available for sprinkling, PDRY0. If the drying out time is longer than the initial dry period, there will not be any sprinkling and PDRY0 equals zero. If the soil will dry to STOP0 before the end of the initial dry period, the number of days available for sprinkling is the number of days remaining in the period.

\[ \text{PDRY0} = \text{MAX}(0.0, \text{PDRY} - \text{DO}) \]  

(5.11)

The last step is to adjust the sprinkling days to take into account low evapotranspiration rates. This follows from the DSM where the farmer, once he starts sprinkling, will continue to sprinkle as long as his field loses moisture at rate equal to or greater than the design evapotranspiration rate of 2.5 mm/day. But he will reduce his sprinkling if the moisture loss, EPINC, is less than this rate.

\[ \text{SD0} = \text{PDRY0} \times \text{MIN}(1.0, \text{EPINC} / 2.5) \]  

(5.12)
5.4.2. Calculations for Rain Period

At this point, we calculate the soil moisture levels for sprinkled and unsprinkled sets at the beginning and end of the rain period. Note that the soil moisture levels at the end of the rain period have not been truncated so they may exceed the field capacity, SMAX. These soil moisture levels will be used in determining sprinkling days in the ending dry period and in estimating drainage.

We estimate the soil moisture levels for unsprinkled sets at the start of the rain period, SMB1, and at the end of the rain period, SMR1. At the beginning of the period, unsprinkled sets have been drying out for PDRY days at the rate EPINC. At the end of the period the soil moisture will have increased by the amount of rain less the evapotranspiration during the period.

\[ SMB1 = SMOIST - PDRY \times EPINC \]  \hspace{1cm} (5.13)

\[ SMR1 = SMB1 + RDAYS \times (RMAX - EPINC) \] \hspace{1cm} (5.14)

We also estimate the soil moisture level for the sprinkled sets at the beginning of the rain period, SMBS, and at the end of the rain period, SMRS. The sprinkled sets will have received the full gift unless the number of sprinkling days, SDO, are less than 1.0. Their soil moisture level will be higher than that for unsprinkled sets by the amount sprinkled. If this level is higher than field capacity, water will have drained off and the moisture level, SMBS, will be equal to the field capacity, SMAX. At the end of the period, moisture level is equal to the level at the beginning of the period plus the rain minus the evapotranspiration during the period.

\[ SMBS = \text{MIN}(SMAX, SMB1 + \text{GIFT} \times \text{MIN}(1.0, SDO)) \]  \hspace{1cm} (5.15)

\[ SMRS = SMBS + RDAYS \times (RMAX - EPINC) \] \hspace{1cm} (5.16)

5.4.3. Sprinkling After Rain

Here we calculate the number of sprinkling days required in the ending dry period. We distinguish between the part of the field that was not sprinkled in the beginning dry period from the part that was. We refer to the first as unsprinkled sets and the second as sprinkled sets. The distinction is made between the two kinds of sets to permit the use of different critical soil moisture levels and to account for changes in soil moisture separately.

The calculations for the unsprinkled sets depend on how many sets were sprinkled in the previous dry period. Because the moving
interval is 24 hours, one set is sprinkled each day. Thus, the number of sprinkling days, SD0, in the previous dry period is equal to the number of set that were sprinkled. Furthermore, we envision the sprinkling equipment sitting on set SD0+1 at the beginning of the second dry period.

The critical level for unsprinkled sets is lower than the critical level, STOP0, used in the first period by an amount equal to the design evapotranspiration of 2.5 mm/day times the number of sprinkling days in the first period. This amount cannot be larger than the entire gift. When this amount is equal to the gift, the whole field has been sprinkled.

\[
\text{STOP2} = \text{STOP0} - \text{MIN(GIFT,2.5*SD0)}
\]  

(5.17)

In order to determine whether or not there is a requirement for sprinkling these sets, we calculate the number of days that it will take them to dry out to the critical soil moisture level. Recall that the estimated soil moisture level for these sets at the end of the rain period has not been truncated to field capacity. We therefore first do this if needed, then subtract the critical level, and divide the result by the daily evapotranspiration rate, EPINC. This number of days cannot be less than zero. Nor can it be greater than the number of days, DRYDAY, in this period.

\[
D2 = \text{MIN(DRYDAY,MAX(0.,(MIN(SMR1,SMAX)-STOP2)/EPINC))}
\]  

(5.18)

We calculate the number of days remaining in the irrigation cycle so that we can ensure that we will not sprinkle into the next irrigation cycle. The remaining days, REMDAY, equal the number of days in the cycle less the number of days used for sprinkling in the initial dry period. The remaining days cannot be less than zero.

\[
\text{REMDAY} = \text{MAX(0.0,DAYIRR-SD0)}
\]  

(5.19)

Finally, we calculate the number of sprinkling days for the unsprinkled sets. After allowing for drying out time, the number of days available for sprinkling unsprinkled sets in this period equals DRYDAY – D2. This number, of course, cannot exceed the number of days remaining in the irrigation cycle. At this point, we adjust the number of sprinkling days to take into account low evapotranspiration rates as was described in Sec. 5.4.1.

\[
\text{SD2} = \text{MIN(DRYDAY-D2,REMDAY)*MIN(1.,EPINC/2.5)}
\]  

(5.20)
The critical level for sprinkled sets, STOP0, is the same as the critical level in the initial dry period. First, we estimate the number of days, DS2, to reach the critical level. As before, we ensure that the soil moisture level at the beginning of this period does not exceed field capacity, and subtract the critical level and divide by EPINC, to estimate the number of drying days. This estimate cannot be less than zero nor greater than the number of days in this period.

\[ DS2 = \text{MIN}(\text{DRYDAY}, \text{MAX}(0., \text{MIN}(\text{SMRS}, \text{SMAX}) - \text{STOP0}) / \text{EPINC}) \] (5.21)

The number of sprinkling days available for sprinkled sets is just the total days less the drying time, or DRYDAY-DS2. Since the drying time was constrained so that it would not exceed the total days, the available days will never be less than zero. The available sprinkling days have been adjusted to take a low evapotranspiration rate into account (see above). If the drying out time in the beginning dry period took up all of that period, then no sets were sprinkled in the initial period and we set the sprinkling days for this null category of sets equal to zero.

\[
\text{SDS2} = \begin{cases} 
(D\text{RYDAY}-D\text{S2}) \times \text{MIN}(1.0, \text{EPINC}/2.5), & \text{if } D0 < PD\text{RY} \\
0 & \text{if } D0 > PD\text{RY}
\end{cases}
\] (5.22)

The number of sprinkling days in the ending dry period, ADD2, is estimated to be the average of the adjusted sprinkling days for sprinkled and unsprinkled sets. The number of days to the start of sprinkling in this period, D2, is the total number of days minus the sprinkling days.

\[ ADD2 = .5 \times (SD2 + SDS2) \] (5.23)

\[ D2 = D\text{RYDAY} - ADD2 \] (5.24)

5.4.4. Total Sprinkling for Decade

The total number of sprinkling days in the decade is the sum of the sprinkling days before and after the rainfall. Note that no sprinkling occurs during the rainfall. Moreover, the number of sprinkling days can not exceed the number of days in the decade. The amount of water sprinkled, SPRKLN, is calculated using the sprinkling days in the decade and an average water application rate of 2.5 mm
per day of sprinkling. When the daily moisture loss rate, EPINC, exceeds the design rate of 2.5 mm/day, we allow the sprinkler system to be speeded up to supply EPINC mm/day up to the system capacity.

$$\text{SPRDAY} = \text{SDO} + \text{ADD2}$$  \hspace{1cm} (5.25)

$$\text{SPRKLE} = \text{MIN(XLDEC,SPRDAY)}\times\text{MAX}(2.5, \text{MIN(SPRCAP,EPINC)})$$  \hspace{1cm} (5.26)

5.5. DRAINAGE

5.5.1. Drainage from Sets Sprinkled Before Rain

We assume that the gift is applied instantaneously at the start of sprinkling and estimate the soil moisture level, S1, at that point. We also estimate the soil moisture level at the conclusion of sprinkling just before the rain begins, S1A. The number of days that the sprinkled sets are above field capacity is determined next and assigned to T1. Note that T1 can not exceed the number of sprinkling days, SDO. The drainage from sprinkled sets, ROFF1, is estimated by taking the average amount in excess of field capacity and multiplying by the fraction of total sets that have been sprinkled in the initial dry period.

$$\text{S1} = \text{SMOIST} - (\text{PDRY-SDO})\times\text{EPINC} + \text{GIFT}\times\text{MIN}(1.0,\text{SDO})$$  \hspace{1cm} (5.27)

$$\text{S1A} = \text{SMB1} + \text{GIFT}\times\text{MIN}(1.0,\text{SDO})$$  \hspace{1cm} (5.28)

$$\text{T1} = \text{MIN}(\text{SD0},\text{MAX}(0.,(\text{S1-SMAX})/\text{EPINC}))$$  \hspace{1cm} (5.29)

$$\text{ROFF1} = 0.5\times(T1/\text{DAYIRR})\times(\text{MAX}(0.,\text{S1-SMAX}) + \text{MAX}(0.,\text{S1A-SMAX}))$$  \hspace{1cm} (5.30)

5.5.2. Drainage from Rain for All Sets

We calculate the fraction of total sets sprinkled before the rain, T3, and then estimate the drainage during the rain period, ROFF3, as the weighted average of the excess above field capacity for sprinkled sets and for unsprinkled sets.

$$\text{T3} = \text{MIN}(1., \text{SD0/DAYIRR})$$  \hspace{1cm} (5.31)

$$\text{ROFF3} = T3\times\text{MAX}(0.,\text{SMRS-SMAX}) + (1.-T3)\times\text{MAX}(0.,\text{SMR1-SMAX})$$  \hspace{1cm} (5.32)
5.5.3. Drainage from Sets Sprinkled After Rain

The weighted average soil moisture level, S3, for sprinkled and unsprinkled sets at the end of the rainfall period, is calculated first. Drainage in the ending dry period will occur only for sprinkled sets, so we calculate the average soil moisture level at the start of sprinkling, S4, assuming that the gift is applied instantaneously, and the average soil moisture at the end of sprinkling, S4A. We then estimate the number of days, T4, that sprinkled sets exceed field capacity. Finally, the drainage during this period, ROFF4, is estimated by taking the average amount in excess of field capacity and multiplying by the fraction of total sets that have been sprinkled in this ending dry period.

\[ S3 = T3 \times \text{MIN}(S_{\text{MAX}}, SMRS) + (1.-T3) \times \text{MIN}(SMR1, S_{\text{MAX}}) \]  

(5.33)

\[ S4 = S3 - D2 \times \text{EPINC} + \text{GIFT} \times \text{MIN}(1., ADD2) \]  

(5.34)

\[ S4A = S4 - ADD2 \times \text{EPINC} \]  

(5.35)

\[ T4 = \text{MIN}(ADD2, \text{MAX}(0., S4 - S_{\text{MAX}})/\text{EPINC}) \]  

(5.36)

\[ \text{ROFF4} = .5 \times (T4/\text{DAYIRR}) \times (\text{MAX}(0., S4 - S_{\text{MAX}}) + \text{MAX}(0., S4A - S_{\text{MAX}})) \]  

(5.37)

5.5.4. Total Drainage for Decade

Total drainage for the decade is the sum of the drainages from the initial dry period, the rain period, and the ending dry period.

\[ \text{RUNOFF} = \text{ROFF1} + \text{ROFF3} + \text{ROFF4} \]  

(5.38)

5.6. MODEL EVALUATION

The only thing we have against which to compare the results of the decade sprinkling algorithm is the output from the DSM. This comparison has been made for the extremely dry year (1976), the normal year (1967), and the extremely wet year (1965).

The amount of sprinkling required depends heavily on the weather. Figure 5.1 shows the decade rainfall and evapotranspiration, during the growing season, for each of the three selected years. Rainfall and open water evaporation reflect measurements at the weather station in De Bilt. Potential evapotranspiration is estimated at 80 percent of the open water evaporation. For each of the years, the rainfall
comes intermittently throughout the growing season while the evapotranspiration is relatively constant, except in the 1976, where it peaks significantly midway through the growing season. Clearly there is a surplus of rain in 1965 and a deficit in 1976. In the normal year, the rain is less than the evapotranspiration during most of the growing season, but near the end there are substantial amounts of rain and the evapotranspiration tails off.

For validation purposes, the decade sprinkling algorithm was run as a self-contained model. The soil moisture was set to field capacity at the beginning of the growing season. A weather scenario was specified. The algorithm estimated the amount of water to be sprinkled and the amount of water that was lost to drainage. The model estimated the actual evapotranspiration using the same procedure as is employed in the Plot Model. Decade rain plus the water sprinkled minus drainage and actual evapotranspiration were added to the beginning soil moisture to estimate the soil moisture at the beginning of the next decade. The model steps through each decade in the growing season and the results are compared with the output from the DSM for the same weather scenarios (see Figs. 5.2 through 5.6).

A comparison of the amount of water sprinkled by both the DSM and the decade sprinkling algorithm is shown for each of the three years in Fig. 5.2. For both the extremely dry year and the normal year, where there is a substantial amount of sprinkling required, the algorithm and the DSM produce essentially the same results. However, the decade sprinkling algorithm sprinkles considerably more than the DSM in the extremely wet year. While there is some difference in almost every decade, the major disagreement occurs in the period about two-thirds of the way through the growing season.

The DSM does not require any sprinkling in decades 20 through 22 of 1965 while the decade algorithm sprinkles a little less than 10 mm in each decade. In the DSM, there was enough rain so that on no single day was sprinkling required. When this same weather scenario was viewed on a decade basis, the potential evapotranspiration was sufficiently high to cause all of the rain to be placed in a small fraction of the decade. The remaining part of the decade was therefore long enough for the soil to dry out and for sprinkling to be required. When accumulated over the growing season, the sprinkling algorithm sprinkles almost 40 percent more. However, the difference does not seem a significant problem since our concern with sprinkling is in dry rather than wet periods and the comparison improves with the dryness of the year.

Figures 5.3 through 5.5 show the amount of water lost to drainage and the ending soil moisture by decade for each of the three years. For the wet year (1965), the two models give results that are substantially the same. The decade algorithm overestimates drainage a bit in decades 20 through 22 and generally underestimates the soil moisture in all decades. The overestimate of drainage is for the same reasons that the amount of sprinkling was overestimated (see
above). The overestimate of sprinkling when combined with the overestimate of drainage combine to underestimate the soil moisture. The comparisons of drainage and soil moisture are virtually the same for the two drier years--drainage is overestimated in most decades with a concomitant underestimation of soil moisture.

The large difference in the simulation time steps between the daily and the decade models generates a need for final calibration of the decade algorithm. Figs. 5.3 through 5.5 indicate that the decade algorithm results in an underestimate of soil moisture. This follows from our calibration to make good estimates of actual evapotranspiration. We can tolerate an error in soil moisture better than we can an error in actual evapotranspiration as the latter is the primary independent variable used to estimate crop damage.

The comparison of sprinkled amounts in Fig. 5.2 shows that the algorithm provides estimates of sprinkling that are quite sensitive to the dryness of the growing season. In Fig. 5.6 we compare the amounts sprinkled in the normal year for two different gifts--20 mm and 30 mm. The agreement between the DSM and the decade algorithm is satisfactory for both gifts. Furthermore, a bit more water is sprinkled with the 30 mm gift. This is logical because with the larger gift, more water is applied per irrigation.

In summary, the decade algorithm gives results that are sufficiently comparable to those of the DSM that we have used it in all PAWN models where requirements for sprinkling are estimated. Where differences exist, the decade algorithm tends to estimate sprinkling requirements in the direction of more realism rather than less. A plot is a collection of fields belonging to many farmers. Not all farmers will operate in lock step. Rain will not fall on all fields at the same time in the same amounts. Consequently, some farmers will begin to sprinkle before others and, thus, the application of water will be spread out over time more uniformly. Indeed the decade algorithm tends to estimate more even sprinkling requirements than the DSM. Furthermore, not all farmers will follow the sprinkling policy exactly. At times, some farmers will apply less than the full gift. They may apply more but are limited on the high side by the sprinkler system capacity. This would result in less sprinkling during wet periods and more during dry periods than the estimates by the DSM.
Fig. 5.1--Decade rainfall and potential evapotranspiration at de Bilt in 1965, 1967, and 1976
Fig. 5.2--Amount of water sprinkled by decade: DSM vs. decade sprinkling algorithm
Fig. 5.3a--Drainage in extremely wet year (1965): DSM vs. decade sprinkling algorithm

Fig. 5.3b--Average soil moisture in extremely wet year (1965): DSM vs. decade sprinkling algorithm
Fig. 5.4a--Drainage in normal year (1967): DSM vs. decade sprinkling algorithm

Fig. 5.4b--Average soil moisture in normal year (1967): DSM vs. decade sprinkling algorithm
Fig. 5.5a--Drainage in extremely dry year (1976): DSM vs. decade sprinkling algorithm

Fig. 5.5b--Average soil moisture in extremely dry year (1976): DSM vs. decade sprinkling algorithm
Fig. 5.6—Effect of GIFT on amount sprinkled
Table 5.1

DECADE SPRINKLING ALGORITHM: INPUTS AND OUTPUTS

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of days in decade</td>
<td>Amount of water sprinkled in decade (mm)</td>
</tr>
<tr>
<td>Total potential evapotranspiration in decade (mm)</td>
<td>SPRKLN</td>
</tr>
<tr>
<td>Total rainfall in decade (mm)</td>
<td></td>
</tr>
<tr>
<td>Critical soil moisture level (mm)</td>
<td></td>
</tr>
<tr>
<td>Amount of water to be applied per irrigation (mm)</td>
<td>SPRTCAP</td>
</tr>
<tr>
<td>Soil moisture level at beginning of decade (mm)</td>
<td></td>
</tr>
<tr>
<td>Field capacity of soil (mm)</td>
<td></td>
</tr>
<tr>
<td>Sprinkling capacity (mm/day)</td>
<td></td>
</tr>
<tr>
<td>XLDEC, EPOT, DRAIN, START, GIFT, SMOIST, SMAX</td>
<td>SPRKLN, SPRTCAP</td>
</tr>
</tbody>
</table>


Chapter 6

LEAST-COST SPRINKLER SYSTEMS

6.1. INTRODUCTION

6.1.1. Purpose

In this chapter we are going to select a moving interval and number of laterals for the Buiss and the type of haspel unit for the Haspel that result in a least-cost sprinkler system for each combination of the eight sprinkler configurations, three different gifts (20, 25, and 30 mm), and fields ranging in size up to 40 ha. The sprinkler system operating costs reflect operating under average weather conditions during the growing season, which are approximated by a constant evapotranspiration rate of 2.5 mm/day and a requirement to sprinkle a total of 90 mm of water. Then we prepare sprinkling cost functions for use in other PAWN models where the sprinkling design and cost models would be too expensive to use.

The number of laterals and the moving interval for the Buiss systems and the type of Haspel for the Haspel systems are chosen so as to minimize total annualized sprinkling cost. Total annualized cost is the sum of annualized investment and annual operating cost. We used it to obtain the least-cost envelopes because it offered a convenient way of combining initial investment and annual operating cost into a single figure. A least-cost envelope is a curve of lowest total annualized cost vs. field size for sprinkler systems having the same configuration and designed to apply the same gift. It is obtained by superimposing curves of total annualized cost vs. field size for all of the candidate sprinkler systems and connecting the points of lowest cost.

Having identified the least-cost systems, we prepared four other cost functions—total investment cost, annualized investment cost, labor cost per move, and energy cost per millimeter of water sprinkled—related to field size for each configuration and gift. The functions resulted from plotting the value of each of these variables (from the cost model output for the least-cost systems) against field size. These functions, in turn, become inputs to the Sprinkler System Allocation and Cost Model (see Chap. 7).

The assumptions made and the exact process used are discussed fully in the remainder of this chapter.

6.1.2. Representative Fields

Since it was impractical to consider every field shape that might be sprinkled, we chose two that we believe are sufficiently representative of all fields in the Netherlands: square and
rectangular. For reasons we state below, we selected one or the other of these depending on field size and system configuration.

In the lowlands, fields are typically divided into rectangles by irrigation ditches that are no more than 300 m apart. Thus, we have assumed that all lowlands fields have one dimension that is equal to or less than 300 m. In the Buis configuration B2, a field has one dimension equal to 300 m unless the area of the field is less than 9 ha, in which case the field is assumed to be square. In the Haspel configuration H1, a field has one dimension equal to 300 m when Haspel type C-75 or C-90 is used and, when the Junior is used, this dimension is fixed at 200 m (the maximum hose length of the Junior).

Fields in the highlands are typically not delineated by ditches so there was no obvious way to define field shape. We performed a cost analysis and found that sprinkler system costs were quite insensitive to field shape as long as a main distribution pipe was used. As it seemed likely that ditches would not be available in the highlands and that a main distribution pipe would be essential, we assume that all Buis systems, in the highlands, would be used on square fields.

Haspel systems in the highlands presented a somewhat different problem. Each Haspel--C-90, C-75, and Junior--has a fixed nominal hose length and we were led to believe that most farmers would not purchase Haspels with odd hose lengths. As long as Haspels have a fixed hose length, each set also has one of its dimensions fixed (length or width). The other set dimension is equal to the effective spray width and, as that varies so little, both set dimensions and consequently the area of the set are essentially fixed.

Exactly how sets (of a fixed size) should be located on a field is not obvious. Several possibilities come to mind. Sets might be located to minimize moving distance or to minimize the length of the main distribution pipe. In some cases, the geography of the field may dictate exactly how the sets should be located. We were unable to use any of these because necessary information about the particular fields was not available.

We simply took one dimension of the field equal to the Haspel hose length and assumed that the sets were located side by side. This rule tends to overstate the size and cost of the main distribution pipe for very large fields, but it also understates the cost of moving. All sets are assumed to be immediately adjacent to each other so the distance moved is always the width of one set. In reality, one or several sets might be located some distance from the other sets--perhaps on a completely different part of a farm.

Thus, Buis configurations B1, B3, B4, and B5 always imply square fields and Haspel configurations H2 and H3 imply fields with one dimension set equal to 300 m or 200 m, depending on whether the Haspel is C-75/C-90 or Junior.
6.2. INPUTS TO DESIGN AND COST MODELS

The inputs used to obtain the least-cost envelopes are shown in Tables 6.1 through 6.4. Tables 6.1 and 6.2 contain the inputs that are common to all systems. Tables 6.3 and 6.4 show the inputs that are specific to the Buis and Haspel systems, respectively.

As shown in Table 6.1, we used field sizes ranging up to 40 ha, which include the majority of fields found on farms in the Netherlands.

We used an evapotranspiration rate of 2.5 mm per day, which is a rough average for the Netherlands during the growing season. Each system sprinkles 90 mm of water during the growing season—an estimate of the average soil moisture deficit during the growing season for the years 1911 through 1975 [6.1].

Three different amounts of water applied per irrigation were used—20, 25, and 30 mm. According to informal sources in the Netherlands, these values are typical of the gifts generally applied. Indeed, the Haspel systems have difficulty applying much more than 30 mm per irrigation. We included a moderate range of values so that some matching of the gift to the moisture-holding capacity of the root zones of different crops could be accomplished.

Sprinkler efficiency is the ratio of the amount of water that leaves the sprinkler heads to the amount of water that finds its way into the root zone. The exact value is dependent on such things as the relative humidity, velocity of prevailing winds, temperature, etc. In hot, dry, windy locations one would expect a low sprinkling efficiency. However, in the Netherlands, relative humidity is generally high and temperatures are moderate to low so sprinkling efficiencies of the order of 0.85 to 1.0 seem to be appropriate. At the time the analysis discussed in this chapter was undertaken, we had no good estimate, although later on we obtained an estimate of 0.85 and used it in subsequent sprinkling analyses (see Chap. 7). For initial design and cost purposes, we assumed that the sprinkling efficiency was 1.0.

Pump efficiency and tractor specific fuel consumption reflect average performance for agricultural pumps and tractors in the Netherlands.

After examining the effect of allowable pressure drop in the main and lateral pipes on the size and cost of those pipes, we chose ten percent as reasonable. For smaller values, the pipes become very large and expensive. Larger values would result in larger pumps and more pumping energy than desirable.

Transit time is the time spent by the farmer going to and from the field being sprinkled. We assume that he makes this trip every time he moves his equipment. Our observations indicate that the transit time is subject to considerable variation, but that one-half hour is a reasonable average.
Table 6.2 shows the interest rate used to calculate the capital recovery factors and the useful lives of the sprinkler system components. The interest rate, ten percent, is the rate Dutch farmers paid for borrowing money in 1979. Banks in the Netherlands were lending money at that rate to finance the purchase of farm equipment. The useful lives of all system components except the Haspel unit were obtained from Ref. 6.2 and the useful life of the Haspel unit was obtained informally from the Netherlands. We assumed that at the end of a piece of equipment's useful life, its salvage value is zero.

Table 6.3 shows the inputs for the five Buis configurations. We considered both one and two-lateral systems. More than two laterals result in higher cost systems and so were not considered. We examined moving intervals ranging from 12 hours up to 144 hours. Each moving interval is a multiple of 12 hours so that the farmer can move his sprinkler system on a convenient schedule.

When multiplied by the nozzle spray diameter, the fraction CA gives the spacing between nozzles on a lateral, and the fraction CB gives the spacing between laterals. These factors are applied in order to ensure uniform water distribution given wind velocity and direction. The values chosen for these factors reflect low wind velocity (less than 7 mph) and random wind direction.

Lateral pipes are typically available in six-meter segments, which explains the value for LP in Table 6.3. This is a convenient length to be carried from one set to the next. Lateral pipes are sized so that the pressure drop in the pipe will be ten percent of the nozzle pressure (see discussion of main pipe above).

We have assumed that the farmer walks at a rate of 4.5 km/hr (approximately 3 mph) when moving the pipe segments and that he spends approximately one minute in coupling or uncoupling a pipe segment.

Electric motor efficiency is set at 0.7, which we think is reasonable for electric motors used in an agricultural environment.

The field dimension, FD, parallel to the lateral pipe is discussed in Sec. 6.1.2.

The inputs for the Haspel systems are shown in Table 6.4. We considered three Haspel configurations and assumed that there would always be only one Haspel unit per sprinkler system. A Haspel unit is a very expensive piece of equipment and it seems unlikely that more than one would be used on farms of the sizes considered here. The specifications for the three types of Haspel units were obtained directly from Cebeo-Handelsraad [6.3]. The field dimension, FD, parallel to the Haspel hose is set equal to the nominal hose length for the particular Haspel unit.
6.3. OBTAINING LEAST-COST ENVELOPES

6.3.1. Buis System

We fixed the system configuration and the gift and then plotted the total annualized cost against field size, separately for each moving interval-number of laterals combination. The lower envelope of these curves identified a least-cost system for each field size. Note that the number of laterals and the moving interval for the least-cost systems varies with field size. In fact, there is a different least-cost sprinkler system for each configuration, gift, and field size.

The least-cost envelopes for Buis configuration B1 are shown in Fig. 6.1. Because they are quite similar, the least-cost envelopes for the other four Buis configurations are presented in the Appendix. Total annualized cost vs. field size is shown for three different amounts of water applied per irrigation. The moving interval and number of laterals appropriate to each segment of the curves are indicated. Total annualized cost increases with field size and decreases with the amount of water applied per irrigation. Large moving intervals are preferred for small fields and smaller ones are preferred for large fields. One lateral pipe is used for small fields and two lateral pipes are used for large fields.

Figure 6.2 shows the derivation of the least-cost envelope for Buis configuration B1 and a WA of 20 mm. Total annualized cost including value-added tax is shown on the vertical axis and the area of the sprinkled field is shown on the horizontal axis. Curves are drawn for each combination of moving interval and number of laterals. The least-cost envelope, shown as a solid line, is the lower envelope of the collection of curves.

There are two points of particular interest on the least-cost envelope: the point where the least-cost systems switch from a 12-hour moving interval and one lateral to a 12-hour moving interval with two laterals; and the point where the least-cost systems switch from a 24-hour moving interval and one lateral to a system with a 12-hour moving interval and one lateral. At the transition points the total annualized costs are equal, so to understand the reason for the transitions, we look at the situations on either side of the transition points.

We consider switching from one to two laterals first. This occurs at a field size of about 22 ha. As there is no change in the moving interval, the number of sets and the area per set remain the same. However, with one-lateral, the area covered by the lateral equals the area of the set, while in the other case, each lateral covers only half the area. In the neighborhood of the transition point, the investment cost for the two-lateral system is less than that for the one-lateral system, and the difference is almost all due to the lower cost of pipes. Because of the larger area, the one-lateral
system requires larger pipes and the cost of pipes increases exponentially with pipe size (see Chap. 3). The operating cost is always lower for the one-lateral system as it is cheaper to move one lateral per set than two.

In the area just to the left of the transition point, the one-lateral system is cheaper because the savings in operating (moving) cost is large enough to offset the larger investment. However, as field size increases, the investment cost--mainly pipe cost--increases much more rapidly for the one-lateral case than for the two-lateral case. In fact, immediately to the right of the transition point, the investment is so large that the savings in operating cost are no longer enough to make the one-lateral system cheaper.

At approximately 5 ha, the systems on the least-cost envelope switch from a 24- to a 12-hour moving interval. In either case, there is one lateral. With a 24-hour moving interval, there are half as many sets as with a 12-hour moving interval. The length of the sets is the same in both systems (half the width of the field), but with half as many sets, the width is doubled. In the area of the transition point, the system with the 12-hour moving interval has the lower investment cost because the smaller sets use smaller and hence cheaper pipes. The operating cost is always less for the system with the 24-hour moving interval because fewer moves are required to complete an irrigation. The number of moves equals the number of sets. While the cost per move increases as the size of the sets increases, this increase is not enough to offset the decrease resulting from fewer moves.

To the left of the transition point, the case with the 24-hour moving interval is cheaper because the extra investment cost is more than offset by the savings in annual operating cost. However, to the right of the transition point, the investment cost increases faster than the operating cost so that the savings in operating cost is no longer enough to offset the extra investment cost and hence the system with the 12-hour moving interval is cheaper.

6.3.2. Haspel System

We fixed the system configuration and the gift and plotted total annualized cost against field size--one curve for each Haspel type (all systems considered had only one Haspel unit). The lower envelope of these curves identifies the least-cost Haspel system for each field size. This was repeated for each Haspel configuration and gift combination.

Figure 6.3 shows the least-cost envelopes for the three Haspel configurations--H1, H2, and H3. The important design variable is the Haspel type. For configuration H1, the Junior is the cheapest until the field size reaches just over 30 ha. At that point the curve take a jump upwards and the C-90 becomes the least-cost system. This switchover occurs because both the Junior and the C-75 become
infeasible by our criterion, which requires that systems not exceed 75 percent utilization.

Configurations H2 and H3 differ only in that configuration H2, the higher cost system, requires a well. In both configurations a main distribution pipe is required. It is the cost of the main distribution pipe that results in the crossover from the Junior to the C-75 at field sizes in excess of about 9 ha. As in configuration H1, here also the C-90 replaces the C-75 and the Junior when the utilization rate for those Haspels exceeds 75 percent.

Figure 6.4 shows the moving interval, the nozzle flow rate, and the utilization curves corresponding to the least-cost envelope for configuration H2 with 25 mm of water applied per irrigation. In the range of field sizes where the Junior is preferred, the nozzle flow rate is a constant equal to the minimum flow rate of the Junior.

Recall that for the Junior, the spray width is a constant and the set dimension parallel to the hose is set equal to the maximum hose length. Thus, the area per set is a constant and the number of sets increases in proportion to the area of the field. Further, as the moving interval is equal to the soil moisture cycle time (a constant) divided by the number of sets, the moving interval decreases as field size (number of sets) increases.

The utilization rate, which was defined as the proportion of the moving interval taken up by sprinkling, increases linearly with the area of the field. In Chap. 2, we derived an expression for the utilization rate as a function of the area of the field, the nozzle flow rate, and other input variables that remain constant for the configuration (Eq. 2.63). The utilization rate is directly proportional to the area of the field and inversely proportional to the nozzle flow rate. In the range of field sizes for which the Junior is preferred, the nozzle flow rate is a constant and the utilization rate increases linearly with field size.

Around nine hectares the C-75 becomes the least-cost Haspel. The nozzle flow rate drops to the minimum for the C-75, which is lower than that for the Junior. The spray diameter corresponding to the C-75 minimum flow rate is higher than that for the Junior and the maximum hose length, which dictates the length of each set, increases to 300 m. As a result, the area per set is larger and the number of sets is smaller. With fewer sets, the moving interval increases substantially.

The utilization rate increases at the switchover point because the nozzle flow rate has dropped (see Eq. 2.63). In the range of field sizes over which the C-75 is preferred, the utilization rate increases linearly until it reaches the maximum allowable of 75 percent. This occurs when the field size is about 18 ha. For larger field sizes it is necessary to increase the nozzle flow rate in order to maintain the utilization rate at 75 percent. Note that the nozzle flow rate is proportional to the field size when the utilization rate is constant.
The moving interval drops inversely with the field size between the switchover point and 18 ha, in which range the area per set is a constant. When the nozzle flow rate must be increased, as is the case for fields larger than 18 ha, the spray width and hence the area per set increases. This tends to reduce the rate at which the moving interval drops. The overall effect, however, is small. At the minimum flow rate, the spray diameter is 71 m, while at the maximum flow rate, the spray diameter is about 80 m, yielding a maximum increase of about 0.37 ha in the area per set. The field size increases by over ten hectares between the point where the flow rate starts to increase and the point where it reaches the maximum.

At about 29 ha, the C-75 becomes infeasible. The Junior continues to be feasible up to around 30 ha, but its investment and operating costs are both higher than those of the C-90. Thus, the C-90 is the preferred system for larger field sizes. When the C-90 takes over, it is already operating at 75 percent utilization and a nozzle flow rate equal to the maximum rate for the C-75. Because of its higher maximum nozzle flow rate, the C-90 can handle fields of up to 43 ha without violating the 75 percent utilization criterion. Larger fields would require adding a second Haspel unit.

6.4. COST FUNCTIONS

A cost function expresses a component of sprinkler system cost as a function of sprinkler system characteristics for the least-cost systems. Separate functions were obtained for initial investment cost, annualized investment cost, labor cost per move, and energy cost per mm of water sprinkled. Annual sprinkler maintenance cost is estimated at 3.5 percent of investment cost. We used these functions in other PAWN models to estimate total sprinkler system cost as a function of configuration, gift, field size, number of moves, and amount of water sprinkled.

6.4.1. Buis Systems

Having identified the least-cost Buis systems, we obtained the remaining four cost functions by plotting the costs for each component of cost against field size for the systems identified by the least-cost envelope. Here we discuss the cost functions for Buis configuration B1. As most of what we have to say about this Buis configuration applies equally well to the four other Buis configurations, we show the latter in the Appendix. Total investment costs are shown in Fig. 6.5, annualized investment costs in Fig. 6.6, labor costs per move in Fig. 6.7, and energy costs per millimeter of water applied in Fig. 6.8.

According to the least-cost envelopes, the total annualized costs are equal at the points where a transition from one sprinkler system design to another was made. However, as shown by the individual cost functions, the component costs are not.
Below, we describe in some detail why they are different. There are several points along the cost function curves where an abrupt change in cost occurs. Notice that this happens where there is a change in one of the design variables—moving interval or number of laterals. Also, each of the curves shifts downward as the value of WA increases. As the reasons for the cost differences are more dependent on system design changes than on field size, we talk about two field sizes only. A 5-ha field is selected to describe the effect of changing from a 24- to a 12-hr moving interval and a 35 ha field is used to describe the effect of changing from a 20- to a 30-mm gift and from 1 to 2 laterals.

Cost and design model outputs are shown, for five cases, in Table 6.5. Two of the cases are for a 5-ha field—one uses a 24-hour moving interval and the other uses a 12-hour moving interval. Both designs use a single lateral. Three additional cases are for a 35-ha field. Two of these compare systems with a 20- and a 30-mm gift. Each uses one lateral and has a 12-hour moving interval. The final case shows a system with a 30-mm gift, a 12-hour moving interval, and 2 laterals and will be compared with the adjacent case to see the effect of shifting from 1 to 2 laterals.

6.4.1.1. Total Investment Cost. This discussion applies equally to both investment and annualized investment. The curves shown in Figs. 6.5 and 6.6 indicate first, that the investment cost is lower for larger values of WA, second, that investment cost decreases when the moving interval changes from 24 to 12 hours, and third, that it also decreases when the number of laterals increases from one to two. The moving interval is changed at several different field sizes and the number of laterals changes at a field size greater than 20 ha. The exact size differs with the value of WA.

Larger values of WA result in lower investment costs. All other design variables are held constant for this comparison. More water applied per irrigation makes the soil moisture cycle longer and, as the moving interval does not change, the number of sets increases. The area per set decreases accordingly and smaller sets mean a lower application rate, a smaller spray diameter, and a lower rate of flow through the main and lateral pipes. Smaller spray diameters mean smaller less costly sprinkler heads and lower flows mean cheaper pipes and fittings. Lower flows also require smaller pumps and motors. Thus, increasing WA causes a reduction in the cost of almost every component of investment cost.

Varying the moving interval from 24 to 12 hours while holding WA and the number of laterals constant causes the investment cost to decrease. For a given WA, halving the moving interval means doubling the number of sets, and for a given field size, twice as many sets means that each set is half the size. From this point the logic as to why the investment costs are lower for smaller moving intervals follows as in the paragraph immediately above.
Doubling the number of laterals from one to two, while holding WA and the moving interval constant, also causes a reduction in investment cost. Because the moving interval and WA remain the same, the number of sets remains the same. However, with two laterals per set instead of one, the area per lateral is cut in half and the flow per lateral drops to about one-quarter. The flow in the main pipe drops to one-half.

Because of the much lower flow requirements, the two laterals cost a little less than the single lateral. However, the cost of the main pipe (two-lateral case) is a lot lower—about two-thirds of the cost. Other investment costs that are driven by flow in the main pipe—pump, motor, control equipment—drop accordingly. There are about four times as many smaller sprinkler heads in the two-lateral case but the cost of sprinkler heads is only slightly higher. As would be expected, there are twice as many fittings in the two-lateral case and, even though they are smaller, they cost significantly more in total. As total investment cost is, in large part, the cost of the pipes, it is about 20 percent lower for the two-lateral case.

6.4.1.2. Labor Cost per Move. The labor cost per move curves are shown in Fig. 6.7. In general, the cost per move is only slightly lower for higher values of WA. When the moving interval changes from 24 to 12 hours the labor cost per move decreases. Yet, when the number of laterals changes from one to two, the labor cost per move increases substantially. The change due to increasing WA is so slight that we will ignore it here. However, the reader should be aware that increasing WA results in fewer irrigations being required and hence, with a constant cost per move, the labor cost will be less in total.

The cost per move reflects the time per move, which consists of three parts: time spent carrying lateral pipes, time spent coupling and uncoupling lateral pipe segments, and one-half hour, which is used to travel to and from the field each time the sprinkling equipment is moved.

Consider the case where the moving interval is changed from 24 to 12 hours while WA and the number of laterals are held constant. This happens for field sizes just below ten hectares (see Fig. 6.7).

As the moving interval decreases, from 24 to 12 hours, with WA and the number of laterals held constant, the labor cost per move decreases a little. With this change, the number of sets approximately doubles and the area of each set is reduced by one-half (field size the same). The field dimension parallel to the lateral is fixed (input quantity) so the reduction in the size of a set is accompanied by a proportional change in the width of the set, which is also the distance between sets. For the field sizes of interest here (5 to 10 hectares), this distance goes down by about 40 percent and there is an accompanying reduction in the time required to carry lateral pipe.
The reduction in the size of a set is accomplished by making the nozzle spray diameter half of what it was before, which means that there are more, but smaller, nozzles per lateral and that the lateral pipe is longer and consists of more segments and joints. The length of the lateral pipe is equal to one-half the width of the field minus one-half of the nozzle spray diameter. Here, the length of the lateral and the number of pipe joints that need to be coupled and uncoupled increase by about ten percent. The time spent performing these operations increases accordingly. Given the relatively small field, much more than half of the moving time is spent coupling and uncoupling pipes.

Thus, after the change, carrying pipes takes considerably less time but consumes only about one-third of the total moving time. Coupling and uncoupling pipes takes slightly more time and it accounts for a much larger part of the total moving time. The one-half hour spent going to and from the field is the same. The net result is that the time per move and consequently the cost per move goes down by about ten percent.

Doubling the number of laterals, from one to two, while holding WA and the moving interval constant causes a substantial increase in the cost per move. This is shown in Fig. 6.7 for field sizes between 35 and 40 ha. The cause for the large increase in cost is that with two laterals, the number of pipe joints and the number of pipe fittings has essentially doubled and a large fraction of the moving time is spent coupling and uncoupling pipe joints. There are two laterals rather than one to be moved, but the distance is half, so, in total, the time spent carrying pipe is largely unchanged.

The distance that each of the two lateral pipes needs to be moved is about one-half the distance that the original lateral had to be moved but the length of lateral pipe is about double, so there is more pipe to be carried and there are more joints to be coupled and uncoupled. In fact, for a field of 35 ha, the time spent carrying each of the two-lateral pipes is about 55 percent of the time spent carrying the pipe in the single-lateral case. Thus, the time spent carrying both of the lateral pipes, in the two-lateral case, is 10 percent more than it was before.

The time spent coupling and uncoupling pipes is more for each of the new lateral pipes (two-lateral case) by about five percent for one pipe and as there are two pipes, the increase is about 10 percent over the one-lateral case. However, in the two-lateral case, coupling and uncoupling takes about twice as much time as carrying pipe.

6.4.1.4. Energy Cost per Millimeter Sprinkled. Curves of energy cost per millimeter of water applied vs. field size are shown in Fig. 6.8. Cost decreases with increasing values of WA, independent of field size. Cost also decreases when the moving interval shifts from 24 to 12 hours with WA and the number of laterals held constant and
again when the number of laterals shifts from one to two with WA and the moving interval held constant.

This cost is for electric energy to run the motor that drives the pump and the amount of energy used depends on the size of the motor, the length of time the motor must run per set, and the number of sets. Of course, the energy used per millimeter of water applied is inversely proportional to the amount of water applied, WA. The motor horsepower is proportional to the flow through the pump and the pumping head. Further, the flow through the pump depends on the flow through a nozzle and the number of nozzles.

When the amount of water applied per irrigation, WA, is increased from 20 to 30 mm, the energy cost per millimeter of water sprinkled decreases by about 15 percent. With a 50-percent increase in the amount of water applied per irrigation, there is a comparable increase in the length of the soil moisture cycle and, as the moving interval remains constant, in the number of sets. For a given field size, the increase in the number of sets is accompanied by a decrease in the area per set and, as there is only one lateral, in the area per lateral.

The length of a lateral is fixed at approximately one-half the dimension of the field parallel to the laterals, so the change in the area per lateral must be accomplished by reducing the nozzle spray diameter. A smaller spray diameter means more smaller nozzles, each with a smaller flow rate. With smaller nozzle flow rates, more time is required to apply a given amount of water. In this case, the time is more than doubled. The flow through the pump is also reduced by about one-half and there is a small reduction (about 15 percent) in the pumping head. Less nozzle pressure is required with the reduced spray diameters.

Decreasing the moving interval from 24 to 12 hours while holding WA and the number of laterals constant results in a reduction of about 20 percent in the energy cost per millimeter of water applied. The number of sets doubles, pump flow rate and head pressure are reduced by about 75 and 25 percent respectively, and the time required to apply WA almost doubles.

The amount of water applied and the length of the soil moisture cycle are unchanged, so the reduction in the moving interval necessitates a comparable increase in the number of sets. In fact, the number of sets increases by a factor of two. As field dimensions remain fixed, twice as many sets means that each set has one-half of the area and that the reduction in area is accomplished by using more smaller nozzles--each with about one-half the spary diameter. Smaller nozzles have lower flow rates as well as smaller diameters so the time to apply a given amount of water becomes longer--it almost doubles. Smaller spray diameters mean reduced nozzle pressure and consequently the pumping head goes down by about 25 percent.
Finally, increasing the number of laterals from one to two, while keeping the amount of water applied per irrigation and the moving interval fixed, results in a saving of about 20 percent in the energy cost per millimeter of water applied. The reasoning behind this is much like that for the case where the moving interval was reduced from 24 to 12 hours. With two laterals, each covers one-half of the area, so smaller nozzles, with smaller spray diameters, lower application rates, and longer times to apply a given amount of water are used. Smaller nozzles also mean less pumping head and flow rate. The time to apply WA doubles, the flow rate is down by approximately 50 percent, the pumping head is down by about 20 percent, and the number of sets is unchanged.

6.4.2. Haspel Systems

Having identified all of the least-cost Haspel systems, we obtained the remaining four cost functions by plotting the particular cost against field size for the systems identified by the least-cost envelope. The total investment costs of Haspel systems lying on the least-cost envelopes are shown in Fig. 6.9. The annualized investment costs are shown in Fig. 6.10. The labor costs per move for these systems are shown in Fig. 6.11, and the energy costs per millimeter of water applied are shown in Fig. 6.12.

6.4.2.1. Total Investment Cost. The discussion here applies equally well to investment, shown in Fig. 6.9, and to annualized investment, shown in Fig. 6.10. We observe, first, that investment cost is independent of the amount of water applied per irrigation, WA; second, that increasing field size has almost no effect on investment in configuration H1; and third, that investment cost always jumps when we switch from a Junior or a C-75 to a C-90. Note that in configuration H1, the C-75 is never used.

The amount of water applied, WA, has no effect on investment cost. A system designed to apply 20 mm of water can be used to apply 30 mm simply by reducing the sled velocity. Changing the sled velocity has no effect on the flow rate, head pressure, hose length, etc.--the variables that determine the investment cost.

Increasing field size, up to forty hectares, has almost no effect on the investment required for configuration H1. The only two investment items required in that configuration are the Haspel unit and a tractor pump. The Haspel unit accounts for 90 percent or more of the total investment cost. Most of the cost of the Haspel unit is accounted for by a large fixed component. A small part is due to the hose length and that part varies slightly with the spray width, WS. The spray width is, in turn, determined by the nozzle flow rate, QN, for Haspel types C-75 and C-90 while it is a constant 62 m for the Junior. Increasing the nozzle flow rate and hence the spray width affects the hose lengths of the C-75 and the C-90 by about one percent. It has no effect on the Junior. Thus, for all of the systems, the cost of the Haspel unit changes insignificantly.
The cost of the tractor pump is a function of the flow rate and head pressure. As long as the Haspel is operating at the minimum flow rate, the head pressure does not change and the cost of the pump remains constant. Only when field sizes become so large that it is necessary to use a nozzle flow rate that is greater than the minimum does the cost of the tractor pump increase. This happens at approximately 18 ha for the C-75 and the C-90 and at about 22 ha for the Junior.

The observed increase in investment cost with increase in field size for configurations H2 and H3 is largely due to the use of a main pipe and its accompanying fittings. Moreover, configuration H2 uses a well which also increases in cost with increasing field size. The cost of the Haspel unit and the tractor pump are almost independent of field size (see discussion of configuration H1 above).

The cost of the main pipe is a function of the diameter and the length of the main pipe. The diameter is, in turn, a function of the flow through the pipe, the length of the pipe, and the pressure. The length of the pipe increases with field size. So, as both the length and diameter increase with field size, the cost is doubly affected. It increases because there are more meters of pipe to purchase and also because the pipe has a larger diameter. For example, the cost of the main pipe for the C-90 on a 30 ha field is about 35 percent of the total investment cost. It is less than the cost of the Haspel unit but not by much.

The cost of fittings is proportional to the diameter of the main pipe and the number of sets, which also increases with field size. The cost of the well is also a function of field size. The contribution from fittings and the well is less than half that of the main pipe.

The investment cost jumps when a C-90 substituted for either the Junior or a C-75. The substitution is made when the Junior or the C-75 become infeasible because the 75-percent utilization rate would be exceeded. The jump is due almost entirely to the difference in the costs of the Haspel units when we shift from the Junior or C-75 to the C-90. The C-90 costs some 16 percent more than does the C-75. The C-90 has a larger hose diameter but the same hose length as the C-75. The flow through the two hoses is the same at the point where the switch occurs, so the hose inlet pressure is smaller for the C-90. With a smaller hose inlet pressure, we allow a smaller drop in the main pipe (10 percent of the hose inlet pressure). With the same flow, the diameter of the pipe must be increased to accommodate the smaller pressure drop. The reduced hose inlet pressure and drop in the pipe means that the total pumping head is also less. The smaller pumping head will reduce the cost of the tractor pump while the larger pipe diameter will increase the costs of pipe and fittings.

When we go from the Junior to the C-75, the investment cost increases due to the increased cost of the Haspel unit. However, this increase is partially offset by a decrease in the cost of the main pipe and
fittings. Both the flow rate and the pressure drop through the main pipe are less and the two work in opposite directions. A smaller flow tends to reduce pipe cost and a smaller pressure tends to increase pipe cost. In this instance, the change in flow is the dominant effect.

6.4.2.2. Labor Cost per Move. The labor cost per move shown in Fig. 6.11 has three interesting features. First, the cost per move is independent of WA. Second, the labor cost per move is less for the Junior than for the C-75 and the C-90. Third, field size has almost no effect on the labor cost per move.

The labor cost per move reflects the time per move and consists of three components: time spent moving the hose and reel with the tractor, ten minutes for takedown and setup etc., and one-half hour to travel to and from the field. The only component that can change with the design is the time spent moving the hose and the reel and this time, in turn, varies with the hose length and the spray width.

The amount of water applied per irrigation, WA, has no effect on either the spray width or the hose length, and thus will not affect the cost per move. Increasing field size, for a given Haspel type, will affect the spray width and hose length only when the nozzle flow rate must be increased and, as was discussed in Sec. 6.4.2.1, the effect on spray width and hose length is small. Hence, we see only a very slight indication of increased cost per move. The cost for moving the Junior is noticeably smaller than for moving the C-75 and C-90 because the Junior has a much smaller hose length and hence requires less time per move. The difference in hose lengths results in about a six-percent higher cost per move for the C-75 than for the Junior.

6.4.2.3. Energy Cost per Millimeter Sprinkled. Figure 6.12 shows the energy cost per millimeter of water applied to fields ranging up to 40 ha in size. There are two energy cost curves, one for configuration H1 and the other for configurations H2 and H3. The costs are independent of WA, increase with field size, and drop when the least-cost systems switch to using the C-90.

Energy cost includes only the cost of diesel fuel consumed by the tractor while driving the pump and the amount of fuel consumed depends on the size of the motor, the length of time the pump is in operation per set, and the number of sets. The only variable affected by WA is the sprinkling time per set, and the energy cost of applying the amount WA to the entire field is directly proportional to WA. The energy cost per millimeter sprinkled, obtained by dividing WA into the cost of sprinkling the total WA, is thus independent of WA. Indeed, when we work through all the steps required to relate the energy cost per millimeter to input variables, we find that the cost increases with hose length, nozzle flow rate and size of field, and decreases with hose inside diameter.
When the least-cost systems switch from the Junior to the C-75 (configurations H2 and H3), at around nine hectares, the energy cost decreases slightly, but not enough to show up on the scale used in Fig. 6.12. The C-75 has a longer hose length, but uses a lower nozzle flow rate at the switch point. The net effect is a slight decrease in the fuel consumption and thence the energy cost.

The energy cost increases linearly with field size until the utilization constraint of 75 percent requires the nozzle flow rate to be increased above the minimum. This occurs for field sizes in excess of 18 ha for configurations H2 and H3, and in excess of about 22 ha for configuration H1. As was seen in Fig. 6.4, the required QN increases linearly with field size beyond these points. Energy cost goes up with QN (specifically, as QN**1.9), and the net effect on energy cost of the increasing QN and AF is the noticeable upturn in the energy cost curves.

The energy cost drops when the least-cost system switches to the C-90. When going from the C-75 to the C-90, the nozzle flow rate and hose length remain essentially unchanged, but the C-90 has a larger hose diameter and so the energy cost drops. In changing over from the Junior to the C-90, the nozzle flow rate does not change (it is at the Junior's maximum), but both the hose length and the hose diameter increase. The increased hose diameter reduces the energy cost by more than the hose length can increase the cost. The net result is a drop in energy cost, although the drop is smaller than it was when going from the C-75 to the C-90.

6.5. OBSERVATIONS

Here, we use the least-cost envelopes to compare the costs of using alternative sprinkler system configurations. Each system applies 25 mm of water per irrigation. Given the eight configurations, there are three separate comparisons between the Buis and the Haspel systems because not all of the systems are competitive. Configurations B4, B5, and H2 are used in the highlands when groundwater is available. These configurations are compared in Fig. 6.13. Configurations B1, B3, and H3 are typically for the highlands and use surface water. They are compared in Fig. 6.14. Finally two configurations, B2 and H1, which are strictly for use with surface water in the lowlands, are compared in Fig. 6.15.

While these comparisons are indicative of the least-costly system in each of these three cases, the actual selection, in PAWN, was not made on the basis of cost alone. For example, a Haspel system would not be used to sprinkle bulbs even though it was cheaper than a Buis because its spray would damage the plants. Thus, cost is an important, but not the only, basis for choosing one system over the other.

Looking first at the highlands groundwater configurations (see Fig. 6.13), there are three alternatives—two Buis systems and one Haspel
system. Each system includes a well, a pump, and a main distribution pipe. The Haspel and Buis configuration B5 use a tractor to provide power for the pump. A stationary electric motor is used for this purpose in Buis configuration B4.

Buis configuration B4 costs slightly more than B5 independent of field size and the difference is due almost exclusively to the cost of the electric motor and related control equipment. We do not count the investment in tractors for sprinkling as we assume that their major use is elsewhere on the farm and that their costs should appropriately be charged to these other activities. The costs of all of the systems increase with field size but more rapidly for the Buis configurations than for the Haspel. The Buis is cheaper for small fields and the Haspel is cheaper for large fields. The cost of the Buis and the Haspel are equal when the field size is about 18 ha. A Buis is quite readily tailored to fields of different sizes and the costs reflect this fact. On the other hand, because of the relatively large fixed cost of the hose and reel, the Haspel system cost varies less with field size.

The Buis configurations show almost no economies of scale as the cost per hectare is about the same independent of field size. On the other hand, the Haspel indicates significant economies of scale. At 10 ha, the cost per hectare is about 700 Dfl while at 40 ha it drops to less than 500 Dfl.

The comparison for the highlands with surface water available is shown in Fig. 6.14. Buis configurations B1 and B3 are compared with Haspel configuration H3. These system are identical to the ones described immediately above with the single exception that they do not include a well. Surface water is obtained directly from a nearby ditch. Without the well, these systems have somewhat lower costs but otherwise show the same relationships among themselves.

The two configurations used exclusively for surface water in the lowlands are compared in Fig. 6.15. Buis configuration B2 consists of a single lateral that extracts water directly from a nearby ditch. A tractor-driven pump and a tractor are used to provide pumping power. The Haspel configuration is the same with the Haspel substituted for the lateral pipe. These two configurations reflect the lowest cost systems that we examined.

The Buis is still cheaper for small fields and more expensive for large fields but the difference between it and the Haspel is much less pronounced that it was for the highlands configurations. Furthermore, both systems exhibit significant economies of scale. The Buis has a cost of roughly 400 Dfl per ha at 10 ha and less than 300 Dfl per ha at 40 ha. The Haspel shows even stronger economies of scale with about 450 Dfl per ha at 10 ha and only 225 Dfl per ha at 40 ha. The two systems have equal cost when the field size is about 12 ha.
REFERENCES


Fig. 6.1—Least cost envelope for a typical Buis system (configuration B1)
Fig. 6.2—Annualized total cost function for Buis configuration B1
Fig. 6.3--Annualized total cost functions for Haspels
Fig. 6.4—Moving interval, utilization rate, nozzle flow for least-cost Haspel configuration H2
Fig. 6.5—Investment cost functions for Buis configuration Bl
Fig. 6.6--Annualized investment cost functions for Buis configuration B1
Fig. 6.7--Labor cost functions for Buis configurations B1, B3, B4, and B5
Fig. 6.8—Energy cost functions for Buis configurations B1 and B4.

Energy cost per millimeter of water applied (CSPRIK) (DM)

Area of sprinkled field, AF (ha)

Water applied per irrigation
WA = 20 mm
WA = 25 mm
WA = 30 mm

CONFIG = 4
1.1
1.2
1.2
2.2
2.2

Moving interval, number of laterals
Fig. 6.10—Annualized investment cost functions for Haspels
Fig. 6.11—Labor cost functions for Haspels
Fig. 6.12--Energy cost functions for Haspels
Fig. 6.13—Comparison of Buis and Haspel configurations: groundwater, highlands
Fig. 6.14—Comparison of Buis and Haspel configurations: surface water, highlands
Fig. 6.15—Comparison of Buis and Haspel configurations: surface water, lowlands
Table 6.1

GENERAL INPUTS TO SPRINKLER SYSTEM DESIGN AND COST MODELS
FOR CALCULATING LEAST-COST ENVELOPES

<table>
<thead>
<tr>
<th>Variable Description</th>
<th>Variable</th>
<th>Value</th>
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<tbody>
<tr>
<td>Area of field (ha)</td>
<td>AF</td>
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<tr>
<td>Design evapotranspiration rate (mm/day)</td>
<td>RE</td>
<td>2.5</td>
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<tr>
<td>Total amount of water sprinkled per year (mm)</td>
<td>WSPRIK</td>
<td>90.0</td>
</tr>
<tr>
<td>Amount of water to be applied per irrigation (mm)</td>
<td>WA</td>
<td>20, 25, 30</td>
</tr>
<tr>
<td>System parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkling efficiency</td>
<td>ES</td>
<td>1.0</td>
</tr>
<tr>
<td>Pump efficiency</td>
<td>EP</td>
<td>0.6</td>
</tr>
<tr>
<td>Tractor specific fuel consumption (1/hp-hr)</td>
<td>SFC</td>
<td>0.28</td>
</tr>
<tr>
<td>Allowable pressure drop in main pipe as a fraction of inlet pressure</td>
<td>DELTAM</td>
<td>0.1</td>
</tr>
<tr>
<td>Transit time to and from field (hr)</td>
<td>TKM</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 6.2

FINANCIAL INPUTS TO SPRINKLER SYSTEM COST MODELS
FOR CALCULATING LEAST-COST ENVELOPES

<table>
<thead>
<tr>
<th>Variable Description</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual interest rate (fraction)</td>
<td>INTRST</td>
<td>0.1</td>
</tr>
<tr>
<td>Equipment useful lives (years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler heads</td>
<td>SPKLIF</td>
<td>8.0 (a)</td>
</tr>
<tr>
<td>Lateral pipe</td>
<td>LPLIFE</td>
<td>15.0 (a)</td>
</tr>
<tr>
<td>Main pipe</td>
<td>MPLIFE</td>
<td>15.0</td>
</tr>
<tr>
<td>Fittings</td>
<td>FTGLIF</td>
<td>8.0</td>
</tr>
<tr>
<td>Pump</td>
<td>PUMLIF</td>
<td>15.0</td>
</tr>
<tr>
<td>Motor</td>
<td>MOTLIF</td>
<td>25.0 (a)</td>
</tr>
<tr>
<td>Control equipment</td>
<td>CNTLIF</td>
<td>10.0 (a)</td>
</tr>
<tr>
<td>Well</td>
<td>WELIF</td>
<td>25.0</td>
</tr>
<tr>
<td>Haspel unit</td>
<td>HASLIF</td>
<td>10.0 (b)</td>
</tr>
</tbody>
</table>

SOURCE: Useful lives obtained from Ref. 6.2.

(a) Buis system only.

(b) Haspel systems only.
### Table 6.3
BUIS SYSTEM INPUTS TO SPRINKLER SYSTEM DESIGN AND COST MODELS FOR CALCULATING LEAST-COST ENVELOPES

<table>
<thead>
<tr>
<th>Variable Description</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System configuration</td>
<td>CONFIG</td>
<td>B1, B2, B3, B4, and B5</td>
</tr>
<tr>
<td>Number of laterals</td>
<td>NL</td>
<td>1 or 2</td>
</tr>
<tr>
<td>Moving interval (hr)</td>
<td>M</td>
<td>12, 24, 48, 72, 96, 144</td>
</tr>
<tr>
<td>Fraction of nozzle spray diameter effective along the lateral</td>
<td>CA</td>
<td>0.6</td>
</tr>
<tr>
<td>Fraction of nozzle spray diameter effective normal to the lateral</td>
<td>CB</td>
<td>0.7</td>
</tr>
<tr>
<td>Length of lateral pipe segment (m)</td>
<td>LP</td>
<td>6.0</td>
</tr>
<tr>
<td>Allowable pressure drop in lateral as a fraction of lateral inlet pressure</td>
<td>DELTAL</td>
<td>0.1</td>
</tr>
<tr>
<td>Walking speed when moving lateral (km/hr)</td>
<td>CM</td>
<td>4.5</td>
</tr>
<tr>
<td>Time to couple (uncouple) a pipe joint (hr)</td>
<td>UM</td>
<td>0.017</td>
</tr>
<tr>
<td>Electric motor efficiency</td>
<td>EM</td>
<td>0.7</td>
</tr>
<tr>
<td>Field dimension parallel to lateral pipe (m)</td>
<td>FD</td>
<td>(a)</td>
</tr>
</tbody>
</table>

(a) The value of FD depends on CONFIG and AF (see Sec. 6.1.3).

### Table 6.4
HASPEL SYSTEM INPUTS TO SPRINKLER SYSTEM DESIGN AND COST MODELS FOR CALCULATING LEAST-COST ENVELOPES

<table>
<thead>
<tr>
<th>Variable Description</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System configuration</td>
<td>ICON</td>
<td>H1, H2, and H3</td>
</tr>
<tr>
<td>Type of Haspel unit</td>
<td>I</td>
<td>Junior</td>
</tr>
<tr>
<td>Minimum nozzle flow rate (m³/hr)</td>
<td>QMIN</td>
<td>1</td>
</tr>
<tr>
<td>Maximum nozzle flow rate (m³/hr)</td>
<td>QMAX</td>
<td>30.0</td>
</tr>
<tr>
<td>Nozzle pressure (mww)</td>
<td>PN</td>
<td>65.0</td>
</tr>
<tr>
<td>Hose inside diameter (mm)</td>
<td>DH</td>
<td>61.2</td>
</tr>
<tr>
<td>Field dimension parallel to Haspel hose (m)</td>
<td>FD</td>
<td>200.0</td>
</tr>
</tbody>
</table>
### Table 6.5

COMPARISON OF ALTERNATIVE BUH SYSTEM DESIGNS: CONFIGURATION B1
SHOWING EFFECT OF WA, MOVING INTERVAL, AND NUMBER OF LATERALS

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<thead>
<tr>
<th>System Description</th>
<th>1</th>
<th>1</th>
<th>1</th>
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<tbody>
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<td>Configuration</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>30</td>
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<tr>
<td>Amount of water to be applied per irrigation (mm)</td>
<td>79.2</td>
<td>85.4</td>
<td>105.5</td>
<td>69.6</td>
<td>34.1</td>
</tr>
<tr>
<td>Moving interval (hr)</td>
<td>24</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Number of Buhs laterals</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Field dimensions (m)</td>
<td>223.6</td>
<td>223.6</td>
<td>591.6</td>
<td>591.6</td>
<td>591.6</td>
</tr>
<tr>
<td>Area (ha)</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Field dimension parallel to lateral pipe (m)</td>
<td>223.6</td>
<td>223.6</td>
<td>591.6</td>
<td>591.6</td>
<td>591.6</td>
</tr>
<tr>
<td>Length of field normal to hose (m)</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Number of irrigations</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Design Variables</td>
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<tr>
<td>Feasible system design</td>
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</tr>
<tr>
<td>Water application rate (mm/hr)</td>
<td>9.5</td>
<td>5.1</td>
<td>12.2</td>
<td>8.5</td>
<td>4.6</td>
</tr>
<tr>
<td>Nozzle discharge rate (mC21/hr)</td>
<td>25.1</td>
<td>3.2</td>
<td>57.2</td>
<td>17.4</td>
<td>34.1</td>
</tr>
<tr>
<td>Effective spray width or width (m)</td>
<td>55.4</td>
<td>27.2</td>
<td>73.9</td>
<td>48.7</td>
<td>23.9</td>
</tr>
<tr>
<td>Number of sprinkler heads per lateral</td>
<td>2.3</td>
<td>4.7</td>
<td>4.6</td>
<td>7.0</td>
<td>14.4</td>
</tr>
<tr>
<td>Number of sprinkler heads in system</td>
<td>2.3</td>
<td>4.7</td>
<td>4.6</td>
<td>7.0</td>
<td>28.8</td>
</tr>
<tr>
<td>Pressure at sprinkler head (mC21)</td>
<td>48.1</td>
<td>36.7</td>
<td>53.6</td>
<td>45.8</td>
<td>35.0</td>
</tr>
<tr>
<td>Area covered by one lateral (mC21)</td>
<td>6198.5</td>
<td>3041.2</td>
<td>21861.1</td>
<td>14413.8</td>
<td>14413.8</td>
</tr>
<tr>
<td>Number of sets required</td>
<td>8.0</td>
<td>16.4</td>
<td>16.0</td>
<td>24.2</td>
<td>24.7</td>
</tr>
<tr>
<td>Sprinkling time per set (hr)</td>
<td>2.1</td>
<td>1.6</td>
<td>1.6</td>
<td>3.5</td>
<td>6.6</td>
</tr>
<tr>
<td>Drying time (hr)</td>
<td>192.0</td>
<td>192.0</td>
<td>192.0</td>
<td>268.0</td>
<td>286.0</td>
</tr>
<tr>
<td>Soil moisture cycle time (hr)</td>
<td>194.1</td>
<td>195.9</td>
<td>193.6</td>
<td>291.5</td>
<td>294.6</td>
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<tr>
<td>Size of system components</td>
<td></td>
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</tr>
<tr>
<td>Length of a lateral pipe (m)</td>
<td>88.0</td>
<td>100.1</td>
<td>264.1</td>
<td>274.9</td>
<td>285.5</td>
</tr>
<tr>
<td>Flow through lateral pipe (mC21/hr)</td>
<td>59.2</td>
<td>15.7</td>
<td>267.3</td>
<td>123.3</td>
<td>123.3</td>
</tr>
<tr>
<td>Inside diameter of lateral pipe (mm)</td>
<td>92.5</td>
<td>60.6</td>
<td>200.0</td>
<td>155.0</td>
<td>99.7</td>
</tr>
<tr>
<td>Pressure at inlet to lateral pipe (mC21)</td>
<td>53.4</td>
<td>40.8</td>
<td>59.6</td>
<td>50.9</td>
<td>38.9</td>
</tr>
<tr>
<td>Length of main pipe (m)</td>
<td>195.8</td>
<td>210.7</td>
<td>544.6</td>
<td>567.2</td>
<td>579.6</td>
</tr>
<tr>
<td>Flow through main pipe (mC21/hr)</td>
<td>59.2</td>
<td>15.7</td>
<td>267.3</td>
<td>23.3</td>
<td>23.3</td>
</tr>
<tr>
<td>Inside diameter of main pipe (mm)</td>
<td>106.3</td>
<td>68.8</td>
<td>227.1</td>
<td>175.5</td>
<td>146.4</td>
</tr>
<tr>
<td>Pressure at inlet to main pipe (mC21)</td>
<td>59.4</td>
<td>45.4</td>
<td>66.2</td>
<td>56.5</td>
<td>43.2</td>
</tr>
<tr>
<td>Number of toes</td>
<td>8.0</td>
<td>16.4</td>
<td>16.0</td>
<td>24.2</td>
<td>49.4</td>
</tr>
<tr>
<td>Number of end plugs</td>
<td>9.0</td>
<td>17.4</td>
<td>17.0</td>
<td>25.2</td>
<td>51.4</td>
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<tr>
<td>Labor, power, and energy requirements</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Transit time to and from field (hr)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Time for one man to move lateral (hr)</td>
<td>0.862</td>
<td>0.784</td>
<td>2.965</td>
<td>5.85</td>
<td>2.180</td>
</tr>
<tr>
<td>Number of men required to move one lateral</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Time to move one lateral (hr)</td>
<td>0.862</td>
<td>0.784</td>
<td>2.965</td>
<td>5.85</td>
<td>2.180</td>
</tr>
<tr>
<td>System idle time (hrs)</td>
<td>21.0</td>
<td>7.2</td>
<td>7.3</td>
<td>5.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Time moving equip. per man per irrig. (hr)</td>
<td>10.9</td>
<td>21.1</td>
<td>55.4</td>
<td>74.9</td>
<td>120.2</td>
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<tr>
<td>Motor horsepower (metric)</td>
<td>21.7</td>
<td>4.4</td>
<td>109.2</td>
<td>43.0</td>
<td>17.5</td>
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<tr>
<td>Electricity per irrigation (kwh)</td>
<td>389.8</td>
<td>300.8</td>
<td>3034.3</td>
<td>3904.2</td>
<td>3016.0</td>
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</table>
Table 6.5 (continued)

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<tr>
<th>System Description</th>
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<tbody>
<tr>
<td><strong>Configuration</strong></td>
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</tr>
<tr>
<td>Amount of water to be applied</td>
<td>20</td>
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<td>20</td>
<td>30</td>
<td>30</td>
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<tr>
<td>per irrigation (mm)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Moving interval (hr)</td>
<td>24</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Number of Buis laterals</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Field dimensions (m)</td>
<td>5</td>
<td>5</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Area (ha)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field dimension parallel to lateral pipe (m)</td>
<td>223.6</td>
<td>223.6</td>
<td>591.6</td>
<td>591.6</td>
<td>591.6</td>
</tr>
<tr>
<td>Length of field normal to hose (m)</td>
<td>223.6</td>
<td>223.6</td>
<td>591.6</td>
<td>591.6</td>
<td>591.6</td>
</tr>
<tr>
<td>Number of irrigations</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>3.0</td>
<td>3.0</td>
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<tr>
<td><strong>Sprinkler System Costs</strong></td>
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<td></td>
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<tr>
<td>Investment costs (DFl)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>Sprinkler heads</strong></td>
<td>1300.2</td>
<td>540.6</td>
<td>7295.4</td>
<td>2682.3</td>
<td>2704.3</td>
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<tr>
<td>Lateral pipes</td>
<td>1484.9</td>
<td>1010.1</td>
<td>25136.4</td>
<td>12687.9</td>
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<tr>
<td>Main distribution pipe</td>
<td>4125.0</td>
<td>2977.7</td>
<td>81734.8</td>
<td>36794.9</td>
<td>23280.4</td>
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<tr>
<td>Fittings</td>
<td>1399.0</td>
<td>1565.1</td>
<td>6475.9</td>
<td>7163.3</td>
<td>11303.6</td>
</tr>
<tr>
<td>Electric motor driven pump</td>
<td>1377.2</td>
<td>1047.7</td>
<td>5492.4</td>
<td>1930.0</td>
<td>1289.3</td>
</tr>
<tr>
<td>Electric motor</td>
<td>2233.5</td>
<td>856.0</td>
<td>7066.3</td>
<td>3412.6</td>
<td>3003.2</td>
</tr>
<tr>
<td>Control equipment for electric motor</td>
<td>472.7</td>
<td>359.6</td>
<td>1885.4</td>
<td>662.5</td>
<td>442.6</td>
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<tr>
<td>Total investment cost (excluding BTW)</td>
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<td>7797.2</td>
<td>135086.7</td>
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<td>Total investment cost (including BTW)</td>
<td>12794.9</td>
<td>8109.1</td>
<td>140490.1</td>
<td>67515.0</td>
<td>53913.4</td>
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<tr>
<td><strong>Annual operating costs (DFl)</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Labor</strong></td>
<td>914.8</td>
<td>1756.8</td>
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<tr>
<td><strong>Electricity</strong></td>
<td>140.3</td>
<td>108.3</td>
<td>1092.3</td>
<td>937.0</td>
<td>723.8</td>
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<tr>
<td><strong>Sprinkler system maintenance</strong></td>
<td>430.6</td>
<td>272.9</td>
<td>4728.0</td>
<td>2272.1</td>
<td>1814.3</td>
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<td><strong>Total annual operating cost</strong></td>
<td>1485.8</td>
<td>2138.0</td>
<td>10439.2</td>
<td>7366.6</td>
<td>9213.2</td>
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<td><strong>Annualized investment costs (DFl)</strong></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Sprinkler heads</strong></td>
<td>243.7</td>
<td>101.3</td>
<td>1367.4</td>
<td>502.7</td>
<td>506.9</td>
</tr>
<tr>
<td>Lateral pipes</td>
<td>195.2</td>
<td>132.8</td>
<td>3304.7</td>
<td>1663.1</td>
<td>1422.0</td>
</tr>
<tr>
<td>Main distribution pipe</td>
<td>542.3</td>
<td>317.8</td>
<td>10746.0</td>
<td>4782.9</td>
<td>3060.7</td>
</tr>
<tr>
<td>Fittings</td>
<td>295.3</td>
<td>293.3</td>
<td>1213.8</td>
<td>1342.7</td>
<td>2118.8</td>
</tr>
<tr>
<td>Electric motor-driven pump</td>
<td>181.0</td>
<td>137.7</td>
<td>722.1</td>
<td>253.7</td>
<td>169.5</td>
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<tr>
<td>Electric motor</td>
<td>246.0</td>
<td>94.3</td>
<td>778.4</td>
<td>375.9</td>
<td>220.6</td>
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<tr>
<td>Control equipment for electric motor</td>
<td>76.9</td>
<td>58.5</td>
<td>306.8</td>
<td>107.8</td>
<td>72.0</td>
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<tr>
<td>Total annualized investment (excluding BTW)</td>
<td>1730.7</td>
<td>1136.0</td>
<td>18439.6</td>
<td>9034.1</td>
<td>7570.7</td>
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<td>Excluding BTW</td>
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Chapter 7
THE SPRINKLER SYSTEM ALLOCATION AND COST MODEL

7.1. INTRODUCTION

The PAWN agricultural analysis focused on the costs and benefits to agriculture of changes in the water management of the Netherlands. One of the most important changes has to do with expansion of sprinkling capacity. The associated costs depend on many factors, including crop type, source of water, amount of water sprinkled and the size of the field to be sprinkled. A realistic estimate of sprinkling cost should take all of the above factors into account. However, the amount of detail required to do this is beyond the capability of the PAWN agricultural models.

Therefore, estimating sprinkling cost has been done in two steps: first, the Sprinkler System Allocation and Cost Model (SSACM) considers many of the details explicitly to prepare average sprinkling cost factors; second, these average cost factors are used in other PAWN models. When the sprinkler scenario changes, the cost factors are reestimated.

Most PAWN analyses were performed for plots, where a plot is a unique combination of a crop type, a soil type and, if sprinkled, a source of sprinkling water, within an agricultural district. SSACM creates an output data set arranged in such a way that each plot can be associated with a single set of SSACM outputs.

7.2. OVERVIEW AND APPLICATIONS

7.2.1. Overview

The SSACM estimates sprinkling cost factors for eleven crop types in each of fourteen agricultural regions for at most three sprinkling situations. A sprinkling situation is characterized by landform and/or source of sprinkling water. The landforms are highlands and lowlands and water sources are surface water and groundwater. Three situations are distinguished, i.e., surface water sprinkling in lowlands, surface water sprinkling in highlands, and sprinkling from groundwater (both lowlands and highlands).

An important factor in determining the cost of sprinkling is the size of the sprinkled field. We define a field size as the area that will be (potentially) sprinkled on a given farm. Farm type and structure may vary widely across the country. Since the relevant statistical information was only available for fourteen different agricultural regions, these became a main dimension for the SSACM. Based on the information by agricultural region, we derived a field size distribution for each crop type that was represented by a discrete distribution in five field size classes.
In performing these computations, the SSACM carries out the following steps:

1. Read input data.
2. Allocate sprinkled area across field size classes.
3. Allocate sprinkler systems to field size classes.
4. Compute weighted averages of relevant cost data.
5. Write output files.

In step 1, the SSACM reads its input files. In principle, there are six different input files with various dimensions. Most of them contain specific information by crop, region, field size class, or a mixture of these elements. Section 7.3.1 contains a more detailed description of these input files. The way the actual input data were obtained is described in Sec. 7.4.

In step 2, the sprinkled area by crop and region is allocated to field size classes so that the sum of the sprinkled areas within each field size class equals the total sprinkled area for the crop in the region. In the allocation procedure, a number of factors are taken into account.

- The relative likelihood that a farmer will sprinkle his field, as a function of crop type and field size to be sprinkled.
- A reduced (actually sprinkled) field size base on the potentially sprinkled field size on a farm. The reduction is due to practical constraints, e.g., parceling structure or unfavorably shaped fields.
- Accessibility to surface water and/or groundwater in the region considered.

The allocation takes place for surface water and groundwater sprinkled areas separately. The sprinkled areas are input data. A more detailed description of this part of the SSACM and the underlying assumptions is given in Sec. 7.5.1.

Given the field size class, the crop type, the landform and the water source, in step 3 a sprinkler system configuration is selected on a cost comparison of feasible alternatives. Either one or a mixture of two sprinkler system configurations is associated with each field size class. As a result of this allocation, all relevant sprinkling cost information is known within each field
size class. The allocation procedure is explained in more detail in Sec. 7.5.2.

In step 4, the SSACM compute weighted average sprinkling cost factors by crop and region. These are obtained by averaging the cost data across field size classes, using the sprinkled areas in each field size class as weights. This step is further described in Sec. 7.5.3.

Finally, step 5 produces output files to be used in other PAWN models. These files contain information about the fixed and variable (labor and energy) costs of sprinkling on a per hectare basis. The outputs are described more explicitly in Secs. 7.3.2 and 7.5.3.

7.2.2. Model Applications

We used SSACM to compute sprinkling cost factors that reflected actual sprinkling in 1976. These factors were used by the District Hydrologic and Agriculture Model (see Vol. XII).

The SSACM was also used to support an analysis to determine optimal sprinkler intensities (see Vol. XIV). The optimal sprinkler intensity is the sprinkled area where marginal sprinkling costs and benefits are equal. The SSACM computed average sprinkling cost factors as a function of the amount of sprinkled area. Sprinkled area was varied, in equal increments, from zero to the maximum area that could be sprinkled. The cost factors were used to determine sprinkling cost as a function of area sprinkled. Benefits were estimated with the District Hydrologic and Agriculture Model (see Vol. XII).

In PAWN, the SSACM was generally used with the Distribution Model (see Vol. XI). Since the sprinkling cost factors depend on the amount of sprinkled area, the SSACM had to be rerun each time a different sprinkler scenario was specified. The SSACM obtained sprinkled areas from the plot file---one file for each scenario---and prepared sprinkling cost factors that were valid for the specified scenario. It produced sprinkling cost factors for labor and energy and for annual fixed cost---annualized investment plus annual maintenance cost.

7.3. INPUTS AND OUTPUTS

The SSACM inputs and outputs are presented in Tables 7.1 and 7.2.

7.3.1. Inputs

The SSACM uses six input files: the sprinkler system parameter file, the field data file, the crop data file, the region data file, the
crop and region data file, and the miscellaneous parameters file. Each of these is discussed below.

The sprinkler system parameter file contains the cost functions for the least-cost sprinkler systems (see Chap. 6). These are used to estimate annualized total cost, ANOTOB, total investment, TOTINB, annualized investment, ANINV, energy cost per irrigation, CSPRIK, labor cost per move, CMOVE, moving interval, MOVINT, and number of sets, NSET, as a function of field size. A different set of functions is included for each of the eight sprinkler system configurations assuming each of three GIFTs—20, 25, and 30 mm.

The field data file contains information about the field size distributions. There are 770 records—14 agricultural regions, 11 crop types, and 5 field size classes—in this file. The data elements are the average field size and the number of fields in each field size class. Field size is used in the assignment of sprinkler systems to field size classes. The notion is that the field sizes are representative for the selection of sprinkler systems for the crops under consideration. Because, on many farms, one sprinkler system may be purchased to sprinkle more than one crop, these field sizes are typically larger than the actual planted area for each individual crop.

The crop data file contains two kinds of data for each crop type. First, there are five parameters, W1 through W5, defining a sprinkling likelihood function that is used to estimate the relative likelihood of a field to be sprinkled given the field size. Second, it contains the parameter, GAMMA, which specifies the size of the field where a change in the mix of alternate BuIs systems occurs. Fields smaller than GAMMA are considered "small" fields and fields equal to or larger than GAMMA are considered "big" fields.

The region data file contains one data element for each region, the fraction of the area having access to surface water (SUPFRAC).

The crop and region data file contains data that depend on both crop and region. These are: area sprinkled from surface water, TOTASW, area sprinkled from groundwater, TOTAGW, amount of water applied per irrigation, GIFT, parameters that express the actually sprinkled field size as a function of potentially sprinkled field size, MAREA and BETA, and a factor to adjust the area in the field data file so that it reflects the area actually devoted to the crop (PROP).

The miscellaneous parameters file contains data that are independent of crop type, region, and field size class. There are 12 fractions, SFRAC1 through SFRAC6 and BFRAC1 through BFRAC6, that specify the mix of alternative Buis systems to assign given the crop type, field size (small or big), and the sprinkling situation. A second data element is the variable CRITAR, which specifies the minimum field size above which a Haspel system is always chosen. The sprinkling efficiency, EFF, which indicates the fraction of the total amount of water
sprinkled that effectively enters the root zone, is also included in this file. Finally, this file contains the variables specify the range for sprinkled areas considered, for the analysis to determine optimal sprinkler intensities (see Sec. 7.2.2).

7.3.2. Outputs

The main results produced by the SSACM are the fixed and variable cost factors of sprinkling by crop, region and sprinkling situation. The fixed annual cost, ANCAP, consists of annualized investment and annual maintenance cost and is reported in Dutch guilders (Dfl) per hectare (ha). The variable cost factors, ENERGY and LABOR, give the average cost of sprinkling one millimeter of water on one hectare. Given the area sprinkled in hectares and the annual amount sprinkled in millimeters, the total annual costs of sprinkling a plot can be computed using these cost factors. Moreover, the variable costs of sprinkling can be computed for any timestep separately if the amount sprinkled during the timestep is known.

The variable AVSIZE gives an impression of the average areas sprinkled with a single sprinkler system. It was also used to select representative systems and areas for the analysis of sprinkling policies (see Chap. 8). The variable ANCOST approximates the total annual cost of sprinkling in an average year. It is based on a fixed total annual gift of 90 mm, which is about the right order of magnitude for an average year. This variable provides an estimate of the total cost of sprinkling in a more or less ordinary year. The variable INVEST provides insight into the total investment required per hectare.

7.4. ORGANIZING THE DATA

An extensive data base was prepared to support the development of the SSACM. Data were classified according to 14 agricultural regions, 11 crop types, and 5 different field sizes.

The fourteen regions reflect the way available statistical data about farms, crops, and planted areas (field sizes) were classified. Eleven different crop types were considered in an attempt to account for a significant amount of the variation in observed sprinkling cost. Typically, different kinds of sprinkler systems are used for different size fields and average field sizes and field size distributions differ by crop. Moreover, some crops are much more likely to be sprinkled than are others.

The six input files and the variables they contain are listed Table 7.1.

The data elements contained in the sprinkler system parameter file pertain to least-cost sprinkler systems, and were based on design and cost model outputs (see Chap. 6).
The field data file contains information on field size distributions by crop and region. Three different steps were involved in creating this file:

1. Associating crop types with representative farm types;
2. Determining relative farm size distributions for representative farm sizes;
3. Computing average field sizes by field size class, crop, and region.

These steps will be described in Secs. 7.4.1 through 7.4.3.

The crop data file contains the parameters specifying the sprinkling likelihood functions that will be described in Sec. 7.4.4. Moreover, it contains the criterion GAMMA that is used in the selection of sprinkler systems to decide whether we deal with "big" fields or "small" fields. Big fields are larger than the specified criterion and small fields are smaller than or equal to the criterion. Different areas (criteria) were specified by crop type. Based on our own judgement, we set GAMMA equal to five hectares for grass and arable crops (potatoes, sugar beets, cereals, cut corn, and grains). Horticulture crops (vegetables, bulbs, fruit, and trees) are typically found on smaller fields. For bulbs and vegetables, we set GAMMA equal to two hectares. For the somewhat larger fields of pit and stone fruit, we set it to three hectares, and for the very small tree farms, we used one hectare.

The region data file contains a single data element, i.e., the area having access to surface water, expressed as a fraction of the total area of the region. This variable called SUPFRAC was obtained from the agricultural data base (see Volume XII), which contains information on the area having access to surface water for PAWN subdistricts. The SUPFRAC by region were obtained by aggregating the information for the subdistricts in the region. SUPFRAC applies to surface water accessibility only. Although certain parts of the country have no access to fresh groundwater, no specific constraints on groundwater accessibility were used in the model. Since all parts that cannot be sprinkled from groundwater generally have access to surface water, it was simply assumed that groundwater sprinkling takes place on those parts that do not have access to surface water.

The crop and region data file contains the sprinkled areas from surface water and groundwater, the amount sprinkled per irrigation (the "gift"), two parameters to express the area actually sprinkled as a function of potentially sprinkled area (field size reduction function), and the crop area fraction.
Sprinkled areas for the current situation are based on an inquiry about the sprinkling situation in 1976 (Ref. 7.1). For future situations, sprinkled areas were specified as scenarios. The specification of the "gift" resulted from the analysis of sprinkling policies described in Chap. 8. The field size reduction function will be described in Sec. 7.4.5.

The crop area fraction PROP is used to adjust the area in the field data file so that it reflects the area actually devoted to individual crops. The total area contained in the field size classes by crop and region reflects the sum of the areas of potentially sprinkled fields. This area is larger than the area of the actual crop in the region for which the field size classes are valid because the potentially sprinkled field includes other crop areas on the same farm that may also be sprinkled. Given the field size classes (see Sec. 7.4.3) and the actual crop areas by region (from statistical information of the Netherland's Central Bureau of Statistics, CBS), the values for PROP could be computed directly.

The miscellaneous parameters file contains the sprinkler system assignment parameters (SFRAC1 through SFRAC6, BFRAC1 through BFRAC6, and CRITAR). Section 7.4.6 describes how these were obtained. Moreover, this file contains the sprinkling efficiency factor EFF indicating what fraction of sprinkled water effectively reaches the root zone (the remainder evaporates or immediately leaves the root zone, e.g., because of cracks in the soil). Based on information supplied by Baars (Ref. 7.4) we set it equal to 0.85.

### 7.4.1. Representative Farm Types for Crop Types

Data about farm size distributions were based on statistical information of the CBS for the year 1976. Within four main categories, i.e., cattle farms, arable farms, horticulture farms, and combined farms, the CBS statistics distinguish 37 different farm types. In order to make some estimate of a representative field size distribution by crop type, each crop type had to be associated with one or more of the specific farm types.

The primary selection criterion was that the farm type be considered representative of the circumstances under which the crop is grown. In general, however, each farm as a mix of different crops. When we selected one or more representative farm types for a given crop, these farm types will only cover part of the total crop area, unless we select a large subset of the farm types as the representative group. By that time we will have lost most of the specific information for that crop. The other consequence is that there is a certain area on the representative farm type that is not devoted to the crop for which it was selected as representative. Depending on the other crops on the representative farm, part or all of the remaining area should also be considered for sprinkling.
Table 7.3 gives a description of each crop type, the farm type selected as representative for that crop type, and two percentages. One percentage indicates the part of the crop type actually found on the representative farms and the other reflects the part of the area, on the representative farms, that is devoted to the crop type. The clearest cases exist for grass, bulbs, pit and stone fruit, and trees, where both percentages are high. The worst situation exists where the first percentage is low—the farm type includes but a small part of the area devoted to the crop. This is the case for vegetables where only 39 percent of the crop is on the representative farms. The rest of the area devoted to this crop is distributed over almost all of the other farm types.

The relevant CBS statistics do not distinguish among the three different kinds of potatoes and sugar beets, but treat them as one group. The representative farm type selected is the group of arable farms, which is also representative for cereals. More than two-thirds of the area devoted to potatoes, sugar beets, and cereals is on arable farms, and 80 percent of the area on arable farms is devoted to these crops.

Cut corn is generally found on cattle farms but it accounts for only a small fraction of the total area on these farms. As most of the area is devoted to grass, grass area characteristics have been assumed for cut corn.

7.4.2. Relative Farm Size Distributions for Representative Farms

For each of the farm types used by CBS, a distribution of farm areas is given by region. This is done by defining ten area classes and by indicating how many farms fall into each class. We have transformed this information into a set of relative farm size distribution curves. The advantage of such a curve is that in itself, it is independent of actual farm sizes and number of farms, so that it can be applied more generally.

A typical relative farm size distribution is shown in Fig. 7.1. The number of farms, in order of increasing size, is plotted as a fraction of the total number of farms, on the horizontal axis. The area belonging to these farms, as a percentage of the total area, is plotted on the vertical axis. As indicated, X percent of the smallest farms contain Y percent of the total area. Most of the area is found on large farms. The less uniform the distribution of area among farms, the more the curve will deviate from a 45-degree straight line.

Since we decided to use grass as a proxy for cut corn, we needed distributions for only six of the seven representative farm types shown in Table 7.3. The CBS, Table 701A, provided data from which farm size distributions could be obtained for each of these farm types in each of 14 regions. We found, however, that the relative distributions were essentially the same for all regions, so we used
distributions based on data for the entire Netherlands. The six relative farm size distribution are presented in Figs. 7.2 through 7.7. While the same relative distribution is used independent of region, applying region specific numbers of farms and total areas effectively results in a different distribution for each region.

7.4.3. Average Field Size by Field Size Class, Crop, and Region

We used average field sizes for each class, crop, and region to determine the characteristics of sprinkling systems for sprinkling fields. We used the six relative field size distributions, together with the total area and number of farms (fields) by representative farm type and region, from the CBS data, to calculate an average field size for each field size class for each crop in each region.

Determining the number of farms to assign to each of the six representative farm groups and deciding exactly what area to use for the crops was not straightforward. We obtained the number of representative farms, for each crop type in each region (see Table 7.3), directly from CBS data (Table 701A). Problems arose with determining the number of farms representative for vegetables and for the various arable crops. The representative farm type for vegetables accounts for only 39 percent of the total vegetable area. As vegetables are found on almost all farms, there was little that we could do other than use data on the representative farms selected. As for the arable farms, the data did not distinguish among the three kinds of potatoes and sugar beets. As a result, we were not able to come up with separate field size distributions for these crops. Given the nature of these crop types, there is little reason to believe that the individual distributions would have been very different.

In determining the representative area to be used for the various crops, we needed to define what this area was to represent. Although the relative farm size distributions were based on total farm area, we do not want to consider total farm area here. Instead, we are interested in the distribution of potentially sprinkled fields, since they determine the characteristics of the sprinkler systems to be used. The potentially sprinkled area on a farm is the total area planted with crops for which sprinkling may be worthwhile. For the farm type considered, we know how total area is broken down across crop types (CBS Tables 202, 301, and 401A).

Based on more general insights about the practice of sprinkling (Ref. 7.2), we assume that all crops are potentially sprinkled, except cereals, cut corn, and sugar beets (if not on sand soils). Table 7.4 summarizes the rules for determining potentially sprinkled areas under these assumptions.

More than 90 percent of the area of dairy farms is devoted to grass. The remaining area is mostly cut corn and some other arable crops. Hence, the grass area is a reasonable approximation of potentially sprinkled area. Since on bulb farms, pit and stone fruit farms and
tree farms hardly any area is devoted to the nonsprinkled arable crops, the total farm area is considered to be potentially sprinkled. On vegetable farms there are some arable crops, so 90 percent of total farm area was used here. For the arable farms, the potentially sprinkled area was taken as the total area less that devoted to cereals and cut corn on sandy soils and on non-sandy soils we took the total area less that devoted to cereals, cut corn, and sugar beets.

Although in determining the potentially sprinkled areas to compute the average field sizes, we assumed that some crops would not be sprinkled, these crops were not excluded from sprinkling. When cut corn is sprinkled, sprinkling cost factors are computed using the field size characteristics for grass, excluding the sprinkled area of cut corn. When cereals and sugar beets are sprinkled, we use the field size distribution for potatoes. As long as sprinkled areas of these crops are small (which they are likely to be), this does not introduce serious mistakes.

Computationally, the procedure was simple. Since we chose to reflect the field size distribution by five field size classes, one-fifth of the fields were assumed to be in each field size class. The fraction of the total area in each class was obtained from the relative farm size distributions. Knowing the total area and number of fields in each size class, the average field sizes were computed by dividing the areas in the classes by the number of fields in the classes.

An important assumption underlies this procedure. Since the distribution curves were based on total farm size and they were applied to potentially sprinkled areas only, the assumption is that the same relative distribution holds for the potentially sprinkled parts of the representative farms as for the total farms. In most cases the potentially sprinkled area is the greater part of the total farm area (sometimes it is equal to the total area), so this seems to be a reasonable assumption. Yet it is for this reason that we prefer to speak about a (potentially sprinkled) field size distribution rather than a farm size distribution.

Number of farms and potentially sprinkled areas by farm type and region are summarized in Table 7.5. For arable farms the information is given for potatoes only. Given the assumptions made, the resulting distribution of potentially sprinkled field sizes is valid for all arable crops. Table 7.6 gives an example of a field size distribution for grass in each of the 14 regions.

7.4.4. Sprinkling Likelihood Functions

The parameters describing the likelihood function were based on statistical information of CBS (Ref. 7.3). The information includes the percentage of farms having a sprinkler system as a function of total farm area (for this purpose eight farm size classes were distinguished). We plotted this information for our representative farm types (see Figs. 7.8 through 7.13). The relation between the
percentage of farms sprinkled and the size of the farm can be approximated by two straight lines. For tree farms, a single horizontal line is sufficient. For most other farm types, the percentage tends to increase with farm size up to a point and then stabilizes. Only in the case of vegetable farms does the percentage start to decrease above a certain farm size. Presumably, large vegetable farms grow vegetables that are less valuable or less drought sensitive than the those grown on smaller farms.

Each of the curves can be described with five parameters, i.e., the intercepts and slopes of the two straight lines and the farm size where the two lines intersect. These parameters are denoted W1 through W5, where W1 and W2 give the intercept and slope of the first linear segment, W4 and W5 give the intercept and slope of the second linear segment, and W3 is the farm size at their intersection.

In the SSACM, these functions were used to compute a relative likelihood that a field would be sprinkled as a function of its potentially sprinkled area. These likelihoods served as weights when allocating sprinkled area to field size classes. The functions are based on total farm size rather than potentially sprinkled area. For all but arable farms, the potentially sprinkled area is close to the total farm area, so we used the functions uncorrected. For arable farms, we assumed that the potentially sprinkled area was, on the average, one-third of the total area, and evaluated the function at three times the potentially sprinkled area.

7.4.5. Field Size Reduction Functions

The field sizes associated with each field size class are potentially sprinkled areas. The potentially sprinkled area on a farm may be scattered in a number of separated parcels of land, with each at some distance from the others. Moreover, parcels may be unfavorably shaped so that some parts are less accessible for the sprinkling equipment. For these reasons, farmers would be expected, in general, not to sprinkle all of the potential area. From Ref. 7.1, the area actually sprinkled, as a percentage of total area on farms that have a sprinkler system available, is around 70 percent for both cattle farms and horticulture farms and a little less than 40 percent for arable farms. These percentages account for an area less than that planted with crops worth sprinkling, and so we conclude that not all of the potentially sprinkled area is sprinkled.

We assumed that the actually sprinkled area on a farm is a function of the potentially sprinkled area. We also assumed that the function differs by region and crop since the structure of farms (number and average size of parcels) varies considerably by region and crop. The relation between actually and potentially sprinkled area was expressed as a simple linear function. If the potentially sprinkled area, PSA, does not exceed a certain maximum area, MAREA, the actually sprinkled area, ASA, equals the potentially sprinkled area.
Of the part of PSA in excess of MAREA, only a fraction, BETA, gets sprinkled. This function, consisting of two linear segments, is described by the two parameters, MAREA and BETA, as shown in Fig. 7.14.

From Ref. 7.3, the number of parcels per farm varies considerably across regions. Region 2, Holland and the IJssellake polders, has an average of less than two parcels per farm, the average parcel area being around 15 hectares. On the other hand, Region 5, the Loess area, has an average of ten parcels per farm with an average parcel area of about 2 ha. All the other regions are somewhere in between. We divided the 14 regions into five groups. The two extreme regions, see above, each make up separate groups--Region 2 being very favorable and Region 5 very unfavorable. The other 12 regions make up the remaining three groups ranging from favorable to moderate to less favorable with respect to parceling structure.

The differences across crops come about because crops are associated with different farm types. While parcels of 5 to 10 ha are relatively common on arable farms, they are larger than those usually found on bulb farms. Based on the parceling characteristics of representative farm types, we created four groups of crop types, i.e., grass and cut corn, arable crops, bulbs and trees, vegetables and fruits. We then determined values of MAREA and BETA for each of the 20 combinations of region group and crop group. The values obtained are shown in Table 7.7.

The values for MAREA were selected based on estimates of average parcel areas by crop and region using information from Ref. 7.3. Estimates for BETA reflect our judgments about the effects of parceling structure and crop value on the fraction of the area that would be sprinkled. The results obtained using these estimates in SSACM agree with overall estimates for cattle, horticulture, and arable farms from Ref. 7.1.

7.4.6. Sprinkler System Assignment Parameters

The sprinkler assignment parameters are CRITAR, BFRAC1 through BFRAC6, and SFRAC1 through SFRAC6. Different sprinkler systems may be assigned in the lowlands and in the highlands and to sprinkling with groundwater as opposed to surface water (resulting in three sprinkling situations, see Sec. 7.2.1). We considered a total of eight sprinkler system configurations (see Chap. 1) and at most, three were candidates in any one of these situations. Each set of candidates consisted of two Buis and one Haspel systems.

The sprinkling situation defines the feasible alternative sprinkling systems. In the lowlands, it can be assumed that ditches are all around at distances of, at most, a few hundred meters. Hence, a distribution pipe will not be necessary, unless a fixed motor is used. Feasible systems are B1, B2, and H1 (see Fig. 1.1). In the highlands, the access to surface water generally is less flexible
than in the lowlands and a main distribution pipe is required. Feasible systems are B1, B3, and H3. In the third situation, groundwater is used and a well and a main distribution pipe are needed. Feasible systems are B4, B5, and H2.

The choice between Buis and Haspel is sometimes dictated by the sprinkled area. In principle, the choice between Haspel and Buis is based strictly on a cost comparison. However, for bigger areas, the Buis system becomes less attractive because of the large amount of labor involved. For this reason, an area criterion (CRITAR) was used to ensure that a Haspel system is chosen for fields that exceed a certain size. The criterion was set at 15 ha.

If the Haspel is not selected, then a mix of two Buis systems is used. The only difference between the alternative Buis systems is whether a tractor or a fixed motor is used to drive the pump and the choice depends on crop type, field size and sprinkling situation. On horticulture farms, the presence of a tractor is much less likely than on arable farms. A small farm is less likely to have a tractor available for sprinkling. Moreover, a fixed motor is less appropriate as the field gets bigger. The fixed motor is more likely to be used with a well than with the lowlands ditch system.

The relative mix of the two Buis systems is computed using one of 12 fractions contained in the miscellaneous parameters file. There are six fractions for "big" fields and six fractions for "small" fields. Big fields are larger than a specified area, and small fields are smaller than or equal to this area. The specified area, reflected by the variable GAMMA, is contained in the crop data file.

The fractions indicate the relative amount used of the system with a fixed motor. The estimates for these fractions reflect the notion that a fixed motor is more likely for smaller fields, for horticulture crops and for groundwater sprinkling (see Table 7.8).

7.5. MODEL DESCRIPTION

7.5.1. Allocating Sprinkled Area to Field Size Classes

The allocation of sprinkled area to field size classes is done proportionally to the average field size for each class. In addition, three things are taken into account: a relative likelihood of a certain field to be sprinkled depending on crop type and field size; the fact that a potentially sprinkled area may not be fully sprinkled in reality because of practical constraints (parceling structure, unfavorably shaped fields); and accessibility to surface water/groundwater.

The following computations are made for each crop in each region. First, compute the relative likelihood that a field of a given size will be sprinkled. This will be used as a weight in the allocation.
\[ W(i) = F_1(F_S(i)) \]  \hspace{1cm} (7.1) \\

where \( i \) = field size class index \((i=1,5)\), 
\( W(i) \) = relative likelihood that field of size \( F_S(i) \) will be sprinkled, 
\( F_S(i) \) = average field size in class \( i \), 
\( F_1 \) = relative likelihood function (depending on crop type).

The relative likelihood functions are shown in Figs. 7.8 through 7.13 for representative farm types. The headings in Table 7.5 show which crops are associated with which farm types. Once the appropriate function is identified, the above calculation is repeated for each of the five field size classes. In the case of arable farms, the function is evaluated at three times field size (see Sec. 7.4.4).

Next, compute a reduced (actually sprinkled) field size based on the potentially sprinkled field size.

\[ RFS(i) = F_2(F_S(i)) \]  \hspace{1cm} (7.2) \\

where \( RFS(i) \) = reduced (actually sprinkled) field size of class \( i \), 
\( F_2 \) = field size reduction function (depending on crop and region).

The parameters defining field size reduction functions are given in Table 7.7. The appropriate parameters are selected by locating the crop group and region group to which the crop and region belong. Actually sprinkled areas are then calculated for each field size class.

Next, allocate the total sprinkled area, \( TOTAS \), specified on input, among the field size classes and calculate the number of sprinkled fields in each class.

\[
\begin{align*}
\text{AS}(i) = & \frac{W(i) \times NF(i) \times RFS(i)}{5} \\
& \sum_{j=1}^{5} W(j) \times NF(j) \times RFS(j)
\end{align*}
\]  \hspace{1cm} (7.3) \\

\[ NSF(i) = \frac{\text{AS}(i)}{RFS(i)} \]  \hspace{1cm} (7.4)
where NSF\(_i\) = number of sprinkled fields in class \(i\),
NF\(_i\) = total number of fields in class \(i\),
TOTAS = total area sprinkled of crop in region,
AS\(_i\) = area sprinkled in class \(i\).

The product of the sprinkling likelihood, \(W\), the number of fields, NF, and the actually sprinkled area per field, RFS, yields the estimated total sprinkled area in each size class. The total sprinkled area, TOTAS, which was input, is allocated to field size classes in proportion to the estimated area. The actually sprinkled area per field, RFS, remains unaffected and so the number of sprinkled fields in each size class, NSF, will change in proportion to the sprinkled area.

The allocated area cannot exceed the maximum area that can be sprinkled in each field size class. The maximum area is set equal to the number of fields (unadjusted) times the actually sprinkled field size in the class, corrected for the fact that the crop accounts for only part of the total area representative for the selection of the sprinkler system. If the water source is surface water, the maximum area is reduced further to account for surface water accessibility, using the fraction SUPFRAC. If the water source is groundwater, the reduction fraction used is 1-SUPFRAC (see Sec. 7.4).

\[
ASMAX(I) = NF(I) \times RFS(I) \times PROP \times FRAC
\]  

(7.5)

where ASMAX\(_i\) = maximum sprinkled area of crop type in region in class \((i)\),
FRAC = fraction of region that has access to sprinkling water (surface water, FRAC=SUPFRAC and groundwater, FRAC=1-SUPFRAC),
PROP = factor that expresses the actual area of the crop under consideration as a part of the total area considered representative for the selection of the sprinkler system to sprinkle that crop.

As SUPFRAC is given by region, its use in this equation implies that crops and field size classes are homogenously distributed over the region.

When the sprinkled area allocated to a field size class exceeds the maximum, the sprinkled area for that class is set equal to the maximum and the remainder is reallocated to the other field size classes. The likelihood that a field will be sprinkled increases with field size, so the class with the largest field size saturates first. If more sprinkled area is added, the smaller classes will saturate, too, until the maximum sprinkled area for the crop in the region is reached.
7.5.2. The Allocation of Sprinkler Systems to Field Size Classes

The procedure that allocates sprinkler systems to field size classes takes into account feasible system configurations depending on sprinkling situation, costs, and other criteria that depend on field size and crop type.

For each crop-region combination, the SSACM looks at three different sprinkling situations: surface water sprinkling in lowlands; surface water sprinkling in highlands; and groundwater sprinkling, which occurs mostly in the highlands. All three situations can be found in some agricultural regions. In others, only one or two may exist. The SSACM provides the full menu from which other agricultural models can select the relevant sprinkling situations.

The model now determines whether a Buis or a Haspel sprinkler system should be used. It compares the actually sprinkled area per field, RFS(i), with the variable CRITAR. If RFS(i) is greater than CRITAR, a Haspel system is chosen regardless of cost considerations. When RFS(i) is less than CRITAR, the model identifies the system that costs the least. Using the actually sprinkled area, RFS(i), it obtains the total annual costs of the feasible Haspel system and of the cheaper of the feasible Buis systems by interpolation of the ANTOTB data in the sprinkler system parameter file.

The total annual costs of sprinkling consist of a fixed and a variable part. The latter is based on an estimate of the average annual gift (see Chap. 6). As the area of the sprinkled field increases, it becomes more likely that a Haspel system will be used not only because of cost considerations but also from a labor point of view. Even if for a bigger area, a Buis system is still the cheaper system, the total amount of labor involved in sprinkling the entire field might become prohibitive for selecting such a system.

If a Haspel is selected, no additional choices have to be made and all relevant sprinkler system data for that field size can be obtained by interpolation of the data in the sprinkler system parameter file.

If a Buis system is selected, there is still the option of having two different variations, one system driven by a tractor and the other by a fixed motor. The fractions specifying the relative mix of the two systems were given in Table 7.8. The sprinkled area per field, RFS(i), is first compared against the variable GAMMA. If RFS(i) exceeds the area specified by GAMMA, the field is identified as a big field. If not, it is considered to be a small field. The crop type and sprinkling situation identify which column of Table 7.8 applies. The relevant sprinkler system data for the two systems are averaged, using the relative amounts of each of the two feasible Buis system configurations as weights. The data for the individual systems are obtained by interpolation of the data in the sprinkler system parameter file.
The above allocation is done separately for each field size class, so that five sets of sprinkler system data are obtained for the crop, region, and sprinkling situation.

7.5.3. Computation of Weighted Cost Factors

The representative sprinkler system data by field size class were combined to reflect a single set of factors by crop, region and sprinkling situation. This was done by computing weighted averages over the five field size classes, using the sprinkled areas, AS(i), in each field size class as weights. In this process the information was scaled to per hectare basis.

The energy cost factor, CSPRIK, from the sprinkler system parameter file, gives the cost per mm of water applied to the entire field. The output variable, ENERGY, in Dfl/mm/ha, is obtained by dividing CSPRIK by the actually sprinkled area, RFS, and averaging as above. CMOVE is the cost per move and here we want the moving cost per mm of water applied per ha, LABOR. Because a constant GIFT is used, LABOR is simply the number of sets, NSET, times the cost per move, CMOVE, divided by GIFT and the actually sprinkled area, RFS. ANCAP, the annualized fixed cost per hectare, consists of the annualized investment and fixed annual maintenance cost. The fixed annual maintenance cost is estimated at 3.5 percent of total investment, TUTINB, adjusted to exclude value-added tax. ANCOST and INVEST result from ANTUBE and TUTINB. In each case, the latter values are divided by RFS and then averaged appropriately.

The final output of the model consists of the weighted average sprinkling cost factors for 11 crop types, 14 agricultural regions, and 3 sprinkling situations. In addition, the average sprinkled field sizes are given for the 11 crops and 14 regions, and for surface water and groundwater sprinkling separately. These are just the averages of the sprinkled field sizes in each of the five field size classes.

The only output factors effectively used by other agricultural models are ANCAP, ENERGY and LABOR. The last two reflect the variable cost of sprinkling. Given an area sprinkled in hectares (H) and an amount sprinkled in mm (M), the variable cost of sprinkling directly follows from the expression:

\[
\text{VARIABLE COST} = H \times M \times (\text{ENERGY} + \text{LABOR})
\]  (7.6)

Given an area sprinkled in hectares (H), the annualized fixed cost follows from the expression:
ANNUALIZED FIXED COST = H * ANCAP  

(7.7)

7.6. RESULTS AND EVALUATION

7.6.1. Overview of Results

Results indicate the desirability of using the detailed approach to estimating sprinkling costs described in this report. Had we used a simpler approach of applying gross rules of thumb, we would not have been able to capture anything like this degree of sensitivity to important variables like field size, geographic location, and crop type.

Examples of the output of the SSACM are presented in Tables 7.9 through 7.13. The first three tables are for a "low" sprinkler scenario. Tables 7.9 and 7.10 are for surface water sprinkling in the lowlands. Table 7.11 shows the cost factors for groundwater sprinkling. The last two tables are for a "high" sprinkler scenario.

Table 7.9 shows the factors ANCAP, ENERGY, and LABOR for surface water sprinkling lowlands by crop and region. The results are based on a low sprinkler scenario, i.e., the sprinkling situation of 1976. The annualized fixed cost, ANCAP, is on the order of 175 to 250 Dfl/ha for grass and arable crops, and somewhat higher for horticulture crops. Energy cost, ENERGY, ranges from 0.35 to 0.80 Dfl per mm per ha (equivalent to 0.035 to 0.08 per Dfl/m³, since 1 mm on a hectare equals 10 m³). Labor cost, LABOR, varies from less than 0.50 Dfl/mm/ha to over 2.00 Dfl/mm/ha.

ANCAP is generally higher for horticulture crops because the sprinkled areas are smaller and the cost per ha is higher for smaller fields. However, the differences are not very great since for the bigger fields on arable and cattle farms, the relatively expensive Haspel system is more frequently used. ENERGY is higher and LABOR is lower for nonhorticulture crops because these crops are typically found on large fields. The Haspel system is used for these fields and it requires more energy but considerably less labor than the Buis system.

Table 7.10 shows the average field size, AVSIZE, and the factors ANCOST and INVEST. AVSIZE is smaller for horticulture crops and, as a consequence, the sprinkler system investment costs, INVEST, are bigger than for the nonhorticulture crops. The average annual cost, ANCOST, is bigger for the horticulture crops (especially for the very small areas) with values varying from 300 to 700 Dfl/ha.

Table 7.11 shows the factors ANCAP, ANCOST, and INVEST for groundwater sprinkling based on the low (1976) scenario. Because of the extra investments for the well and the distribution system, both ANCAP and ANCOST are higher by 100 to 200 Dfl than the surface water lowlands situation. INVEST is higher by an amount on the order of 750 Dfl/ha.
Tables 7.12 and 7.13 show the same factors as Tables 7.6 and 7.7, again for surface water sprinkling lowlands, but this time for the high sprinkler scenario. The high scenario is based on optimistic expectations about the growth of sprinkling (see Vol. XIV). Note that with the high sprinkler scenario, sprinkling occurs for additional crop-region combinations. Furthermore, the average field sizes under the high scenario are equal to or less than those under the low scenario. For those crop-region combinations that are sprinkled under both scenarios, the total annual costs, ANCOSTs, are higher by as much as 70 Dfl/ha for the high scenario.

With the increase in sprinkled area, the larger field size classes will saturate, more smaller fields will be sprinkled, and the overall average sprinkled field size will be smaller. Normally this will cause an increase in the sprinkler system investment costs. However, if the shift to sprinkling smaller fields causes more Buis systems to be used, investment costs will decrease and we will observe a simultaneous decrease in energy costs and increase in labor costs. However, the effect of these cost changes on the final sprinkling parameter values will be limited since they are averaged over the entire sprinkled area of the crop.

7.6.2. Evaluation of Results

The SSACM allocates sprinkled areas to field size classes, selects sprinkler systems according to simple rules, and computes weighted average cost factors. The structure of the model is straightforward and not a source of large errors or uncertainties. Consequently, the validity of the results depends on the appropriateness of the inputs. The most important ones are discussed below.

The sprinkler system factors come from the Sprinkler System Design and Cost Model and, thus, depend on the cost information and technical specifications obtained from sprinkler equipment manufacturers (see Chaps. 3 and 4). We believe that these data and the outputs from the design and cost models are quite reasonable.

The field size distributions were based on statistical information provided by the CBS, which should be quite good. However, in organizing these data, we made a number of assumptions that may have affected the validity of the results. Input cost factors depend on the field sizes sprinkled but are relatively insensitive to small variations in field size. We sought to capture the effects on cost of substantial variations in field size and believe that we have accomplished this objective. Moreover, we think that the results are valid even with the errors that we may have introduced into the field size distributions.

The parameters expressing the relative likelihood that a certain field size will be sprinkled and the parameters for the computation of the actually sprinkled area from the potentially sprinkled area
are, for the most part, based on statistical information but they do contain some elements of judgment. Yet, we think that the magnitude of the estimates is correct and that important differences are reflected appropriately.

The parameters for the allocation of sprinkler systems--variable CRITAR, the twelve fractions specifying the mix of alternative Buis systems, and the variable GAMMA--may be questioned. Since the differences in cost between the two alternative Buis systems are small, the final results are relatively insensitive to the values of these variables. The value of CRITAR was chosen in the area where differences in total sprinkling cost, ANTUTB, between Buis and Haspel are small. Hence, CRITAR has little effect on total sprinkling cost, but it will have an impact on the separate variable and fixed cost components. This is not an important problem because for field sizes much different than CRITAR, which system to choose is obvious. We think that the value of 15 hectares for CRITAR (meaning that no Buis system is used for fields bigger than 15 ha) is reasonable for current Haspel systems. We expect that this value will decrease, in the future, when a larger variety of (more flexible) Haspel systems become available.

In trying to compare our results with existing cost estimates we found that only limited information was available. In fact, the lack of adequate cost estimates broken down by crops, regions, and by fixed and variable cost components was the main reason to carry out a sprinkling cost analysis in the first place.

The Handbook of Cattle Breeding [7.5] gives estimates for the investment in sprinkling equipment on a per hectare basis for a number of variations of Buis and Haspel systems. Excluding pumps, wells and distribution systems, these estimates range from 500 to 600 Dfl for the Buis system and 1000 to 2000 Dfl for the Haspel system. Our Haspel estimates fall within the range indicated in Ref. 7.5. Our estimates for the Buis are higher. There are several possible explanations but as we do not have detailed documentation from Ref. 7.5, we can not explain the differences. Our estimates reflect the costs of the least annualized total cost systems where we probably allowed for additional investment because it reduced the labor cost. Furthermore, we do not know what field sizes were used to get the estimates shown in Ref. 7.5. We suspect that they were larger than the average field sizes we used. We would have used a Haspel for all fields larger than 15 ha. Finally, we included the cost of pumps, wells, and distribution pipes, thus making our estimates higher.

Doornbos [7.6] computed sprinkling costs for Buis and Haspel systems for sprinkled areas ranging from 6 to 12 ha. The annual fixed costs were around 200 Dfl/ha for the Buis and 400 to 600 Dfl/ha for the Haspel system. Our numbers for the Buis tend to be a little higher because our sprinkled areas (mostly horticulture crops) are smaller. On the other hand our numbers for the Haspel tend to be smaller, since our average sprinkled areas (mostly grass and arable crops) are higher than the 6 to 12 ha used by Doornbos. The energy cost computed in
this report is around 0.50 Dfl/mm/ha for the Buis and around 1.10 Dfl/mm/ha for the Haspel. In general, our estimates are a bit lower. Since Ref. 7.6 did not include labor cost, we have no comparison for that cost element.

In the report Water to Drenthe [7.7], the total annual costs of sprinkling are estimated at 370 Dfl/ha, based on a 15-ha field and an average year. Energy cost is estimated at 0.70 Dfl/mm/ha. For a comparable field size, our estimates are essentially the same. The energy cost estimate is in agreement with our results.

Finally, a few remarks about the cost of energy and labor are in order. Our energy costs reflect data for 1977 and 1978. Since then, the prices of diesel fuel and electricity have gone up considerably. The cost of energy should be multiplied by a factor of at least 2 to reflect 1981 prices. Given that SSACM generates fixed and variable cost components separately, this adjustment can be made easily.

No estimates of sprinkling labor cost were available. Apparently, this is a controversial topic. Some people are inclined to consider the farmer's labor for sprinkling as free. Other people claim that it should be valued quite highly, since the work is unattractive and there may be other demands on the farmer's time and he might not even be able to find time for sprinkling. We feel his time should be valued at the average wage for farm labor. If the farmer invests his own time, he should be rewarded appropriately. If he cannot find the time, he should be able to hire sprinkling labor. This view was adopted in our modeling approach. However, since the labor component is computed separately, the results could be modified to reflect other views as well.

REFERENCES

7.4. Baars, C., Ontwerpen van Regeninstallaties (The Design of Sprinkler Systems), Agricultural University, Wageningen, 1972.
7.5. Proefstation voor de Rundveehouderij, Handboek voor de Rundveehouderij (Experimental Station for Cattle Breeding,


Fig. 7.1--Typical relative farm size distribution
Fig. 7.2—Relative farm size distribution:
dairy farms

Fig. 7.3—Relative farm size distribution:
arable farms
Fig. 7.5—Relative farm size distribution: vegetable farms

Fig. 7.6—Relative farm size distribution: bulb farms
Fig. 7.6—Relative farm size distribution
pit/stone fruit farms

Fig. 7.7—Relative farm size distribution
tree farms
Fig. 7.8--Sprinkling likelihood: dairy farms
Fig. 7.9—Sprinkling likelihood: arable farms

- SOURCE: Roberts (1978)
Fig. 7.12--Sprinkling likelihood: pit/stone fruit farms
Fig. 7.13—Sprinkling likelihood: tree farms

SOURCE: Reinds (1978)
Fig. 7.14--Actual sprinkled area vs. potential sprinkled area
Table 7.1
INPUTS TO SSACM

<table>
<thead>
<tr>
<th>Sprinkler System Parameter File</th>
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<tbody>
<tr>
<td>Annualized total cost including BTW (Df1)</td>
<td>ANTOTB</td>
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<tr>
<td>Total investment cost including BTW (Df1)</td>
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</tr>
<tr>
<td>Total annualized investment excluding BTW (Df1)</td>
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<td>Energy cost per irrigation (Df1/mm)</td>
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<td>Labor cost per move (Df1/move)</td>
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<td>Number of sets</td>
<td>NSET</td>
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<td>Configuration</td>
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<td>Field size class (i=1,2,...,5)</td>
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<td>Average field size in field size class i (ha)</td>
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<td>Number of fields in field size class i</td>
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<td>Farm size at intersection (ha)</td>
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<td>Slope</td>
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<td>Second segment (FS&gt;W3)</td>
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<td>Slope</td>
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<td>Field size for distinguishing between alternate mixes of Buis systems (ha)</td>
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<td>Fraction of area with access to surface water</td>
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<td>Crop</td>
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<td>Area sprinkled from surface water (ha)</td>
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<td>Maximum field size for which reduction is zero (ha)</td>
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<td>Slope of function for fields larger than MAREA</td>
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<td>Fraction of total field area devoted to crop</td>
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Table 7.1 (continued)

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<th>Miscellaneous File</th>
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<td>Fractions giving relative mix of alternative Buis systems</td>
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<td>Horticulture, surface water, lowlands</td>
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<tr>
<td>Horticulture, surface water, highlands</td>
</tr>
<tr>
<td>Horticulture, groundwater</td>
</tr>
<tr>
<td>Non-horticulture, surface water, lowlands</td>
</tr>
<tr>
<td>Non-horticulture, surface water, highlands</td>
</tr>
<tr>
<td>Non-horticulture, groundwater</td>
</tr>
<tr>
<td>Big fields (&gt;GAMMA)</td>
</tr>
<tr>
<td>Horticulture, surface water, lowlands</td>
</tr>
<tr>
<td>Horticulture, surface water, highlands</td>
</tr>
<tr>
<td>Horticulture, groundwater</td>
</tr>
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<td>Non-horticulture, surface water, lowlands</td>
</tr>
<tr>
<td>Non-horticulture, surface water, highlands</td>
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<tr>
<td>Non-horticulture, groundwater</td>
</tr>
<tr>
<td>Field size above which always prefer Haspel (ha)</td>
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<td>Sprinkling efficiency (fraction)</td>
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<td>Looping parameters</td>
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Table 7.2

<table>
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<th>OUTPUTS FROM SSACM</th>
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<tr>
<td>Annualized capital cost (Df1/ha)(a)</td>
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<tr>
<td>Energy cost (Df1/mm/ha)</td>
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<tr>
<td>Labor cost (Df1/mm/ha)</td>
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<tr>
<td>Average size of sprinkled fields (ha)</td>
</tr>
<tr>
<td>Total annualized cost (Df1/ha)</td>
</tr>
<tr>
<td>Total investment cost, incl. BTW (Df1/ha)</td>
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(a) Annual capital cost includes annualized investment and fixed annual maintenance cost.
Table 7.3

REPRESENTATIVE FARM TYPES FOR CROP TYPES

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Farm Type</th>
<th>Percent of Crop on Farm Type</th>
<th>Percent of Farm Type Devoted to Crop</th>
</tr>
</thead>
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<tr>
<td>Code</td>
<td>Name</td>
<td>Description</td>
<td>Code</td>
</tr>
<tr>
<td>1</td>
<td>Grass</td>
<td>Dairy farm</td>
<td>01, 02</td>
</tr>
<tr>
<td>2</td>
<td>Consumption potatoes</td>
<td>Arable farm</td>
<td>SA</td>
</tr>
<tr>
<td>3</td>
<td>Milling potatoes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Seed potatoes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Sugar beets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Cereals</td>
<td>Arable farm</td>
<td>SA</td>
</tr>
<tr>
<td>7</td>
<td>Cut corn</td>
<td>Cattle farm</td>
<td>SV</td>
</tr>
<tr>
<td>8</td>
<td>Bulbs</td>
<td>Bulb farm</td>
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<tr>
<td>9</td>
<td>Vegetables (open air)</td>
<td>Vegetable farm</td>
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<tr>
<td>10</td>
<td>Pit and stone fruits</td>
<td>Pit and stone fruit farm</td>
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</tr>
<tr>
<td>11</td>
<td>Trees</td>
<td>Tree farm</td>
<td>29</td>
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</tbody>
</table>


NOTE: Farm type codes refer to CBS codes. The code SA refers to the collection of arable farms and consists of farm types 18, 19, 20, and 21. The code SV refers to the collection of cattle farms and includes farm types 01 through 17.
### Table 7.4
RULES FOR DETERMINING POTENTIALLY SPRINKLED AREA

<table>
<thead>
<tr>
<th>Crop</th>
<th>Farm Type</th>
<th>Potentially Sprinkled Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>Dairy farm</td>
<td>Grass area</td>
</tr>
<tr>
<td>Cut corn</td>
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<tr>
<td>Potatoes</td>
<td>Arable farm</td>
<td>Sandy soils: total area except cereals and cut corn</td>
</tr>
<tr>
<td>Sugar beets</td>
<td>Arable farm</td>
<td>Nonsandy soils: total area except cereals, sugar beets and cut corn</td>
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<tr>
<td>Cereals</td>
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<td>Bulbs</td>
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<td>Total farm area</td>
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<tr>
<td>Vegetables o.a.</td>
<td>Vegetable farm</td>
<td>90% of total farm area</td>
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<tr>
<td>Pit/stone fruits</td>
<td>Pit/stone fruit</td>
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<td>Trees</td>
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<td>Arable Farm Potatoes Area (ha)</td>
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Table 7.6

**DISTRIBUTION OF POTENTIALLY SPRINKLED FIELD SIZES FOR GRASS**

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<th>Average Field Size (ha) by Field Size Class</th>
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Table 7.7
PARAMETERS USED FOR COMPUTATION OF ACTUALLY SPRINKLED AREA

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<th>Region Group (a)</th>
<th>Parameters, by Crop Group</th>
<th>Grass, Cut Corn</th>
<th>Arable Crops</th>
<th>Bulbs, Trees</th>
<th>Vegetables, Fruits</th>
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<td>MAREA</td>
<td>BETA</td>
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(a) Numbers in parentheses refer to individual regions (see Table 7.5 or 7.6).

Table 7.8
FRACTIONS FOR THE ALLOCATION OF ALTERNATIVE BUIS SYSTEMS

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<td>SW-HL</td>
<td>GW</td>
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NOTE: SW-LL stands for surface water, lowlands. SW-HL stands for surface water, highlands; and GW stands for groundwater.
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For crop types see Table 1.
For regions see Table 2.
Chapter 8
SPRINKLER OPERATING POLICIES

8.1. PURPOSE AND OVERVIEW

The sprinkler operating policies selected here were implemented, together with the decade sprinkling algorithm described in Chap. 5, in the Plot Model (Vol. XII) and the Managerial Strategy Design Model (Vol. V). Subsequent PAWN analyses that made use of these models, and thence of the sprinkling policies, include the screening of waterboard plans, the screening of major infrastructure tactics, management strategy design, and impact assessment.

A sprinkling policy tells when to start sprinkling and how much water to put on a field when sprinkling starts. Selecting a policy involves choosing values for two sprinkling parameters, START and GIFT. START reflects the millimeters of water available in the root zone and is used to indicate a critical soil moisture condition. When a farmer estimates that some part of his field will dry out to START within the time he needs to go around his field, he starts sprinkling. GIFT, also measured in millimeters, is the amount of water to be applied during a single irrigation. In the real world, GIFTs on the order of 20 mm to 30 mm are typical.

Sprinkling policies are selected to minimize the sum of sprinkling variable operating costs and crop damage. Both are dependent on the critical soil moisture level, START. Lower values for START mean less sprinkling and less sprinkling cost but more crop damage. If START is low, it takes a long time for the soil to dry out to that point, and farmers do not sprinkle as frequently as they otherwise would. Hence, they save on operating costs and water. However, if an extended dry period occurs they run a greater risk of not getting around the field in time to avoid damage, so the expected damage will increase. A conservative farmer chooses a high value for START and, if it is high enough, he will be able to avoid almost all damage. He will in many instances, however, also sprinkle when it is not really necessary. Consequently, he will be relatively wasteful of water and have higher operating costs.

We used the DSM to select sprinkling policies for each relevant combination of crop type, soil group, and root zone. In selecting the policies we considered three years—a very wet year, a normal year, and an extreme dry year—and 21 different policies for each year.

8.2. ORGANIZING THE DATA

A considerable amount of data had to be obtained and organized in a form for input before the DSM could be run to simulate sprinkling policies. Included were data describing soil types, crop types, and
weather scenarios. Sprinkler system configurations had to be assigned and field sizes had to be determined for each crop type. Finally, a range of values defining the sprinkling policies for which we wanted simulation results had to be specified.

8.2.1. Aggregation of Soil Types

Crop and soil type combined determine the maximum amount of water available to the crop from the root zone and this amount is very important to the selection of a sprinkling policy. Water held in the root zone may be used by the crop between irrigations and the more moisture that can be held, the longer the crop can wait between sprinklings.

The type of crop determines the depth of the root zone and the soil type determines the moisture holding capacity of the root zone and the ability of the plant to extract that moisture. Specifically, we are interested in the amount of water between field capacity and the reduction point. Field capacity indicates the maximum amount of moisture that the root zone can hold against gravity in an equilibrium state. Additional water will drain off. The reduction point indicates the moisture content of the soil when a reduction in crop yield begins to occur. The amount of water between field capacity and the reduction point depends on the moisture holding characteristics of the soil (the so-called PF-curve, [8.1]) and the depth of the root zone.

Nine soils and 11 (open air) crops were included in the data base for Vol. XII. Because there are only slight differences in the water holding capacities of some of them, the 9 different soils have been collapsed into 4 groups for use in selecting sprinkling policies. Aggregation was on the basis of moisture retention capacity only. Each of the soil groups is assumed to have the moisture retention properties of a single representative soil--sand, loam, clay, or peat. The characteristics of the representative soils are shown in Table 8.1.

For reasons outlined in Vol. XII, the moisture retention properties of clay and sand were adjusted by substituting the properties of other soil types. This is why humus loamy medium coarse sand was selected as the representative soil type for sand, while this soil type itself is represented by loam. For the same reasons, loess loam is selected as the representative soil type for clay soils.

8.2.2. Crop/Root Zone Combinations

Table 8.2 shows the combinations of soil groups and root zone depths that we considered in the selection of sprinkling policies. Relevant crops are shown for each combination. Table 8.2 was obtained by aggregating information from the detailed agricultural data base, presented in Vol. XII, by soil group. If a crop is shown with
different root zone depths under the same soil group, it is because
the soil group includes two or more soil types on which the crop has
different root zone depths.

8.2.3. Assignment of Sprinkler Systems and Average Field Sizes

Sprinkling operating costs, which we use to select policies, depend
on certain characteristics of the sprinkler system (configuration)
and the size of the field to be sprinkled. Thus, to estimate the
cost of sprinkling each crop under a specified policy, we had to
assign a sprinkler system configuration and a field size to each
relevant crop/soil group combination. After examining the eight
sprinkler system configurations (see Chap. 1) and the field size
distributions (see Chap. 7), we found that we needed only four
different configurations--B1, B2, B3, and H1--and three average field
sizes--2.4, 7.0, and 14.0 ha. The configurations and field sizes
we selected are shown in Table 8.3.

The selections were based on the following observations and
assumptions. We were told that the tendency is to sprinkle grass and
arable crops with Haspels and horticultural crops with a Buis. We
have followed this practice. Because they come in large sizes
(horsepower), we have assumed that tractor pumps will be used with
all sprinkler systems for grass, arable crops, and large fields of
horticultural crops. Fixed electric motors will be used for small
fields of horticultural crops.

The choice of a sprinkler system configuration depends on whether it
is to be used in the lowlands or the highlands (see Chap. 1) so we
needed a way to decide whether a crop type/soil group combination
existed in each of these areas. After examining soil maps and other
data, we assumed that clay, peat, and loam are associated with the
lowlands and that sand is associated with the highlands.

Based on the results of the Sprinkler System Allocation and Cost
Model (see Chap. 7), the average sprinkled area for grass and arable
crops, for each of 14 agricultural regions, varies between 10 and 20
ha, and has an overall average of 14 ha. Similarly, for the
horticulture crops grown in the open air--vegetables, bulbs, and
pit-and-stone fruits--the sprinkled areas vary between 3 and 12 ha,
and the average is 7 ha. The average sprinkled area for ornamental
trees is much smaller, only 2.4 ha.

Hasel configuration H1 is chosen for grass and arable crops and the
field size is assumed to be 14 ha. This is a lowlands
configuration consisting of a Haspel installation driven by a tractor
and fed directly from a ditch. For the highlands, we needed a
configuration with a main distribution pipe and, possibly, a well.
Configuration H2 or H3 were indicated. However, the operating cost
factors for these configurations are the same as for configuration H1
so only H1 had to be considered explicitly.
Buis system B2 and a field size of 7 ha was chosen for horticultural crops in the lowlands. In the highlands, B3 and the same field size were selected. Configuration B2 has one lateral, which is fed directly from a ditch by a tractor-driven pump. In the highlands, a main distribution pipe is required to feed the laterals so B3 is indicated. This configuration has a higher investment cost, a lower labor cost per move, and a higher energy cost per unit of water applied. The labor cost is lower because fewer pipe sections need to be moved. The cost of energy, per unit of water applied, increases because of the main distribution pipe.

Buis configuration B1 and a field size of 2.4 ha is used for ornamental trees. This system uses laterals, a main distribution pipe, and a pump, which is driven by a fixed electric motor. The average field size is small enough that this configuration is used in both the highlands and in the lowlands.

8.2.4. Weather Scenarios

Fourteen years of daily rain data were available for simulating sprinkling policies. The data were measured in the Netherlands at the De Bilt weather station and cover the years 1959 through 1971 and 1976. To examine these data, we ran the DSM, without sprinkling, for each of the fourteen years and each of the 12 soil group/root zone combinations (see Table 8.2) and obtained estimates of total rainfall, potential evapotranspiration, drainage, and crop damage in each year. The weather-related results, shown in Table 8.4, provided a means for comparing the weather scenarios while holding other variables constant.

The net moisture loss is obtained by subtracting potential evapotranspiration and drainage from rainfall. Drainage varies with the moisture holding capacity of the soil root zone. The smaller the capacity, the more the drainage. We show the minimum and maximum values over the 12 soil-root zone combinations for each year.

To reduce the number of simulation cases, we actually used only three of the fourteen years of rain data to simulate our sprinkling policies. We chose 1976 to represent a very dry year, 1967 to represent a normal year, and 1965 to represent a very wet year.

We chose 1976 as our dry year because most people had the circumstances that arose during that year firmly in mind and because a considerable amount of ancillary data describing the drought of 1976 were readily available.

We selected 1967 for our normal year because it had a net moisture loss during the growing season roughly equal to the 90-mm soil moisture deficit for the average of the 65 years shown in Ref. 6.1 and an evapotranspiration rate close to the 2.5 mm per day used to design least-cost systems. The three candidate years in our data
base were 1967, 1969, and 1970. Of these, 1967 was best with respect to net moisture loss. The average daily potential evapotranspiration rate in 1967 was less than 2.5 mm per day for about 60 percent of the growing season. During the rest of the time it exceeded 2.5 mm per day, with a high of 3.5 mm per day, and a mean of about 2.9 mm per day. Furthermore, drought damage estimates for the three candidate years indicated that 1967 fell somewhere between the other two years.

The year 1965, our very wet year, had the most rain during the growing season. Its total potential evapotranspiration was among the lowest, but total drainage was the highest. Net moisture loss was also very low in this year. For about half the growing season, the average daily evapotranspiration was slightly below our design rate of 2.5 mm per day. In only one decade did the daily average exceed 2.5 mm—then it averaged 3.3 mm. For the remaining half of the growing season, the daily average evapotranspiration loss was substantially below 2.5 mm. The fact that, in 1965, some shallow rooted crops did incur slight damage suited it to our use because we wanted a wet year in which some sprinkling might be profitable.

8.2.5. Sprinkling Policies Simulated

We simulated individual policies for each of the crops found on the 12 different soil/root zone combinations in Table 8.2, with the three GIFTs used to determine the least-cost sprinkling systems—20, 25, and 30 mm—and seven values of STOP.

Describing a policy requires stating a target soil moisture when sprinkling should begin, START, and an amount of water to apply, GIFT. When applying a policy, the most the soil will be allowed to dry out to is START. When this happens, and GIFT is added, there will be START plus GIFT millimeters of water in the soil. This total is STOP. The same STOP values were specified for each GIFT and values of START were calculated by subtracting GIFT from STOP.

Seven values of STOP were chosen such that, during the simulations, the moisture in the soil would range from well below to well above the point were crop damage occurs. These values and the associated values of START are shown in Table 8.5. Of course, lower values of STOP result in less sprinkling and more crop damage. The maximum STOP value of 32 mm, above the damage level, reflects the moisture holding capacity of 300 mm (the shallowest root zone) of sand between field capacity and the damage point. Other soil/root zone combinations hold about the same or more water. The other STOP values were chosen at 5 mm increments below the maximum.

8.3. INPUTS TO THE DSM FOR A POLICY SIMULATION

We consider a single policy simulation run, which is made for a selected crop/soil group combination. It looks at three values of GIFT combined with seven values of START and under three weather
scenarios. Each of the important inputs (see Table 4.1) is discussed briefly below.

The weather prediction parameters, TLOOK and ETDES, and the ratio of potential to open-water evaporation, C, were fixed at 12 hrs, 2.5 mm per day, and 0.8, respectively, for all of the policy runs. These parameters and the values assigned to them have been dealt with in earlier parts of this report.

The daily rainfall data were available directly from our data tapes but daily open water evaporation had to be calculated by spreading decade data uniformly over the days in the decade.

A soil moisture function is selected from the 12 shown in Table 8.6. This function expresses the millimeters of water above the wilt point as a function of EA/EP. It allows the DSM to calculate actual evapotranspiration, EA, and hence crop damage from moisture in the root zone. The curves, one for each soil group/root zone combinations, are based on data from Ref. 8.1 and work presented in Vol. XII. Reference 8.1 gave the percent of soil moisture (by volume) as a function of soil moisture tension and relationship between EA/EP, and soil moisture tension was obtained from Vol. XII.

Sprinkler system characteristics are obtained by first consulting Table 8.3 to determine which system (configuration) and field size to use. The operating characteristics and costs come from the cost functions discussed in Chap. 6. They vary with GIFT and are summarized in Table 8.7.

The final set of inputs required for the simulation specify the crop damage function. An exhaustive set of parameter values is shown in Tables 8.8 and 8.9. These values are the same as those reported in Vol. XII with the following exceptions. The crop values per hectare for the three potatoe crops shown here are slightly different than those presented in Table 1.1. The latter are based on information that was obtained after the sprinkling policy simulations were completed. The reduction point for trees was also lowered somewhat.

8.4. OUTPUTS FROM THE DSM

Table 8.10 shows a typical set of outputs from the DSM. These reflect a simulation to obtain a sprinkling policy for consumption potatoes on loam. A separate run of the DSM was made for each of the three years--1965, 1967, and 1976--and for seven different values of START. We note that for 1965 the total rain was 643 mm and the potential evapotranspiration was 378 mm. This gives a net rain of 265 mm. The net rain was -54 mm in 1967 and -295 mm in 1976. GIFT was held at 25 mm for all of these cases. A total of 21 runs were made with the DSM to obtain the information shown in the table.

The same START values, 36 mm in steps of 5 mm to 66 mm, were used for each of the years. These values were obtained by adding the entries
in Table 8.5, for GIFT = 25 mm, to the damage point for consumption potatoes on loam. From Table 8.2, we note that the relevant root zone is 400 mm and from Table 8.6, that the damage level is 59 mm. The remaining entries are selected results from the simulations.

The drainage is highly correlated with the net rain and for any given year it varies directly with the value of START. The latter is explained by noting that the higher the value of START, the less room there is in the soil to accumulate rain.

The amount sprinkled and the number of moves are directly related to each other. The number of moves divided by the total number of sets for the sprinkler system gives the number of irrigations of the field. The amount sprinkled is simply the number of irrigations multiplied by the amount per irrigation—in this case, 25 mm—and so reflects the average amount applied to the entire field.

The amount sprinkled and the number of moves increase as the net rain decreases and as the value of START increases. The higher the START value, the less the soil will dry out before sprinkling, so sprinkling will be done more frequently. Inasmuch as the amount sprinkled at one time is the same (25 mm), more will be sprinkled in total.

Sprinkler operating cost includes labor to move the sprinklers and energy for pumping. Both are proportional to the amount of water sprinkled. Here we make a decision about how to operate a sprinkler system assuming that it has been purchased. The investment costs and the fixed annual maintenance cost were relevant when making the investment decision but, when it comes to deciding how to operate the system, they are sunk costs and no longer relevant.

Damage is highest in 1976, the extremely dry year, and quite small in the normal and the extremely wet years of 1967 and 1965. Small values of START result in more damage than do larger values. The lower the value of START, the more the soil is allowed to dry out between successive irrigations. While the damage shown for 1976 looks quite large relative to that shown for the other two years, it is actually quite small relative to that which would have been incurred with no sprinkling at all.

The final column of the table shows the total of variable sprinkler operating cost and damage as a function of START. These are the figures that we used to select the sprinkler operating policies. In 1967, there is a clear minimum cost plus damage that occurs at a START value of around 56 mm. Such a minimum does not appear for either of the other two years. In 1965, the extremely wet year, there is essentially no crop damage, with or without sprinkling, so a very low START value to minimize sprinkling cost is clearly desirable. In 1976, damage occurred even for the largest START value and it appears that a higher START value would have been desirable. However, a higher START value is clearly undesirable in 1965 and not needed in 1967.
8.5. SPRINKLING POLICIES

In general, sprinkling policies are selected to minimize the sum of variable sprinkling operating costs and crop damage. However, this criterion was seldom able to distinguish among the alternate gifts. For START values around the optimum, the sum of variable sprinkling operating cost and damage was almost insensitive to GIFT.

We chose a GIFT of 30 mm for the horticulture crops with root zones that hold a reasonable amount of water. This is because a Buis system, which is relatively labor-intensive, is used for these crops. Provided a root zone holds enough water, labor cost can be reduced by putting on more water per irrigation. Even though the differences were small, we selected GIFTs of 25 mm for all other crop/soil group combinations.

Choosing values for START was more complicated because the optimum value differed with the weather scenario. A START that does well in a dry year may not do well at all in a wet year and vice versa. For this reason, selecting a value for START is a matter of compromise. A high START value will ensure against the drought damage that would come in a rare dry year while to ensure against the expected damage in a normal or wet year, a lower START value would be selected. In Fig. 8.1, the sum of sprinkling operating costs and crop damage, for consumption potatoes on loam, is shown as a function of START, for the three scenario years.

In the wet year, cost increases as START increases and, with a very conservative policy, some sprinkling would take place, while there is actually no drought damage to be prevented. In a normal year, a very low START would cause a noticeable drought damage, but as START increases the sum of damage and sprinkling costs becomes nearly constant, indicating an almost equal trade-off between damage and sprinkling cost. In the extreme dry year, drought damages are very high with low STARTs. Total cost plus damage decreases with increasing START, and even at the most conservative policy considered, the minimum is not yet reached.

Obviously, we want a policy that will do a reasonable job in a normal year. The graph for the normal year shows an indifference zone wherein the costs vary only slightly with changes in START. Exactly where, within that zone, we choose a policy depends on whether we want it to do best in an extremely dry or an extremely wet year. The dashed line connects the optimum point for the extremely dry year with the optimum point for the normal year. It appears that it also will intersect the extremely wet year curve at a point that is very close to optimum (highest value of START with zero cost).

Initially we selected a dry year policy because we were concerned with protecting against crop damage. To this end we chose a point on the dashed line roughly one-third of the way from the normal to the extremely dry year. In calibrating the Plot Model, we found that this policy used too much sprinkling water. To ameliorate this, we
selected a different policy that was biased toward the wet year (still within the indifference zone for the normal year). Both the dry year and the wet year policy are shown in Fig. 8.1.

We selected both a dry year and a wet year policy for all combinations of crop types and soil groups. These are shown in Table 8.11, together with the root zone depth and the millimeters of water in the root zone at field capacity and at the damage point. In general, the START values for the dry year policies are close to the damage points, while START values for the wet year policies are substantially below the damage points. The lower the START values, the less sprinkling will be done. In all but three cases, the GIFT remains the same for both the dry and the wet year policies. In the three exceptions—bulbs, vegetables, and trees on loam—the GIFT was lowered from 30 mm to 25 mm for the wet year policies because the latter was preferable in the normal and the wet years.

Given the amounts of sprinkling water that farmers actually seem to use in an extremely dry year [8.2], the wet year policy appears to be more realistic than the dry year policy. Furthermore, the extremely dry year is very extreme. It is not very likely that a farmer will base his daily operations on a low probability occurrence. Since the actions required for sprinkling interfere with his normal tasks, he will probably not sprinkle until he really sees the need for it. Moreover, sprinkling too soon increases the risk of root zone saturation and damages from water excess in wet periods. These damages have not been taken into account, but would have made the dry year policy less favorable from a total cost point of view. Based on these considerations, we decided to use the selected wet year policies in the actual analysis.

REFERENCES

Fig. 8.1—Choosing a sprinkling policy: example
Table 8.1

AGGREGATED SOIL TYPES

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<tr>
<th>Soil Group Code</th>
<th>Representative Soil Name</th>
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<th>Soil Types in Group Name</th>
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<td>Sand</td>
<td>Humus loamy medium coarse sand</td>
<td>22</td>
<td>Loamy medium coarse sand (29.3)</td>
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<tr>
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<td></td>
<td></td>
<td>Light loamy medium coarse sand (29.3)</td>
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<td>Loam</td>
<td>13</td>
<td>Loam (24.8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Humus loamy medium coarse sand (24.8)</td>
</tr>
<tr>
<td>Clay</td>
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<td>Sandy clay loam (28.8)</td>
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<td></td>
<td></td>
<td>Light clay (23.2)</td>
</tr>
<tr>
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<td></td>
<td>Silty clay (23.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Basin clay (23.2)</td>
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<tr>
<td>Peat</td>
<td>Peat</td>
<td>20</td>
<td>Peat (64.9)</td>
</tr>
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</table>

NOTE: The numbers shown in parentheses above are the soil moisture in the root zone at the damage point as a percent of the root zone.
Table 8.2
CROP ROOT ZONES FOR SOIL GROUPS

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>300 mm</th>
<th>400 mm</th>
<th>600 mm</th>
<th>800 mm</th>
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<tr>
<td></td>
<td>Crops, by Root Zone</td>
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<td></td>
</tr>
<tr>
<td>Sand</td>
<td>Grass</td>
<td>Consumption potatoes</td>
<td>Sugar beets</td>
<td></td>
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<tr>
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<td>Bulbs</td>
<td>Milling potatoes</td>
<td>Cereals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vegetables (a)</td>
<td>Seed potatoes</td>
<td>Cut corn</td>
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</tr>
<tr>
<td></td>
<td>Trees</td>
<td>Sugar beets</td>
<td>Cut corn</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cereals</td>
<td>Fruits (b)</td>
<td></td>
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<tr>
<td>Loam</td>
<td>Grass</td>
<td>Consumption potatoes</td>
<td>Sugar beets</td>
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<td>Vegetables (a)</td>
<td>Seed potatoes</td>
<td>Cut corn</td>
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<tr>
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<td>Trees</td>
<td></td>
<td>Fruits</td>
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<tr>
<td></td>
<td>Trees</td>
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</table>

SOURCE: PAWN agricultural data base (see Vol. XII).

NOTE: On sand soils, sugar beets, cereals and cut corn have a root zone depth of 400 mm on soil type 21 and 800 mm on soil type 23. On loam soils, they have a root zone depth of 600 mm on soil type 13 and 800 mm on soil type 22.

(a) Grown in open air, not in glasshouses.
(b) On loamy medium coarse sand (type 21). Not found on soil type 23.
### Table 8.3

**Allocation of Sprinkler Systems by Soil Group and Crop**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Field Size (ha)</th>
<th>Sprinkling System, by Soil Group</th>
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<tr>
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Table 8.4
WEATHER SCENARIOS

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<th>Year</th>
<th>Rain (mm)</th>
<th>EP (mm)</th>
<th>Excess (Rain - EP) (mm)</th>
<th>Drainage Minimum (mm)</th>
<th>Drainage Maximum (mm)</th>
<th>Net loss Minimum (mm)</th>
<th>Net loss Maximum (mm)</th>
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SOURCE: Simulation results from DSM, using daily weather data recorded at DeBilt.
NOTE: EP is potential evapotranspiration, estimated at 80 percent of open water evaporation.

Table 8.5
SPRINKLING START AND STOP VALUES USED IN SIMULATION

<table>
<thead>
<tr>
<th>Stop Value (a) (all GIFTs)</th>
<th>Start Value (a) GIFT=20 mm</th>
<th>Start Value (a) GIFT=25 mm</th>
<th>Start Value (a) GIFT=30 mm</th>
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</table>

(a) Measured in mm above damage level.
Table 8.6

SOIL MOISTURE FUNCTIONS BY SOIL GROUP AND ROOT ZONE

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<th>Soil Group</th>
<th>EA/EP</th>
<th>Soil Moisture (in mm), by Root Zone</th>
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<tr>
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<tr>
<td></td>
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<td></td>
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<td>1.000(a)</td>
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<td>1.000(b)</td>
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SOURCE: Based on data from Ref. 8.1.

NOTE: EA/EP is the ratio of actual to potential evapotranspiration.

(a) Damage level.
(b) Field capacity.
<table>
<thead>
<tr>
<th>System</th>
<th>Field Area (ha)</th>
<th>Gift Rate (mm/hr)</th>
<th>No. of Sets</th>
<th>Sprinkling Rate (mm/hr)</th>
<th>Moving Time (hr)</th>
<th>Moving Cost (Dfl/mC31)</th>
<th>Energy Cost (Dfl/ha)</th>
<th>Annualized Investment Cost (Dfl/ha)</th>
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<td>0.0361</td>
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**SOURCE:** Sprinkler system design and cost model output for least-cost systems, given the configuration, field size, and gift.

**NOTE:** All systems have a 24-hour moving interval. The sprinkling efficiency is assumed to be 1.0 for all systems.
Table 8.8
CROP VALUES AND DAMAGE COEFFICIENTS USED IN SELECTING SPRINKLING POLICIES

<table>
<thead>
<tr>
<th>Crop</th>
<th>Value (Dfl/ha)</th>
<th>Reduction Point</th>
<th>Death Point</th>
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Table 8.9
PERCENT OF CROP DAMAGED AT REDUCTION POINT AND REMAINING YIELD

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Table 8.10
SUMMARY SPRINKLING STATISTICS FOR
CONSUMPTION POTATOES ON LOAM

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<th>Drainage (mm)</th>
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<th>Number of Moves</th>
<th>Operating Cost (Dfl/ha)</th>
<th>Damage Cost (Dfl/ha)</th>
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Normal Year: 1967

| 66         | 93.4          | 140.0                 | 56              | 155.20                   | 0.13                 | 155.33                                   |
| 61         | 88.4          | 135.0                 | 54              | 149.66                   | 0.93                 | 150.59                                   |
| 56         | 81.0          | 127.5                 | 51              | 141.34                   | 5.28                 | 146.62                                   |
| 51         | 76.6          | 122.5                 | 49              | 135.80                   | 25.90                | 161.70                                   |
| 46         | 68.5          | 112.5                 | 45              | 124.71                   | 90.31                | 215.02                                   |
| 41         | 58.8          | 97.5                  | 39              | 108.09                   | 284.68               | 392.76                                   |
| 36         | 55.7          | 87.5                  | 35              | 97.00                    | 534.09               | 631.09                                   |

Extremely Dry Year: 1976

| 66         | 4.9           | 272.5                 | 109             | 302.09                   | 277.07               | 579.16                                   |
| 61         | 2.3           | 262.5                 | 105             | 291.00                   | 352.46               | 643.46                                   |
| 56         | 0.0           | 255.0                 | 102             | 282.69                   | 412.87               | 695.56                                   |
| 51         | 0.0           | 242.5                 | 97              | 268.83                   | 595.49               | 864.32                                   |
| 46         | 0.0           | 227.5                 | 91              | 252.20                   | 834.80               | 1087.00                                  |
| 41         | 0.0           | 210.0                 | 84              | 232.80                   | 1087.70              | 1320.50                                  |
| 36         | 0.0           | 190.0                 | 76              | 210.63                   | 1379.28              | 1589.91                                  |

NOTE: Sprinkler system is Haspel configuration H1. Amount of water applied per irrigation, Gift, is 25 mm.
Table 8.11

SPRINKLING POLICIES

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<th>Field Capacity (mm)</th>
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NOTE: Field capacity, Damage point, and START are measured in millimeters above the wilt point. They are normalized for use in the PLOT Model. To make the conversion, subtract the damage point from the START value, divide by the root zone depth, and add the result to the moisture content in the root zone at the damage point (see Table 8.1). The START values shown in Vol. XII were rounded to the nearest 0.5 percent.
Appendix

SPRINKLER SYSTEM COST FUNCTIONS FOR BUIS CONFIGURATIONS
B2 THROUGH B5
Fig. A.1—Annualized total cost functions for Buis configuration B2
Fig. A.2--Annualized total cost functions for Buis configuration B3
Fig. A.3--Annualized total cost functions for Buis configuration B4
Fig. A.4—Annualized total cost functions for Buys configuration B5
Fig. A.5—Investment cost functions for Buis configuration B2
Fig. A.6--Investment cost functions for Buis configuration B3
Fig. A.7—Investment cost functions for Buis configuration B4
Fig. A.8--Investment cost functions for Buis configuration B5
Fig. A.9—Annualized investment cost functions for BuIs configuration B2
Fig. A.10--Annualized investment cost functions for Buis configuration B3
Fig. A.11—Annualized investment cost functions for Buis configuration B4
Fig. A.12—Annualized investment cost functions for Buis configuration B5
Fig. A.13—Labor cost functions for Buis configuration B2
Fig. A.14—Energy cost functions for Buis configuration B2.
Fig. A.15--Energy cost functions for Buis configurations B3 and B5