WATER RESEARCH COMMISSION

THE DEVELOPMENT OF PROCEDURES FOR DESIGN AND EVALUATION OF IRRIGATION SYSTEMS

UMBRELLA REPORT

MURRAY BIESENBACH AND BADENHORST INC
CONSULTING ENGINEERS AND ARCHITECTS
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PREFACE

The work presented in this report relates to research, funded by the Water Research Commission, into the development of computer based procedures for the selection and design of irrigation systems. The work has been limited to *pressurized* irrigation, excluding centre pivot and other mechanical move type systems.

The reports on this research have been compiled into three documents, *viz :*

The **Technical Report,** which amalgamates into one document the work presented previously in three annual progress reports for 1982/83, 1983/84 and 1984/85 respectively, as well as the work carried out over the past year (1985/86). The technical report consists of nine chapters, containing detailed presentations of the following :

* Rationale and basic philosophy underlying the research;
* State of the art reviews;
* Analyses of the newly developed algorithms;
* Program flow charts and selected listings;
* Reporting of results of applications of the computer programs.

The **Umbrella Report,** which provides the background to the work carried out over the past four years, as well as a **guide** to the more detailed analyses presented in the technical report. It is intended to give perspective on the routes followed during the course of the research (within the framework of the original commission) and the extent to which the original objectives of the project have been fulfilled. This document is presented in three sections, *viz:*

* **Background to the Project Development.** A brief discussion of the historical development of the project, starting from the original proposal and going through the yearly work programmes;
* **Summary of the Technical Report.** A chapter by chapter summary of the Technical Report;
* **Conclusions.** A summary of the research results and discussion on some directions for future research.

The **Executive Summary,** which is a brief document prepared principally for presentation to the Commissioners of the Water Research Commission. It has been drawn up in the form of a synopsis of the Umbrella Report.

The personnel involved in the research over the past four years have been :

In South Africa (MBB) : J.K Murray, M.A. Todes, J.W Badenhorst and B. Whittall.

In Israel (Karper Engineering) : D. Karmeli, G.Peri, E.Sabbagh and E. Erez.

Computer programming for the block design model was done in conjuction with F. Korb in Pretoria.

Writing of the reports was done by M.A. Todes

The Evaluation Committee responsible for this project consisted of the following members:

Mr D S van der Merwe (WRC) (Chairman)	
Mr J K Murray (MBB) (Vice- chairman)	
Mr C T Crosby	(Directorate of Agricultural Engineering and Water Supply)
Mr F J C Hugo	(- do -)
Mr D J du Rand	(- do -)
Mr F B Reinders	(- do -)
Mr A A Louw	(- do -)
Dr A J van der Merwe (Soil and Irrigation Research Institute)	
Dr G C Green	(WRC)
Mr D J van Rensburg (MBB)	
Mr P F Pretorius (Department of Water Affairs)	
Dr P C M Reid	(- do -)
Mr F P Marais (WRC) (Committee Secretary)	

The researchers would like to express their gratitude to the WRC for its support ; and also to the members of the Evaluation Committe for their input during the course of the work.

Murray, Biesenbach and Badenhorst Inc

April 1987

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1. BACKGROUND TO THE PROJECT DEVELOPMENT

1.1 Motivation

A research proposal for "The Development of Procedures for the Selection of Appropriate Irrigation Methods and for the Design of Irrigation Systems" was submitted by Messrs Murray, Biesenbach and Badenhorst Inc. (MBB), in association with Karper Engineering, to the Water Research Commission (WRC) in August 1981.

The principal objectives of the proposed research were listed as being :

"...to develop a **comprehensive procedure for the selection and design of irrigation systems**, such that :

(a) The selected methodology will be the most appropriate in terms of efficient use of water, energy, labour and other relevant economic factors.

(b) The design will consider all system parameters (pump characteristics, local headlosses, flow-pressure relations at each outlet, etc.), and will therefore be accurate.

(c) The expected irrigation performance of a given design will be related to the system and its operating conditions, so that the design can be evaluated, in order to enable the selection of optimal systems."

It was proposed that these objectives could be realized through the development of **computer based irrigation design models** and that the research would therefore concentrate on the development of these models. More specifically, the models would be structured to provide the designer with a series of parameters that enabled an evaluation of the designed system.

It was proposed furthermore that these parameters could be used to generate some general cost versus performance relationships which could be incorporated into normal design practice. For this purpose it was proposed that the research effort would include an analysis of a number of South African farms, using the design models.

Discussion held during the clearance meeting for consideration of the proposal (October 1981), centered around two main issues. Firstly it was considered important that **the design models should be practically applicable at a farm level**, rather than being purely theoretical. Secondly, the need to incorporate a thorough, **economically based, cost/benefit evaluation of the designed systems** was stressed. Accordingly, these two issues were incorporated as specific objectives of the research.

A budget for a three year research project was approved in March 1982, and work commenced in June of that year.

MBB entered into an agreement with Professor D. Karmeli of Karper Engineering Ltd. (Israel) to carry out the work on a joint project basis. Professor Karmeli was appointed as Principal Researcher, and under his direction, two separate research teams were appointed. The first, which consisted of engineers from Karper based in Israel, worked on the theoretical aspects related to the model development. The second team of engineers from MBB, based in South Africa, worked on the field-based data collection.

1.2 First Year

The work during the first year of the research was divided into six specific tasks as follows :

Task 1 : Classification of irrigation practice in South Africa on a regional basis, for the purpose of identifying the most suitable areas for an in depth survey of selected farms (task 2). A brief report on this work was compiled and the work was then extended into a review and analysis of the state of the art in the development of crop water-yield relationships. These relationships were seen as being the key to the economic evaluation of the designed systems.

Task 2 : In depth surveys of the irrigation systems operating on a number of selected farms, with the aim of using the information from these surveys to test the design models once they were operational.

Difficulties were experienced with this aspect of the work on two counts : firstly, original design data on the operating systems was difficult to come by and in many instances was incomplete. Secondly, this work was carried out simultaneously with the work in tasks 3 and 4, which concentrated on the development of the design models. Thus at that stage the exact requirements of the design models were not fully defined and it was difficult to establish the precise needs from the surveys. This problem was exacerbated by the fact that the design models were being developed by a team working in Israel, whilst the surveys were being carried out in South Africa.

Task 3 : A review of the state of the art of current design practices, aimed at identifying the specific shortcomings of current practice, and developing approaches for the development of the proposed computer based design models. This work resulted in a classification of the design process into three distinct modules, namely preliminary design, block design and mainline design. For each of these modules a set of specific design parameters was formulated.

Task 4 : This task concentrated on the mathematical formulation of the algorithms to be incorporated into the proposed computer based design procedure. Separate models were formulated for each aspect of the design process, as identified in task 3.

Task 5 : A review of the state of the art in the evaluation of irrigation systems. Most of the work in this subject relates to the evaluation of systems already in operation in the field. However it was felt that this work could provide a basis for the required evaluation model.

Task 6 : Extension of the work in task 5 to the formulation of an evaluation model, to be incorporated into the computerized procedures. A model was proposed for the overall evaluation of a completely designed system. It incorporated an assessment of the expected yield that would result from the designed system and a dynamic programming routine to optimize the operating regime for the designed system.

1.3 Second Year

The work during the second year concentrated principally on utilizing the work done in the first year, in tasks 3 to 6, to develop the proposed computer models. The programs were written in PASCAL for the HEWLETT PACKARD 9816 computer. Three specific sets of programs were developed, as follows :

Preliminary Design/Emitter Selection : The computer programs for preliminary design incorporated : a data base containing information on the operating characteristics of emitters, to be used in the selection of an emitter; a program to calculate the basic agronomic parameters regulating the preliminary design process; and a program to incorporate the agronomic parameters with the information in the emitter data base in order to generate a list of feasible emitters for a given design.

Block Design : The block design process involves determination of the diameters of the in-field pipe network, together with their operating hydraulic characteristics. The computer models that were developed during this phase of the work utilized poly-plot type algorithms for determination of the pipe diameters, and incorporated a block evaluation program. This latter program provided an assessment of the various economic factors related to the block design.

Mainline Design : The computer programs developed for mainline design incorporated a linear programming algorithm for optimization of the trade off between capital and operating costs.

1.4 Third Year

The third year of the research entailed using the design models to design systems for the farms surveyed as part of task 2, described above. These designs were then to be compared with the existing designs on these farms, in order to derive conclusions about both the effectiveness of the new design procedures and the prevailing cost versus performance relationships for South African conditions.

1.5 Fourth Year

At the end of each year of the research, a comprehensive report on the work carried out during the preceding year was presented. At the end of the third year, a Subcommittee of the Project Evaluation Committee was convened by the WRC, with a brief to consider the three annual reports, prior to their final acceptance at a concluding meeting of the Evaluation Committee. This Subcommittee called for comments on the three progress reports from various people involved in the research and a set of documents was issued six months after the end of the third year, summarizing these comments.

In general, it was felt that :

* the models did not provide the type of economic evaluation that had been specified as part of the objectives of the project;
* the three progress reports did not satisfy the WRC's requirements for final project reporting; and that a single document synthesizing the work covered in the progress reports should be produced.

In addition, some conceptual errors in the design algorithms and arithmetic errors in the evaluation algorithms were identified.

In order to enable MBB to attend to these comments, the WRC extended the project by a further six months. Initially, the work involved trying to utilize the computer programs that had been developed by Karper in Israel during the first three years of the research. The computer models had to be modified in order to rectify the errors that had been identified previously and to provide the required evaluation capabilities. However, this proved to be difficult and it was decided that it would be easier to redevelop the programs.

Two new sets of programs were developed. The first, written in BASIC for the IBM PC, covered mainline design; and the second, written in PASCAL also for the IBM PC, covered the block design problem. In developing these programs, the work concentrated firstly on making the evaluation algorithms as comprehensive as possible and secondly on making the computer programs as "user friendly" and flexible as possible; thereby addressing the objectives of the project as summarized above.

2. SUMMARY OF THE TECHNICAL REPORT

The technical report is divided into three parts as follows :

* **Part 1 : Basic Theory.** This section deals with the motivation for the research, and covers the theory that forms the basis of the research work.

* **Part 2 : The Models.** This section gives a full analytical description of the design models that have been developed.

* **Part 3 : Results.** This section describes some applications of the models, and summarizes the conclusions that have emerged from the work.

Within each of these sections, the individual chapters are as follows :

Part 1 : Basic Theory

Chapter 1 : Rationale
This chapter covers the motivation for the project.

Chapter 2 : Systems Analysis of the Design Process
This chapter provides an analysis of the irrigation design problem, identifying each different aspect of the process and the respective design parameters.

Chapter 3 : Review of Irrigation Quality Analysis
A review of the state of the art of evaluation of irrigation systems, leading to proposals for the computer model.

Part 2 : The Models

Chapter 4 : Block Design
Details of the block design model, and the associated computer programs.

Chapter 5 : Evaluation of the Block Design
Details of the evaluation model that forms part of the block design process.

Chapter 6 : Mainline Design

Details of the mainline design model and computer programs.

Part 3 : Results

Chapter 7 : Applications of the Block Design Programs

Description of some applications using the models.

Chapter 8 : Applications of the Mainline Design Programs

Description of some applications using the models.

A summary of each of these chapters is presented in the following pages.

2.1 Chapter 1 : Rationale

This chapter presents a basic motivation for the research project. Two specific topics are discussed. The first concerns the irrigation design problem itself and the aims of the work in terms of improving current approaches to irrigation design. The second topic is the impact of recently developed computer aided design technologies in engineering design. Discussion is given on the potential advantages of incorporating these technologies into the irrigation system design process.

A brief review of the irrigation design process is given, in which the design problem is related to the determination of two sets of characteristics, namely hardware and system characteristics. The hardware characteristics include the physical attributes of an irrigation system, such as the type and size of the emitters, the pipes and the accessories (valves, fittings and pumps). The system characteristics include the non-physical attributes of a system, such as the system capacity, the operating regime, the layout of the pipes and the system performance.

A generalized design process consisting of five distinct steps is outlined. These steps are respectively :

a) Establishing the operating constraints.
b) Selecting an emitter and thereby establishing the actual operating regime.
c) Block design.
d) Mainline design.
e) Establishing the pumping and control systems.

From a description of these five steps, the basic criteria currently used for the design of irrigation systems are identified as :

* An operating regime defined by pre-determined soil, plant and field-geometry characteristics.

* Uniformity of application defined by adherence to the 20% rule (maximum variation of pressure in a given block limited to 20%).

* Minimum system and operating costs.

* Maximum yield.

A number of shortcomings of current approaches to irrigation design are then discussed. These include :

* The use of the minimum cost/maximum yield criteria rather than a maximum profit approach. In this regard, the potential for so called "deficit irrigation", or deliberate under-irrigation in order to achieve higher returns on investment, is discussed.

* The need to rationalize the final design in terms of a well defined set of objectives.

* The need to measure the expected performance of the final design on the basis of a set of explicit parameters, rather than on the basis of the 20% rule, which is a surrogate measure.

* The need to identify and understand the implications of the various trade-offs involved in the design process, such as cost versus performance, system versus operating costs, block network versus mainline network and flexibility of operation.

The research attempts to address these shortcomings in the formulation of the models.

Finally, the development of computer aided design (CAD) technologies in the engineering design process is discussed. The different types of systems are described, and the fact that these systems do not provide an "A to Z push button" solution to the design process is stressed. Rather, they provide the engineer with a tool to investigate aspects of the specific design problem that could not practically be considered previously. The research aims to incorporate the full potential of CAD technology into the development of the design models.

In summary the aims of the research are given as :

* The carrying out of a comprehensive systems analysis of the design process.

* The formulation of measurable performance and quality of irrigation related design criteria, for use in the design process.

* The development of a suite of programs for computer based design of irrigation systems, utilizing the full potential of CAD technologies.

* Formulation of cost versus performance relationships based on a sensitivity analysis of the various design parameters.

2.2 Chapter 2 : Systems Analysis of the Design Process

This chapter aims to provide a systematic analysis of the whole process involved in the design of irrigation systems. This is done for the purpose of structuring and then developing the computer based design models. The analysis is carried out in four parts, as follows :

* Firstly, the requirements of the design process are examined, leading to an identification of the individual components of an irrigation system that have to be designed.

* The second step is to identify the phases involved in the design process. In other words, to assign the design of the numerous components identified in the first step described above, to a series of distinct design phases and thereby build up a structure for the design process.

* The third step involves more detailed analysis of each of the design phases, in order to identify the specific design problems associated with each of these phases. This entails identifying : the input requirements for each phase; the individual design steps contained within each phase; the general design routines and constraining factors related to each of these design steps; and finally, the output from each phase.

* The last part of the systems analysis looks at the principles involved in the structuring and design of the actual computer programs.

In the first part of the analysis, the components that have to be designed are classified into two groups, as mentioned in the review of Chapter 1 above. These are, respectively, hardware and system characteristics. Table 2.1 shows a list of the components contained in each of these groups. The actual design requirements in each case are listed under the component, and the right hand column shows the design parameters which affect the design of each component.

From this classification, a structure for the complete design process has been developed, as shown in figure 2.1. It can be seen from the figure that the basic process consists of three distinct phases, namely input, design and output. Within the design phase, a further three sub-phases or "modules" have been identified. These are respectively :

Table 2.1 System components and associated design parameters

	Component	Design Parameters
	Hardware	
i.	Emitters - type	Spacing; Nominal operating pressure; Costs; Pressure/discharge relationship; Operating regime;
ii.	Block network - lateral pipe diameters - manifold diameters	Hydraulic grade line; Allowable pressure variation; Coefficient of uniformity; Pipe alignments; Topography; Pipe costs;
iii.	Mainline network - pipe diameters	Hydraulic grade line; Pipe costs; Energy costs; Flow and pressure requirements;
iv.	Control elements - valves : type, size; - flow and pressure regulators : if needed, type, size - meters : if needed, type, size - automation equipment : if needed, type - filters : if needed, type, size	Flow and pressure requirements; Hydraulic grade line; Discharge volumes; Water quality; Costs;
v.	Pumps - main pump size - booster pump sizes - fertilizer injection equipment : if needed, type, size	Hydraulic grade line; Discharge volumes; Flow and pressure requirements; Costs;
	System characteristics	
i.	Capacity - maximum system discharge - flow and pressure distribution - system application rate - maximum application depth	Pump size; Pipe sizes; Emitter discharge; Max. block size; Emitter pressure; Emitter spacings; Irrigation set time;
ii.	Layout and alignments - division of field into blocks - emitter spacings - orientation of laterals - positioning of manifold - location of block valves - configuration of mainline network	Operating regime; System application rate; Pressure and flow requirements of emitters; Maximum length of a single or double diameter pipe; Topography; Pressure and flow requirements of valves;
iii.	Control system - location of control elements - degree of automation	
iv.	Operating regime - irrigation set time - irrigation cycle length - timing of irrigation sets (i.e. times of the day, days of the week) - sequencing of block valves - filter flushing programme - fertilizer injection programme	Readily available soil moisture; Peak daily irrigation requirement; Number of irrigation blocks; System capacity; System application rate; Degree of automation;
v.	Pumping requirements - maximum pumping capabilities - the pumping regime, including operation of booster pumps	System capacity; Operating regime; Hydraulic grade line; Flow requirements;
vi.	Performance - coefficient of uniformity - application and requirement efficiencies - capital and operating costs - return on investment	All design components

* **Preliminary design;**
* **Block design;** and
* **Mainline design.**

Figure 2.1 illustrates the fact that the design process does not involve starting at a particular point and working steadily through a number of routines until the design is complete. The inter-relations between the various components are complex, and the design process therefore involves continuous iteration, both within and between each module.

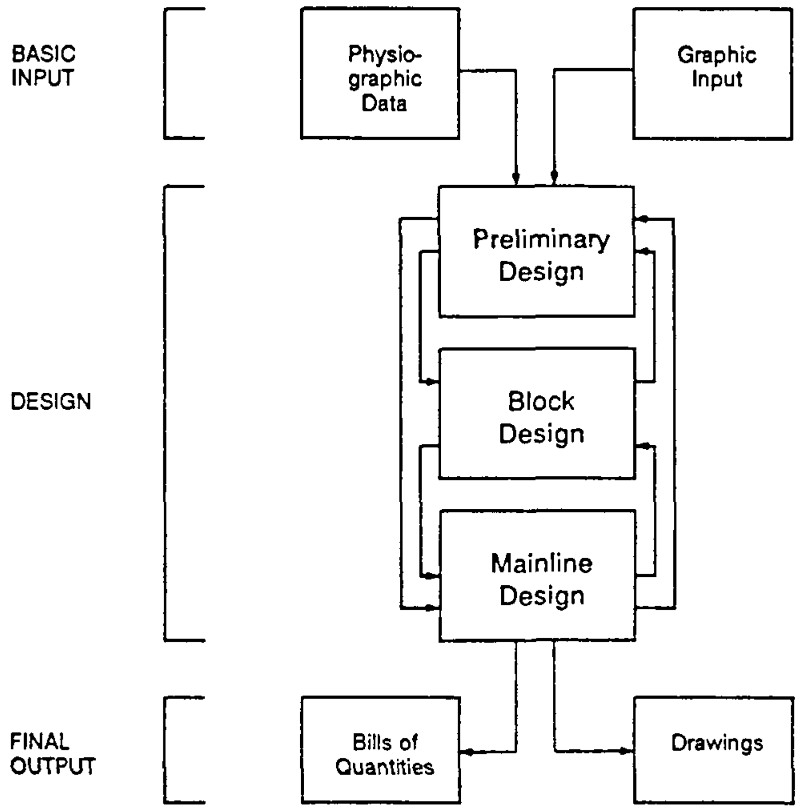


Figure 2.1 : Phases in the Design Process

Figure 2.2 shows the individual design steps in each of the three modules, together with the input requirements and the output from each of these steps. An analysis of the specific design problem related to each step is given in the technical report.

The design and structuring of the computer programs is considered to be an important aspect of the research, since their utility as a design tool is directly affected by their efficiency of use and their accuracy. The more flexible they are, the greater the extent to which the

INPUT	MODULE	OUTPUT
	PRELIMINARY DESIGN	
* Soil, climatic, crop data * Emitter operating characteristics * Topography, field size, operating regime	* Calculate soil/plant/water constraints * Select emitter * Calculate operating characteristics * Subdivide the field into blocks	* Operating regime : -irrig. cycle length -irrig. set time -timing of sets * Layout : -division into blocks -emitter spacing * Emitters : -type -nominal discharge * Capacity : -system applic. rate -max. applic. depth
	BLOCK DESIGN	
* Pipe alignments, topography, allowed head loss * Crop yield & economic data	* Determine pipe-network alignments * Carry out hydraulic calculations to determine lateral pipe diameters * Same for manifold diameters * Calc. system performance	* Block Network : -pipe diameters * Capacity : -pressure & flow requirements * Performance : -all values * Control : -valve sizes & locations * Layout : -alignments of laterals & manifold * Operating regime : -operating point
	MAINLINE DESIGN	
* Valve pressure & flow requirements, topography, energy costs	* Establish the layout * Sequence the valves * Optimize diameter selection & pumping requirements * Establish control elements	* Mainline Network : -pipe diameters * Pumping : -main & booster pump sizes -pumping regime * Operating Regime : -valve sequencing * Capacity : -max. discharge in the system * Layout : -mainline configuration * Control : -all elements

Figure 2.2 : The Design Modules

designer can explore different design considerations. Good software design relates to three aspects of a program's operation. These are firstly the actual analysis routines, secondly the the process of validation of input data prior to executing the various analyses and thirdly the nature of the man-machine interface.

The program is operated via an interactive dialogue with the designer. The purpose of this dialogue is to assist the user in inputting the required data and then to guide him through the design process. In this latter regard the interaction should not be an inflexible step by step process, whereby the user's role is a passive one of merely inputting the data and then reading the results of the analysis. Since ultimately all design decisions should be made by the designer, the interactive procedure should ensure that the user receives full information regarding all options in a multi-objective problem, and in such a form that he is able to make a correct and well informed decision.

2.3 Chapter 3 : Review of Irrigation Quality Analysis

This chapter consists of a review and analysis of the literature related to the evaluation of irrigation systems, for the purpose of formulating an evaluation model as part of the design procedure. Most of the reported work relates to the evaluation of irrigation systems operating in the field. Such evaluation generally entails measuring the quantities of water released by the system throughout the field. On the basis of these measurements a number of different statistics can be derived, which characterize the quality of the irrigation.

These statistics can be classified into two groups as follows :

* **Efficiency,** which measures the extent to which the water drawn into the irrigation system is usefully used.

* **Distribution Uniformity,** which measures the extent to which the quantity of water applied during an irrigation varies throughout the field.

A large number of different efficiency and uniformity measures have been proposed in the literature, and these are all reviewed in the technical report. An analysis of all of these statistics shows that a combination of two of the efficiency measures and one of the uniformities provides an adequate picture of the irrigation quality, and that in fact all of the other measures can be equivalenced to these three statistics. They are, respectively :

* **Water Application Efficiency,** which is the fraction of the total irrigation application that is made available to the plant, rather than being lost to evaporation and deep percolation.

* **Water Requirement Efficiency,** which is the fraction of the plant water requirement at the time of irrigation that is met by the irrigation.

* **Christiansen Uniformity Coefficient (UCC),** which is given by :

$$UCC = 100\left[1 - \left(\sum_{i=1}^{N} \left|X_i - \bar{X}\right|\right) / N\bar{X}\right] \qquad (1)$$

Where N = the number of observations X_i

$\bar{X}$ = the average application depth.

These three measures are therefore incorporated into the evaluation model, as discussed in Chapter 5. In order to extend this analysis further, to include measures of the economic cost/benefit ratios resulting from a designed system, it is necessary to be able to estimate the crop yield that will result from the use of the irrigation system. This in turn requires the use of the so called *yield/water* functions that have been formulated in the literature. Crop yield has been found to be dependent on numerous factors and it is difficult to isolate the crop response to water on any consistent basis. Nevertheless, some empirically based relationships have been proposed in the literature, and these can be used for the required analysis.

The total yield, Y, expected from a field of area A_t is given by the integral :

$$Y = \int A_t \, y(i) \, f(i) \, di \qquad (2)$$

Where
$y(i)$ = the yield per unit area achieved as a function of the irrigation depth i.
$f(i)$ = the frequency distribution function of irrigation depths, for a given irrigation.

Then, given the total yield, Y, a profit maximizing objective function can be expressed by :

$$\text{Max[NE]} = Y(P_y - K_y) - V_a C_w \qquad (3)$$

Where
NE = the net earnings achieved through irrigation.
P_y = the price earned per unit of yield.
K_y = total production costs per unit of yield.
V_a = the total volume of water applied in the field.
C_w = the irrigation system capital and operating costs, rationalized over the expected life of the system and expressed in terms cost per unit of water.

The constraints required to formulate the full optimization problem consist of the complex set of functions determining the cost C_w and the volume V_a, together with the integral in equation 2. One of the most significant problems related to the above models is the obtaining of sufficiently accurate yield/water functions. It is believed however, that with the on-going research and development of these relationships, various adaptations of the models will increasingly be incorporated into the design process. One such adaptation is proposed in Chapter 5 of the Technical Report.

2.4 Chapter 4 : Block Design

The main elements of the block design problem are :

* determination of the pipe alignments;
* determination of the pipe sizes;
* evaluation of the system performance resulting from the designed system.

2.4.1 Pipe alignments

These are normally established largely on the basis of the designer's intuition. The lateral pipes are aligned parallel to the planted rows; and the manifold then transects the laterals. The position of the manifold is determined on the basis of both practical convenience and hydraulic considerations.

Practical convenience is dictated by factors such as accessibility to pipes in the field and the position of existing elements. The hydraulic considerations arise out of the fact that the manifold may divide the laterals into two sets, lying on either side of the manifold. Ideally, the manifold should be positioned such that the lengths of the laterals running uphill away from the manifold are maximized, within the constraints of the allowable pressure loss in the system.

2.4.2 Pipe diameters

The pipe diameters are established using the allowed pressure variation in the system as a design parameter. The general procedure for a given pipe involves first of all establishing a pressure envelope, defined by the topographic elevations along the length of the pipe and the allowable pressure variation within the pipe. The upper and lower limits of the envelope represent the maximum and minimum allowable *hydraulic grade lines* respectively, along the pipe being designed. Then, starting at the furthest end of the pipe with the smallest available diameter, the pressure head in the pipe is calculated for points along its length, working back towards its inlet. This pressure head will increase exponentially as the flow in the pipe increases because more and more outlets are included along the length being considered. Considering this curve in the other direction (i.e. in the direction of flow in the pipe), the exponential shape represents the decreasing rate of head loss due to friction, per unit length, as the flow in the pipe decreases. As soon as the **actual** hydraulic grade line for the diameter of pipe being considered starts to rise steeply towards the upper limit of the allowed envelope, the pipe is replaced by a larger diameter, thereby reducing the rate of pressure loss due to friction. The process then continues until the inlet is reached. In this way a set of diameters and their respective lengths are determined, such that the pressure variation in the lateral is contained within the allowable limits.

Several algorithms for carrying out this design process and simultaneously obtaining a least-cost design have been proposed in the literature. They are reviewed in the technical report. The model developed as part of the research program is based on the widely used "poly-plot" graphical process, as formalised for computer applications by Professor Perold at the University of Stellenbosch (see the technical report for full references). A feature of the model is that it incorporates accurate calculations of the emitter flow/pressure relationship, rather than assuming a constant discharge along the length of the pipe.

The full block design process entails carrying out the diameter design for each lateral in turn, and then using the results from the lateral design in a similar procedure for the manifold. At the end of this process, the pressure and flow required at the block valve, for irrigation of the block, are known.

2.4.3 The computer models

The computer models for block design have been integrated into a single package, as shown in the synoptic map in Appendix 1. The package is menu driven and consists of three principal modules : the **layout module**, the **design module** and the **evaluation module.**

Layout entails specifying details of the system alignments such as :

* the emitter and lateral spacings;
* the lengths of the laterals and the manifold; and
* the elevations of the pipes.

Once this has been done, then the actual pipe design can be carried out.

The pipe diameters for individual laterals can be designed using the algorithm described above. Output from this procedure includes :

* a display of the pipe flow and pressure characteristics;
* a graphical plot of the allowed pressure envelope and the pipe hydraulic grade-line (see figure 4.1); and
* a summary table of the operations performed in the design proces.

Alternatively a series of laterals can be designed by proportional extrapolation of results previously obtained for two other laterals that have already been designed. This facility enables the designer to ensure that the positions of any pipe changes lie along a straight line in a field. This greatly facilitates the installation of the system.

Once a lateral has been designed by the computer, the designer may alter the design manually by editing a displayed table of the design results, as shown in figure 4.2. As can be

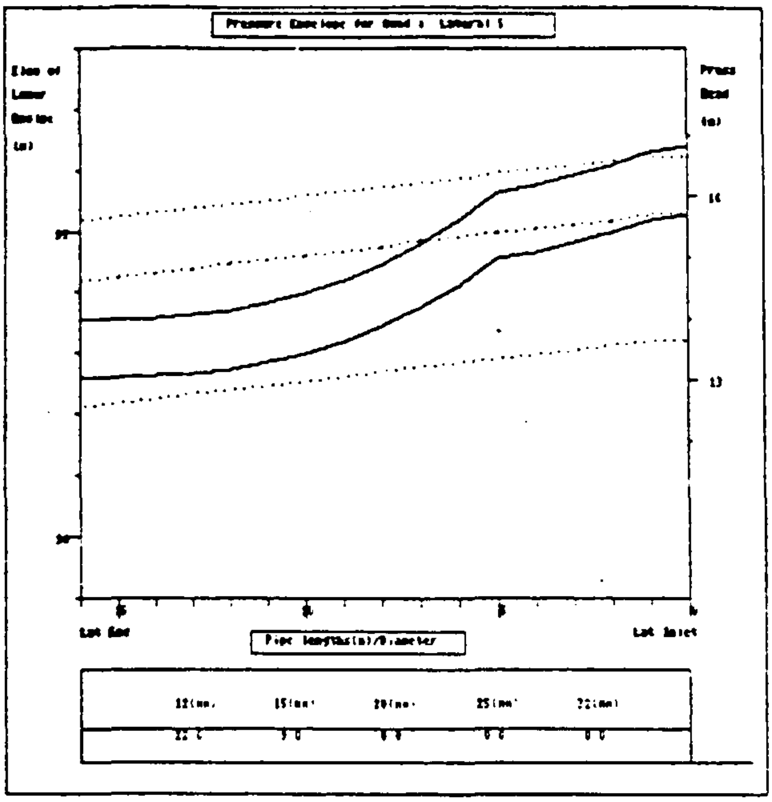


Figure 4.1 : Graphical plot of the pressure profile resulting from the lateral design process

seen in this figure, the designer has a continuously updated display of the cost of each lateral, the total cost of all designed laterals and the total lengths of each pipe diameter used. Thus the effects of any changes can be monitored by the designer.

In addition to the three principal modules, a series of **"pop-up" utilities** have been developed as an aid to the operator. These utilities can be evoked at any stage during operation of the main program by pressing the relevant function key on the computer keyboard. They operate by popping up a separate window, over the current display on the computer screen, without altering whatever is currently displayed.

<Proj - 1> * MBB 30/09/86

LATERAL DESIGN (lengths / elevations / pressure heads in meters)

<Quad a> <Quad b> <Quad c> <Quad d>

Lat	15(mm)		20(mm)		25(mm)		32(mm)		40(mm)		Totals		
#	Len	#Em	Len	#Em	Len	#Em	Len	#Em	Len	#Em	Len	#Em	Cost
1	24	8	10	3							34	11	25.64
2	27	9	10	3							37	12	26.73
3	30	10	10	3							40	13	27.82
4											00	00	00.00
5											00	00	00.00
6											00	00	00.00
7											00	00	00.00
8											00	00	00.00
											00	00	00.00
	81		30		00		00		00		111		R80.19

[* 3/ 20]

Figure 4.2 : Table of results of the lateral design process

The utilities provided are respectively :

* A **maximum length calculator**, which enables a rapid calculation of the maximum lengths of pipe for two diameters, that can be used for a given emitter operating on a given slope at a predefined nominal pressure and with a predefined allowable pressure loss. This facility is useful for determining the optimal positioning of the manifold.

* paging through and updating both the **pipe and emitter databases**. These databases provide all relevant information on available equipment, such as costs, sizes and in the case of the emitters, performance characteristics.

Figure 4.3 illustrates the computer screen during simultaneous operation of the maximum length calculator and the emitter database. The designer can page through the available emitters to find the required one and then transfer it across to the maximun length calculator.

The block design programs also include the evaluation models, which are discussed in Chapter 5.

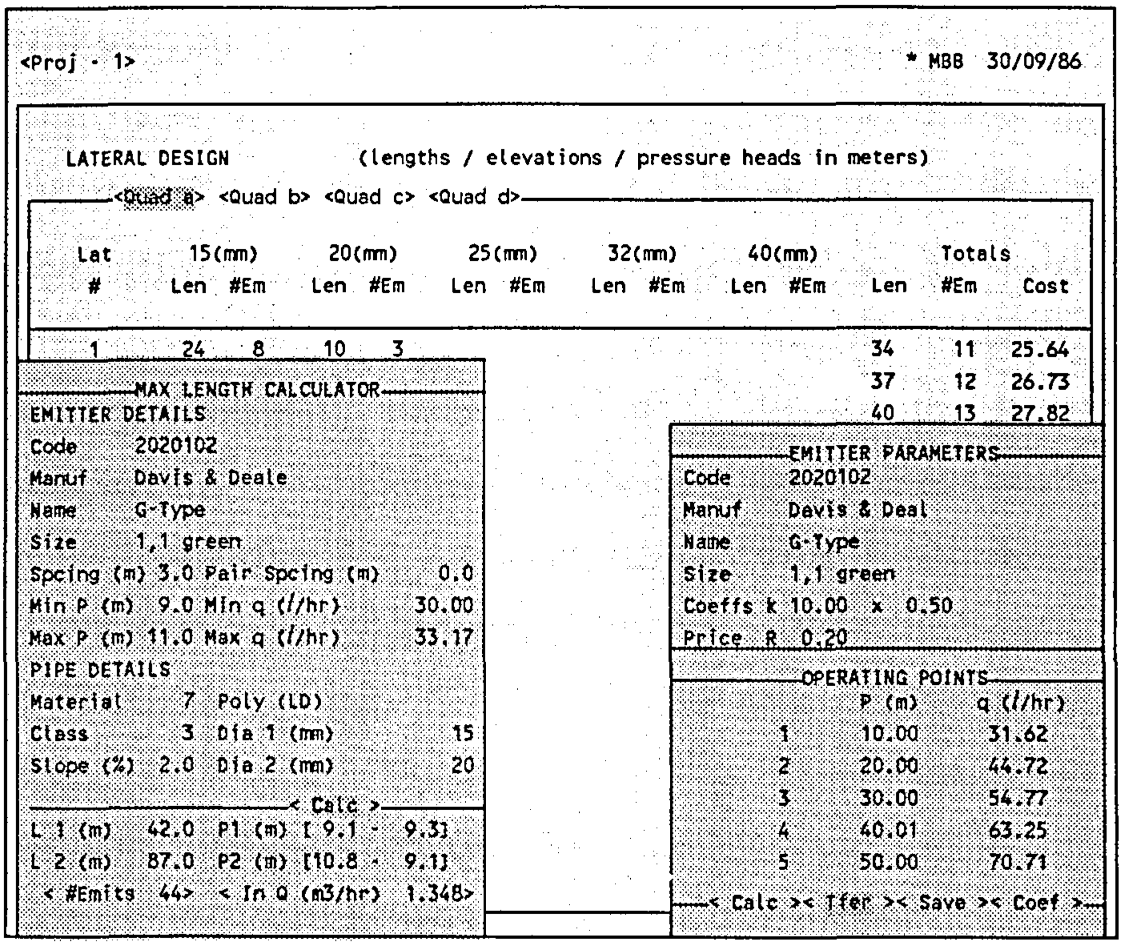


Figure 4.3 : The maximum length calculator and emitter database "pop-up"

2.5 Chapter 5 : Evaluation

This chapter extends the work reviewed in Chapter 3, leading to the formulation of an evaluation model that forms part of the block design process. The chapter is presented in five sections as follows :

2.5.1 Basic Model Structure

The proposed model contains two distinct evaluation phases. The first looks at the *water distribution uniformity* that will result from the designed system and the second involves the *economic cost/benefit analysis*. An outline of the basic input and output in each of these analyses is shown in figure 5.1.

The water distribution pattern resulting from the designed system will in fact vary depending on the pressure at the inlet to the block. For this reason the evaluation is carried out for four different inlet pressures, thereby enabling the designer to develop a feeling for the sensitivity of the overall system performance to this parameter. The particular parameters that are considered in this analysis are listed under the "OUTPUT" column in figure 5.1.

Using these parameters, the designer is able first of all to assess the overall performance of the designed system in terms of its distribution functions, and secondly to establish the optimal inlet pressure at which to operate the system.

The second evaluation analysis entails estimating the yield that will result from the designed system and then comparing the income resulting from the yield with the various costs involved in generating this yield. The evaluation is carried out on the basis of the economic return, both per unit area and per unit of water used. The specific parameters generated by this analysis are shown in figure 5.1.

The main measure of *financial return*, generated by the analysis, is the **equivalent annual worth (EAW)**, which is established as follows : the Net Present Worth (NPW) of the system is calculated using diferent inflation rates for *energy costs*, other *production costs* and *producer prices* respectively. The EAW is then the NPW, converted back to an annual figure on the basis of the expected life of the system and the prevailing *general* rates of inflation and interest, which reflect the overall cost of money.

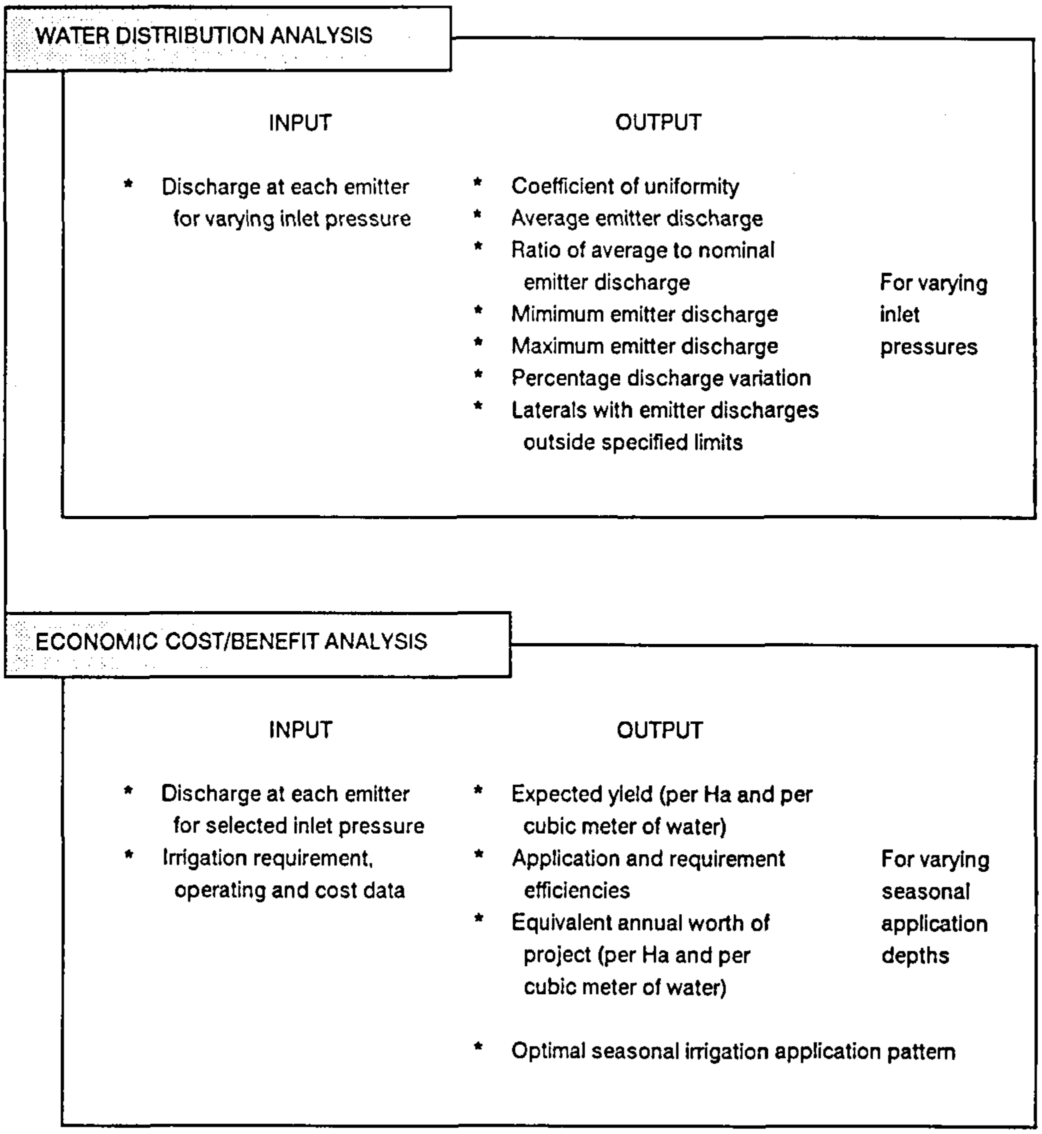


Figure 5.1 : Evaluation Model for Irrigation System Design

2.5.2 Operating Point

All of the parameters that result from the economic evaluation are dependent on the actual seasonal application depth. This depth is a function of the real time operation of the system and can in fact be varied within a range from zero up to the capacity of the system. It is therefore referred to as the "operating point" of the system.

Since a system is normally designed to meet the expected seasonal irrigation requirement at minimum cost, this requirement level should correspond to the capacity of the system. The irrigation requirement is defined as the amount of water required to produce maximum yield. If the system is operated throughout the season at less than its capacity, then the yield may not be maximized, but the *operating* costs will be reduced. There is thus a trade off which may imply a better economic return from so called **deficit irrigation.** The economic return may be further improved by purposely designing the system for a lower capacity (less than the seasonal requirement), thereby also reducing the *capital* costs.

The evaluation model includes an analysis of this aspect of the design. A dynamic programming algorithm has been developed to determine the optimal seasonal operating point for the designed system, based on the expected requirement in individual periods during the season. The parameters listed above for the economic evaluation are generated for five different operating points and the results plotted on a graph which shows the sensitivity of the system to the operating point.

2.5.3 Yield

The question of the water/yield function is a sensitive one as the issue is not fully resolved in the literature. In practice, any accepted function could be incorporated into the analysis. The model which has been used is the linear one, which is given by :

$$\begin{aligned} (1 - Y_a/Y_m) &= k_y\,(1 - I_a/ET_m) \qquad \text{for } I_a < ET_m \\ Y_a &= Y_m \qquad \text{for } I_a >= ET_m \end{aligned} \tag{4}$$

Where
- Y_a = the actual yield,
- Y_m = the maximum achievable yield,
- I_a = the irrigation application,
- ET_m = the maximum evapotranspiration, and
- k_y = is a factor relating the sensitivity of the specific crop to under-irrigation.

This model is supported by a wide body of literature, which is reviewed in the technical report.

2.5.4 Economic Analyses.

The most appropriate method of cost/benefit analysis to be incorporated into the evaluation model is also a contentious issue, since it is dependent on the objectives of the specific project being designed.

Specific issues that must be considered include :

* The **cost of water.** The basic cost of the water used for irrigation may be charged directly to the user by the supplier, in which case it is quite straight forward to calculate. However, in some cases, the water supply may be subsidized and then the rate to be included in the calculations depends on the purpose of the analysis.

When the available supply of water is limited and a number of alternative uses are being considered, then an *opportunity* cost can be attached to the cost of the water. This represents the potential additional benefits that could be derived from using the water elsewhere. The opportunity cost of water is particularly relevant in the case of deficit irrigation, where reduced application will result in a saving of water.

* The **interest (discount) rate** employed in the analysis. For normal investments of a private nature, the opportunity cost of the investment represents a reasonable measure for calculating the economic worth of the project. In other words, the discount rate can reasonably be taken as being equal to the prevailing bank rate, which is equivalent to the basic cost of money. However, there is varying opinion with regard to the evaluation of agricultural projects. One school of thought proposes that farmers generally take a long term view of their operations, and that any development cannot be evaluated purely in terms of the immediate return on investment that will be realised from the development. This would mitigate for lower interest rates. However, an opposing approach argues that the discount rate should reflect the high risk involved in all farming operations and should therefore be pitched somewhat higher than prevailing bank rates.

* **Inflation.** Several different methods exist for the incorporation of the effects of inflation into economic analysis. In the case of agricultural projects, the economic forces controlling the various facets of the project result in a number of different prevailing inflation rates. These include the rate of energy cost inflation, the inflation rate relating to production costs, inflation of producer prices and finally the general rate of inflation on the overall cost of money.

The analysis used in the proposed evaluation model uses a direct comparison of earnings versus costs. Apart from the provision for inclusion of the opportunity cost of the water, no attempt is made to formulate monetary values of any *indirect* costs or benefits that may accrue from the project.

2.5.5 The Computer Models

The computer model for evaluation attempts to provide the user with full flexibility to consider all the aspects of the evaluation which have been discussed above. The model operates from six different pages, or "screens", which the user can select at will from the evaluation menu.

The first two pages present the results from the *uniformity* evaluation, as shown in figures 5.2 and 5.3 respectively. The results are shown for four different inlet pressures. The user may input a new inlet pressure, for which the uniformity evaluation will be calculated or, alternatively, he can select the inlet pressure to be used for the *economic* evaluation.

Pages 3, 4, and 5 are used for inputting the required data for the economic evaluation and page 6 represents the results of this evaluation, as shown in figure 5.4.

<Proj - 1> * MBB 30/09/86

Evaluation of Block J1 : Page 1 - Uniformity Analysis

Inlet Pressure (m)	14.3	16.1	17.9	19.7
Inlet Flow (m3/hr)	12.4	14.5	16.9	19.5
Uniformity (%)	84.1	87.1	85.3	85.1
Ave q (*l*/hr)	26.4	30.7	33.0	34.8
Ave q/q nom	0.88	0.96	1.04	1.10
q min (*l*/hr)	21.4	24.7	32.7	31.0
q max (*l*/hr)	28.8	33.6	36.4	38.4
q variation (%)	18.1	19.2	20.3	21.4

Figure 5.2 : Results from the uniformity analysis of the block evaluation model

<Proj - 1> * MBB 30/09/86

Evaluation of Block J1 : Page 2 - High/Low Pressures

Laterals with Pressure Profiles Beyond Allowable Limits

Inlet Pressure (m)			
14.3	16.1	17.9	19.7
18a	None	1a	1a
19a		2a	2a
20a			3a
			4a
			5a
			6a

Figure 5.3 : Results from the uniformity analysis of the block evaluation model

GRABOUW APPLES 28/01/87

Economic Evaluation : ANALYSIS FOR CU = 98% : Av q = 48.6/hr

DEPTH (mm)	530	590	604	625	640
VOL ('000 m3)	1.06	1.18	1.21	1.25	1.28
YIELD					
Tons/ha	48.6	52.5	52.8	52.9	52.9
kg/m3	9.2	8.9	8.7	8.5	8.3
EFFICIENCY					
Applic - Ea (%)	99	98	96	93	91
Reqmnt - Er (%)	89	98	99	99	99
EQUIV.ANNUAL WORTH					
EAW (R/ha)	7348	8607	8672	8604	8549
EAW (R/m3)	1.39	1.46	1.44	1.38	1.34

OPTIMAL OPERATING POLICY DURING SEASON

PERIOD	1	2	3	4	5	6	7	8	TOTAL
Reqmnt (mm/cycle)	25	40	30	20					590
Applic (mm/cycle)	26	40	31	21					604

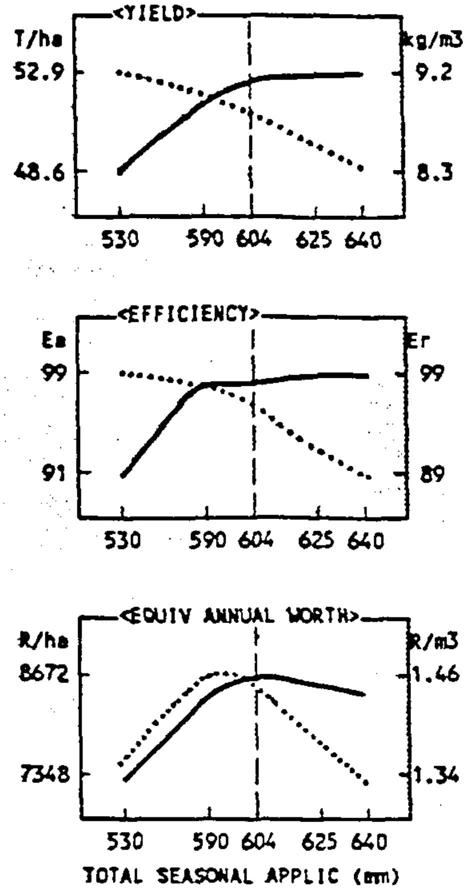


Figure 5.4 : Results from the cost/benefit analysis of the block design evaluation model

2.6 Chapter 6 : Mainline Design

The mainline design problem consists of three distinct elements, namely :

* The network layout;
* The sequencing (or scheduling) of the valves during operation; and
* Sizing of the pipes and pumps.

These three problems are inter-dependent, so that the solution to any one problem will affect the results of the other two. It is therefore difficult to establish a global optimum solution to the whole design problem. For this reason, the approach adopted has been to develop locally optimized solutions for each module, which can then be modified by a manually directed iterative process, based on the results obtained in each of the other design modules.

2.6.1 Network Layout

The layout problem consists of finding the lowest cost arrangement for connecting the source to each block valve.

In its simplest form, the solution to this problem might be seen to be the layout for which the total length of piping is minimized. However, there are trade-offs in the pipe sizing problem which involve exploiting the prevailing topography to offset pressure losses due to pipe friction. These may mitigate against selecting the shortest path layout. Thus the optimal layout is one for which both the capital costs of the pipes and the energy requirements for operation are minimized.

A practical optimization procedure has proved difficult to establish, since the number of possible layouts for any given situation is theoretically infinite. The proposed procedure entails the designer specifying a layout, which is then subjected to a rapid evaluation by the computer. The result of this evaluation yields a "first shot" estimate (prior to optimization of the pipe sizing problem) of the capital and operating expenses for the proposed layout. The designer may evaluate several different layouts before selecting a final one for further analysis.

2.6.2 Valve Sequencing

The objectives of the valve sequencing problem are twofold :

a) To minimize the pumping energy required at each irrigation shift.
b) To distribute the flow as widely as possible throughout the network in each shift, thereby minimizing the pipe sizes needed in the network.

This is a difficult optimization problem, which is not readily solved by any known techniques. It is further complicated by the fact that often, practical considerations override any sequencing patterns that may have been logical in order to satisfy the abovementioned objectives. For example it may be required to have blocks of the same soil-type grouped together in each schedule. Alternatively the schedule may be dictated by a pesticide spraying pattern which has an associated drying-off requirement.

The solution procedure therefore aims to produce an approximation of the optimum, which is both close to the optimum and efficient in its derivation. The algorithm developed in the research is based on the concept of the *degree of coincidence* of any candidate valve with the valves already allocated to the schedule under consideration. The degree of coincidence is calculated as the product of the length of a section times the flow in that section in excess of the established minimum flow, summed over all sections in the network. The steps of the algorithm are as follows :

1. The valve with the largest discharge requirement is allocated to the first shift.
2. For each remaining valve its *degree of coincidence* with the allocated valve is calculated and these valves are then ranked in order of increasing coincidence.
3. One valve is allocated to each remaining shift, starting from the valve that has the highest coincidence with the allocated valve and working down in decreasing order of coincidence.

An iterative procedure is now followed, starting with the first shift and then working with each shift in turn :

4. The tolerance, δ_j, by which the total discharge in shift j may deviate from the average shift discharge is set to 0.05 (ie. 5%).
5. The degree of coincidence of each of the remaining unallocated valves with the valves already allocated to shift j is calculated and the valves are ranked in order of increasing coincidence.
6. An allocation is attempted on the basis of :

    Working from lowest to highest coincidence;

    Keeping the total shift discharge less than $(1 + \delta_j)$ x the average shift discharge.
7. If no allocation was possible, then the value of δ_j is increased by 0.05, and the process returns to step 5.

    Alternatively if an allocation was made and j>1, then a backwards checking function is performed as follows :

    For each valve already allocated to a previously completed shift, the possibility is examined of improving the allocations by swapping with the valve that was allocated to shift j in step 6. A swap is made if :

* the discharges in each shift after the swap remain within the respective allowed tolerances of the average; and
* the combined degrees of coincidence of the swapped valves with the other valves in the respective shifts is less than for the swapped valves in their original shifts.

If a swap is made, the backwards checking function continues through the remaining allocated valves, with the last swapped valve in shift j as the candidate for the next swap.

8. If the discharge in shift j is now greater than $(1 - \delta_j)$ x the average then the shift is fully allocated. The algorithm returns to step 4 and continues for the next shift. If the shift is not yet complete, then the algorithm returns to step 5 and the process is repeated.

The whole process continues until all the valves are allocated.

2.6.3 Pipe and pump sizing

A trade-off exists between the pipe and pump sizes. The higher the pump pressure (higher pumping costs), the greater the amount of pressure that can be lost through friction in the pipes and hence the smaller the diameters (and the cheaper the cost) of the pipes needed in the network. By carrying out a present value analysis on the cost of pumping over the expected life of the system, the energy costs can be expressed in terms of current Rands per meter of pumping head supplied at the source. The cost of the pipes can be expressed in terms of current Rands per meter length of each diameter used in each pipe section. The problem can then be formulated as a *linear programming problem* (LPP), as follows :

* For each section ij of the network, a set of candidate diameters, m, is defined.

* The **decision variables** are then :

  X_{ijm} = the length of each candidate diameter used in each pipe section ij;

  XPM = the maximum pumping head available from the source pump;

  $XP(l)$ = the pumping head provided at each schedule l.

* The associated **costs** for each unit of the decision variables are respectively :

  C_{ijm} = the cost per meter length of pipe of diameter m.

  $K(l)$ = the present value cost per meter pumping head of operating the pump during schedule l

* The **objective function** is given by :

$$\text{Min}[K] = \sum_{ij} \sum_{m} C_{ijm} X_{ijm} + \sum_{l} K(l) XP(l) \qquad (5)$$

Where $\sum_{l}$ = the summation of all schedules l;

$\sum_{m}$ = the summation of all candidate pipe diameters, m, for pipe ij.

$\sum_{ij}$ = the summation of all pipes ij.

K = the total (present value) cost of the system.

* There are four **constraints** as follows :

Non-negativity, implying that the decision variables must all be non-negative.

Head loss, implying that for each valve, the combined head loss due to pipe friction and topographic differences, between the source and the valve, must not be greater than the difference between the source pressure and the required pressure at the valve.

Length constraint, which stipulates that the total length of all the candidate diameters in each section must add up to the length of the section.

Pumping head, which implies that the operating head in each schedule must not be greater than the maximum capacity of the pump.

Solving this LPP yields the optimum pipe diameter for each section of the network, together with the optimum pumping pressure at the source. If required, the problem formulation can be expanded to incorporate the inclusion of booster pumps. The operating pressure head of the booster pump becomes an additional decision variable in the objective function; and this pressure head is included in the calculations of the head loss constraint for affected valves.

2.6.4 The computer models

A synoptic map of the computer models for mainline design is shown in appendix 1. The programs are menu driven, with data input at each stage being in a tabular, fully editable format rather than on a line by line basis.

Figures 6.1 and 6.2 illustrate the output from the quick layout evaluation process. Figure 6.1 shows the details of each pipe section : connecting points, length, material, expected maximum operating pressure, first shot diameter selection and estimated cost. The selected diameters can be edited by the user and the new costs will be displayed immediately.

PROJ : GO 824 EVALUATION OF LAYOUT 1 : PIPING COSTS

Sect.	From	To	Length (m)	Material	Max Q (m3/hr)	Max H (m)	Class	Diam (mm)	Cost (R)
1	Srce	V 4	10.0	PVC	47	42	6	160	172.60
2	V 4	V 2	50.0	PVC	47	42	6	160	863.00
3	V 2	V 1	82.0	PVC	14	41	6	63	387.04
4	V 2	V 3	72.0	PVC	44	41	6	140	1 110.24
5	V 3	V 5	82.0	PVC	44	39	6	125	1 116.02
6	V 5	V 6	10.0	PVC	44	38	6	140	154.20
7	V 6	V 7	50.0	PVC	33	38	6	125	680.50
8	V 7	V 8	142.0	PVC	33	37	6	110	1 817.60
9	V 8	V9A	142.0	PVC	27	35	6	110	1 817.60
10	V9A	V9B	25.0	PVC	27	33	4	110	230.75
11	V9B	V10	187.0	PVC	18	33	4	90	1 170.62
12	V10	V11	84.0	PVC	18	32	4	90	525.84
13	V11	V12	84.0	PVC	18	32	4	75	440.16
TOTAL			1,020.0						10 486.17

Figure 6.1 : Results of layout evaluation process in mainline design

Figure 6.2 shows the analysis of energy costs for the proposed layout. The main table shows the expected power and energy requirements for the system for each irrigation schedule, together with the associated yearly and present value costs. Under the main table, ten separate parameters which affect the results in the main table are shown. These parameters can be edited by the user and the effects of any changes will be displayed immediately in the main table.

PROJ : GO 824 EVALUATION OF LAYOUT 1 : ENERGY COSTS

Sched.	Load Factor	Effic. (%)	Power (KW)	Energy (KWHrs/Season)	Seasonal Cost (R/Season)	Discounted Cost (R/m)
1	0.50	75	7	4 832	149	152
2	0.50	75	6	4 227	158	163
TOTAL (MAX) :			7	9 059	297	
CAPITAL/PRES. VAL. COST (R)			2 148		10 563	315

Power Capital Cost (R/KW)	300.00	Load Cost (R/KVA/Mnth) :	15.00
Pumping Hrs/Day :	18.	Fixed Costs (R/Mnth) :	0.00
Pumping Days/Cycle :	5.	Analysis Period (Yrs) :	25.
Pumping Cycles/Season :	15.	Interest Rate (%) :	15.0
Energy Cost (c/KWHr) :	8.	Energy Cost Inflation (%) :	18.0

Figure 6.2 : Results of layout evaluation process in mainline design

2.7 Chapter 7 : Applications of the Block Design and Evaluation Models

A typical apple orchard, located in Grabouw, has been used as a **test case for the design and evaluation models.** A first "base case" design has been carried out, and this has then been used for comparison with the results from a number of sensitivity analyses.

2.7.2 The Design Algorithms

Completion of the designs for this test case provided a good opportunity for making adjustments to the design algorithms. In particular, the mainline for the test caser is situated on a slope of 27%, and proved to contain all of the notoriously difficult elements of **steep slope design.**

Notwithstanding these difficulties, the algorithms performed well, and produced very satisfactory results. The mechanisms for introducing a "choking diameter" and for widening the allowable pressure variation envelope, worked appropriately for the steep slope case. Also, the feature of having the design parameters readily available through a "pop-up" window, proved to be most successful.

2.7.3 Sensitivity Analysis

The sensitivity analysis was divided into two categories. The **first** dealt with variations of the design parameters, and the **second** with variations of the input parameters of the economic evaluation model.

In the first set of tests, the most significant results were obtained for a series of variations of the allowable pressure variation, between 10% and 40%. When considering a 15% analysis period, the system capital cost had little influence on the overall profitability of the scheme and an allowable variation of 10% gave the best return on investment. However, if a shorter term analysis period (5 years) was considered, then the traditional 20% variation was shown to be optimal.

2.8 Chapter 8 : Applications of the Mainline Design Model

Four different farm irrigation mainline networks have been analysed, in order to test both the efficiency of the design routines and the range of different types of applications for which the models can be used. The networks tested were as follows :

1. **Ncera - Ciskei Agricultural Corporation;**
2. **Theron-Treurnicht - Eastern Transvaal;**
3. **Bushbuckridge - Eastern Transvaal;**
4. **Beyers Trust - Western Cape.**

2.8.1 Ncera

The **first** network consisted of a highly ramified network with 24 valves, which had already been designed and installed. The results obtained from re-designing using the computerised model were compared with the original design. This case proved to be a good test for the valve sequencing algorithm. The manual design schedules were significantly improved on by the computer selected schedules, and this results in a reduction in both the capital and operating costs of the network.

2.8.2 Theron-Treurnicht

The **second** network was a real design case that was solved using the computer model. A dam is located in the middle of the farm, with lands both above and below it. The question arises of whether to install a single network, with adequate pumping capacity to supply the upper lands, thereby providing excess pressure for the lower lands and enabling small diameters to be used, or alternatively to install two separate networks, thereby reducing the pumping costs for the lower system. The results showed clearly that although the second option was more capitally expensive, the reduced **pumping costs** rendered the overall **total costs** significantly lower than those for the single network case.

2.8.3 Bushbuckridge

This is a large mainline supplying 17 different regions, all operating simultaneously. The computer model was used to investigate the possible benefits of installing booster pumps along the network. A number of economically beneficial positions for booster pumps were identified.

2.8.4 Beyers Trust

This is an existing network which has developed incrementally over a period of several years. The farm lands are situated well below a supply dam and the irrigation system has operated satisfactorily under gravity since its initial installation. With the increasing use of the mainline network however, the available pressure at the valves has decreased significantly. The question of whether to install a pump into the mainline was investigated using the computer models.

The computer models were run on the existing pipes, to establish an optimal set of operating schedules. These schedules successfully obviated the need to install a pump.

2.8.5 Conclusions

The computer models for mainline design were extremely successful, and they have in fact been incorporated into regular use in the Consultants' offices. An interesting observation that emerged from the results of the test cases was that common design practice tends to underestimate the effects of energy costs, and existing manual designs are therefore generally smaller than would be optimal if a full economic evaluation was made.

3. SUMMARY AND CONCLUSIONS

3.1 Principal Results

The Authors believe that the work on this project, over the past four years, has contributed to the state of the art in a number of specific areas :

3.1.1 Structuring of the design process

The research has resulted in a complete and formal specification of the irrigation systems design process, *viz* :

* Classification of the requirements of the design process into **system and hardware characteristics**, and identification of the individual components within these two groups;
* Formulation of **three main design modules** (preliminary, block and mainline) incorporating all of the required components;
* Identification of the **specific design routines** within each module;
* Specification of the input, output, **design parameters and design objectives** involved in the execution of each routine; and
* Specification of the **links** between various routines.

An overview of this structure is provided in table 2.1 and figures 2.1 and 2.2, together with the synoptic maps in Appendix 1. Documenting this structure constitutes, to the Authors' knowledge, the first such comprehensive specification of the design process. It provides a reference wherein each element of the design process is placed in its full context; as such it formed an essential first step in the development of the complete design model. The Authors feel further that it will prove to be a useful tool for teaching Irrigation Engineering.

3.1.2 Comprehensive evaluation models

Both the mainline design and the block design modules contain comprehensive evaluation processes which enable the designer :

* to assess the extent to which the design satisfies his objectives;
* to generate alternative designs; and then
* to compare these alternative designs.

Appropriate use of these evaluation models will provide the designer with an insight into the performance of the irrigation system that he has not had up till now.

The models are based on a thorough study of the state of the art in measuring irrigation performance, leading to the formulation of a set of performance parameters which have been incorporated into the models. These parameters are discussed in detail in Chapters 3, 5 and 6 of the Technical Report.

The main evaluation model at the end of the block design process provides the designer with information on :

- the **uniformity of distribution** that will result from the designed system;
- the **expected yield** per unit area and per unit of water applied, that will be attained using the system;
- the **requirement and application efficiencies** that will be achieved by the system;
- the estimated **financial return on investment** per unit area and per unit of water applied, that will be achieved; and
- information on the **optimal application depths** during the irrigation season.

It is important to note further that the principle of evaluation has been incorporated into the *whole* design process. Thus, apart from the *main* evaluation model described above, more *general* evaluation is carried out continuously throughout the design process. The models have been structured so that whenever the designer wants to investigate the effects of possible adjustments to the design, he is able to consider these effects in terms of immediately updated evaluation parameters. For example :

* In the **lateral and manifold design routines** of the Block Design module, the designer has the choice of (a) letting the computer carry out the design, either by the "poly plot" routine or by extrapolation of results obtained from previously desgned pipes, or (b) he may specify the design himself, by inputting the required lengths and diameters. Once the design is complete, the table in which the design details are listed (figure 5.2) is updated with statistics on :
    - the cost of the pipe being designed;
    - the total cost of the whole block;
    - the total length of the pipe being designed; and
    - the total lengths, for the whole block, of each diameter of pipe being used.

    If the designer now wishes to change the design, for example by altering the length of one of the pipe sections used for a specific lateral, he will be able to consider the effect of this change on the cost of the lateral and on the overall block costs. Furthermore, having made the change, he can then obtain a graphical plot or a numeric listing of the pressure envelope, and thereby investigate the hydraulic effects of this change.

* In the **valve sequencing routine** of the mainline design module, once again the designer has the choice of either letting the computer determine the schedules or of specifying his own schedules. Once the valves have been fully allocated, the resulting schedules are displayed in a table which also lists a summary of the flow required in each schedule. If the designer decides to alter any of the schedules, the table is updated and the designer is therefore able to monitor the extent to which the flow requirements in each schedule are balanced.

* In the **quick evaluation of layouts** routine of the mainline design module, the results of this evaluation are presented in two tables. The first lists the estimated *capital* costs of the mainline, based on "first shot" pipe diameter selections (figure 6.1). The second lists the estimated *operating* costs, based on prevailing energy cost tarrifs, the expected efficiency of the pumping system and the rates used for the present value analysis (figure 6.2).

  Both of these tables can be edited by the designer and the effects of any changes will be updated immediately. Thus for example, he can investigate the sensitivity of the overall network cost to changes in any of the selected pipe diameters. Alternatively, he can test the sensitivity of the operating costs to changes in the energy tarrifs or interest/inflation rates.

* Similarly, the **linear programming** routine of the mainline module presents the results of the optimization in two tables; one showing the optimum pipe diameters and their associated lengths for each section of the network, and the second showing the resulting pressures at each valve and at the pump.

  The designer may change any of the selected pipe diameters or their lengths, and the effects of such changes will be shown in the cost summaries and in the pressures table.

3.1.3 New design algorithms.

A number of new or modified design algorithms have been developed. These include:

* the valve sequencing algorithm for mainline design;
* the Dynamic Programming optimization of the irrigation operating point, which forms part of the block design evaluation process;
* the Linear Programming optimization of the pipe diameters and pumping points in the mainline design process. Although this procedure is based on well documented algorithms, it has been modified to provide flexibility in the handling of the candidate

diameters constraint and the question of uniform or varied pumping heads in different schedules.

* the lateral and manifold pipe design procedures in the block design. These are also based on well documented algorithms. However, they have been considerably modified in order to make them efficient and stable for common design situations; as well as to incorporate accurate calculation of the pipe and emitter hydraulics.

3.1.4 Rationalization of the design process

Although the design model does not provide a completely rationalized solution to the design problem at this stage (as discussed in Chapter 1), it does enable the designer to carry out a quantitative study of the various trade-offs involved in the design process. For example :

* the suitability of the 20% allowable head loss criterion can be investigated on a case by case basis ;
* the *maximum yield* criterion can be modified to a *maximum profit* criterion, which allows for the possibility of deficit irrigation ; and
* the ratios of cost vs performance, system vs operating costs and block network vs mainline network costs can also be investigated.

3.1.5 Computer aided design (CAD)

The computer programs have been designed to exploit, to the fullest possible extent, the impact of computer aided *design* (as opposed to computer aided *draughting*) on the general Engineering Design process. The Authors believe that they constitute a significant contribution to the state of the art of CAD in the field of Irrigation Engineering.

3.2 Development of the computer programs

The structuring and design of the computer programs played an important part in the successful development of the design models. The programs evolved in three distinct phases, as experience was gained in the use of computer aided design techniques. These phases can be characterized by the nature of the man/machine interface in each case :

3.2.1 Phase 1 : The original PASCAL programs for emitter selection, block and mainline design, written on the Hewlett Packard 9816 computer

These programs employed a *consecutive input* dialogue, followed by a *unidirectional* operating procedure. This meant that the required data was input on a line by line basis, and the designer then sat back while the computer carried out the calculations. Once the design was complete the designer could study the results in order to decide on any changes he might want to investigate further. These changes would then be incorporated into a new set of input data and the programs would be rerun from the start, using the new data.

The rigidity of this structure precluded the type of continuous evaluation throughout the design process described in section 3.1.2 above.

3.2.2 Phase 2 : The BASIC programs for mainline design, written on the IBM-PC

These programs employ a *tabular input* dialogue and a *multidirectional* operating procedure. This implies that the data are input through fully editable tables. The designer can make any additions or corrections he wants to the tables, before continuing with the various calculation routines. The results of the calculation procedures are also presented in tables on the computer screen, and the designer can once again edit these result tables for use in any on going calculations. Furthermore, the designer does not have to run the program in a fixed order of steps, but can rather move between the various routines at will.

These programs incorporated the continuous evaluation principles discussed above.

3.2.3 Phase 3 : The PASCAL programs for block design, written on the IBM-PC

These programs are operated by similar processes to those of the phase 2 programs. However, they are considerably more flexible in their ability to move between different routines. The prevailing philosophy is one of letting the user determine the path followed through the program, rather than the program directing the user.

3.3 Conclusions

3.3.1 Main conclusions

* The programs work well and provide their users with the hoped for design capabilities. In particular, the design evaluation process has proved to be very successful.

* The phase 1 programs enabled rapid "number crunching", but their structure did not allow for flexible and creative approaches to the design problem.

* The phase 2 and 3 programs are therefore a considerable improvement on the phase 1 programs. Not only do they enable the designer to create any number of design scenarios, but the continuous evaluation facilitates accurate sensitivity analyses.

* Experience during the course of the research has shown that both the on-line availability of the various evaluation facilities, and the user friendly and interactive man/computer dialogue, encourages the designer to undertake a more broadly based and investigative approach to the design problem than was possible in the past.

* The research team was unable to fulfil the project objectives relating to the *application* of the models (see "Attainment of Objectives" below), because the development of the computer programs required considerably more time than was originally anticipated. However, results obtained from some initial applications indicate that the models have good potential capabilties to provide the type of analyses that were hoped for.

3.3.2 Attainment of Objectives

The objectives of the research, are listed in

* Section 1 (page 5) of this report, which highlights the *principal* objectives;
* Appendix 2 (page 52), which provides the *full* list of objectives, goals and expected output from this research, as specified in the original research contract.

In general terms, the *main* objectives relate to the *development* of computer based irrigation design procedures which incorporate full cost/benefit evaluation into the design process (see objectives (b) and (c), goals (a) and (b) and outputs (a) and (b) in Appendix 2).

These objectives have been fully attained through the models discussed in Chapters 4 to 6 of the Technical Report.

In view of the concern about the level at which the models will be applied, expressed by the Evaluation Committee at the outset of the research, it is important to note that the models are used for real *farm level* situations. They are applied in the design office, using a desk-top personal computer with locally developed databases, rather than on any remote main-frame facility with hypothetical data.

A *second* set of objectives (goals (c) to (f) and outputs (c) to (e) in Appendix 2), relate to the *application* of the models on real design cases in order to :

* characterize South African irrigation design practice;
* develop strategies for (a) optimal selection of irrigation method and (b) optimal design under various conditions.

As mentioned above, these objectives have not been fully met, principally because the development of the design models required considerably more time than was originally anticipated. At this stage, only limited application of the design models has been possible.

3.4 The Future

The Authors hope that the impetus generated by the project will continue along two distinct paths, *viz* :

3.4.1 Technology transfer

It is felt that the results of the research can be applied in the following ways :

* The overall design process, as specified by the detailed structure and all the individual routines, should be **incorporated into common practice.** To this end, the design approaches used in the models should be taught to students of Irrigation Engineering; and the possibility of giving seminars on these procedures, to practicing Designers, should be considered. The Technical Report can be used as a complete teaching manual for this purpose.

  The Authors would like to dispel a common misconception that the computer programs can be operated by unskilled personnel to "churn out" irrigation designs. On the contrary, in order to be used successfully they require a good understanding of both the principles of irrigation design and the principles employed in the various design routines.

* Once the results of more applications have been acquired, they can be used to develop a set of design norms that could form the basis of a **code of practice** for the Industry. For example, recommendations could be formulated on the following :
  - The most appropriate overall system *coefficients of uniformity*, under different conditions;
    Expected *application and requirement efficiencies* under different operating conditions.
  - Allowable pressure variation within a system;
  - Appropriate ratios of block versus mainline and hardware versus operating costs;
  - The most economical pipe sizes to be used in mainlines, with due consideration to the cost of energy in the overall cost of the system.
  - One of the most interesting parameters in this category, as far as the Authors are concerned, is the potential for *deficit irrigation* under varying conditions.

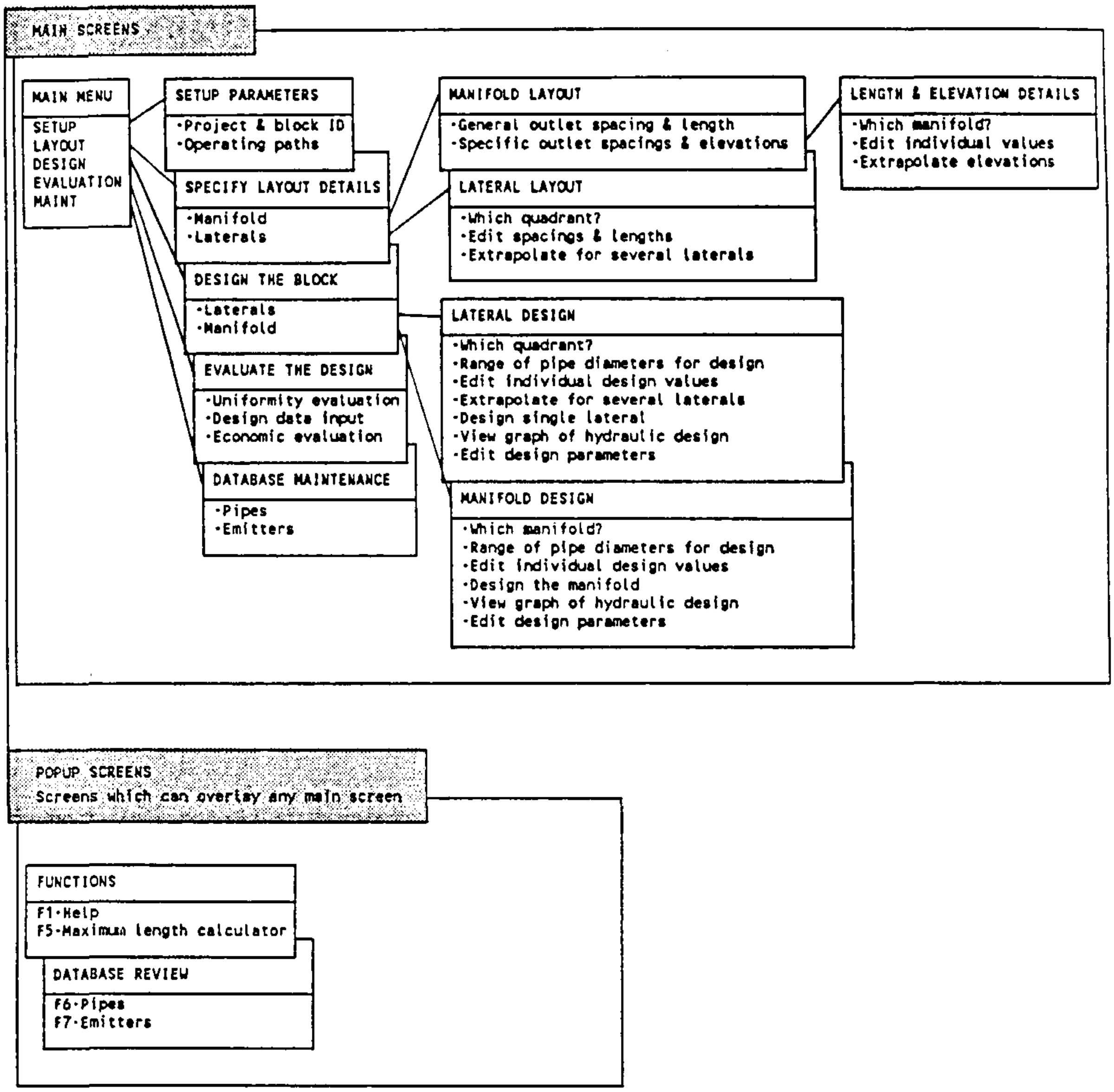
3.4.2 Continued research

The Authors would like to see the research continued in two main areas. The first would involve the application of the models for the development of the design norms discussed above. The second would involve the continued development of the models themselves. This latter aspect of the work would entail :

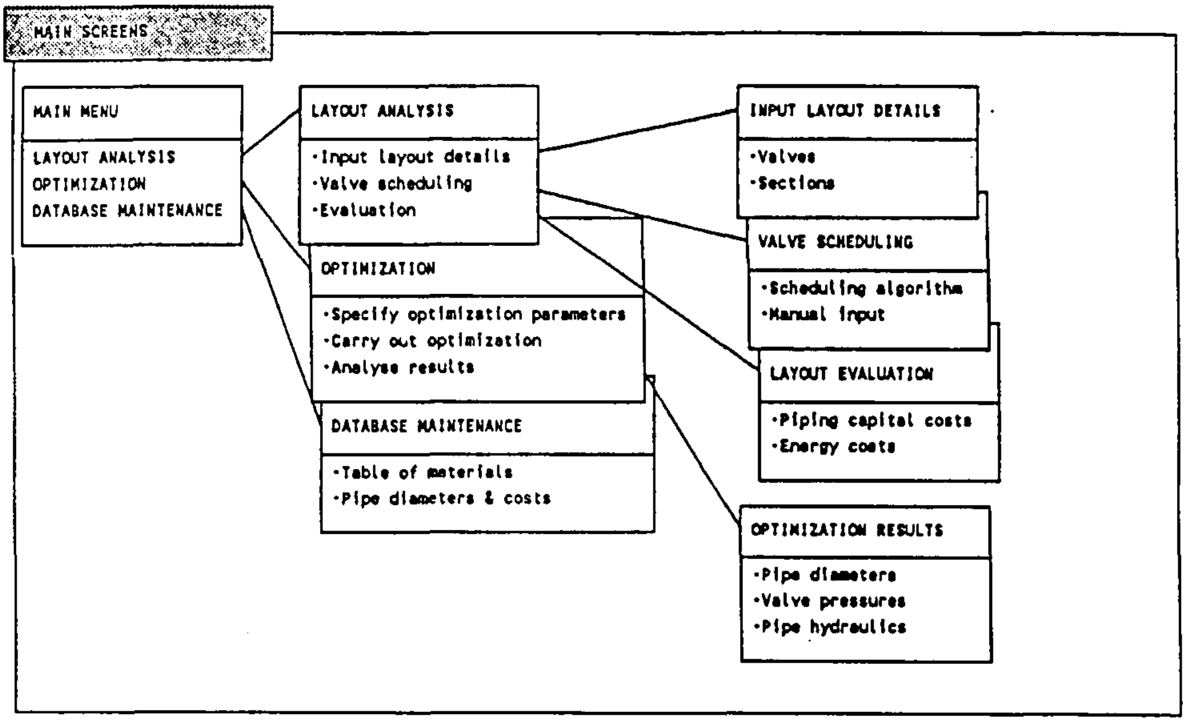
- Integration of all three existing design modules (preliminary, block and mainline) into a single package utilising shared data input and output routines and similar operating procedures.
- Interfacing of the existing *design* package with a computer based *draughting* package, as well as other computer databases; both for the input of data and for the production of final design drawings.
- The development of a complete irrigation equipment database to be used in the design process and also for the drawing up of bills of quantities after completion of a design.

Appendix 1 : Synoptic Maps of the design Models

APPENDIX 1a : Synoptic Map of the Block Design Process



APPENDIX 1b : Synoptic Map of the Mainline Design Process



Appendix 2 : Project Objectives

The Research Contract lists the following objectives, goals and expected outputs from the project :

1. Objectives

The overall objectives of the research will be to develop a comprehensive procedure for the selection of an irrigation method, and for the design of an irrigation system, such that :

a) The selected methodology will be the most appropriate in terms of efficient use of water, energy, labour and other relevant economic factors.

b) The design will consider all system parameters (pump characteristics, local headlosses, flow-pressure relations at each outlet, etc.), and will therefore be accurate.

c) The expected irrigation performance of a given design will be related to the system and its operating conditions, so that the design can be evaluated, in order to enable the selection of optimal systems.

2. Goals

a) To develop a package of computer programs for the design of irrigation systems. These packages will incorporate all aspects of design, including pressure and flow distributions, operating characteristics and costs.

b) To develop a model of the relationship between expected irrigation performance and system characteristics.

c) To characterise existing irrigation practice in several different regions in South Africa, in terms of irrigation performance, cost and utilization of resources.

d) To develop criteria for the optimal allocation of resources for an irrigation system.

e) To develop a model, based on the abovementioned computer package, for the selection from a range of feasible designs of a system which will be optimized in terms of cost and performance.

f) To integrate the results of the abovementioned goals to produce a strategy for the selection of an irrigation method and for the design of an irrigation system, such that the various resources will be optimally allocated and the benefits of the system will be maximal.

3. Outputs of the research

The results of the research will provide the following :

a) A model for rationalized design of irrigation systems.
b) A computerised tool for irrigation system design.
c) A classification of irrigation practice in South Africa, both on a geographical basis and in terms of levels of efficiency of resource utilization.
d) A comparison between different irrigation methodologies in South Africa, in relation to their efficiencies of resource utilization.
e) Strategies for the selection of appropriate irrigation methods and for the optimal design of irrigation systems.