ODA

ZIMBABWE

Ministry of Lands
Agriculture and
Water Development

Institute of Hydrology

1995/081

Development of small-scale irrigation using limited groundwater resources

Fourth Interim Report

DEVELOPMENT OF SMALL-SCALE IRRIGATION USING LIMITED GROUNDWATER RESOURCES

FOURTH INTERIM REPORT

M. Murata[1], C.H. Batchelor[2], C.J. Lovell[2], M.W. Brown[1], A.J. Semple[2],
E. Mazhangara[1], A. Haria[2], S.P. McGrath[2] & R.J. Williams[2]

November 1995

IH Report ODA 95/5

[1] Lowveld Research Stations, P.O.Box 97, Chiredzi, Zimbabwe
[2] Institute of Hydrology, Wallingford, Oxon OX10 8BB, UK

Cover:- Aerial view of trials on the collector well garden at the Chiredzi Research Station

Executive Summary

In semi-arid areas, the lack of rainfall is the main constraint on agricultural production. During drought years and dry seasons, crops and, in particular, vegetables can only be produced using irrigation. In many African countries, there is a long tradition of women growing vegetables on small irrigated gardens both for domestic consumption as a relish and for sale. In rural areas these gardens are generally flood or surface irrigated using water carried to individual plots in buckets from wells or other water sources. As the area irrigated is often governed by the limited availability of water or labour to carry water, there is much interest at the village level in adopting techniques that improve irrigation efficiencies on these gardens. Improvements in irrigation efficiency allow the gardeners, who are usually women, to cultivate larger areas or to devote more time to other activities.

This report is the fourth and final interim report on two ODA-funded research projects (R5851 and R5849) that were carried out in south-east Zimbabwe during the period 1988-1994 by the Zimbabwean Department of Research and Specialist Services and the Institute of Hydrology in collaboration with the British Geological Survey. The main objectives of this project have been to study the feasibility of using shallow aquifers as a source of water for small-scale irrigation and to compare and develop methods of low-cost, high-efficiency irrigation methods which are suitable for use on small irrigated gardens. The work reported here was carried out as one component of a much larger programme of work in south-east Zimbabwe that is seeking to reduce environmental degradation and promote sustainable agricultural development. Recommendations from the research projects have already been used by an ODA-funded TC project that, to date, has implemented an additional eight community gardens in south-east Zimbabwe at the same time as investigating the institutional and socio-economic criteria for widespread development of community gardens in semi-arid areas.

The experiments reported here include three replicated water use efficiency trials that compared subsurface pipe irrigation with flood irrigation; four replicated salinity trials that compared subsurface irrigation and flood irrigation using good and poor quality irrigation water; and an observation trial to study subsurface irrigation frequency. In agreement with trials reported in earlier interim reports, subsurface irrigation using clay pipes was shown to increase yields, crop quality and water use effectiveness when compared to traditional flood irrigation. This was achieved by reducing soil evaporation losses and by creating and maintaining soil moisture conditions favourable to crop growth. Economic analysis of trial results showed subsurface irrigation to be cost-effective and on-farm trials demonstrated that subsurface irrigation is easy to use and adaptable. The results from the salinity trials showed that the advantages of subsurface irrigation over flood irrigation were maintained when poor quality irrigation water was used.

The ODA Engineering Division funded the first off-station collector well garden. This community garden, which has forty-eight members, is located in the Romwe Catchment in Chivi District. Results of the socio-economic monitoring of the garden during the 1992/93 summer and 1993 winter season are given in this report. These results confirmed that the garden was viable from an economic standpoint.

The potential benefits of increased vegetable gardening in semi-arid areas of Zimbabwe and elsewhere are discussed, as is the need for more participative research into cropping strategies that utilise more efficient methods of irrigation at the same time as other aspects of crop husbandry (e.g. integrated pest and disease control, improved irrigation scheduling and production of vegetables during summer months). Recommendations are also made for more participative research into cropping strategies that minimise risk and optimise the returns to the gardeners by ensuring that demands of the market are met in terms of crop quality and the timing of production.

Contents

		Page
EXECUTIVE SUMMARY		
1.	INTRODUCTION	1
1.1	Project objectives	1
1.2	Background to Project	2
1.2.1	Sustainable agricultural development	2
1.2.2	Garden Irrigation	2
1.2.3	Basement aquifers	4
1.2.4	Improved irrigation efficiency	6
2.	LVRS COLLECTOR WELL GARDEN	7
2.1	Location and soil type	7
2.2	Climate	7
2.3	Water quality	7
3.	WATER USE EFFICIENCY TRIALS	10
3.1	Introduction	10
3.2	Experiment 92/2: Rape trial	11
3.2.1	Expt 92/2 materials and methods	11
3.2.2	Expt 92/2 results and discussion	14
3.3	Experiment 93/1: Okra trial	22
3.3.1	Expt 93/1 materials and methods	22
3.3.2	Expt 93/1 results and discussion	22
3.4	Experiment 93/3: Tomato trial	29
3.4.1	Expt 93/3 materials and methods	29
3.4.2	Expt 93/3 results and discussion	29
3.5	General discussion and conclusions	35
3.5.1	Irrigation scheduling	35
3.5.2	Irrigation frequency	36
3.5.3	Irrigation method	36
3.5.4	On-farm trials	36
4.	IRRIGATION WATER QUALITY TRIALS	38
4.1	Introduction	38
4.2	Experiment 91/4: Maize trial	38
4.2.1	Experiment 91/4 materials and methods	38
4.2.2	Experiment 91/4 results and discussion	41
4.3	Experiment 92/1: Tomato trial	45
4.3.1	Experiment 92/1 Materials and methods	45
4.3.2	Experiment 92/1 results and discussion	48

			Page
	4.4	Experiment 93/2: Sweet cabbage trial	50
		4.4.1 Experiment 93/2 materials and methods	50
		4.4.2 Experiment 93/2 results and discussion	53
	4.5	Experiment 93/4: Rape trial	54
		4.5.1 Experiment 93/4 materials and methods	54
		4.5.2 Experiment 93/4 results and discussion	55
	4.6	Fallow period: October 1993 - April 1994	57
	4.7	General discussions and conclusions	57
		4.7.1 Water quality	57
		4.7.2 Water quality on-farm trials	60
5.	IRRIGATION FREQUENCY TRIALS		61
	5.1	Introduction	61
	5.2	Experiment 93/5: Covo trial	61
		5.2.1 Experiment 93/5 materials and methods	61
		5.2.2 Experiment 93/5 results and discussion	62
		5.2.3 Experiment 93/5 conclusions	64
6.	ROMWE COLLECTOR WELL GARDEN		65
	6.1	Introduction	65
	6.2	1992/93 Summer Season	65
		6.2.1 Introduction	65
		6.2.2 Cropping operations	65
		6.2.3 Production	66
		6.2.4 Gross margin analysis	67
		6.2.5 Comment	67
	6.3	1993 Winter Season	68
		6.3.1 Cropping pattern	68
		6.3.2 Irrigation	68
		6.3.3 Plant protection	69
		6.3.4 Fertilisation	69
		6.3.5 Production	70
		6.3.6 Gross margin analysis (whole garden)	71
		6.3.7 Economic performance of the collector well garden	72
7.	ANCILLARY STUDIES		75
	7.1	Use of Time Domain Reflectometry to monitor water use efficiency on off-station gardens	75
		7.1.1 Introduction	75
		7.1.2 Materials and methods	76
		7.1.3 Results and discussion	76
		7.1.4 Conclusions	79
	7.2	Crop water use and production modelling	79

Page

7.2.1 Introduction 79
7.2.2 LEACHM-W Model 80
7.2.3 PARCH Model 80

8. GROUNDWATER RESOURCES IN SOUTH-EAST ZIMBABWE 84

8.1 Introduction 84
8.2 Review of recharge estimates 84
8.2.1 Recharge in semi-arid areas 84
8.2.2 Recharge estimates for South-East Zimbabwe 85
8.2.3 Recharge estimates for other African basement areas 85
8.3 Availability and sustainability of groundwater resources in South-East Zimbabwe 86
8.3.1 Groundwater resources 86
8.3.2 Land use change, land degradation and groundwater recharge 86
8.3.3 Reversing land degradation 88
8.4 Impact on increased groundwater development on environment 89
8.4.1 Groundwater abstraction and low flows 89

9. GENERAL CONCLUSIONS 91

9.1 Irrigation trials 91
9.1.1 Irrigation method 91
9.1.2 Irrigation scheduling 93
9.1.3 Irrigation with poor quality water 93
9.1.4 On-farm trials 93
9.2 Water resources 94
9.2.1 Collector wells 94
9.2.2 Availability of groundwater resources 94
9.3 Irrigated gardens 94
9.3.1 Socio-economic benefits 94
9.3.2 Environmental benefits 95
9.4 Scope of work carried out by projects R5851 and R5849 95

10. RECOMMENDATIONS 97

10.1 Development of garden irrigation in basement areas 97
10.2 Improved garden management 97
10.3 Irrigation scheduling 97
10.4 Irrigation with poor quality groundwater 97
10.5 Microirrigation decision support system 98

ACKNOWLEDGEMENTS 99

REFERENCES 100

1. Introduction

1.1 PROJECT OBJECTIVES

In October 1988 the Institute of Hydrology (IH) began an ODA-funded collaborative research project with the Zimbabwean Department of Research and Specialist Services (DRSS) and the British Geological Survey. The project, which was based at the Lowveld Research Station (LVRS), had the following wider objectives :-

i) To improve the availability of water for food production and the sustainability of agriculture in semi-arid areas;

ii) To reduce poverty and improve nutrition, particularly of women and children in semi-arid areas;

iii) To provide guidelines and methodologies for governments, aid agencies and extension services that can contribute to arresting the degradation of catchments in semi-arid areas.

The specific objectives of the ODA-funded project (ODA reference numbers: R5851 and R5849) were :-

i) To study the feasibility of using shallow basement aquifers as a source of water for small community or allotment-type gardens;

ii) To compare and assess simple low-cost irrigation methods that can be used to improve water use effectiveness on these gardens when irrigating with good and poor quality water;

iii) To develop ways of effectively transferring research findings and techniques to potential users.

This report describes the experimental work and on-farm trials that were carried out by the project during the period April 1992 to October 1993. Previous results from the project can be found in three interim reports (Batchelor *et al.*, 1990; Lovell *et al.*, 1990; Lovell *et al.*, 1992). Information on the groundwater component of the project can be found in Chilton and Talbot (1992) and on groundwater exploration in south-east Zimbabwe in Carruthers *et al.* (1993).

The project reported here was supported by ODA Engineering Division TDR Funds. The success of the first phases of this project in demonstrating the potential of collector well gardens in semi-arid areas has led to the implementation of a further eight collector well gardens. Six of these garden were installed and are being monitored as part of an ODA TC funded project. Details of this project, which has involved Agritex and other departments of the Zimbabwean Ministry of Lands Agriculture and Water Development, can be found in five progress reports (Lovell, 1993; Lovell *et al.*, 1993, 1994a, 1994b & 1995).

1.2 BACKGROUND TO PROJECT

1.2.1 Sustainable agricultural development

Land degradation and desertification are taking place at an alarming rate throughout the semi-arid world. These processes increase the vulnerability of agricultural production and have a serious impact on the quality of life of rural communities. The main processes of land degradation in south-east Zimbabwe are deforestation, overgrazing and soil erosion. These result from poor management of land resources in a country characterised by high rate of population growth, high livestock numbers, a lack of financial and manpower resources for sustainable land management and a land tenure system which promotes overgrazing (IIED, 1992). Since 1980, the Government of Zimbabwe has adopted policies aimed at improving the management of land resources in rural areas. However, the successful implementation of these policies remains elusive, as does the goal of sustainable agricultural development.

Sustainable agricultural development is defined by the FAO (1990) as "the management and conservation of the natural resource base and orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development conserves land, water, plant and animal genetic resources, is environmentally sound, technically appropriate, economically viable and socially acceptable." Experience is showing that sustainable development can only be achieved by adopting an integrated or holistic approach to resource management, preferably, at the catchment or watershed level. As many of the problems affecting land and water resources are inter-related and cannot be solved individually, strategies of integrated resource management are necessarily complex. Strategies must include consideration of crop production, livestock management and forestry as well as socio-economics, health, gender issues and education. In this context crop production includes rainfed and irrigated cropping.

The work reported here was carried out as part of programme that is aimed at developing and evaluating strategies of sustainable agricultural development that could be implemented in semi-arid areas of Zimbabwe and elsewhere.

1.2.2 Garden irrigation

In areas where sufficient water resources are available, large-scale irrigation projects are feasible. However, in semi-arid areas of Africa, such schemes have proven to be expensive, relatively inefficient and difficult to reconcile with traditional farming systems (Underhill, 1990; Carter, 1992). Large irrigation projects can also cause a range of health-related and environmental problems and necessitate considerable social adjustments. In contrast, experience and research to date suggests that informal garden irrigation can be economically viable and appropriate to farmers, especially women farmers, for whom it is already a traditional component of the farming system. In organisational terms, there are a number of different types of garden that can be found in semi-arid areas of Africa. These include: *private gardens* whereby one farmer or one household fence and manage there garden using water from their own well, from a river or a public water point; *community* or *allotment-type gardens* whereby a number of farmers or households have plots within a fenced area and water is obtained from a public water point; and *collective gardens* whereby a garden is operated by the community and the produce is shared. The type of gardening practised depends on a number of factors that include: availability of water resources, social and

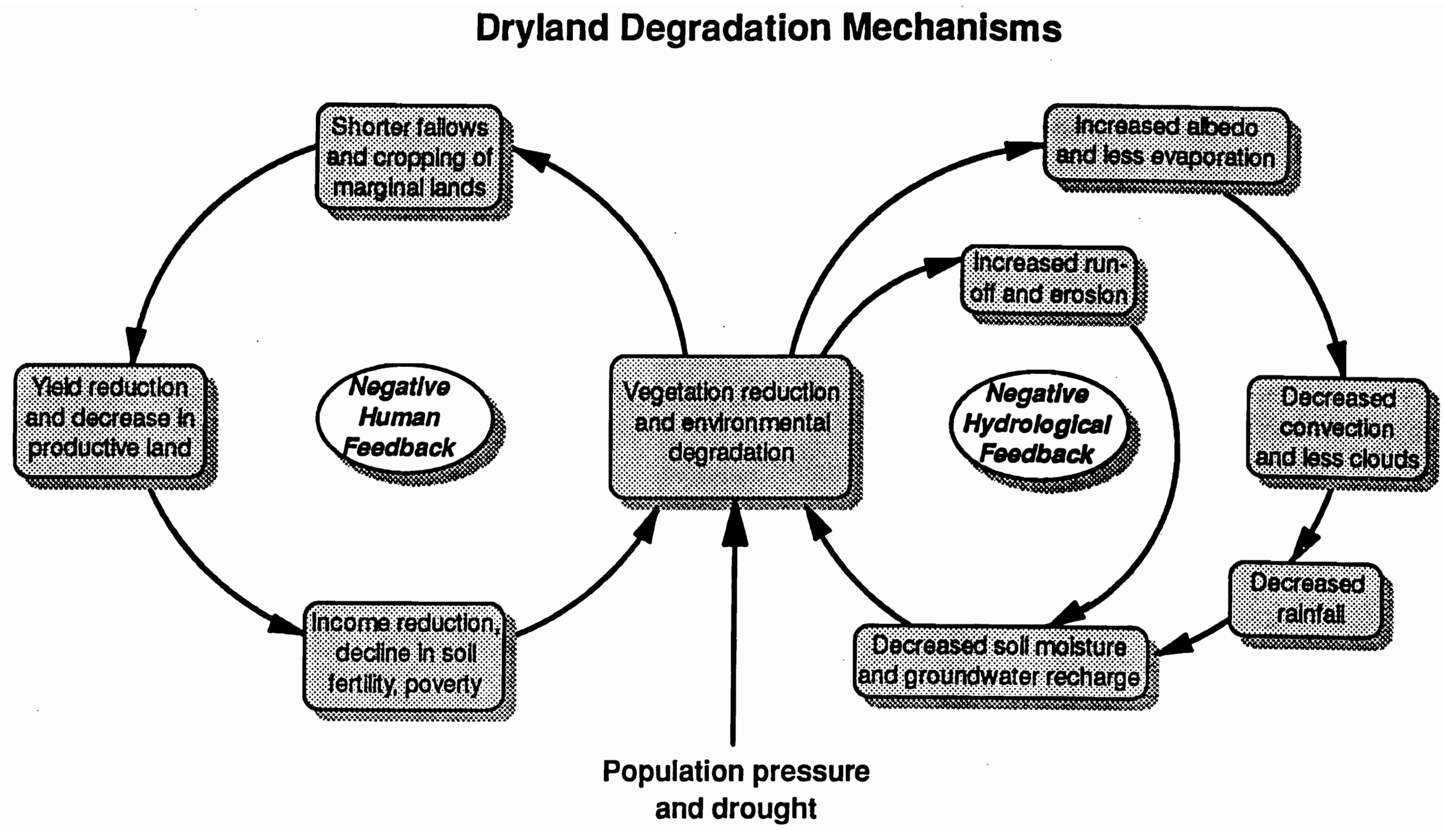


Figure 1 *Negative feedback mechanisms that lead to environmental degradation*

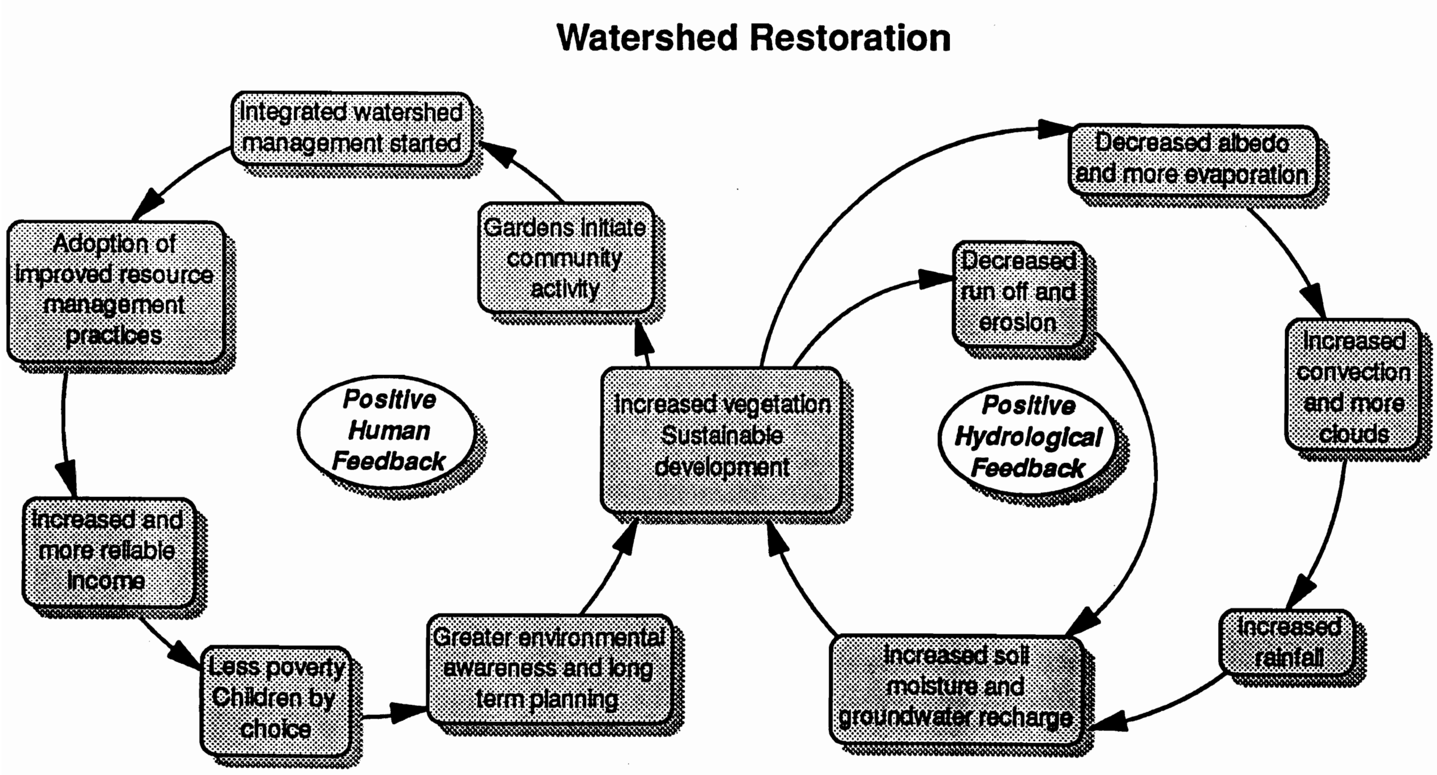


Figure 2 *Positive feedback mechanisms that lead to restoration degradation*

institutional factors and the advice given to communities by extension services. Availability of water is a major constraint on gardening in basement aquifer areas to such an extent that few farmers are able to implement groundwater-based private gardens because there is insufficient groundwater beneath their land or because the cost of accessing groundwater is prohibitively expensive. Although there are some collective gardens, most rural communities in Zimbabwe, when given the choice, prefer some type of community garden.

As well as the obvious advantages that can be derived from the production of vegetables, community gardens can have the major benefit of providing the initial step towards improved resource management at the village or catchment level. Figure 1 is a schematic diagram that shows some of the main processes and negative feedback mechanisms that lead to environmental degradation in semi-arid areas. Figure 2 is a schematic diagram that identifies processes and positive feedback mechanisms that can lead to a reversal of land degradation and sustainable agricultural development these areas. The importance of community-based activities in programmes of improved catchment resource management cannot be understated (Blackmore, 1994). Community gardens, in many cases, give rural communities their first experience of the institutions needed to make community-based activities successful. This experience and the confidence gained from implementing a successful community garden can be the vital springboard to other community-based activities such as improved livestock management or community forestry.

1.2.3 Basement aquifers

Although availability of water is a prime constraint on gardening in semi-arid areas of Zimbabwe, it is a fallacy to assume that garden or small-scale irrigation can be practised successfully wherever water and suitable soils are available. The many human, institutional and economic factors that influence the development of irrigated gardens are crucial in determining the success or failure of new gardens (Carter, 1992). One of the aims of the programme of research in south-east Zimbabwe is to assess the technical, socio-economic and institutional feasibility of using shallow aquifers as a source of water for irrigated garden projects of up to one hectare in area. In particular, the project is assessing the potential of using collector wells as a means of abstracting sufficient water from shallow basement aquifers to meet domestic and stock water requirements and still provide enough water to meet the requirements of an irrigated garden. A collector well is a shallow, hand-dug well of large diameter with horizontal boreholes drilled radially from the bottom of the well to a distance of approximately 30 metres (Wright, 1992).

Basement aquifers are of particular importance in tropical and sub-tropical regions because of their widespread extent and accessibility and because there is often no readily available alternative source of water supply, particularly for rural communities (Wright, 1989; Wright, 1992; Howard & Karundu, 1992; Howard *et al.*, 1994). In general, the water in basement aquifers occurs within the weathered residual overburden (the regolith) and the fractured bedrock. Development of the regolith aquifer component is normally carried out by digging wells or drilling shallow boreholes. Development of the fractured bedrock component is normally carried out by drilling boreholes. However, work during the last ten years has shown that collector wells can be used to maximise and optimise groundwater abstraction from basement aquifers (Anon, 1994). This work has demonstrated the feasibility of obtaining substantially larger yields from collector wells than from slim boreholes with the added advantage of low drawdowns. Safe yields from eight wells in Zimbabwe and Malawi and 20 in Sri Lanka have been calculated at 2.7 ls^{-1} (ranges of 1.1-6.6 and 0.5-8 ls^{-1} respectively) with drawdowns of 2-3 m. These results can be compared with typical yields in the range 0.1-0.7 ls^{-1} for slim boreholes at pumping drawdowns in excess of 30 m (Wright, 1992).

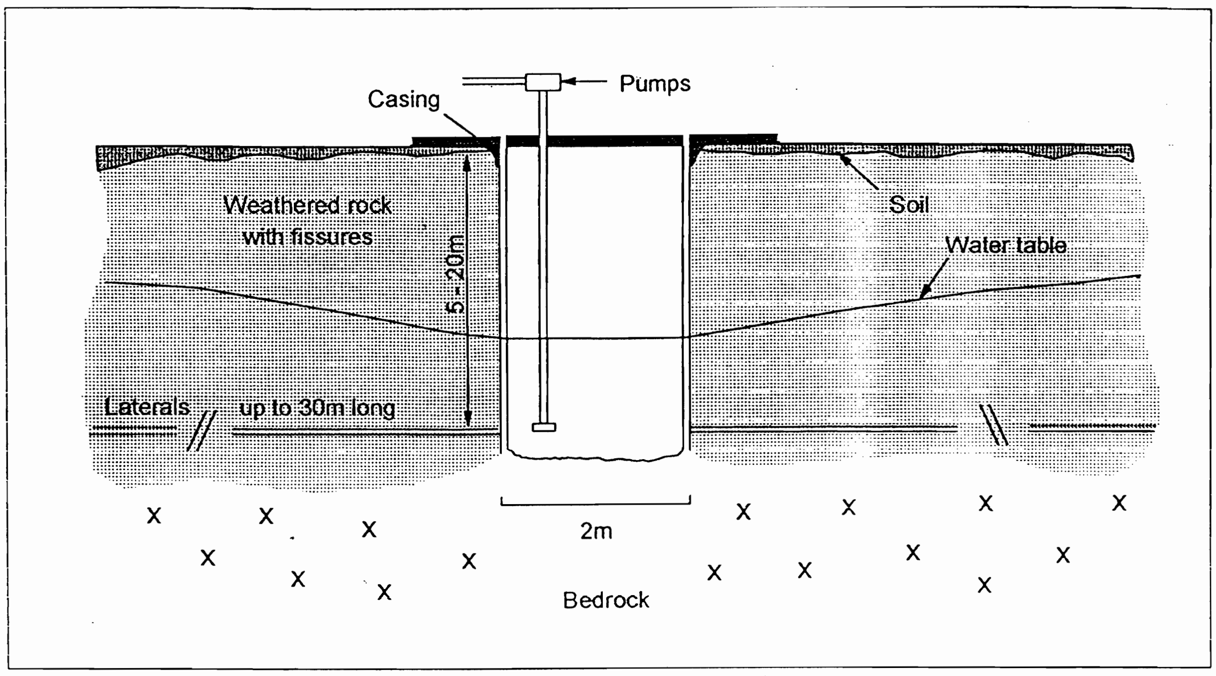


Figure 3 *Schematic diagram of a collector well*

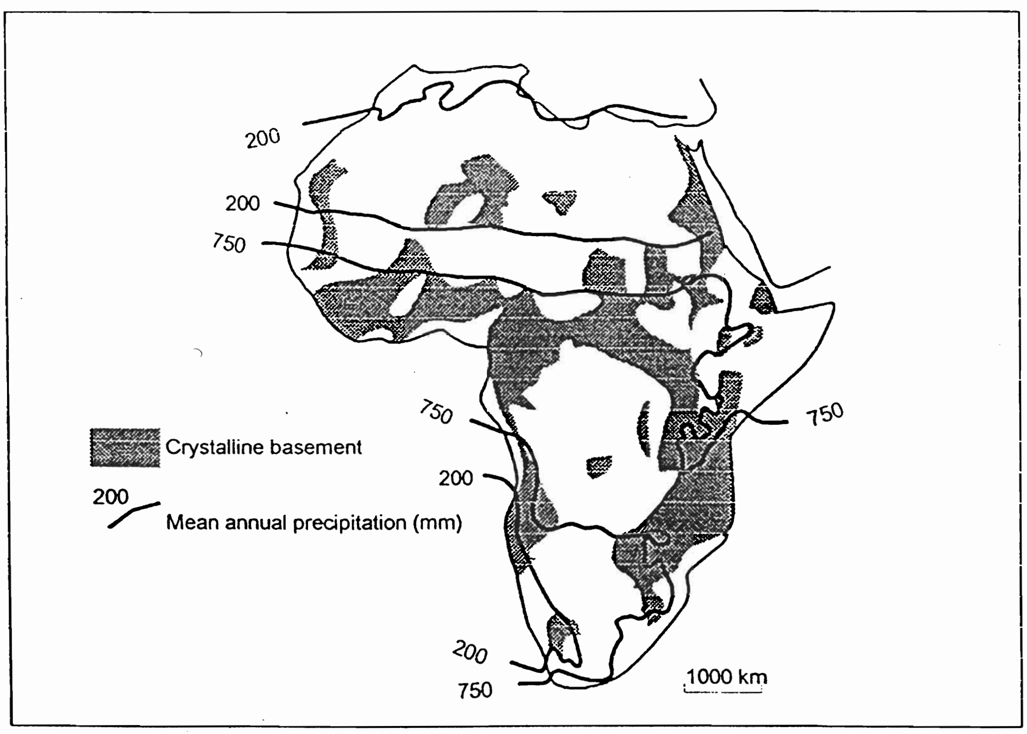


Figure 4 *Distribution of basement aquifers in Africa*

1.2.4 Improved irrigation efficiency

Experience with collector wells constructed in basement areas in Zimbabwe and elsewhere would suggest that collector wells can give safe yields in excess of domestic and stock water requirements. This excess yield is typically sufficient for irrigated gardens of between a half and one hectare in size, which can provide vegetables for up to one hundred households if each household has a 100 square metre plot, or allotment, within the garden perimeter. As stated earlier the main objective of the work reported here is to compare different methods of improving the water use effectiveness on irrigated gardens. As water and labour availability are the principal constraints in determining the size of a garden that can be cultivated, there are obvious benefits to be gained from using water as efficiently as possible. Water use effectiveness on gardens can be increased by improving: (i) irrigation scheduling, (ii) irrigation methods, (iii) water delivery and distribution systems, and (iv) varietal selection, crop husbandry and pest management. Experiments and preliminary on-farm trials have been carried out to evaluate and quantify the benefits of different strategies of increasing water use effectiveness using irrigation water of good and poor quality.

2. LVRS collector well garden

2.1 LOCATION AND SOIL TYPE

The LVRS collector well garden is located at the Chiredzi Research Station in south-east Zimbabwe (21°S, 31°E, elevation 429 m). The collector well at this site was constructed in February 1989. The garden, which is 1 ha in size, has been used since March 1989 for experimental and demonstration purposes. Figure 5 is a map of south-east Zimbabwe that shows the location of the Chiredzi Research Station and the first nine off-station collector well gardens.

The soil type at the LVRS garden is a dark reddish-brown sandy clay loam derived from basic gneiss and classified as a clayey, mixed hyperthermic Udic Rhodustalf (USDA, 1988). A more detailed description of this soil can be found in USDA (1988) and information of the soil hydraulic properties can be found in earlier interim reports (Batchelor *et al.*, 1990; Lovell *et al.*, 1990; Lovell *et al.*, 1992).

2.2 CLIMATE

The climate of south-east Zimbabwe is semi-arid with annual rainfall between 250 and 750 mm (coefficient of variation approximately ±40%). Most rainfall occurs as high intensity thunderstorms during the period November to April. Maximum temperatures in excess of 30°C occur throughout the year and temperatures exceeding 40°C are not unusual during summer months. Rainfall and meteorological data are collected at the LVRS meteorological site and by an automatic weather station (Didcot Instruments Ltd., UK) located at the LVRS garden.

Figure 6 shows weekly rainfall for the period November 1991 to November 1993. The high rainfall during the period December 1992 to February 1993 was well above the long-term mean and in direct contrast to the very low rainfall during the 1991/92 summer season.

2.3 WATER QUALITY

The water used for the irrigation experiments that was pumped from the LVRS collector well was of "high" salinity hazard (USDA, 1954), typically having an electrical conductivity of 1 mS/cm. Water from Lake Mtilikwe that was used in the water quality experiments was largely free from salts and of "low" salinity hazard (USDA, 1954) with an electrical conductivity typically of about 0.2 mS/cm. Chemical analyses of the Mtilikwe and LVRS collector well water are given in Tables 1 and 2.

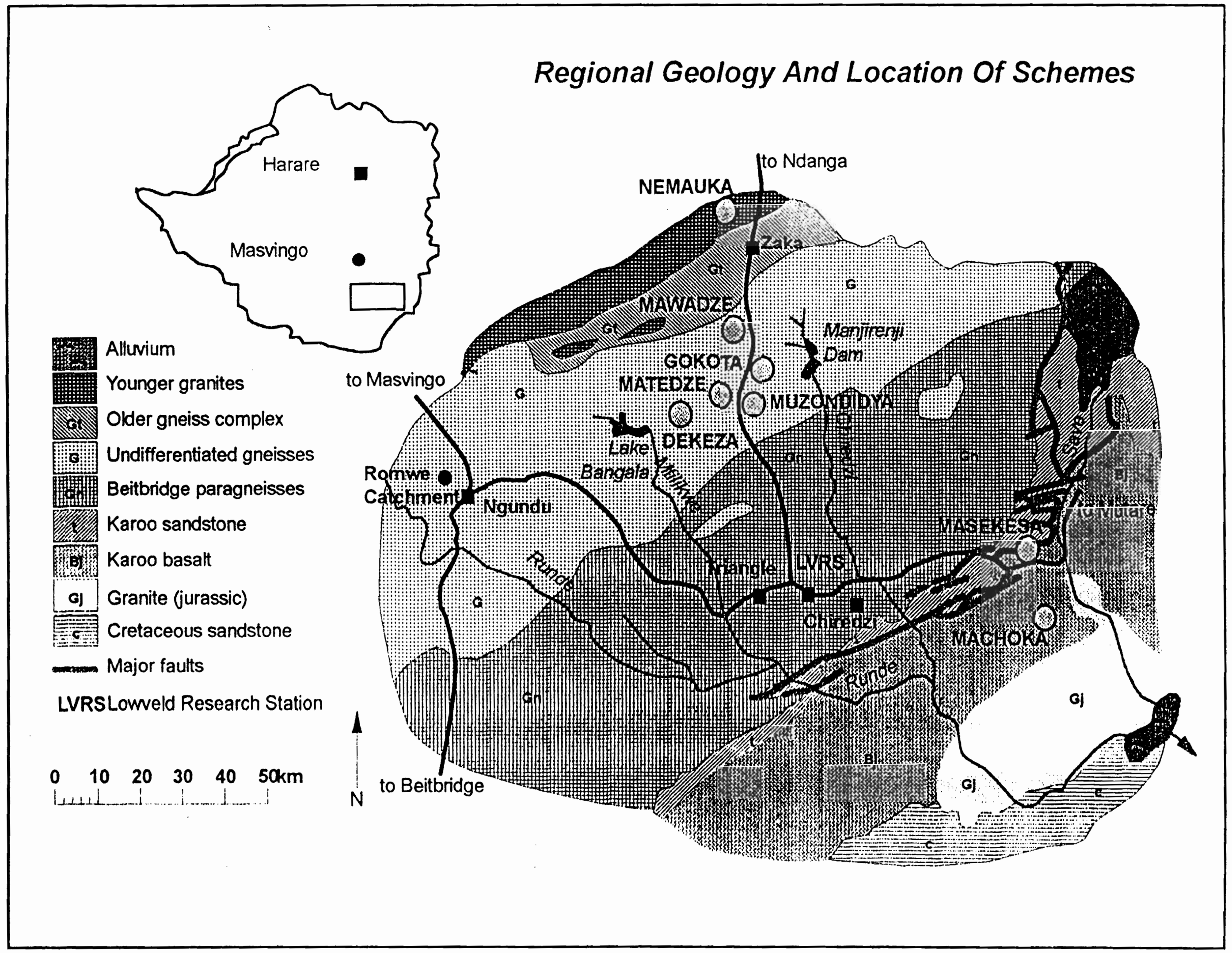


Figure 5 Geology of area around Chiredzi and location of collector well gardens (*)

Table 1 *Chemical analyses of water taken from the LVRS collector well and of treated water taken from Lake Mtilikwe (6/6/90) (taken from Chilton et al., 1990)*

	EC (mS/cm)	Na	K	Ca	Mg	Alk. (HCO_3)	SO_4	Cl	NO_3-N	Si	Sr	Fe
C.Well	0.990	86	1.0	68.7	66.4	604	41.3	60.5	0.5	27.6	0.38	0.02
Kyle	0.078	6.6	2.3	5.5	2.7	41	3.0	4.5	0.08	6.7	0.04	0.37

* All figures in mg/l unless stated

Table 2 *Values of sodium-adsorption ratio (SAR) and residual sodium carbonate (RSC) calculated for water taken from the LVRS collector well and of treated water taken from Lake Mtilikwe*

	SAR	RSC (meq/l)
C.Well	3.69	0.034
Kyle	1.20	0.172

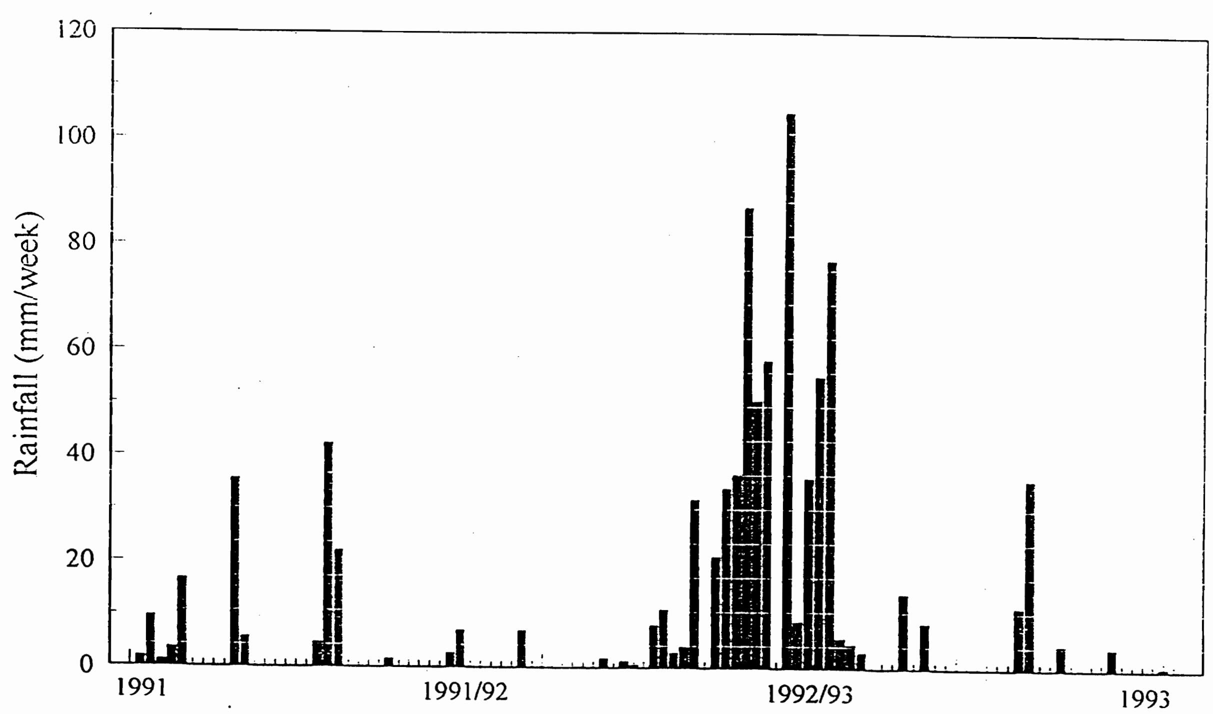


Figure 6 *Weekly Rainfall at Chiredzi Research Station*

3. Water use efficiency trials

3.1 INTRODUCTION

Limited water supplies and availability of labour are the principal constraints that determine the size of irrigated gardens in semi-arid areas. There is merit, therefore, in adopting irrigation practices that increase irrigation efficiency and lead to a combination of reduced labour requirements, expansion in the size of the garden, increased yields and/or improved crop quality. Previous research at the Lowveld Research Stations has demonstrated that a number of low-cost irrigation techniques can be used to improve water use effectiveness on irrigated gardens (Murata & Vamadevan, 1989; Batchelor *et al.*, 1990; Lovell *et al.*, 1990; Lovell *et al.*, 1992). These methods include low-head drip irrigation, pitcher irrigation, improved flood irrigation and subsurface irrigation using clay or slotted bamboo pipes. A summary of the relative advantages and disadvantages of these methods is given in Table 3.

Of the methods evaluated to date, subsurface irrigation using clay pipes and improved flood irrigation using mulches have shown the most promise. They have the major advantages of being low cost and easy to use as well as being more efficient than traditional flood irrigation. Good initial results obtained with subsurface irrigation in comparisons with other low-cost techniques prompted the series of more detailed replicated water use efficiency trials reported in this section. Although the irrigation regimes were altered, the same experimental design and plot lay-out was maintained for each of the three seasons reported. The design of the trials was chosen as a result of earlier comparisons of water use effectiveness under flood and subsurface irrigation. These earlier comparisons showed that biases in results were caused by choice of irrigation regime particularly if the regimes of a trial were based on the water requirements of only one of the irrigation methods. Therefore, the objectives of the water use efficiency trials reported here were:-

i) To compare the water use, yield and water use effectiveness of traditional flood and subsurface irrigation over a range of irrigation regimes;

ii) To obtain information on the crop water requirements, growth and yield of rape, tomatoes and okra grown using subsurface irrigation;

iii) To acquire practical information on the operation, maintenance and management of subsurface pipe irrigation;

iv) To compare and evaluate the economics of traditional flood and subsurface pipe irrigation.

Table 3 *Advantages and disadvantages of simple micro-irrigation methods in low-cost vegetable production*

Irrigation Method	Advantages	Disadvantages
Flood irrigation	Traditional, well-known method. Easy to perform. Good crop establishment. Minimum additional inputs required	Not efficient in water use. No inherent control against over-irrigation. Labour intensive.
Low-head drip irrigation	Improved water use efficiency. Good uniformity of wetting. Reduced drudgery and effort of carrying water	Cost and availability of materials. Degree of management skill required. Water filtration required. No inherent control against over-irrigation
Subsurface pipe irrigation	Improved water use efficiency. Pipes can be made locally. Robust method. Low labour requirement. Some inherent control against over-irrigation. Good uniformity of wetting. Low-cost, simple method, easy to learn. Once installed pipes can be used over several seasons	Initial labour and skill requirement for manufacture and installation. Crop establishment can be poor if initial irrigation only via pipes.
Pitcher irrigation	Improved water use efficiency. Inherent control against over-irrigation. Can be positioned next to individual plants or in centre of small plots. Good on undulating land	Initial skill and labour requirement for manufacture and installation. Less robust than clay pipes. More labour intensive, pots have to be filled individually. Porosity of pots decreases with time. Difficult to cope with high water requirements.
Improved flood irrigation (mulch)	Improved water use efficiency. Low skill requirements and easy to carry out. Good crop establishment. Protects fruit from damp soil. Prevents soil capping and reduces soil erosion.	Potential for increase in pests and diseases. Mulches are not always readily available

3.2 EXPERIMENT 92/2: RAPE TRIAL

3.2.1 EXPT 92/2 materials and methods

Experimental design

The experiment was carried out on the experimental collector well garden at the Chiredzi Research Station using water pumped from the collector well. As mentioned previously, the same experimental design was used throughout the series of water use efficiency trials reported here. Consequently, once they were buried, the subsurface pipes were left *in situ*. The twelve treatments of the trial are described in Table 4. The trial consisted of two methods of irrigation and six irrigation schedules, replicated four times and laid out using a lattice design. Each plot comprised of two beds, each 3 m x 1 m and surrounded with a low earth bund and a 0.5 m pathway between the beds.

Irrigation regimes

Treatments 1 and 7 received irrigation on demand that is irrigation equivalent to 100% of the soil moisture depletion measured by neutron probe. Apart from Treatments 6 and 12, the other flood and subsurface treatments were given irrigations that were fixed proportions of the amounts applied to Treatments 1 and 7. Treatments 6 and 12 received irrigation according to the traditional irrigation schedule that was identified in a survey of irrigation practices conducted in Chivi Communal Area (Lovell *et al.*, 1992). For a 3 m x 1 m bed, this schedule consisted of an application of eight 20 l buckets of water in the first week after planting (equivalent to 53.3 mm) and six buckets per week thereafter (equivalent to 40 mm/week) for the duration of the crop.

Table 4 *Experiment 92/2 treatments*

Treatment	Irrigation Method	Irrigation Schedule	
1	Flood	Neutron Probe	
2	"	Trt. 1 irrigation	x 0.85
3	"	" "	x 0.70
4	"	" "	x 0.55
5	"	" "	x 0.40
6	"	Traditional	
7	Subsurface	Neutron probe	
8	"	Trt. 7 irrigation	x 0.85
9	"	" "	x 0.70
10	"	" "	x 0.55
11	"	" "	x 0.40
12	"	Traditional	

Subsurface clay pipe manufacture and layout
Subsurface clay pipes were made at the research station using a simple mould and fired in a shallow bark filled pit. Further details are given by Lovell *et al.* (1990). The pipes were 0.24 m in length and the inside and outside diameters were 0.075 and 0.115 m respectively. They were placed along the centre line of beds, simply laid end to end in a level trench then backfilled with 0.15 m of soil above them (see Figure 7). To allow filling, an inlet was formed at one end of the bed by tilting the first pipe section, the lower end of which was angled during manufacture to joint smoothly with the second, level pipe section. At the other end of the bed, the subsurface pipe system was blocked with a large stone. Although some water permeated through the pipe walls during irrigations most water seeped directly into the root zone via the joints between pipe sections.

Soil moisture measurements
Initially two neutron probe access tubes were installed on one bed of each treatment to a depth of 1 m at a spacing of 0.125 and 0.375 m to one side of the centre line. A third access tube was added after Expt. 93/1 at a spacing 0.625 m to one side of the centre of the bed in a line with the other tubes. However, for most purposes, only the access tube nearest the centre of the bed was used. Time constraints dictated that soil moisture measurements had to be kept to a minimum so that neutron probing, data processing and irrigation could be carried out on the same day. Statistical analysis of data from previous trials showed that using one access tube was acceptable at least for measurement of differences in soil water content during dry season trials.

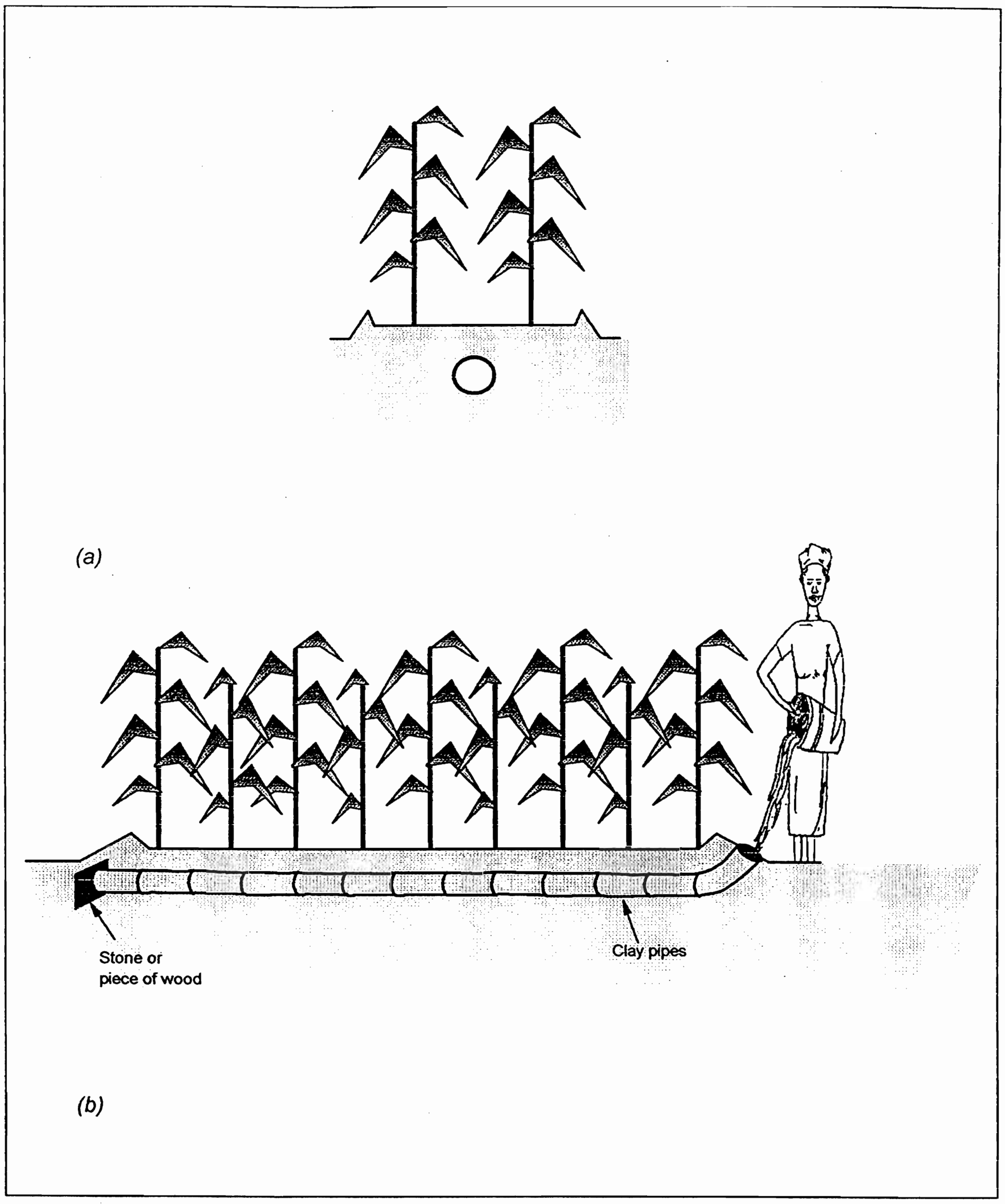


Figure 7 *Schematic diagrams of subsurface irrigation: a) End view showing position of pipes in a bed and b) Side view showing irrigation taking place.*

Soil water content was measured twice per week, early in the morning of the day of irrigation and 24 hours later and after any rainfall. Crop water use from the soil profile to a depth of 0.9 m was calculated using a simple soil water balance equation:-

$$ET_c = R + I - \Delta\theta$$

where ET_c was weekly crop water use, R was the rainfall during the previous week, I was the irrigation applied at the beginning of the previous week and $\Delta\theta$ was the change in soil water content.

3.2.2 EXPT 92/2 results and discussion

Weather during the crop season

Table 5 presents the mean monthly meteorological data measured during the crop season. Temperatures were above average, particularly during September, rainfall was below average, but generally the dry sunny winter season was typical for the region.

Table 5 *Mean monthly meteorological data*

MONTH	TMAX	TMIN	TDRY	TWET	TDRY	TWET	WIND	SUN	RAIN	PAN	ET
					am	am	pm	pm			
	°C	°C	°C	°C	°C	°C	km/d	hrs	mm	mm	mm
JUN	26.8	10.5	15.8	12.2	25.9	15.8	55.2	8.8	9.6	4.1	3.0
JUL	26.1	10.1	15.2	11.7	25.4	15.1	67.2	8.8	7.0	4.1	3.3
AUG	27.0	11.8	16.9	12.9	26.3	15.6	81.6	8.5	0	5.2	3.9
SEP	32.9	15.0	21.9	16.8	32.2	18.5	112.0	9.1	1.7	8.1	6.2

ET = Potential evaporation (Penman 1963)

Agronomy
Rape seedlings ("Giant English"; *Brassica oleracae* cv Napus) were transplanted on 4 June 1992. Twenty seedlings were planted in two rows per bed at a spacing of 0.3 m x 0.3 m, giving a plant population of 30,770 plants/ha. Before planting, 80 kg ha^{-1} P_2O_5 as single superphosphate and 60 kg ha^{-1} as muriate of potash were incorporated by hoe. A total of 100 kg ha^{-1} N as ammonium nitrate was applied in three increments; one third at one week after transplant establishment and the other two thirds at three and six weeks after transplanting.

Growth and Yields
The first leaf harvest was at 36 days after transplanting and the final harvest at day 113. Total yield was determined for each treatment by summing the fresh weight of marketable leaves produced per bed; pathways were included in areal calculations. Dry matter production; average leaf weight and number of leaves per plant were also recorded. Table 6 compares the average crop yields, water use and water use effectiveness (WUE) of the different treatments.

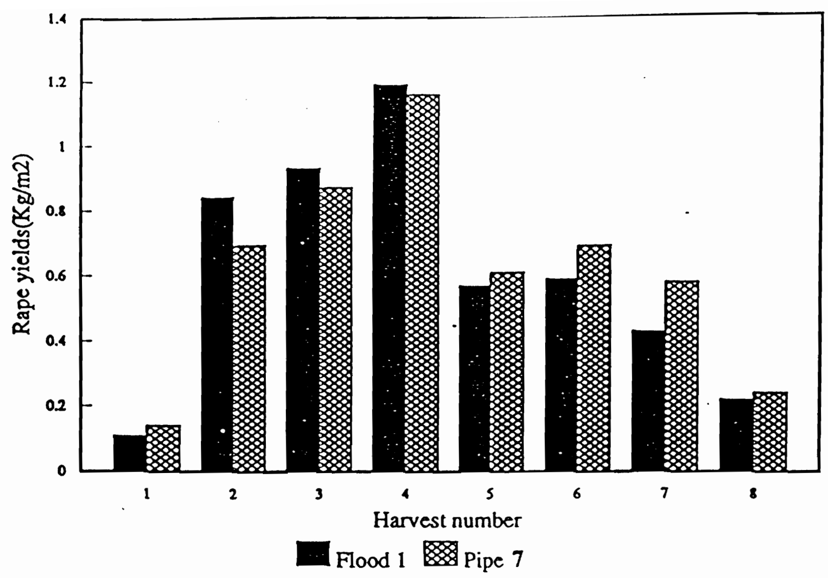
Table 6 *Average crop yields, water use and water use effectiveness (WUE)*

Treatment	**Yield**	**Leaves per plant**	**Ave. leaf weight**	**Leaf dry matter**	**Water use**	**WUE**
		(t/h)	**(g)**	**(t/ha)**	**(mm)**	**kg/m³**
1	45.9	44	34.1	8.0	569.2	8.1
2	41.6	45	30.2	6.7	490.0	8.5
3	32.52	40	26.4	6.3	416.5	7.8
4	8.9	36	25.1	6.4	329.0	8.8
5	20.4	31	21.4	3.6	255.2	8.0
6	54.4	42	42.3	7.6	642.0	8.5
7	46.9	45	33.6	8.3	463.3	10.1
8	41.5	45	30.3	9.1	406.7	10.2
9	37.1	42	29.1	7.2	349.6	10.6
10	33.1	36	30.0	5.4	280.2	11.8
11	23.9	37	21.2	5.6	206.1	11.6
12	57.6	46	41.0	10.6	643.3	9.0
S.E. irrig. method	0.66	0.77	0.60	0.15		0.20
S.E. irrig. regime	1.14	0.81	0.96	0.25		0.34
CV (%)	8.2	8.5	10.6	9.1		9.9

The subsurface pipe irrigation treatments gave higher yields than comparable flood irrigated treatments in all cases but one and, in this case, the yields were similar. The highest yields were attained under the communal area schedule, however, this was also the schedule that resulted in the most irrigation water being applied. The amount of irrigation received by the communal area treatments was nearly 40% greater than that received by the most profligate subsurface treatment. Consequently, the water use effectiveness of the communal area schedules was lower than that achieved on all the other subsurface treatments. In all cases, the water use effectiveness of subsurface treatments was higher than that of comparable flood irrigated treatments.

Figure 8 compares the yields obtained at the eight harvests on two subsurface and two flood treatments. Although there is evidence of better yields on the subsurface treatments towards the end of the harvest period, it can be seen that the yield distributions for comparable subsurface and flood treatments were similar.

For leaf vegetables, both leaf yield and leaf quality are important. People choose leaves to eat based on colour of leaves and length of stalk. The treatments that received 70%, 55% and 40% of the irrigation of the control treatments exhibited a lighter blue/green colour and smaller and coarser leaves. Both these characteristics are evidence of water stress. In a census of quality, leaves from these treatments were not the first choice in preference (Table 7). Leaves from the communal area treatments, although green, were considered less than ideal because of the long stalks and big leaves which had a tendency to break during midday. The subsurface treatments that were irrigated at 100% and 85% of the control were preferred because of their better quality.



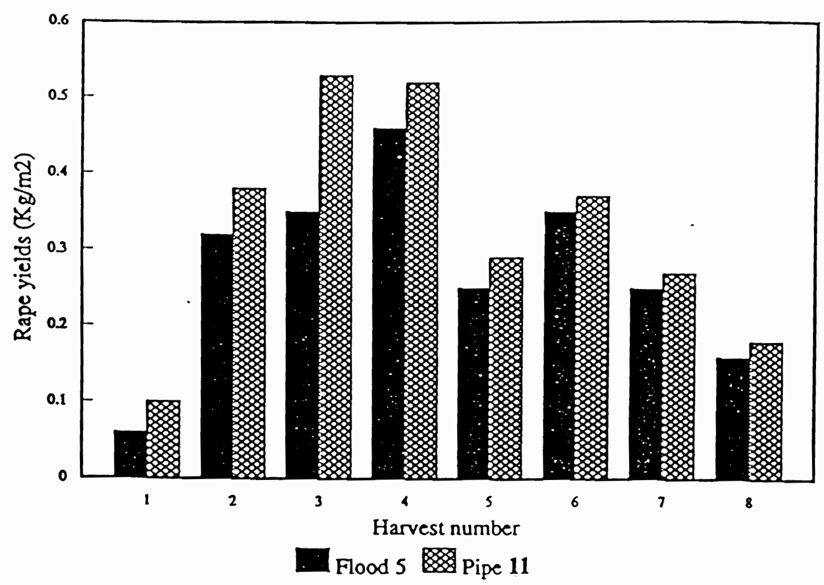


Figure 8 *Expt. 92/2: yields from harvests on a) Treatments 1 and 7 and b) Treatments 5 and 11*

Table 7 *Preferred irrigation treatment in terms of leaf quality*

Treatments	Frequency in Sample %
1	8
2	4
3	0
4	10
5	0
6	4
7	16
8	12
9	2
10	4
11	0
12	10

Water use

In this section water use is taken as the sum of crop evaporation, soil evaporation and drainage. Figure 9(a) compares the water use of the subsurface and flood treatments that were irrigated according to soil moisture depletion measured by neutron probe. Although the flood treatment used more water each week throughout the season, the relative difference in water use was greater during the first part of the season when soil evaporation was a major component of the water balance on the flood treatment. The relative difference in water use declined towards the end of the crop season. This result is consistent with the yield results (Figure 8(a)) which showed better late yields on the subsurface treatments.

Figure 9(b) compares the water use of the subsurface and flood treatments that were irrigated at 55% of the control treatments. Water use on both treatments was relatively high during the first two weeks after planting as a result of the 55 mm of irrigation that was applied to establish the transplants. During the weeks three to seven, water use was greater on the flood treatment as a result of soil evaporation losses. During the middle of the season, water use of the two treatments was comparable. However, the better yields achieved on the subsurface treatment would suggest that relatively more water was being used or lost as crop evaporation on the subsurface treatment during this period.

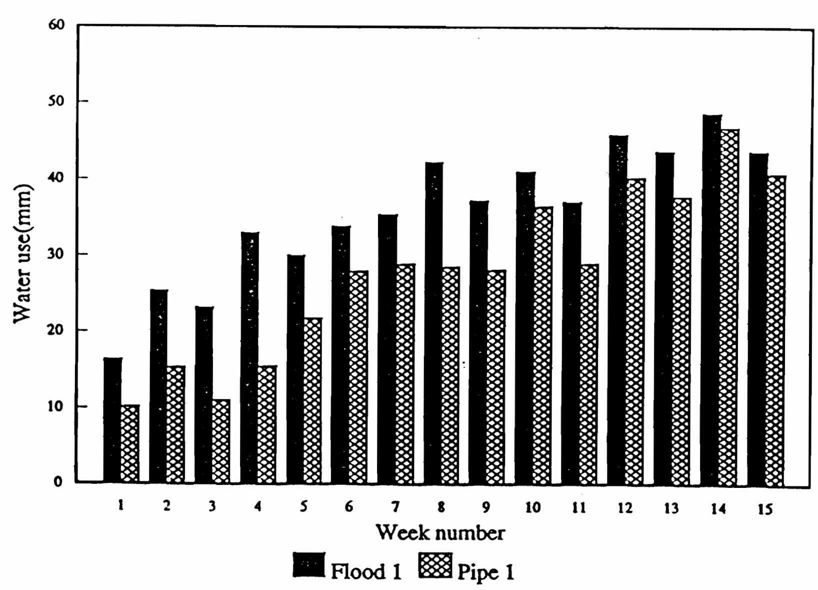


Figure 9(a) *Expt. 92/2: weekly water use of Treatments 1 and 7*

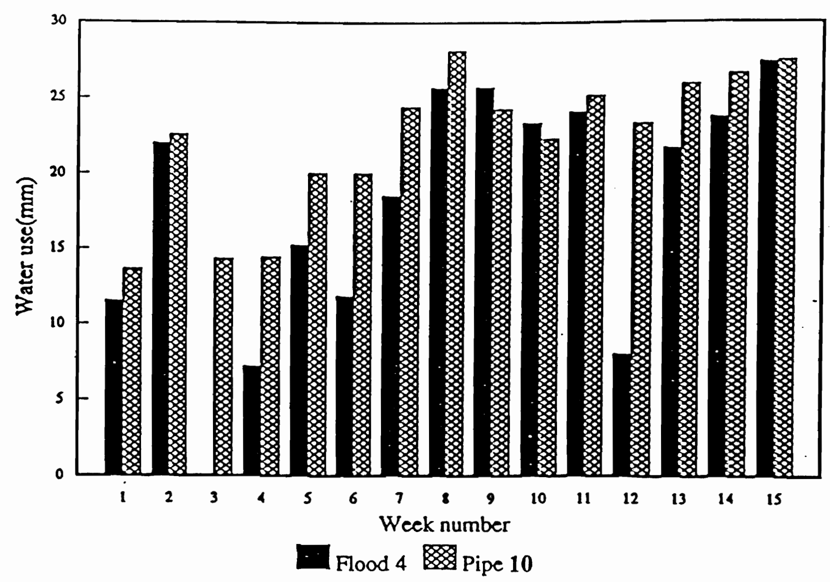


Figure 9(b) *Expt. 92/2: weekly water use of Treatments 4 and 10*

Drainage

Figure 10 compares drainage losses from beneath the different treatments. Drainage losses for the flood treatments were estimated by calculating separately, the soil water balances for the one day after irrigation and the subsequent six day period. This analysis showed that, even after making allowances for high soil evaporation losses during the one day after irrigation, significant drainage was occurring on the treatments receiving most irrigation. Rapid drainage appeared to cease after the first 24 hours after irrigation on the treatments whose irrigation was controlled by neutron probe. The communal area flood treatment was anomalous in that, during the first half of the season, rapid drainage was less apparent during the day after irrigation than during the subsequent six day period.

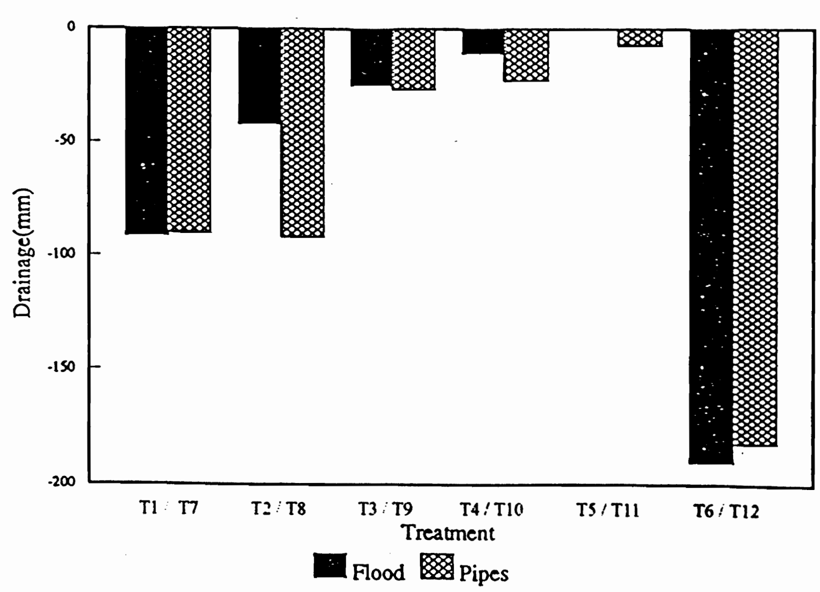


Figure 10 *Expt. 92/2: total drainage from each treatment of trial*

It was not possible to estimate drainage from the subsurface treatments using the same water balance technique as used for flood treatment. The single neutron probe access tube that was read frequently did not measure soil water content changes resulting from subsurface irrigation adequately. This is a consequence of subsurface pipes being a line water source. Water movement in the soil around subsurface pipes is two-dimensional. Water balances were calculated for the subsurface treatments on a weekly basis as opposed to biweekly for the flood treatments. In addition to estimating drainage, crop factors were calculated for the subsurface treatments using the Penman (1963) equation to calculate potential evaporation. Figure 11 compares the weekly crop factors for the subsurface treatments that were irrigated at 100%, 70% and 40% the control treatment. The low crop factors of the 40% treatment throughout the season and the 70% treatment during the second half of the crop season are evidence of the moisture stress experienced by these treatments. The high crop factor values of the 100% treatment in the middle of the season suggests that there was some drainage from this treatment.

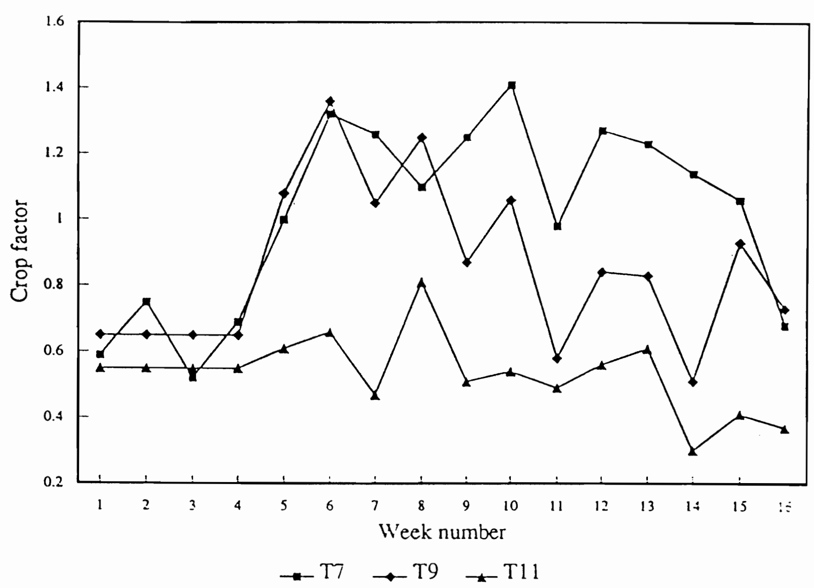


Figure 11 *Expt. 92/2: crop factors calculated for Treatments 7, 9 and 11*

Figure 12 presents the drainage estimates plotted against irrigation applied for all the treatments. It can be seen that the subsurface and flood treatment points fall approximately on the same curve. As soil evaporation losses were higher for the flood treatments, this suggests that drainage from beneath subsurface treatments was higher than flood for the same available soil water content. This is reasonable given that a localised area or plume of drainage might be expected along a line beneath the pipes.

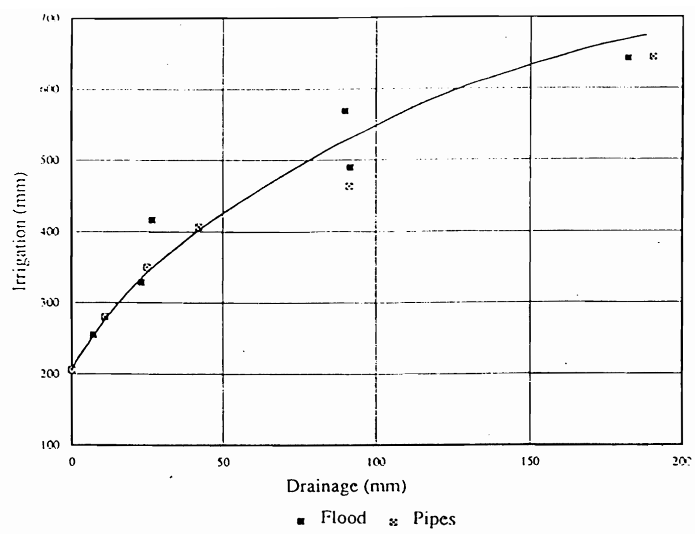


Figure 12 *Expt. 92/2: relationship between irrigation applied and drainage*

Water use effectiveness (WUE)
The water use effectiveness of each treatment is presented in Table 6. As mentioned in the yield section, the water use effectiveness of the subsurface treatments was consistently higher than that achieved on comparable flood treatments. Figure 13 compares the water use effectiveness of subsurface pipe and flood irrigation methods plotted against total seasonal water use. The water use effectiveness of the flood treatments remain relatively low regardless of the amount of irrigation applied and hence the water used. As less water is applied to the flood treatment, although there is less drainage, proportionally more water is lost as soil evaporation and hence yields decline in line with reduction in the irrigation applied. By contrast, there is an increase in water use effectiveness on the subsurface treatments as water use and irrigation applied decrease. This can be explained by there being lower drainage losses on the subsurface treatments that received less irrigation. It is also possible that some crop physiological responses to moisture stress play a role here. The reduced canopy radiation interception, and hence increased soil evaporation, after each leaf harvest certainly contributed to the differences in water use effectiveness of the two irrigation methods.

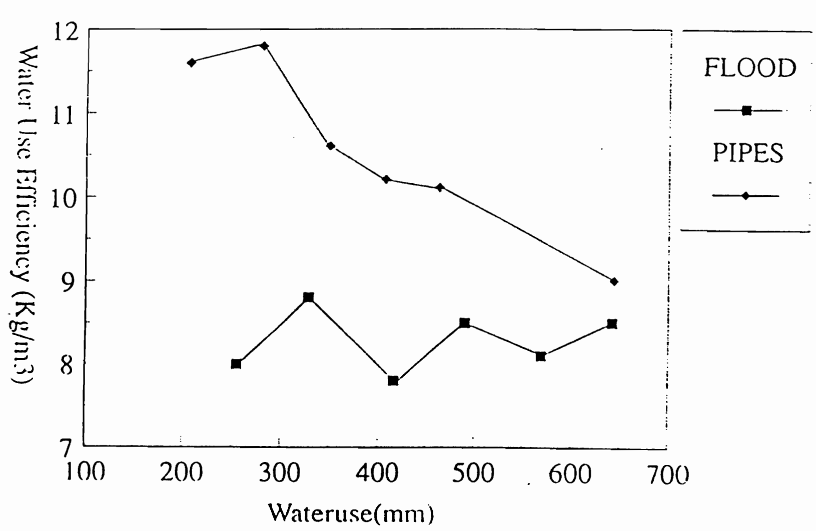


Figure 13 *Expt. 92/2: seasonal water use plotted against water use effectiveness*

Economic analysis

Table 8 is a partial budget to compare differences in returns between three of the irrigation regimes and the two application methods. The value of revenue per bed are the gross revenues less the cost of the subsurface pipes. Details of the economic parameters and assumptions used in the calculations are given in the next sub-section.

The analysis shows that flood irrigation is capable of returning the highest yields per hectare provided that water and labour for applying it are in abundance. However a succession of drought years have shown that water cannot be regarded as an abundant resource, while a recent survey of the Romwe Collector Well Garden revealed that pumping and carrying water was the most laborious task faced by gardeners. As Table 8 shows, although supplying water according to the 85% and 55% regimes via the subsurface pipes reduces yields per unit area and, similarly, the value of vegetables produced per bed, it maximises the yield of vegetables per unit of water. Table 8 also translates this into labour requirements and suggests that using pipes and applying water at the 55% regime requires only 2.9 hours per bed for irrigation compared with 3.4 hour per bed for the equivalent flood method. The result is that for every hour spent pumping and watering, the gardener can earn $2.7 worth of vegetables; an improvement of 19.5% over the $2.3 per hour which would be earned by flood irrigation based on the traditional high water input regime. Adopting the 55% regime also has the merit of earning the best returns to flood irrigation labour if the practitioner is unable or unwilling to use pipes.

Although by irrigating at the 55% rate water use efficiency is maximised, the quality of the crop is compromised (Table 7). If better quality of rape is desired while still saving water, it might be preferable to apply water at the 85% irrigation regime. By using the subsurface pipes this still makes a saving in labour compared with the traditional practice.

Table 8 Economic comparison

Irrigation method	Flood	Flood Pipes		Flood Pipes	
Regime	Traditional	85%		55%	
Treatment No.	T6	T2	T8	T4	T10
Yield (t/ha)	54.4	41.6	41.5	28.9	33.1
Water Ise (mm)	642	490	407	329	280
Revenue $/bed	14.9	11.4	9.9	7.8	7.7
Labour hours/bed	6.6	5.0	4.2	3.4	2.9
Return $/hour	2.3	2.3	2.4	2.3	2.7

Assumptions and parameters used in economic analysis

Gross revenues

These were calculated at a price of $0.52 per kg fresh rape. This was the average farm gate price charged by the Romwe Garden over the period June to September 1992.

Subsurface Pipes
These are costed at $0.50 per pipe for 12 pipes per bed which is sufficient to include a cost for installation which takes approximately one to two hours per bed. The resulting capital cost of $6 per bed is amortised over three years at 13% interest (AFC rate for communal farmers) to give an average capital cost of $1.35 per bed per crop, assuming two crops are grown per year. This cost has been deducted from the gross revenue figures for the pipes in Table 8.

Labour
The labour figures are based on hand pumping at a rate of 0.3 litres per second then carrying the water at a rate of three minutes per 20 litre container.

3.3 EXPERIMENT 93/1: OKRA TRIAL

3.3.1 EXPT 93/1 Materials and Methods

Experimental design and irrigation scheduling
The experimental design and plot layout was the same for Expt 93/1 as was used for Expt 92/2 (see Section 3.2.1). The main differences between these trials were the choice of crop and the irrigation schedules. The irrigation schedules, which are given in Table 9, were based on the control treatments which were T1 and T7 for the flood and subsurface treatments respectively.

Table 9 Experiment 93/1 treatments

Treatment	Irrigation Method	Irrigation Schedule	
1	Flood	Neutron Probe	
2	"	Trt. 1 irrigation	x 1.40
3	"	" "	x 0.80
4	"	" "	x 0.60
5	"	" "	x 0.40
6	"	Traditional	
7	Subsurface	Neutron probe	
8	"	Trt. 7 irrigation	x 1.40
9	"	" "	x 0.80
10	"	" "	x 0.60
11	"	" "	x 0.40
12	"	Traditional	

3.3.2 EXPT 93/1 results and discussion

Weather during the crop season
Table 10 presents the mean monthly meteorological data measured during the crop season. The 1992/93 summer season was characterised by well-distributed rainfall and above average rainfall during the period December to February. As would be expected mean air temperatures were lower than those experienced during the "drought" summer season of 1991/92.

Agronomy

The okra planted for this trial was an indeterminate variety (*Hibiscus esculentus L.* cv Clemson Spineless). This was despite the original trial design specifying a determinate variety. The consequence of using an indeterminate variety was a prolongation of the crop vegetative phase and growth continuing up until the onset of senescence.

The plots were cultivated and a basal fertiliser consisting of 432 kg/ha Phosphate, 289 kg/ha Nitrogen and 80 kg/ha Potassium was incorporated. The crop was sown on 22 December 1992 and eventual spacings were 0.3 m between plants and 0.3 m between rows. *H.esculentus* originated in tropical Africa and is now widely grown throughout the tropics for local consumption.

Growth and Yields

Table 11 presents the harvest results. Figure 14 is a barchart that compares the average total weight of marketable fruit for all the treatments. There is an interesting trend of higher yields on the treatments that were flood irrigated at rates which were at or in excess of the okra water requirements. In fact the combination of the high rainfall and the method of irrigation scheduling used on this trial led to severe overirrigation on some treatments. This overirrigation appeared to have a more deleterious effect on the yields of subsurface treatments than on those of flood treatments. The relatively lower yields of the 140% irrigation regimes compared to the 100% irrigation regimes is further evidence that overirrigation was an important factor in this trial. The effects of soil aeration and overirrigation on okra yields were also noted and reported by Iremiren and Okiy (1986) in a sowing date trial.

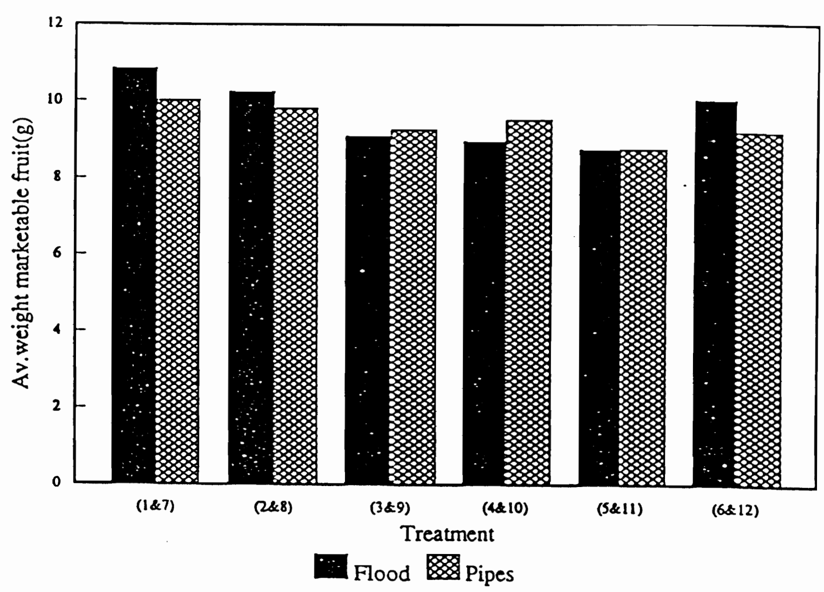


Figure 14 *Expt. 93/1: average weight of marketable fruit*

Table 10 *Mean monthly meteorological data during Expt. 93/1*

Month	TMAX °C	TMIN °C	TDRY °C	TWET °C	TDRY °C	TWET °C	Wind Km/d	Sun hrs	Rain mm	Pan mm/d	ET mm/d
1992											
OCT	33.4	19.6	24.1	19.0	32.5	20.1	220	8.1	15.3	8.8	6.5
NOV	33.5	20.9	25.2	20.0	32.1	20.9	213	7.4	43.8	8.1	6.5
DEC	34.1	22.0	26.9	21.9	31.9	22.1	152	7.9	81.7	8.0	6.2
1993											
JAN	31.7	20.2	24.9	22.0	30.7	22.6	117	8.7	96.7	6.0	5.7
FEB	30.6	21.2	24.1	22.1	29.3	23.3	118	8.3	189.2	4.3	5.2
MAR	30.3	18.7	22.9	20.6	29.6	21.6	93	8.0	10.7	5.1	4.7
APR	31.4	16.7	22.3	19.1	30.3	20.5	97	8.8	22.7	5.5	4.3
MAY	30.3	13.3	19.3	16.3	29.5	19.3	73	9.0	0.0	4.2	3.4

Table 11 *Expt 93/1 harvest results*

Treatment	Fruit per plant	Av. fruit weight* (g)	Yield (t/ha)
1	57.3	10.8	23.8
2	73.3	10.2	23.7
3	66.9	9.1	22.6
4	63.7	8.9	20.1
5	54.0	8.7	17.9
6	60.1	10.0	21.7
7	62.3	10.0	23.5
8	63.5	9.8	26.9
9	64.2	9.3	22.9
10	55.8	0.5	21.3
11	54.0	8.7	17.9
12	62.1	9.2	22.9

* Average weight of fruit considered to be marketable

At irrigation regimes that were less than the okra water requirements, the trend was for subsurface treatments to have relatively higher yields than the flood treatments. Previous trials have also shown that there is a yield advantage in favour of subsurface irrigation at lower irrigation regimes. It should be noted that the rainfall during this trial was in excess of the okra requirements for most of the crop season. It was only during the latter part of the crop season that the irrigation regimes had a significant influence on soil water availability.

In general the yields of this trial were quite low, although they were similar to okra yields reported by Purseglove (1979). The low yields were partly a consequence of the use of an indeterminate variety. They were probably also a result of the wet conditions during the crop season prolonging the okra vegetative phase. Okra requires mild moisture stress for flowering to commence otherwise the vegetative phase is protracted (Purseglove, 1979).

Okra water use, run-off and drainage

Okra water use, run-off and drainage were calculated for all the treatments by computing bi-weekly soil water balances. Inputs were taken as rainfall and irrigation and the neutron probe data were used to estimate soil water content change during each period. Drainage was calculated for periods of low rainfall during which run-off (and run-on) were assumed to be insignificant. Figure 15 is the plot of these drainage estimates against irrigation and rainfall. During periods of high rainfall, run-off and drainage were partitioned in the water balance by using the relationship established in Figure 15.

Table 12 presents the seasonal components of the soil water balance for each treatment. Total rainfall for the crop season was 426 mm and total evaporation (soil and crop) was estimated to be 651 mm for all treatments. The evaporation estimates were based on the assumption that the high well-distributed rainfall resulted in evaporation being at near potential rates on all treatments. Canopy interception losses were assumed to be insignificant as most storm events were intense and of relatively short duration. The following inferences can be drawn from Table 12:

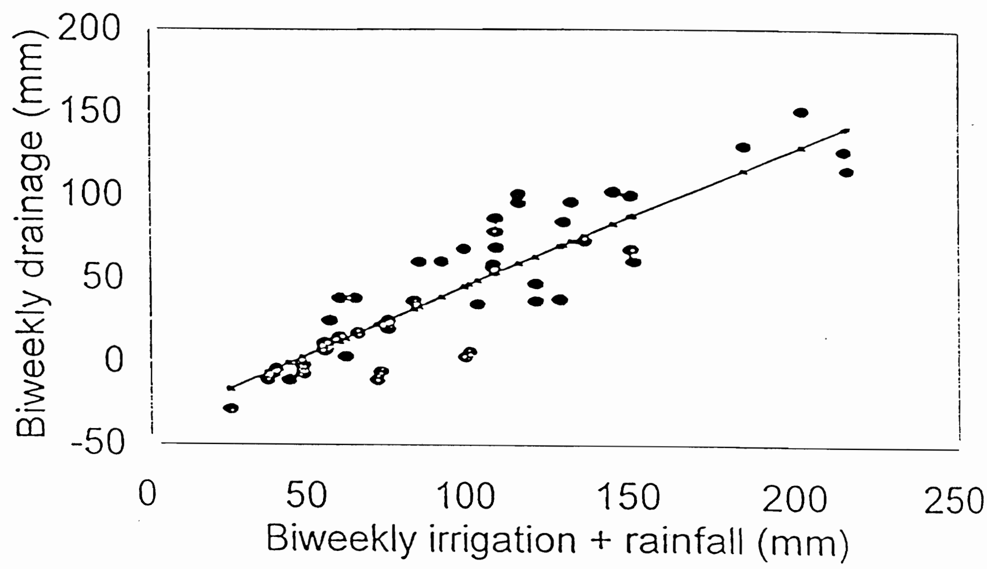


Figure 15 *Expt. 93/1: biweekly irrigation and rainfall plotted against biweekly drainage*

i) <u>Irrigation</u> The irrigation applied to the treatments was very high as indicated by the 100% flood treatment receiving 300 mm of irrigation more than the potential evaporation during the season. The high irrigation applications were a result of the method of irrigation scheduling used. Unfortunately, the scheduling rules used during this trial did not take sufficient account of the drainage losses and, as a consequence, replenishment based on the neutron probe measurements also included "replenishment" of drainage. It can be seen that even the 80% irrigation regimes were irrigated at a rate that exceeded the actual okra water requirements. As seen in earlier trials, the traditional irrigation regime resulted in overirrigation during the first part of the crop season;

ii) Run-off Run-off losses were high from all treatments at around 50% of the total rainfall. This is despite tied ridges being used to reduce run-off. The similarity in run-off estimation for all the treatments indicates that run-off was more closely correlated with rainfall intensity than with irrigation regime. Soil moisture deficit differences would have had little effect because the profiles of all the treatments were uniformly wet during at least the first half of the season. It can be argued that increasing the size of the tied ridges might have reduced run-off losses. However, the net benefit to the crop would have been minimal as the reduced run-off would have been lost as drainage from the saturated soil. Nevertheless, increasing size of ridges would probably improve groundwater recharge and reduce the risk of soil erosion.

iii) Drainage In contrast to run-off drainage was closely correlated with irrigation regime (see Figure 16). As noted above, the very high drainage losses were primarily a result of the method of irrigation scheduling. Only the 40% irrigation regimes had low drainage losses. Figure 17 presents the seasonal drainage estimates for all the treatments. Comparing similar irrigation regimes, it is interesting to note that drainage losses were consistently higher under flood irrigation as compared to subsurface irrigation. However, it seems probable that these differences were caused by differences in irrigation applied rather than irrigation method

iv) Water Use Water use was defined as the sum of soil and crop evaporation, drainage, run-off and change in soil moisture storage during the season. As would be expected the high rainfall during this experiment in conjunction with the excessive irrigation led to water use that was extremely high.

v) Adjusted Water Use Adjusted water use was calculated as water use (defined above) with the run-off losses subtracted. It should be noted that it was not possible to obtain an independent estimate of crop evaporation from water balance calculations as a consequence of the consistently high drainage losses.

Water use effectiveness

Table 13 compares the water use effectiveness (wue) of the all treatments calculated using the water use and adjusted water use data presented in Table 12. As would be expected adjusted water use effectiveness (wue') calculated using adjusted water use values was higher than wue calculated using unadjusted values. Figure 18 plots wue' against irrigation and rainfall for all the treatments while Figure 19 presents yield and wue' on the same figure. These figures show that, in general, wue' increased with decreasing irrigation and rainfall. The highest wue' for the flood treatments was achieved with the 60% irrigation regime. Whereas for the subsurface treatment, the highest wue' was obtained with the 40% irrigation regime. It is possible, given the high rainfall and irrigation, that even higher wue' values would have been achieved with subsurface treatments at even lower irrigation regimes.

Table 12 *Expt 93/1 components of water balance*

Treatment	IRR mm	Change	Wat. Use	Wat. Use (adjusted)	D+RO mm	Drain mm	Run-off mm
1	951	3	1373	1125	722	475	247
2	1311	32	1705	1479	1054	828	226
3	720	-24	1171	900	520	249	272
4	591	-24	1041	772	391	121	269
5	410	-45	881	668	231	18	213
6	903	-47	1377	1078	726	428	298
7	889	-44	1359	1064	708	414	294
8	1224	-28	1678	1393	1027	743	284
9	721	-30	1177	900	526	249	277
10	554	-31	1011	736	361	86	275
11	377	-41	844	669	194	18	175
12	850	-52	1328	1026	677	375	302

Rainfall = 426 mm
Potential Evaporation = 651 mm
Water Use = (Irr + Rain) - Change
Water Use (adjusted) = (Irr + Rain) - Run-off

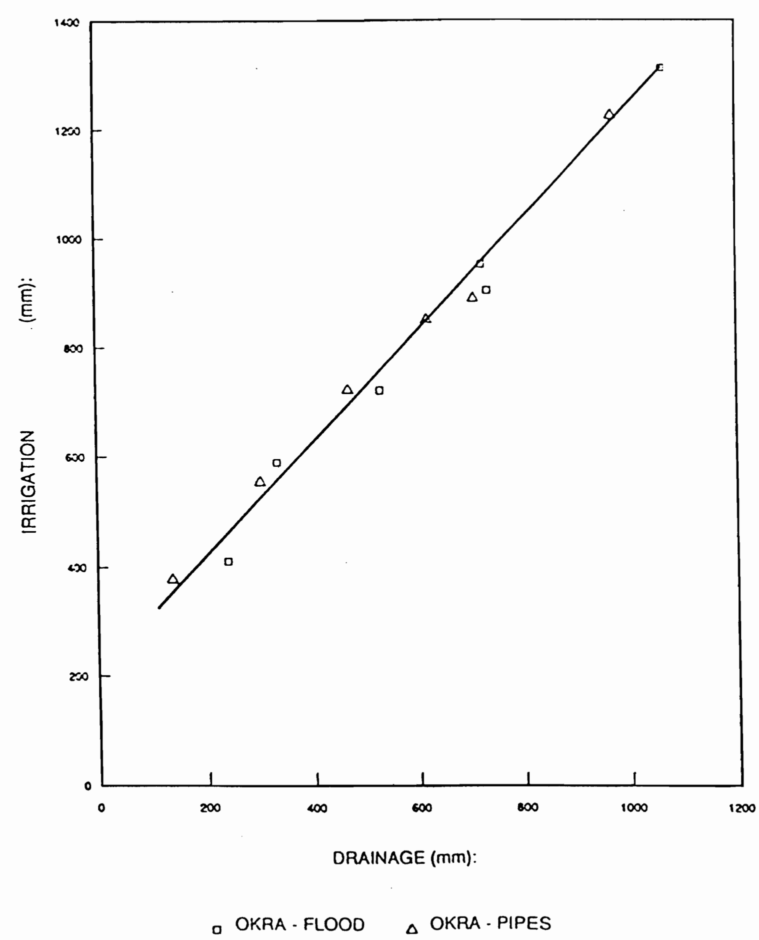


Figure 16 ***Expt. 93/1: seasonal total irrigation plotted against drainage***

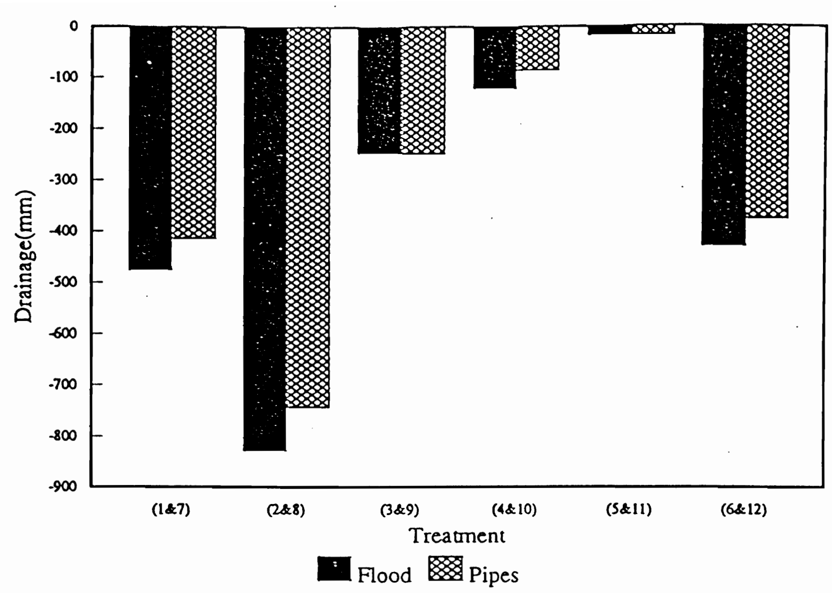


Figure 17 *Expt. 93/1: comparison of seasonal drainage from all treatments*

Table 13 *OKRA - Yield and water use effectiveness data*

Treatment	Yield (t/ha)	Water use effectiveness (kg/m³)	Water use effectiveness' (kg/m³)
1	23.53	1.7	2.1
2	27.91	1.6	1.9
3	22.89	2.0	2.5
4	21.34	2.2	2.8
5	17.91	2.0	2.7
6	22.86	1.7	2.1
7	23.75	1.8	2.2
8	23.69	1.4	1.7
9	22.57	1.9	2.5
10	20.09	2.0	2.7
11	17.87	2.1	2.7
12	21.65	1.6	2.1

Water Use Effectiveness = Yield (kg/ha) / Total Water Used (m)
Water Use Effectiveness' = Yield (kg/ha) / Total Water Used (m) (adjusted)

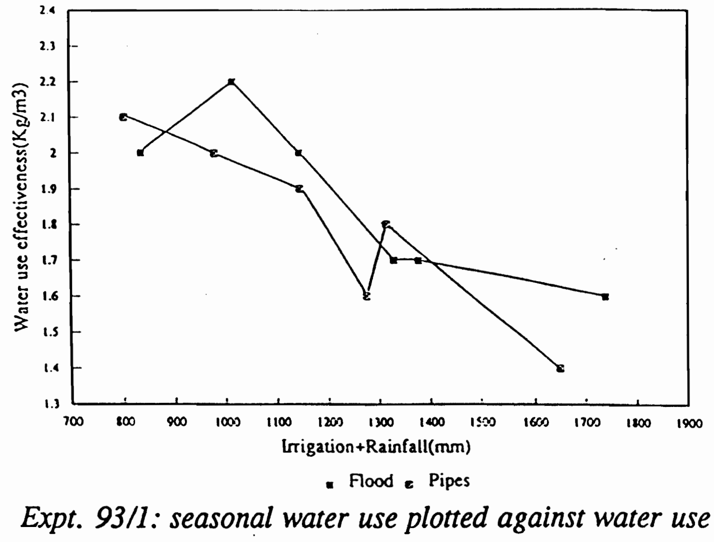


Figure 18 *Expt. 93/1: seasonal water use plotted against water use effectiveness*

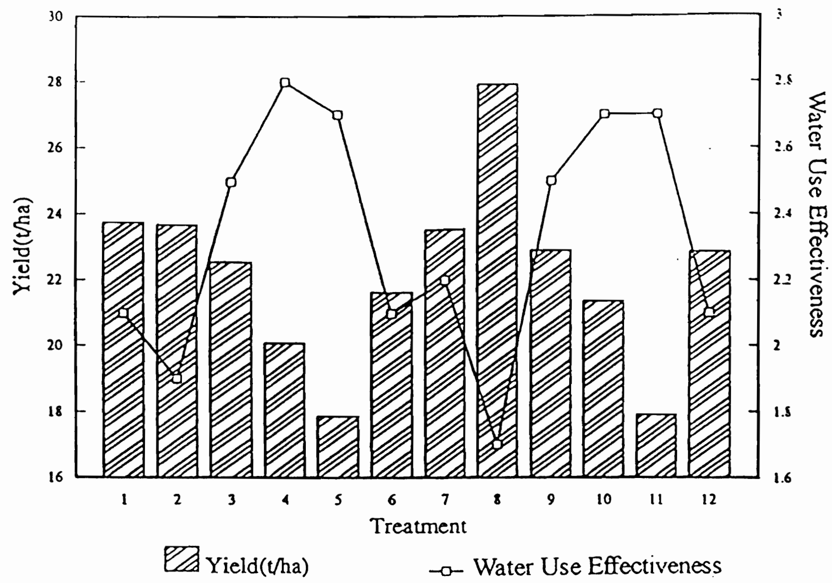


Figure 19 *Expt. 93/1: comparision between yield and water use effectiveness for all treatments*

3.4 EXPERIMENT 93/3: TOMATO TRIAL

3.4.1 EXPT 93/3 materials and methods

Experimental design and irrigation scheduling

The experimental design, irrigation scheduling and plot layout for Expt 93/3 was the same as was used for Expt 93/1 (see Section 3.3.1).

3.4.2 EXPT 93/3 results and discussion

Weather during the crop season

Table 14 presents the mean monthly meteorological data measured during the crop season. The 1993 winter season was notable for the above average rainfall during July 1993. Total rainfall during Expt. 93/3 was 74 mm.

Agronomy

The tomato seedlings (*Lycopersicon esculentum* cv Heinz) were transplanted on 16 June at a spacing of 0.3 m between plants and 0.3 m between rows. The variety Heinz is a determinate bushy tomato. Before planting a fertilizer consisting of 80 kg ha^{-1} phosphate, 50 kg ha^{-1} nitrogen and 40 kg ha^{-1} potassium was incorporated into the soil as a basal dressing. A top dressing consisting of 50 kg ha^{-1} nitrogen and 40 kg ha^{-1} phosphate was then applied 2, 4, 8 and 10 weeks after planting.

Unlike an earlier tomato irrigation trial (Expt. 91/1), the plants in this trial were not staked or wired. Although used by some farmers, staking or wiring of tomato plants is not the normal practice in communal areas in Zimbabwe.

Table 14 *Expt 93/3 - mean monthly meteorological data*

Month	Tmax °C	Tmin °C	Tdry °C	Twet °C	Tdry °C	Twet °C	Wind km/d	Sun hrs	Rain mm	Pan mm	Et mm
1993											
MAY	30.2	14.0	19.5	14.1	28.7	16.8	98	9.3	9.7	5.3	3.9
JUN	26.2	10.2	15.4	12.7	25.4	16.0	82	8.7	6.3	3.6	2.8
JUL	25.3	11.3	15.4	13.9	24.3	16.5	95	7.3	46.2	3.0	2.7
AUG	26.6	10.5	16.4	13.5	25.7	16.5	121	8.8	4.0	4.4	3.6
SEP	31.2	13.8	21.0	16.6	30.7	18.8	142	9.7	11.0	6.6	5.1
OCT	32.8	18.6	24.0	19.4	31.9	20.7	199	9.7	7.2	7.8	6.4

Growth and Yields

The harvest results are presented in Table 15. It can be seen that the highest yield were achieved with the wetter regimes. The 140% regime had the best yield on the flood treatments while the 100% regime had the highest total yield on the subsurface treatments. Drier irrigation regimes, including the traditional regime, had significantly lower yields. In general, the subsurface treatments had fewer tomatoes per plant but these tomatoes were larger and heavier.

Table 15 *Expt 93/3 harvest result*

Treatment	Av. No. Fruit/Plant	% Non-market per hectare	Av. weight marketable fruit (g)	Yield (t/ha)
1	36.4	8.91	94	116
2	35.7	12.7	113	124
3	33.4	9.1	84	98
4	32.6	5.5	72	84
5	26.7	5.6	60	58
6	32.0	6.4	81	93
7	30.3	6.5	109	118
8	31.1	9.6	106	115
9	30.4	5.1	95	103
10	28.2	4.5	83	85
11	24.6	8.2	58	51
12	28.9	4.1	95	102

The field observers noted that tomato quality was superior on the subsurface treatments. This was a consequence of tomatoes on the flood treatments being in contact with the wetted soil surface for at least part of each week. Tomatoes on subsurface treatments rested on dry soil except after rainfall. Although it had the highest yield, the 140% flood treatment also had the highest percentage of non-marketable produce. If yields are adjusted to take account of non-marketable produce, the highest yielding treatment on the trial is the 100% subsurface treatment. Adjusting for non-marketable produce, results also in the 100% flood treatment having a higher marketable yield than the 140% flood treatment.

The yields achieved by the treatments in this trial were similar to those achieved in Expt 91/1 (Lovell *et al.*, 1992). This was a tomato irrigation trial which compared flood and subsurface irrigation using a different experimental design and a different tomato variety. It should be noted that the best yields in both these trials are among the highest tomato yields achieved at the Lowveld Research Station. The yields reported here also compare favourably with yields achieved using deficit irrigation applied by different methods in Hawaii (Sammis & Wu, 1986). However, in a study of the efficiency of subsurface irrigation in California, water use efficiencies calculated using fresh tomato yields were double those achieved in this trial (Phene *et al.*, 1990).

Tomato water use, run-off and drainage

Tomato water use, run-off and drainage were calculated for all the treatments by computing bi-weekly soil water balances. Inputs were taken as rainfall and irrigation and the neutron data were used to estimate soil water content change during each period. Drainage was calculated for periods of low rainfall during which run-off (and run-on) were assumed to be insignificant.

Table 16 *Expt 93/3 water balance components*

Treatment	IRR mm	Change	Wat. Use	D+RO mm	Drain mm
1	1026	33	1065	540	540
2	1412	15	1470	946	927
3	832	16	888	363	358
4	638	1	710	186	168
5	444	7	510	18	18
6	791	9	855	330	318
7	963	37	994	475	475
8	1327	23	1377	852	843
9	783	17	838	313	309
10	601	1	673	148	131
11	420	10	483	18	18
12	791	9	855	330	317

Rainfall = 74 mm
Potential Evaporation = 525 mm
Water Use = (Irr + Rain) − Change
Water Use (adjusted) = ((Irr + Rain) − Change) − Run-off

Table 16 presents the seasonal components of the soil water balance for each treatment. Total rainfall for the crop season was 74 mm and total evaporation (soil and crop) was estimated to be 525 mm for all treatments. The evaporation estimates were based on the assumption that the high irrigation applications and unusually high rainfall resulted in evaporation being at near potential rates on all treatments. This is a reasonable assumption for wetter regimes which received irrigation that was considerably in excess of tomato water requirements. For the two drier treatments (60% and 40% regimes), this assumption probably led to drainage being underestimated. The following inferences can be drawn from Table 16 :-

i) Irrigation The irrigation applied to the treatments was very high as indicated by the 100% flood treatment receiving 501 mm of irrigation more than the potential evaporation during the season. As mentioned in the Expt 93/1 results section, the high irrigation applications were a result of the method of irrigation scheduling not taking sufficient account of rapid drainage losses immediately after irrigation.

ii) Drainage Drainage was closely correlated with irrigation regime. Figure 20 presents seasonal drainage estimates for all treatments. The high drainage losses from this trial and from Expt 93/1 have led to revisions to the method of irrigation scheduling. The high drainage losses have also led to the frequency of subsurface pipe irrigation to be increased from weekly to twice weekly. The subsurface pipe treatments on Expt 91/1 were irrigated four times each week.

iii) Water Use Water use was defined as the sum of soil and crop evaporation, drainage, run-off and change in soil moisture storage during the season. The high values were a direct consequence of the high irrigation applications.

iv) Adjusted Water Use Adjusted water use was water use defined above with the run-off losses subtracted. As would be expected given the low rainfall during this trial, run-off estimates were very small and, consequently, differences between water use and adjusted water use were not important.

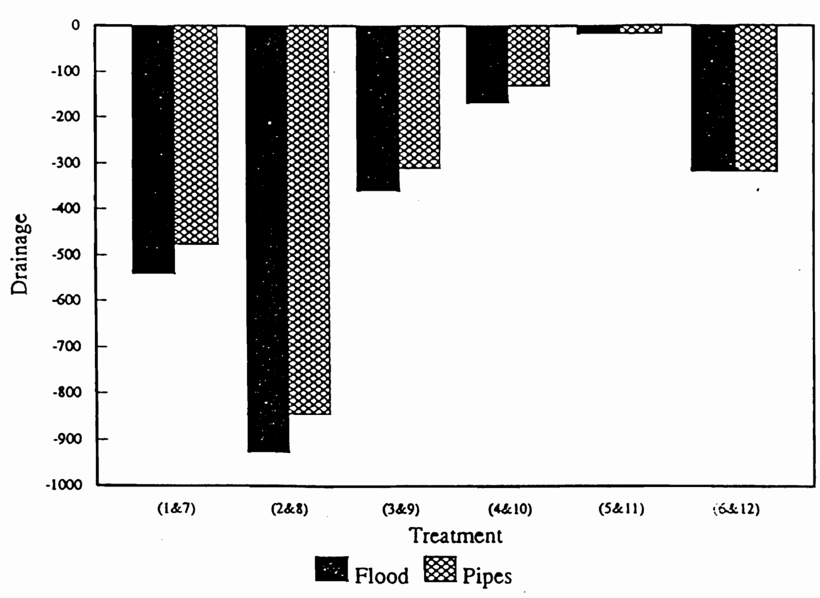


Figure 20 *Expt. 93/3: seasonal drainage totals for each treatment*

In Figure 21, crop yields are plotted against seasonal total water use for all treatments. It can be seen that yield increased linearly with water use up to a water use of around 1100 mm. After this value there was not a significant increase in yield. As the water use estimates contain a large drainage component, it has to be seen whether altering irrigation frequency and irrigation scheduling method will lead to a reduction in the amount of water use required to achieve a certain yield.

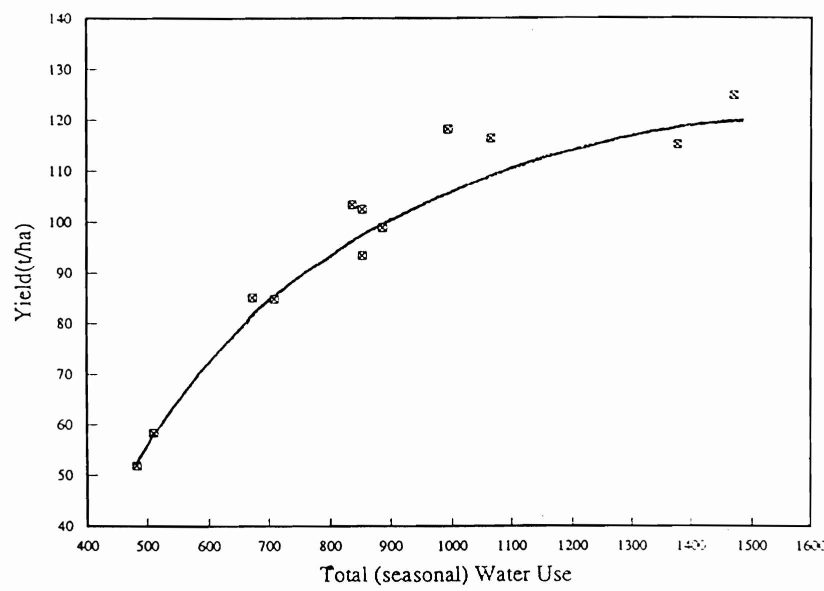


Figure 21 *Expt. 93/3: seasonal water use plotted against yield*

Water use effectiveness

Table 17 compares the water use effectiveness of the all treatments calculated using the water use and adjusted water use data presented in Table 16. Figure 22 plots adjusted water use effectiveness (wue') against irrigation and rainfall for all the treatments while Figure 23 presents yield and wue' on the same figure. These figures show that there were not large differences in the wue' of the 60%, 80% and 100% treatments. The wue' of treatments irrigated at 140% were, however, significantly lower than for other treatments.

Although the yields were similar, the water use effectiveness values for this trial were lower than those reported for Expt 91/1 (Lovell *et al.*, 1992). This difference can be explained by the higher drainage losses on Expt 93/3.

Table 17 *Expt 93/3 Yield and water use effectiveness results*

Treatment	Yield (t/ha)	Water use effectiveness (kg/m³)	Water use effectiveness' (kg/m³)
1	116.38	15.6	10.9
2	124.74	8.5	8.6
3	98.88	11.1	11.2
4	84.88	11.9	12.2
5	58.37	11.4	11.4
6	93.36	10.9	11.0
7	118.17	11.9	11.9
8	115.12	8.4	8.4
9	103.38	12.3	12.4
10	85.14	12.6	13.0
11	51.89	10.7	10.7
12	102.45	12.0	12.2

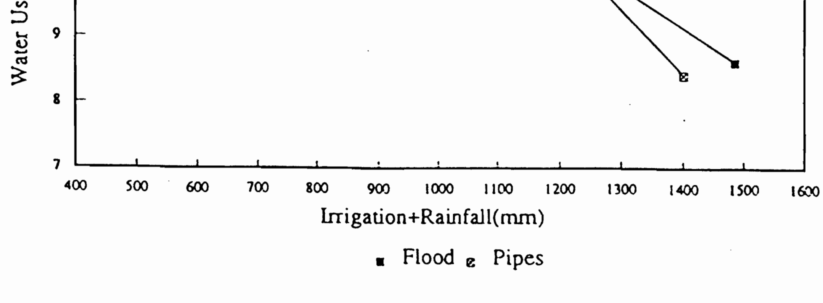


Figure 22 *Expt. 93/3: seasonal water use plotted against water use effectiveness*

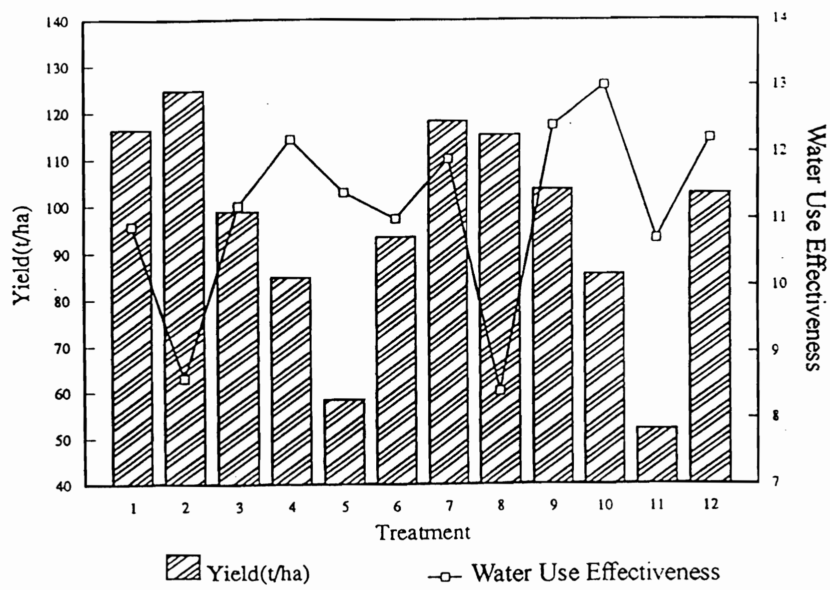


Figure 23 *Expt. 93/3: comparision between yield and water use effectivenss for all treatments*

3.5 GENERAL DISCUSSION AND CONCLUSIONS

3.5.1 Irrigation scheduling

The overirrigation of some treatments that occurred on Expts 93/1 and 93/3 was a result of the irrigation scheduling method used. The scheduling rules for previous trials involved applying sufficient irrigation to return the soil on each treatment to approximately "field capacity". The scheduling rules used on Expts 93/1 and 93/3 were based on applying the equivalent irrigation to the apparent crop water use during the period between irrigations. This approach led to positive feedback, whereby, the more irrigation water that was applied the greater the rapid drainage that took place and, hence, on some treatments, the more irrigation that was applied. Irrigation applications increased to far in excess of weekly tomato water requirements. It should be noted that overirrigation did not take place on Expt 92/2 and, although overirrigation that did take place on some treatments Expts 93/1 and 93/3, this did not have a serious influence on the findings of these trials.

The results presented here showed that the traditional irrigation schedule identified in a survey of agricultural practices in Chivi Communal Area (Lovell *et al.*, 1992) leads to some degree of overirrigation in the earlier part of crop seasons and underirrigation in the later part. This schedule relies on soil moisture storage compensating for shortfalls in irrigation. This is a reasonable strategy on soil types with high water retention. However, on lighter soils, it is a strategy that will lead to crop stress during the more sensitive development stages. A schedule that varies with crop development stage should be used on lighter soils.

3.5.2 Irrigation frequency

A weekly irrigation frequency was adopted for both flood and subsurface treatments for the three trials reported here. The relationships between yield and the sum of irrigation and rainfall for all the trials show that yield continued to increase even when the sum of irrigation and rainfall was considerably in excess of the crop water requirements. It was also seen that drainage losses increased in line with the sum of irrigation and rainfall. This suggests that additional yield resulted from increased lateral movement of soil water on wetter regimes, thereby, making more water available to the crop between irrigations. As this possible lateral movement was achieved at the expense of high drainage losses, a more efficient means of improving soil water availability is to increase irrigation frequency.

On flood treatments, increasing irrigation efficiency will lead to higher soil evaporation losses and, possibly, reduced field application uniformity. However, increased irrigation frequency does not effect water use effectiveness on subsurface treatments because the water is applied directly into the root zone.

3.5.3 Irrigation method

Although subsurface irrigation using clay pipes is not a common practice, subsurface placement of driplines has been a standard procedure for sugar cane since the late 1970's (Batchelor & Soopramanien, 1983). In recent years in some countries, there has been a steady trend towards using buried driplines for a number of other row and orchard crops (Phene *et al.*, 1993). Crops grown using subsurface driplines in California include tomatoes, cotton, lettuce, strawberries, vines, apple, almond, peach and turf. The main advantages of subsurface irrigation include improvements in water use efficiency and field application uniformity as a result of reduced soil evaporation (Phene *et al.*, 1993). However, it should be noted that some trials have only shown only marginal improvements in the water use effectiveness (wue) of subsurface drip as opposed to surface drip (e.g. Constable *et al.*, 1990; Hodgson *et al.*; 1990; Constable & Hodgson; 1990).

The results of trials reported here have shown that there are yield, water use effectiveness and crop quality advantages to be gained by using subsurface irrigation. However, these advantages only materialise when irrigation regimes are closely matched to crop water requirements (Batchelor *et al.*, 1994). The water use effectiveness and yields of crops grown with flood and subsurface pipes are similar when irrigation exceeds crop water requirements. Another important factor is the degree of canopy cover during the crop cycle and, hence, the quantity of water lost as soil evaporation. The rape trial (Expt 92/2) showed a large water use effectiveness advantage for subsurface irrigation that was almost certainly a result of the regular leaf harvests reducing canopy cover and increasing soil evaporation. This advantage was not as apparent for the tomato trial (Expt 93/3) which had a complete canopy cover during the second half of the crop season.

3.5.4 On-farm trials

Although funding constraints led to less work being done by the project on on-farm trials than had been hoped, it is encouraging that there is independent evidence of uptake of project recommendations. Reports from the Intermediate Technology Development Group's Chivi Food Security Project indicate that there has been an increasing use of subsurface irrigation (e.g. Murwira, 1994). Murwira (1994) states "Work on clay pipes was seen to be appropriate for women in Chivi as they already use clay in their pottery work. A total of sixty-two women started the work in 1992 and today we have over 300 women practising the technology. The amount of time spent watering has been drastically reduced from about 20 hours to 5 hours per week.

The following information was taken from Murwira (1995):

> "Traditionally, women in Chivi District have joined with others in their village to form gardening groups. A suitable area is fenced off and, within this garden, each group members tends several beds. Vegetables are grown to supplement family food supply, and any surplus produce is sold for cash. Women are always very busy, because of the competing demands of both running the home, and looking after children, as well as working on the family farm. The gardening group enables the women to assist each other, by sharing their ideas on, and knowledge of, fencing, cultivating weeding and watering techniques.
>
> Water is a continuous problem. Gardens are often on the slopes above a river but, in the dry season, this may well be dry, and wells have to be dug in the river-bed to obtain water. Whatever the season, they have to carry the water to the gardens. This is time consuming and requires many journeys, as only a small amount of water can be carried each trip.
>
> IT's Chivi food-security project organised a trip for gardening group representatives to visit a government agricultural research station at Chiredzi. Here, the women saw a trial using porous clay pipes laid at root level as a way of irrigating small vegetable beds. Each pipe is about a foot long, and a run of them is laid along the length of a bed. The pipes are laid at rooting depth, loosely butting up to each other. One end of the pipe is plugged with a ball of clay. The other end has an angled pipe, so that the end of the final pipe protrudes through the soil surface. Water can be poured into this open end. The water seeps out slowly through the cracks between the pipe sections, and through the porous walls of the pipes. This is a particularly efficient way to deliver water, as it arrives directly at root depth, and evaporation losses are greatly reduced.
>
> The women were particularly interested in this idea, as it addressed a pressing problem. In addition, the women were already skilled potters, making clay pots for cooking and storage, so they felt capable of making their own pipes.
>
> The women's experiments with this system in their own gardens have proved the idea works well and reduces the amount of watering required. This in turn means that they need to spend less time tending their gardens."

Apart from the extension work carried out by IT in Chivi District, the government extension service, AGRITEX, has also been active in promoting subsurface irrigation. This has included setting up demonstration plots at regional shows and at the Harare show. Other users of subsurface irrigation have included a Kellogs-funded garden project in Chiredzi and Friedrick Ebert Foundation projects in the Sangwe/Sengwe communal areas.

4. Irrigation water quality trials

4.1 INTRODUCTION

The Collector Well Garden Project in Zimbabwe (Lovell *et al.*, 1995) has demonstrated that irrigation of community gardens using water extracted from shallow collector wells has enormous potential for improving the quality of life of rural communities in semi-arid areas. One factor that may hinder the widespread replication of groundwater-based community gardens is the prevalence of saline groundwater in these areas. Localised saline groundwater occurs as a result of the low rainfall and high evaporation, which lead to relatively slow downward movement of water through the unsaturated zone. In basement geologies, salts resulting from weathering and mineralisation are often leached into confined aquifers. The exact location of these saline aquifers, or of good quality groundwater, is difficult to predict without exploratory drilling, but typically between a half and three quarters of all boreholes constructed in the drier parts of Zimbabwe are saline to some degree (Source: MLAWD, Masvingo).

Although of poor quality, moderately saline groundwater should be considered a valuable resource. Research and experience in recent years has demonstrated that waters of much higher salinities than those customarily classified as "unsuitable for irrigation" can, in fact, be used effectively for the production of crops given appropriate management and cropping strategies (Rhoades *et al.*, 1992). In a review paper, Shalhevet (1994) assesses the extent to which research has answered practical questions relevant to the use of moderately saline water for irrigation. The main points from this paper are summarised in Table 18. In a second review paper on irrigation with moderately saline water, Oster (1994) states that use of these waters require three changes form standard irrigation practice. These are:

- Selection of appropriately salt-tolerant crops.
- Improvements in water management and in some cases, the adoption of innovative irrigation technology.
- Maintenance of soil-physical properties to assure soil tilth and adequate soil permeability to meet crop water and leaching requirements.

The trials reported in this section of the report were designed to compare the water use efficiency of subsurface irrigation and traditional flood irrigation when using water of low, medium and high salinity, and to provide practical guidelines on the use of subsurface irrigation with the poorer quality waters.

4.2 EXPERIMENT 91/4: MAIZE TRIAL

4.2.1 Experimental 91/4 Materials and Methods

Experiment Design
The experiment was carried out on the experimental collector well garden at the Chiredzi Research Station. Experiment 91/4 adopted the same location and experimental design as used for the first project water quality trial (Expt. 91/2) reported in Lovell *et al.* (1992).

Tables 1 and 2 present the chemical analyses of the medium salinity and low salinity irrigation waters which were pumped from the collector well and from Lake Mtilikwi (formerly "Lake Kyle") respectively.

The experiment was a maize trial (*Zea mays* cv ZS225) of four treatments with four replicates. The four treatments are described in Table 19.

Table 18 *Summary of research findings/recommendations on irrigation with poor quality water.*

Practical problem or consideration		Research findings/recommendations
1.	Varietal differences	Varietal differences in salt tolerance exist mainly in fruit trees. Differences among field and garden crops are not common and are usually small.
2.	Duration of exposure and stage of growth	Plants are more sensitive during the seedling stage than during later stages of growth, but the preponderant temporal effect is the duration of exposure.
3.	Soil fertility	The level of soil fertility has no effect on the tolerance of crops to salinity.
4.	Irrigation requirements	Crop water production functions relating yield to evaporation are not influenced by water salinity. It is still controversial whether reduction in water uptake with increasing salinity is the cause or the result of reduction in growth.
5.	Leaching requirements	Leaching is the key to the successful use of saline water for irrigation. Under normal field conditions with free drainage, the leaching provided by the normal irrigation inefficiencies in irrigation should be sufficient to control salinity. When leaching is necessary, it should be provided when the soil salinity reaches hazardous levels.
6.	Availability of more than one water source	Blending of saline with non-saline water is a questionable practice. It is preferable to use the non-saline water source early in the growing season and the saline water successively.
7.	Irrigation method	Drip irrigation where feasible gives the greatest advantages when saline water is used. Sprinkler irrigation may cause leaf burn on sensitive crops.
8.	Drainage	The critical depth to the water table is determined mainly by the aeration requirement of the crop. The design drainage coefficient is determined by the leaching requirement.
9.	Soil hydraulic conductivity	The higher the sodium absorption ratio (SAR), the greater the reduction in soil hydraulic conductivity. The detrimental effects of high SAR is mitigated as total salt increases.

The sixteen plots were arranged in a Latin square design. Each plot comprised of four beds, each 3 m long by 1 m wide and surrounded by a low earth bund. Grass mulch was applied to each treatment at a rate of 12 t/ha.

On the subsurface pipe treatments, clay pipes were buried along the centre line of each bed. Twelve pipes were used per bed, simply laid end to end in a level trench which was backfilled with soil. The pipes were made at the research station using a simple mould and fired in a shallow bark filled pit. Further details of pipe manufacture are given by Lovell *et al.* (1990). The pipes were of length 0.24 m, internal diameter 0.075 m and external diameter 0.11 m. The depth of soil above the pipes was approximately 0.1 m.

Table 19 *Experiment 91/4 treatments*

Treatment	Irrigation Method	Water Quality
CWF	Flood	Medium salinity
CWP	Subsurface pipes	Medium salinity
KYF	Flood	Low salinity
KYP	Subsurface pipes	Low salinity

Instrumentation
Two neutron probe access tubes were installed to a depth of 1 m on one plot of each treatment at spacings of 0.125 m and 0.375 m to one side of the centre line. However, for most purposes, only the access tube nearest the centre of the bed was used. One plot of each treatment was also instrumented with a two-dimensional tensiometer array. Each array consisted of 12 mercury manometer tensiometers installed at three depths (0.1, 0.4 and 0.7 m) and four positions across the 1 m wide bed (0.125 m and 0.375 m either side of the centre line).

Irrigation
All treatments received the same amount of irrigation based on soil moisture depletion on the subsurface poor water quality treatment (CWP) as measured by one neutron probe access tube located 0.125 m from the centre of the bed. A subsurface treatment was chosen as control because, from previous experience, it was known that these treatments tend to be more efficient than flood treatments. Choosing a flood treatment would have led to over irrigation of subsurface treatments. Irrigation was carried out weekly.

Measurement of soil salinity profiles
Accumulated salts were measured in the soil profiles beneath each treatment and a control area that had not been irrigated at any time and that was approximately 4 m from the experimental area. Soil samples were taken at the surface (0-2 cm) and by auguring at depths 2-20 cm, 20-40 cm, 40-60 cm and 60-80 cm at four positions across the 1 m wide beds (0.125 m and 0.375 m either side of the centre line) to give two dimensional pictures of salt distribution. Samples were taken before and after this experiment and subsequent experiments reported later.

The soil samples were allowed to air dry before being passed through a 2 mm sieve. Electrical conductivity EC_5 (m^s/cm) of a suspension of 1 part (20g) of soil in 5 parts of distilled water, stirred intermittently for 1 hour, was determined at 20°C using a Kent EIL conductivity meter (Model 5007). Replication of this technique was found to give a standard deviation typically of around 6% about the average. pH of a suspension of 1 part (20g) of soil in 5 parts of calcium chloride (0.01 M $CaCl_2$), stirred intermittently for 1 hour, was determined at 20°C using a Pye Unicam pH meter (Model 292). Electrical conductivity of the soil saturation extract EC_8 was determined using the equation:

$$EC_8 = EC_5 \times (500/SP)$$

where SP = saturation percentage, determined using the equation:

$$SP = \frac{\text{moisture content of saturated soil paste}}{\text{weight of oven dry soil}} \times 100$$

and measured for the soil at Chiredzi Research Station as 25%.

Agronomy
The maize was planted on 12 December 1991 in two rows per bed using an in-row spacing of 0.3 m and an inter-row spacing also of 0.3 m. A basal dressing of 400 kg/ha of Compound D (N:P:K - 8:14:7) was incorporated by hoe at planting and a top dressing of 100 kg/ha N was applied by hand 40 days after planting. Carbaryl foliar spray was used to combat leaf eaters and Thiodan was used to control maize stalk borer (*Busseolafusca*) and termites. Irrigation ceased on 16 March 1992 and harvesting was carried out on 30 March 1992.

4.2.2 Experiment 91/4 Results and Discussions

Weather during the crop season
The worst drought to date was recorded during the crop season of 1991/92. Table 20 presents the mean monthly meteorological data measured during this season. Maximum air temperatures were well above the long-term average for much of the summer. Weekly rainfall for the period October 1990 to April 1994 is also presented in Figure 24 showing that the 1991/92 crop season was extremely dry compared to the previous and subsequent seasons.

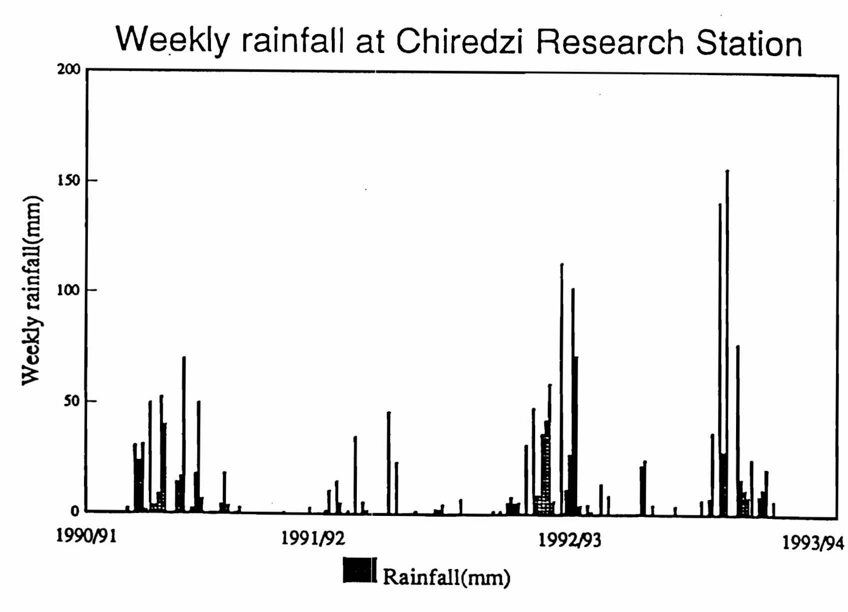


Figure 24 *Weekly rainfall at Chiredzi Research Station*

Table 20 *Mean monthly meteorological data*

Month	TMAX	TMIN	TDRY	TWET	TDRY	TWET	WIND	SUN	RAIN	PAN	ET
	C	C	C	C	C	C	km/d	h	mm	mm	mm
				am	am	pm	pm				
Dec 91	33.1	20.9	25.4	20.2	32.0	21.0	183.0	8.8	21.7	8.1	6.8
Jan 92	34.7	22.1	26.5	21.4	33.7	22.1	176.0	9.7	41.2	9.4	7.1
Feb 92	36.0	23.0	27.5	21.5	35.3	22.2	183.0	11.1	2.0	10.5	7.5
Mar 92	33.7	21.3	24.8	20.5	32.9	21.4	164.0	7.9	70.5	8.1	5.8

Irrigation, water use and drainage
Table 21 presents the seasonal values of irrigation, rainfall, net soil moisture content change to 0.9 m, water use and potential evaporation. Simple water balance calculations computed using weekly data suggested that drainage was low on the treatments of this trial. This is confirmed to some extent by Figure 25 which shows distributions of soil moisture matric potential (kPa) measured by tensiometer 24 hours after an irrigation of 47 mm mid-way through the crop season. A relatively dry soil profile remained at depth beneath all treatments, little drainage likely to occur due to the low hydraulic conductivity of this soil (less than 0.0001 mm/day) at matric potentials less than -25 kPa (Lovell *et al.* 1990).

Differences in crop water use (ET_a) were not significant. This is not surprising given the low rainfall during the crop season and the fact that all treatments received the same amount of irrigation based on neutron probe measurements. Crop water use (ET_a) for the water quality trials was defined as the sum of transpiration, soil evaporation, drainage, run off and canopy interception.

Table 21 *Experiment 91/4 water balance components*

Treatment	CWF	CWP	KYF	KYP
Irrigation (mm)	523.6	523.6	523.6	523.6
Rain (mm)	116.2	116.2	116.2	116.2
ET_{Penman} (mm)	760.2	760.2	760.2	760.2
S.M. Change (mm)	67.9	73.7	85.4	79.2
ET_a (mm)	571.9	566.1	554.4	560.6

Yields and water use effectiveness
The harvest grain yields are presented in Table 22. All yields were low because all treatments on this trial were affected by the prolonged periods of high temperatures and high evaporative demand during the crop season. The conditions were so severe that unshaded leaves senesced prematurely. However, damage was greatest on the flood treatments. It can be seen that there was a significant yield advantage in favour of treatments irrigated using subsurface pipes. It can be concluded that the localised nature of soil wetting on the subsurface treatments

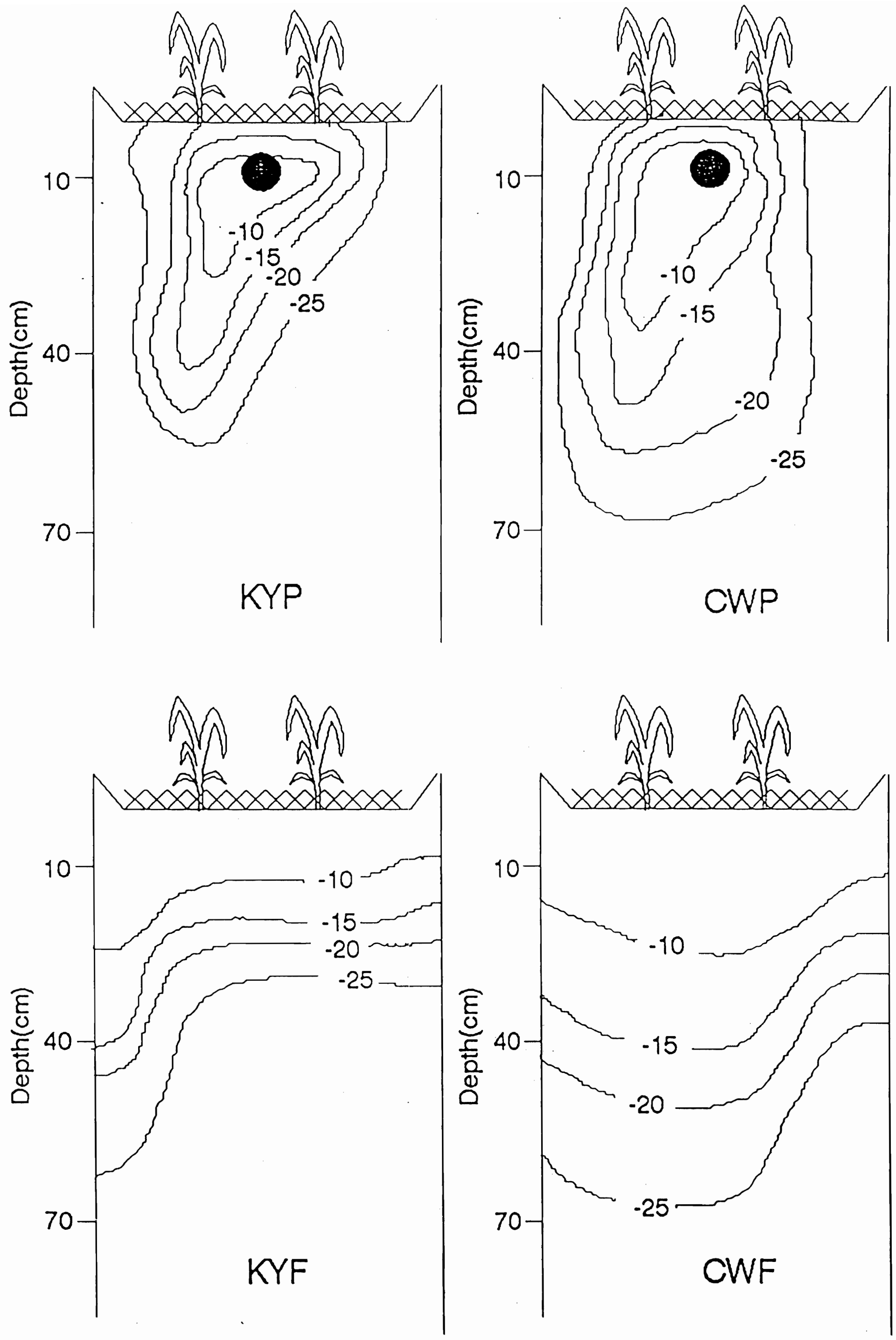


Figure 25 *Distribution of soil moisture matric potential (kPa) beneath each treatment 24 hours after irrigation of 47 mm on 27/1/92.*

(see Figure 25) resulted in soil water being more readily available than on flood treatments. Soil evaporation losses may also have been marginally lower on the subsurface treatments despite a mulch having been used on all treatments. Consequently, during periods of high evaporative demand, the transpiration continued for longer on subsurface treatments keeping leaves relatively cool and minimising the affects of the unusually prolonged periods of high temperature and high radiation load.

Table 22 *Experiment 91/4 yields and water use effectiveness (wue)*

Treatment	Yield (kg/ha)	wue (kg/m³)
CWF	775	0.136
CWP	1506	0.266
KYF	912	0.165
KYP	1227	0.219
CV%	30.9	30.9
LSD(P= .05)	NS	NS

The water use effectiveness (wue) results are presented in Table 22 and plotted in Figure 26. It can be seen that the highest wue values were obtained on the subsurface poor water quality treatment and the lowest wue on the flood poor water quality treatment.

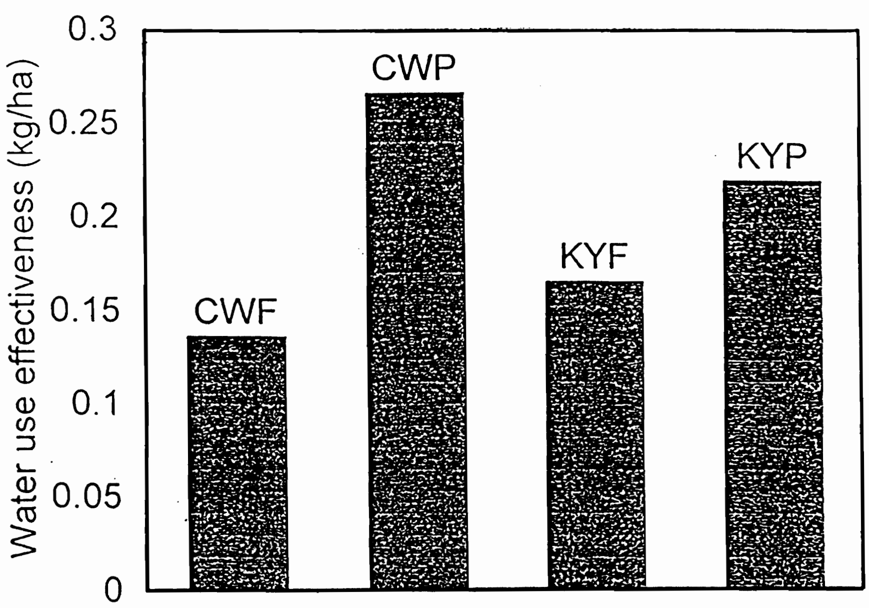


Figure 26 *Expt. 91/4: water use effectiveness of all treatments*

Patterns of salt accumulation

Water quality does not appear to have had a major influence on yield. Figure 27 shows the two dimensional pattern of soil salinity (EC_e) measured beneath each treatment and the control prior to Experiment 91/4. Figure 28 shows the pattern measured after the experiment in March 1992 following 570 mm of irrigation but only 148 mm of rainfall during this extremely poor wet season.

Despite low rainfall, the general trend illustrated is one of slight leaching of salts under all treatments including the control. Low salinity levels measured beneath the irrigated plots prior to this trial indicate leaching of salts during previous Experiment 91/2 (Lovell *et al.*, 1992). These low levels of salinity were maintained during Experiment 91/4 and, with much of the root zone under each treatment remaining at EC_e values less than 2.5 mS/cm, salt would be unlikely to have caused more than a 10% reduction in crop yield if any (Doorenbos & Pruitt, 1977). As mentioned previously, crop yield on all treatments of this trial were severely restricted not so much by salinity as by the extremely high temperatures during drought, particularly during February when on one day, the 26th, the average hourly temperature remained above 40°C between 11am and 6pm. Despite water being available in the root zone, plants of all treatments were unable to transpire sufficiently to remain cool and scorching of the leaves occurred, those plants irrigated by flood being most severely affected.

4.3 EXPERIMENT 92/1: TOMATO TRIAL

4.3.1 Experiment 92/1 Materials and Methods

Experimental Design

The experiment was a tomato trial (Lycopersicon esculentum cv Heinz) of four treatments with four replicates. The four treatments were the same as used in Experiment 91/4 (as described in Section 4.2.1) except that mulches were not used. Treatments were located on the same beds as were used for Experiment 91/4. Subsurface pipes were maintained in position and cultivation was carried out without damaging pipes.

Instrumentation

The same instrumentation was used for Experiment 92/1 as for Experiment 94/1 with the exception that time constraints did not allow the tensiometer arrays to be maintained and read.

Irrigation

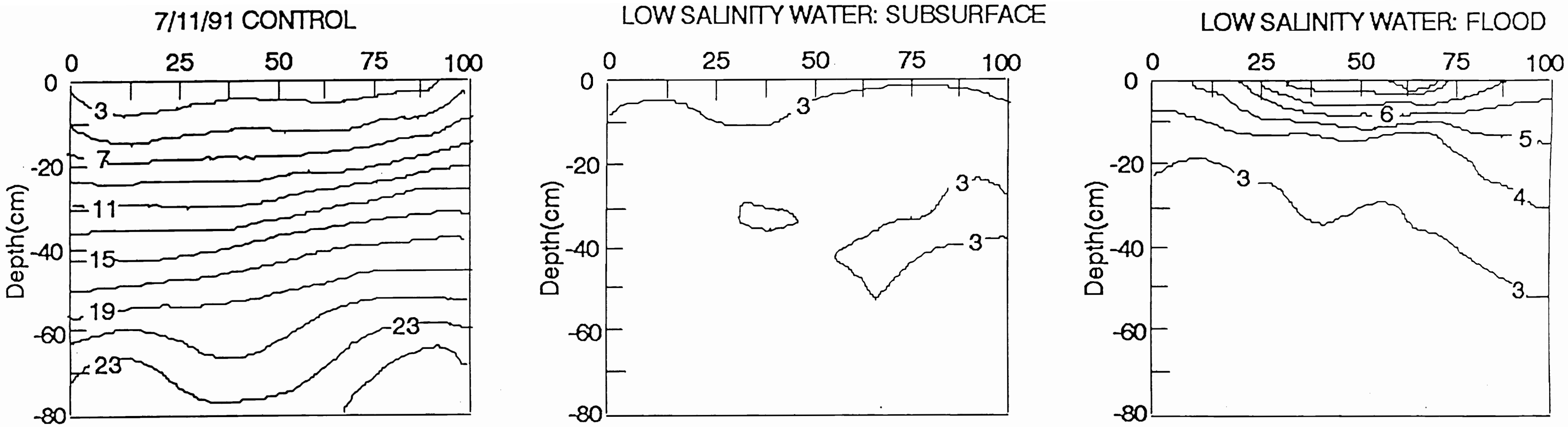
Irrigation was carried out using the same procedures as used for Experiment 91/4.

Measurement of soil salinity profiles

The same procedure as used for Experiment 91/4.

Agronomy

Tomato plants were transplanted on 15 April 1992 in two rows per bed with an in-row spacing of 0.3 m and an inter-row spacing also of 0.3 m. A basal dressing of 80 kg/ha P_2O_5 as SSP, 50 kg/ha N as ammonium nitrate and 40 kg/ha K_2O as potassium sulphate was applied during bed preparation. A top dressing of 50 kg/ha N and 40 kg/ha K_2SO_4 was applied in increments at 2, 4, 6, 8 and 10 weeks after transplanting. Copper Oxchloride and Bravo were applied alternately throughout the growing season to control, in particular early and late blight (alternaria solani and phytophtora infestans respectively). Agrithrin was applied a week after transplanting to combat heliothis bollworm. Carbaryl foliar spray and



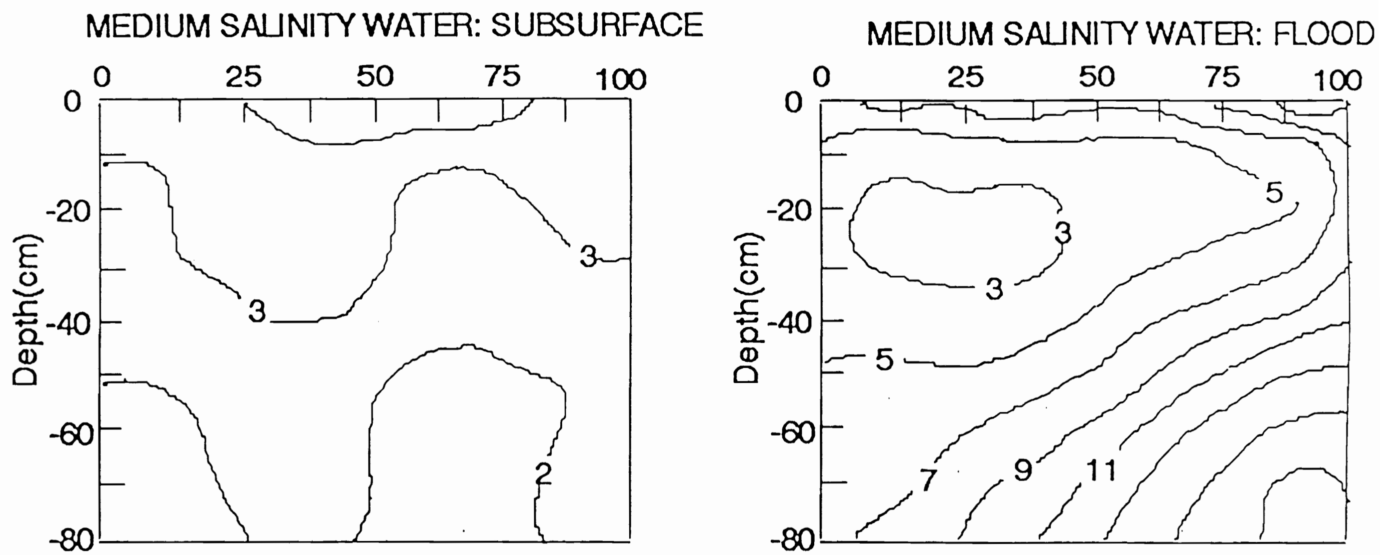


Figure 27 *Soil salinities (ECe, mS/cm) beneath each treatment before wet season (Expt 91/4).*

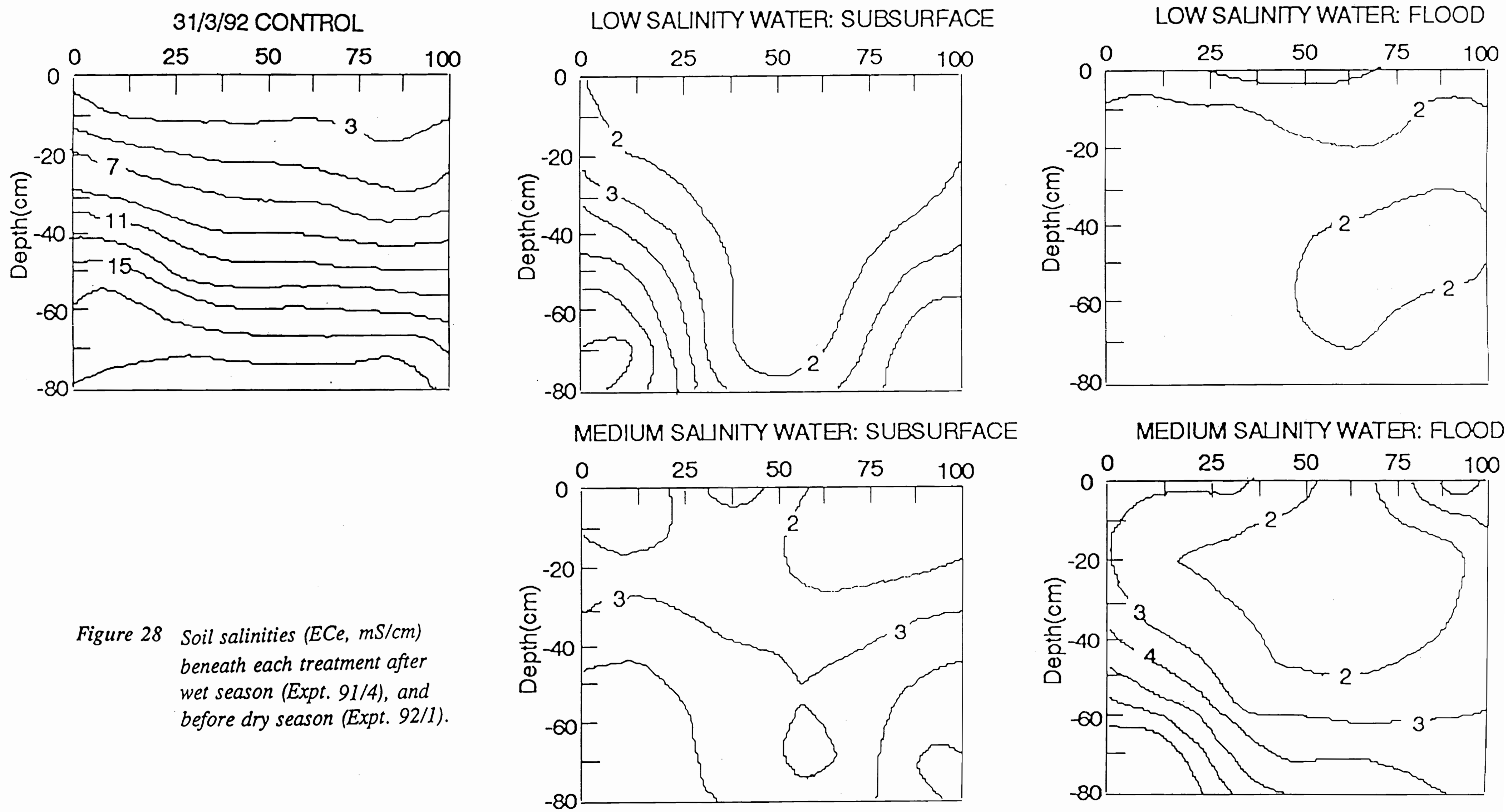


Figure 28 *Soil salinities (ECe, mS/cm) beneath each treatment after wet season (Expt. 91/4), and before dry season (Expt. 92/1).*

Recumin were applied three weeks after transplanting to control cutworms and mice respectively. Harvesting started on 14 July 1992 and continued weekly to 21 September 1992 giving a total of 13 harvests.

4.3.2 Experiment 92/1 Results and Discussion

Weather during crop season
The weather during the crop season is presented in Table 23.

Table 23 *Mean monthly meteorological data*

Month	TMAX	TMIN	TDRY	TWET	TDRY	TWET	WIND	SUN	RAIN	PAN	ET
	C	C	C	C	C	C	km/d	h	mm	mm	mm
				am	am	pm	pm				
April	32.8	17.2	23.4	19.1	30.8	20.0	119	9.4	-	6.2	4.6
May	30.2	14.0	19.5	14.1	28.7	16.8	98	9.3	9.7	5.3	3.9
June	26.8	10.5	15.8	12.2	25.8	15.8	88	8.8	9.6	4.0	3.0
July	26.2	10.1	15.2	11.7	25.4	15.0	103	8.5	7.0	4.1	3.3
August	27.3	11.8	16.9	12.9	26.3	15.5	130	8.0	-	5.2	3.9
Sept	32.9	15.0	21.9	16.8	32.2	18.5	113	9.1	1.7	8.1	6.2

Irrigation, water use and drainage
Table 24 presents the seasonal values of irrigation, rainfall, net soil moisture content change to 0.9 m, water use, potential evaporation and drainage. Simple water balance calculations carried out weekly indicated that differences in crop water use were small although there was a trend for water use to be slightly lower on the subsurface treatments as compared to the flood treatments. Drainage formed a larger component of the water balance in Experiment 92/1 than was the case on Experiment 91/4. The main reason appears to have been the higher rates of irrigation applied to this experiment despite this being a winter crop. The differences in drainage between treatments was small with relatively lower drainage on subsurface treatments as compared to flood treatments.

Yields and water use effectiveness
The overall yields of the trial were high, and higher than anticipated given that the tomatoes which were a determinate variety were not trained on wires so as to better represent the cultivation practices of the communal areas. As with previous trials, the yields of the subsurface treatments were consistently higher than those achieved by flood treatments. This yield difference translated into similar differences between flood and subsurface in water use effectiveness. There appears to be a trend of higher yields on the poor quality treatments that is difficult to explain.

Table 24 *Experiment 92/1 water balance components*

Treatment	CWF	CWP	KYF	KYP
Irrigation (mm)	804.8	804.8	804.8	804.8
Rain (mm)	26.3	26.3	26.3	26.3
ET_c (mm)	658.3	658.3	658.3	658.3
S.M. Change (mm)	-36.1	-15.4	-53.6	-26.9
ET_a (mm)	867.2	846.5	884.7	858.0
Drainage (mm)	207.1	186.0	226.4	199.7

Table 26 presents the yield component of Experiment 92/1. Although there is some inconsistency in the yield component results, it appears that the yield advantage for subsurface treatments was a combination partly of increased tomato number and increased tomato weight. It was noted by the field observers that fruit quality was better on subsurface treatments. This was attributed to the tomatoes being in contact with dry soil rather than wet soil as was the case on flood treatments.

Table 25 *Experiment 92/1 yields and water use effectiveness (wue)*

Treatment	Yield (t/ha)	wue (kg/m^3)
CWF	92.7	10.7
CWP	97.7	11.5
KYF	89.7	10.1
KYP	94.7	11.0
CV%	8.9	-

Table 26 *Experiment 92/1 yields components*

Treatment	Tomatoes (ha^{-1})	Av. Tomato wt. (g)	Stover (kg/ha)
CWF	1270 000	75.4	2954
CWP	1290 000	78.4	3908
KYF	1040 000	84.7	4431
KYP	1170 000	78.1	3908

Patterns of salt accumulation
Again, water quality did not appear to have a major influence on final yield. Figures 28 and 29 show the patterns of salt distribution measured beneath each treatment and the control area before planting the tomatoes in May 1992 and again after harvest in September 1992, following 805 mm of irrigation and negligible winter rainfall. Beneath the control, an upward movement of salt was recorded during this dry period. On the irrigated treatments salt accumulation occurred above both subsurface pipe treatments but not within the profiles irrigated by flood. Values of EC_e measured above the subsurface pipes at the end of the trial were sufficient to reduce tomato yields - values greater than 5 mS/cm and 7.6 mS/cm can cause yield reductions of 25 and 50 percent respectively (Doorenbos & Pruitt, 1977), but values at the beginning of the trial (when the seedlings were most sensitive) were low.

Because salts are usually unevenly distributed in the soil, those roots growing in volumes of soil containing less salt than average can take up relatively more water than those roots growing in volumes containing more than average (Gardner, 1967). With this buffer, it is reasonable to assume that the safe values of salt content measured here beneath the soil surface allowed this crop to grow relatively unaffected by water quality, the salt accumulated at the soil surface likely to become more important during establishment of the next crop.

4.4 EXPERIMENT 93/2: SWEET CABBAGE TRIAL

4.4.1 Experiment 93/2 Materials and Methods

Experimental Design
The experiment was a sweet cabbage trial (Brassica oleracea cv Capitata) of four treatments with four replicates (Table 20).

Instrumentation
The same instrumentation and measurement programme was used for Experiment 93/2 as for Experiment 92/1.

Irrigation
Irrigation was scheduled as for Experiment 92/1.

Measurement of soil salinity profiles
The same procedure as used for Experiment 94/1.

Agronomy
Sweet cabbage seedlings were transplanted on 2 December 1992. Twenty seedlings were planted in two rows per bed at a spacing of 0.3 x 0.3 m, giving a plant population of 30,770 plants/ha. A surface irrigation of 33.3 mm was applied to all treatments to ensure good establishment. Before planting, a basal fertiliser of 80 kg/ha P_2O_5 as single super phosphate and 30 kg/ha K_2O as muriate of potash was incorporated by hoe. A total of 100 kg/ha N as ammonium nitrate was applied as three equal increments at 1, 3 and 6 weeks after transplanting.

Karate foliar spray was applied weekly to combat bagrada bug and diamond back moth (Plutella Xylostella). Crop damage by snails was high, particularly on the KYP treatment which lost approximately 25% of the crop. All treatments were also badly affected by bacterial soft rot (Erwina carotovora). Because of the high incidence of pests and diseases

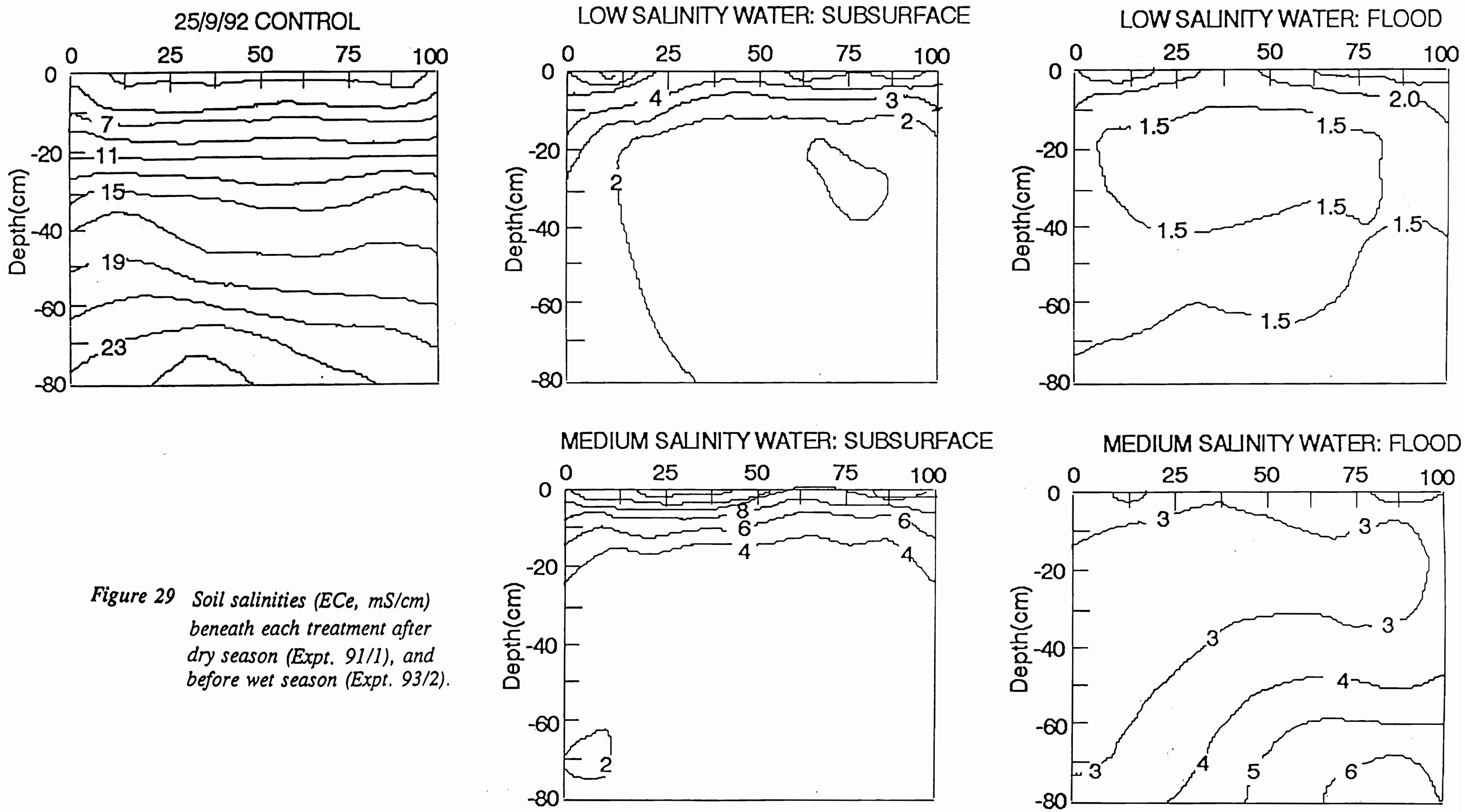
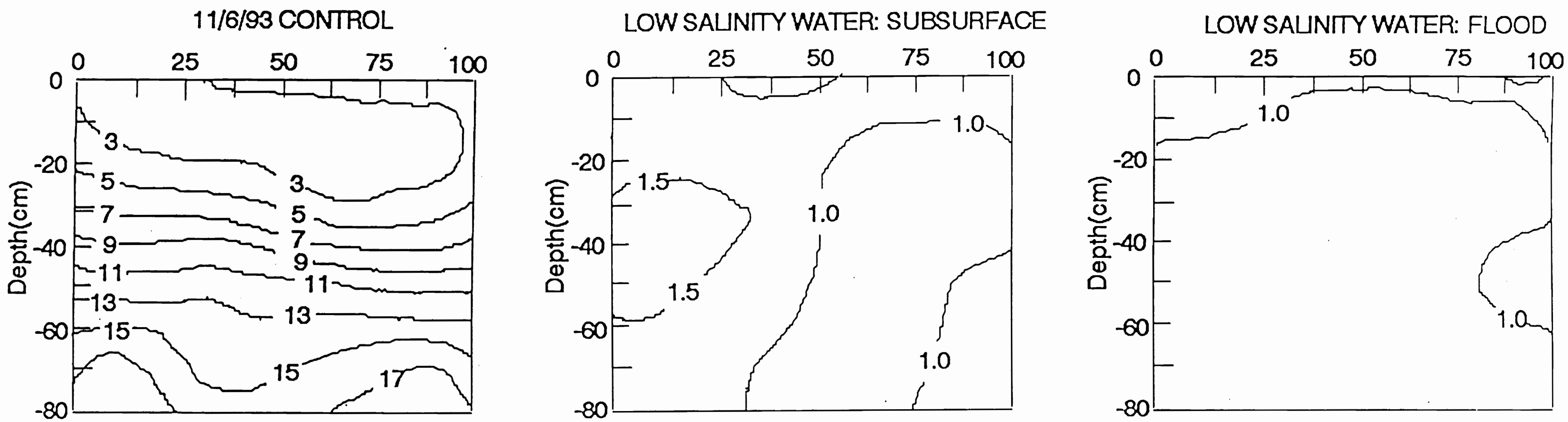


Figure 29 *Soil salinities (ECe, mS/cm) beneath each treatment after dry season (Expt. 91/1), and before wet season (Expt. 93/2).*



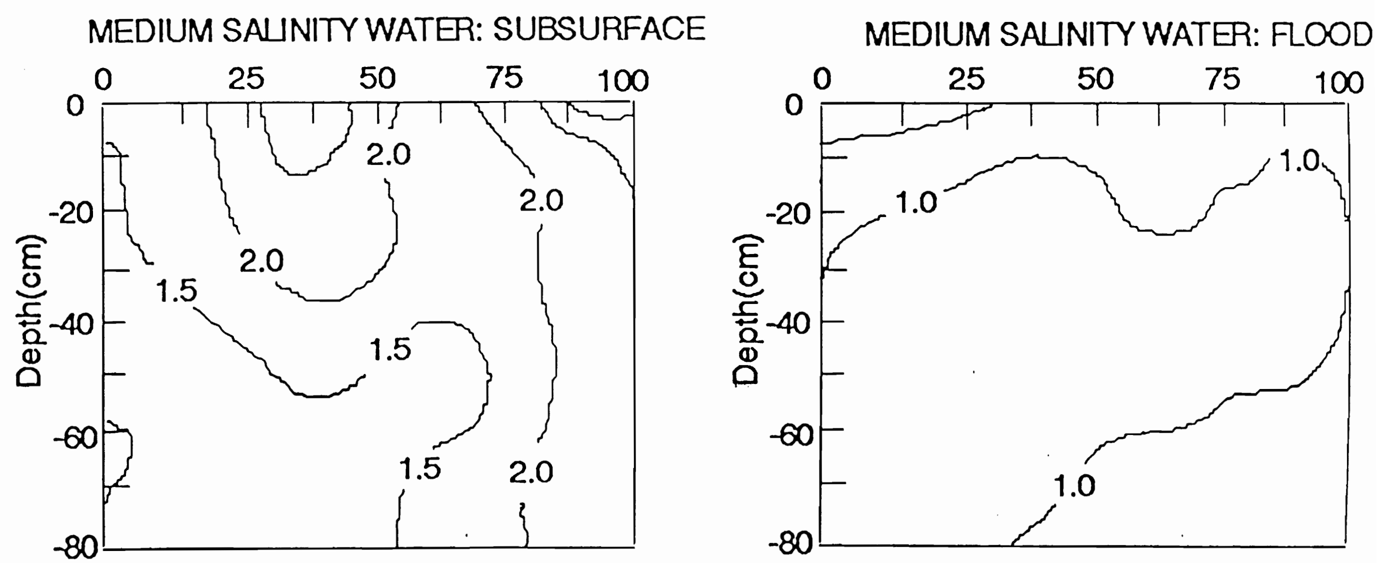


Figure 30 *Soil salinities (ECe, mS/cm) beneath each treatment after wet season (Expt.93/2), and before dry season (Expt. 93/4).*

the crop was poor and had to be harvested early to avoid even greater losses. There were a total of three harvests at 42, 54 and 65 days after transplanting. Total yield was determined for each treatment by summing the weight of marketable heads produced per bed. Pathways were included in the areal calculations.

4.4.2 Experiment 93/2 Results and Discussion

Weather during crop season
The weather during the 1992/93 summer crop season is described in Section 3.3.2.

Irrigation, water use and drainage
Table 27 presents the seasonal values of irrigation, rainfall, net soil moisture content change to 0.9 m, water use, potential evaporation and drainage. Differences in crop water use were small. Drainage was only a very small percentage of the water budget.

Table 27 Experiment 93/2 water balance components

Treatment	CWF	CWP	KYF	KYP
Irrigation (mm)	175.7	175.7	175.7	175.7
Rain (mm)	292.4	292.4	292.4	292.4
ET_{Penman} (mm)	410.6	410.6	410.6	410.6
S.M. Change (mm)	48.2	41.9	53.2	72.2
ET_a (mm)	419.9	426.2	414.9	395.9
Drainage (mm)	9.3	15.6	4.3	0

Yields and water use effectiveness
The yields were not high and crop quality was poor as the heads were small and loose. It can be concluded that cabbage was not an appropriate crop for the season given the hot humid conditions. Nothing of value can be drawn from comparing yields and wue of treatments of this trial.

Patterns of salt accumulation
Figures 29 and 30 show the patterns of salt distribution measured beneath each treatment and the control area before Experiment 93/2 in September 1992 and after the experiment in June 1993 following the 176 mm of irrigation and a total rainfall of 560 mm. Beneath the control, a downward movement of salt was recorded during this wet season. On the irrigated plots, leaching also occurred on both subsurface and surface irrigated treatments. No effect on crop establishment was observed at the beginning of this experiment as a result of surface salts accumulated during prior Experiment 92/1, and EC_e values of less than 2.8 mS/cm measured after the experiment would have caused no reduction in crop yield had pests and diseases not ended this experiment prematurely.

Table 28 *Experiment 93/2 yields and water use effectiveness (wue)*

Treatment	Yield (t/ha)	% non-marketable	Head Wt (kg)	wue (kg/m^3)
CWF	22.0	12	0.81	5.2
CWP	18.9	11	0.69	4.4
KYF	19.7	12	0.73	4.7
KYP	19.4	11	0.75	4.9
CV%	17.9	31.4	15.8	-
LSD (P=0.05)	NS	NS	NS	-

4.5 EXPERIMENT 93/4: RAPE TRIAL

4.5.1 Experiment 93/4 Materials and Methods

Experimental Design
The experiment was a rape trial ("Giant English". Brassica oleraceae cv Napus) of eight treatments replicated four times in a lattice square design of two beds per plot. The eight treatments are described in Table 29.

Table 29 *Experiment 93/4 treatments*

Treatment	Irrigation Method	Water Salinity	Mulch	Landform
CWFL	Flood	High	No	Flat
CWFO	Flood	High	No	Furrow
CWFM	Flood	High	Yes	Furrow
CWP	Pipes	High	No	Flat
KYFL	Flood	Low	No	Flat
KYFO	Flood	Low	No	Furrow
KYFM	Flood	Low	Yes	Furrow
KYP	Pipes	Low	No	Flat

High salinity water (Ec 4 mS/cm) was prepared this time using water from the collector well to which salt was added in the following proportions:

131.2g sodium chloride	|	
149.2g calcium sulphate	|	to 200 litres of water
410.2g magnesium sulphate	|	

This action was taken because groundwater of this salinity and higher is found in southern Zimbabwe, previous research has shown that although yields are reduced water having EC's as high as 5 mS/cm can be safely used (FAO, 1977), and results of the previous water quality trials reported here had not shown significant differences between the saline and non-saline water treatments.

Instrumentation
The instrumentation was the same as for Experiment 93/2.

Irrigation
Irrigation was the same as for Experiment 93/2.

Measurement of soil salinity profiles
The same procedure as was used for experiment 91/4.

Agronomy
Rape seedlings were transplanted on 16 June 1993. Twenty seedlings were planted in the rows per bed at a spacing of 0.3 x 0.3 m, giving a plant population of 30,770 plants/ha. Before planting, a basal fertiliser of 80 kg/ha P_2O_5 as single superphosphate and 60 kg/ha K_2O as muriate of potash were incorporated by hoe. A total of 100 kg/ha N as ammonium nitrate was applied in three increments at 1, 3 and 6 weeks after transplanting. The first and last harvests were at 30 and 121 days after transplanting respectively. Harvesting was carried out once per week for thirteen weeks. Total yield per treatment was calculated by summing the fresh weight of marketable leaves per bed, with pathways included in the areal calculations.

Carbaryl foliar spray was applied a week after transplanting to combat crickets (Brachytrupes membranaceous and B portentous). Hostathion was applied at 16 and 21 days to control red spider mite (Tetranychus cinnabarinus). Agrithrin was applied at 48, 93, 123, and 130 days to combat diamond back moth, American bollworm and centre grub (Hellula sp). Pirimor was applied at 61, 91 and 123 days to combat aphids.

4.5.2 Experiment 93/4 Results and Discussion

Weather during the crop season
The weather during the 1993 winter crop season is described in Section 3.4.2.

Irrigation and water use
Table 30 presents the seasonal values of irrigation, rainfall, net soil moisture content change to 0.9 m, water use and potential evaporation. Although drainage was assumed to be insignificant for this trial, comparison of potential evaporation with the sum of rainfall and irrigation would suggest that there would have been some drainage from all treatments.

The crop water use for each treatment is presented in Table 30. It can be seen that the water use totals of the low salinity water treatments were similar, whereas there was an interesting trend of decreasing water use on the high salinity water treatments. The highest water use by the flat flood treatment (CWFL) and the lowest water use was by the subsurface pipe treatment (CWP).

Table 30 *Experiment 93/4 water balance components*

Treatment	CWFL	CWFO	CWFM	CWP	KYFL	KYFO	KYFM	KYP
Irrigation (mm)	478	478	478	478	478	478	478	478
Rain (mm)	74	74	74	74	74	74	74	74
ET_{Penman} (mm)	481	481	481	481	481	481	481	481
S.M. Change (mm)	-48	14	34	42	-5	-7	2	3
ET_a (mm)	600	538	518	510	557	559	550	549

Yields and water use effectiveness

The harvest results and the water use effectiveness of all treatments is presented in Table 31. It can be seen that the highest yield and wue was achieved by high salinity water subsurface pipe treatment (CWP). The lowest yield was recorded on the low salinity water mulched furrow treatment (KYFM).

Table 31 *Experiment 93/4 harvest results and water use effectiveness*

Treatment	Yield (t/ha)	Leaf Wt. (g) leaves	No. of leaves	Leaf DM (g)	Wue (kg/m^3)
CWFL	52.3	39.8	34	8.3	8.7
CWFO	57.4	39.6	38	8.5	10.7
CWFM	52.9	39.7	41	7.3	10.2
CWP	63.9	40.8	42	8.5	12.5
KYFL	56.6	47.1	33	8.1	10.2
KYFO	54.0	35.2	38	8.1	9.7
KYFM	49.1	35.4	37	8.1	8.9
KYP	52.7	41.4	34	8.0	9.6
LSD 5%	4.3	5.5	ns	0.3	-
CV%	5.5	9.9	11	6.9	-

Patterns of salt accumulation
Figures 30 and 31 show the patterns of salt distribution measured beneath each treatment and the control area before Experiment 93/4 in June 1993 and after the experiment in October 1993 following 478 mm of irrigation and rainfall of 74 mm. Beneath the control, a slight upward movement of salt was recorded during this dry season. On the irrigated plots, significant salt accumulation was recorded in the upper 30 cm of both high salinity treatments and to a lesser extent also above the low salinity water subsurface pipe treatment. For spinach (a plant considered similar to rape) yield reductions of 25 and 50 per cent are predicted at EC_e values of 5.3 and 8.6 mS/cm respectively (Doorenbos & Pruitt, 1977). Such reductions in yield were not recorded here. Somewhat surprisingly, the high salinity water treatments had higher yields than equivalent low salinity water treatments.

4.6 FALLOW PERIOD: OCTOBER 1993 - APRIL 1994

Figures 31 and 32 show the patterns of salt distribution measured beneath each treatment and the control before and after the wet season of 1993/94, during which 567 mm of rain fell but no crop was grown of irrigation applied. Significant natural leaching of salts occurred at this time, even under the control, and all salts applied to the irrigated plots during the previous experiments were moved downward below a depth of 70 cm. Figure 24 shows the weekly distribution of rainfall that caused this leaching. However, it is reasonable to assume that the process occurred predominantly as a result of the good soaking rains of 141 mm that fell at the end of November followed only a few days later by 143 mm that fell on one day, the 10th December. This pattern of events provides a good example of the conditions that are required for deep percolation of rainfall to occur in an environment of normally high evaporative demand.

4.7 GENERAL DISCUSSIONS AND CONCLUSIONS

4.7.1 Water Quality

No significant reductions in crop yield were recorded in this series of experiments due to the use of poor quality irrigation water. In fact, interesting improvements in both crop yield and water use efficiency were actually recorded in some experiments where high salinity water was applied by subsurface irrigation.

Traditionally, vegetables are grown in Zimbabwe during the cool dry winter season. For a range of vegetable crops, good yields have been achieved here during three consecutive winter seasons although water of medium and high salinities has been used for irrigation. This appears to be possible on this soil type due largely to the cyclic leaching of salts that occurs naturally each hot wet season (allowing vegetables to be established in relatively salt free conditions at the start of the following winter) and due to the buffer that is provided during the growing season when part of the soil profile remains low in salt content although salt accumulation occurs near the top of the root zone.

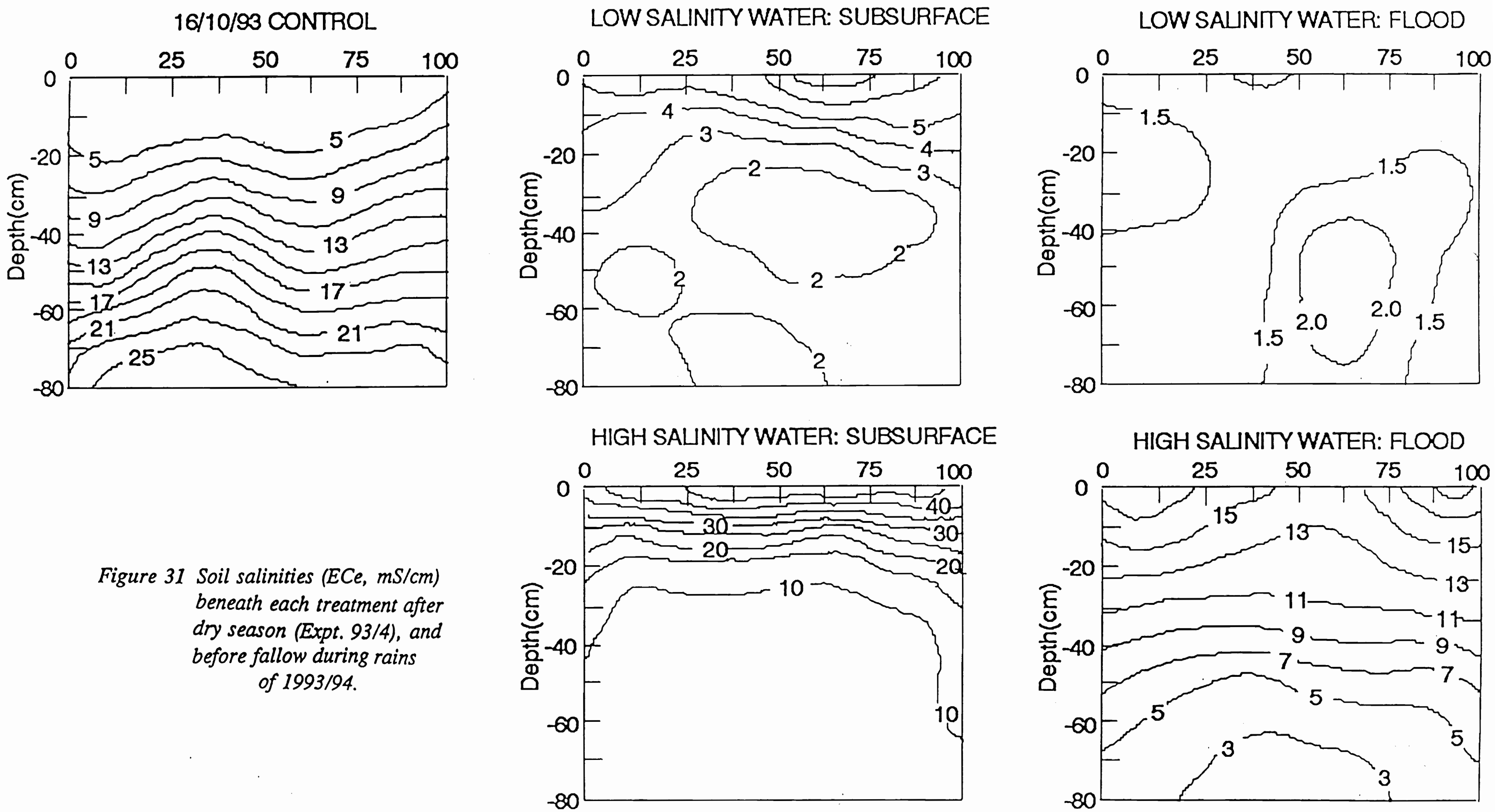


Figure 31 Soil salinities (ECe, mS/cm) beneath each treatment after dry season (Expt. 93/4), and before fallow during rains of 1993/94.

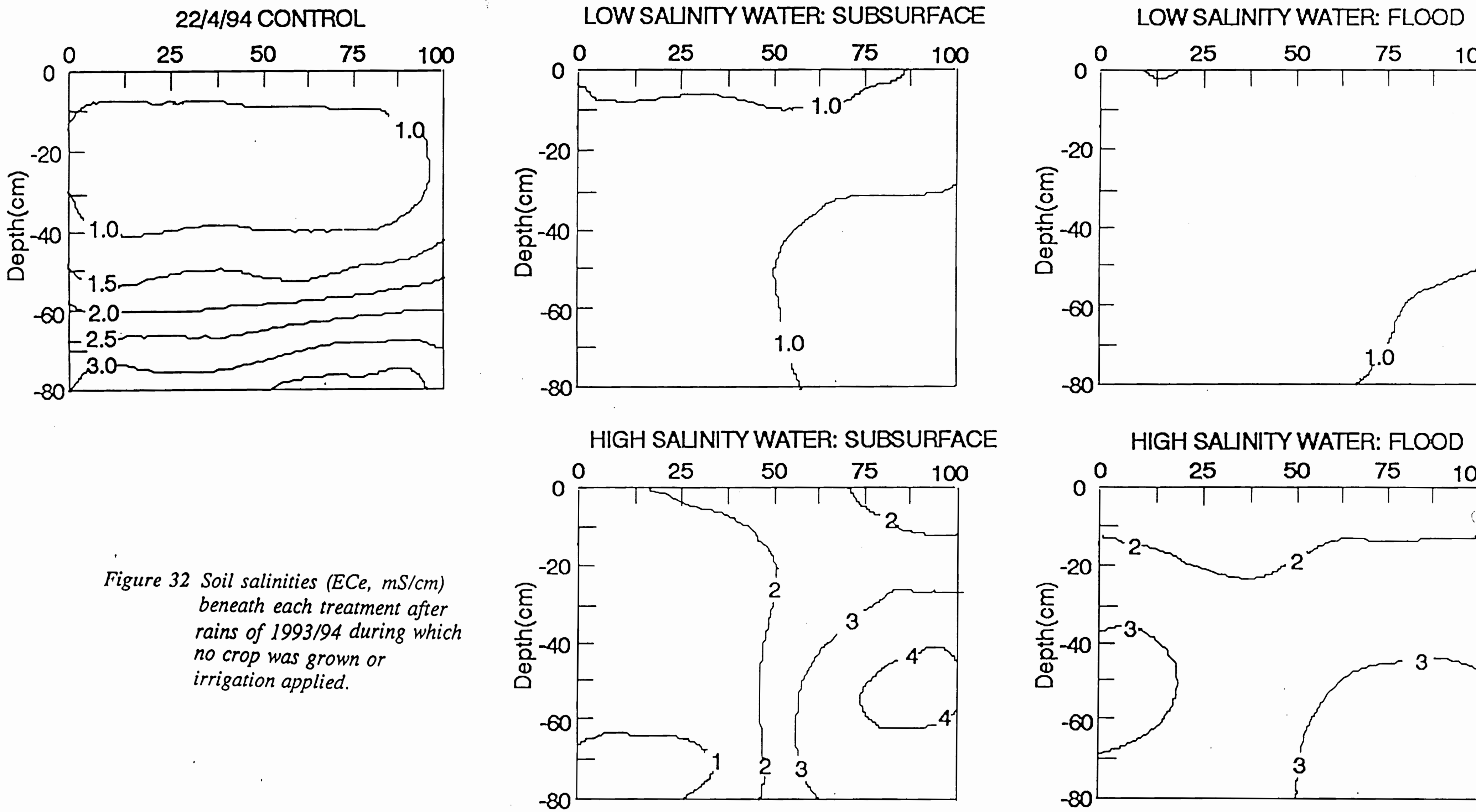


Figure 32 Soil salinities (ECe, mS/cm) beneath each treatment after rains of 1993/94 during which no crop was grown or irrigation applied.

4.7.2 Water Quality On-Farm Trials

The extent of moderately saline groundwater and the potential for exploitation of this resource in semi arid areas is well known (Rhoades *et al.*, 1992). Exploratory drilling carried out by the Collector Well Garden Project has confirmed that in Zimbabwe in many of the driest areas the only water resources available for irrigation are saline to some degree. If these limited resources are to be used, practical guidelines are required. It is, therefore, of great concern to all involved in the work reported here that funding ceased before it was possible to undertake the on-farm trials needed to consider other soil types and to produce the practical guidelines for use by extension workers.

5. Irrigation frequency trials

5.1 INTRODUCTION

Research carried out on subsurface irrigation to date has been conducted using 1 m wide beds with two crop rows per bed. However, the traditional practice on flood-irrigated gardens is to plant three rows per bed. The trial reported in this section was carried out to provide information on subsurface irrigation when three rows are planted per bed. To date also, subsurface irrigation has been carried out bi-weekly. The trial reported here was designed to provide information on the optimal frequency of subsurface irrigation.

5.2 EXPERIMENT 93/5: COVO TRIAL

5.2.1 EXPT 93/5 Materials and Methods

Experimental Design

The experiment was a covo tronchuda trial (*Brassica oleracea* cv Portuguesa) of twelve treatments replicated three times and set out in a randomised block. The treatments are described in Table 32. The plot size was a single 1 x 3 m bed. Irrigation scheduling was based on measurements of soil moisture depletion as measured by neutron probe using the same approach as was used for the water use efficiency trials.

Table 32 Expt 93/5 treatments

Trt.	Irrigation Method	Irrigations per week	Rows per bed
1	Flood	3	2
2	Flood	3	3
3	Flood	2	2
4	Flood	2	3
5	Flood	1	2
6	Flood	1	3
7	Pipes	3	2
8	Pipes	3	3
9	Pipes	2	2
10	Pipes	2	3
11	Pipes	1	2
12	Pipes	1	3

Agronomy

Covo is a very common source of "greens" or relish in communal areas of Zimbabwe. The cultivar "Portuguesa" is mainly propagated by seed, however, there are some local variants of this covo that are known as "Rugare" that are propagated vegetatively.

Covo seedlings were transplanted on 15 November 1993. Depending on the number of rows per bed, 20 or 30 seedlings were planted to a bed giving plant populations of 30,770 and 46,155 plants per ha respectively. Before planting, a basal fertilizer of 80 kg/ha P_2O_5 as SSP and 50 kg/ha N as ammonium nitrate were incorporated by hoe. 50 kg/ha N was applied as a top dressing in increments at 5 and 7 weeks after transplanting.

5.2.2 Expt 93/5 Results and Discussion

Weather during crop season

The weather during the 1992/93 summer crop season was described in Section 3.3.2.

Growth, yield and water use effectiveness

The covo plants differed among themselves in characteristics such as leaf colour, leaf size and shape. Harvesting commenced 36 days after transplanting and finished 85 days after transplanting when the plants flowered. Yields were relatively low because of the early flowering (typical of covo propagated by seed) and the relatively short duration of harvest.

Table 33 shows the influence of irrigation method, irrigation frequency and no. of rows per bed on leaf yield, dry matter and water use effectiveness. Of the three factors studied, only number of rows per bed significantly affected growth and yield.

Table 33 *Effect of irrigation method, irrigation frequency and no. of rows per bed on leaf yield, dry matter and water use effectiveness (wue)*

Treatment	Yield T/Ha	Leaves per plant	Leaves per m^2	Leaf dry matter kg/ha	Ave. leaf weight g	WUE kg/m3
Irrigation method						
Flood	26.81	25.8	121	4309	22.00	5.49
Pipes	26.32	27.8	118	4438	22.27	5.78
SE	0.611	1.944	1.81	176.6	0.540	0.13
Sig.	NS	NS	NS	NS	NS	NS
Irrigation Frequency						
x1 per week	26.07	29.4	120	4436	21.73	5.52
x2 per week	27.40	25.7	121	4278	22.61	5.81
x3 per week	26.22	25.3	118	4407	22.07	5.56
SE	0.748	2.381	2.21	216.31	0.661	0.16
Sig.	NS	NS	NS	NS	NS	NS
Rows per bed						
Three	30.76	23.5	134	4747	22.31	6.14
Two	22.38	30.1	105	4000	21.15	5.12
SE	0.611	1.944	1.81	176.6	0.540	0.13
Sig	***	**	***	***	**	***
CV%	11.27	35.52	7.38	19.78	11.95	11.49

Table 34 shows that the interaction between irrigation method and irrigation frequency had no significant affect on yield or wue. Under flood irrigation, there was a trend of increasing yield and wue with decreasing number of irrigations per week. This was probably a result of smaller soil evaporation losses as the frequency of irrigation decreased. For subsurface irrigation, although the biweekly irrigation treatment had the highest yield and wue, there was no obvious trend.

Table 34 *Effect of irrigation method and irrigation frequency on leaf yield, dry matter and water use effectiveness*

Treatment	Yield T/ha	Leaves per plant	Leaves per m2	Leaf dry matter kg/ha	Ave leaf weight g	WUE kg/m3
Flood 1x/wk	27.56	26.2	123	4310	22.44	5.64
Flood 2x/wk	27.20	25.7	121	4155	22.29	5.56
Flood 3x/wk	25.67	25.6	120	4462	21.26	5.26
Pipes 1x/wk	24.59	32.7	117	4562	21.01	5.41
Pipes 2x/wk	27.60	25.8	119	4401	22.92	6.06
Pipes 3x/wk	26.79	24.9	116	4351	22.86	5.86
SE	1.059	3.37	1.059	305.9	0.93	0.229
Sig.	NS	NS	NS	NS	NS	NS

Table 35 shows that the interaction between irrigation and no. of rows per bed had an affect on yield and water use effectiveness. Under both methods of irrigation, three rows per bed was superior to two rows per bed. However leaf production per plant was higher on the two rows per bed treatments.

Table 35 *Effect of irrigation method and no. of rows per bed on leaf yield, dry matter and wue*

Treatment	Yield T/ha	Leaves per plant	Leaves per m^2	Leaf dry matter kg/ha	Ave leaf weight g	WUE kg/m^3
Flood, 3 rows/bed	32.22	24.1	138	4832	23.5	6.19
Flood, 2 rows/bed	21.40	27.5	105	3786	20.5	4.78
Pipes, 3 rows/bed	29.30	22.8	130	4662	22.5	6.10
Pipes, 2 rows/bed	23.36	32.8	106	4214	22.0	5.45
SE	0.865	2.75	2.55	249.8	0.763	0.187
Sig.	***	NS	NS	NS	NS	**

Table 36 shows that the interaction between irrigation frequency and no. of rows per bed had no significant affect on yield or wue.

Table 36 *Effect of irrigation frequency and no. of rows per bed of leaf yield, dry matter and water use effectiveness*

Treatment	Yield T/ha	Leaves per plant	Leaves per m^2	Leaf dry matter kg/ha	Ave leaf weight g	WUE kg/m^3
Irrig. x1; 3 rows	29.67	23.4	134	4805	22.31	5.91
Irrig. x1; 2 rows	22.48	35.5	107	4066	21.15	5.14
Irrig. x2; 3 rows	31.84	23.7	136	4807	23.55	6.37
Irrig. x2; 2 rows	22.96	27.7	106	3749	21.68	5.25
Irrig. x3; 3 rows	30.76	23.3	133	4629	23.08	6.16
Irrig. x3; 2 rows	21.69	27.2	104	4185	21.05	4.96
SE	1.059	3.37	3.13	305.9	0.935	0.229
Sig.	NS	NS	NS	NS	NS	NS

5.2.3 Expt 93/5 Conclusions

Apart from demonstrating that covo propagated by seed achieves relatively low yields, Experiment 93/5 showed that subsurface irrigation can be used successfully with three rows per bed. Expt. 93/5 also showed that, unlike flood irrigation, subsurface irrigation can be used successfully with a range of different irrigation frequencies.

6. Romwe Collector Well Garden

6.1 INTRODUCTION

In 1991 a first off-station collector well garden was established in Chivi District, Southern Zimbabwe to serve the kraals of Tamwa, Sihambe and Dhobani. This section of the interim report provides a financial analysis of the 1992/93 summer and 1993 winter cropping seasons and a preliminary assessment of the economic viability of the garden.

The community garden commenced cropping in June 1991 and now has 48 members, each with an equal number of beds. Management of the garden is part co-operative and part individual. An elected committee decides on such matters as the cropping pattern, irrigation schedules, sowing dates, plant protection, purchase of inputs and marketing. Individual members tend their own beds and retain the proceeds from their crop sales.

Data were collected at monthly intervals from the garden secretary who keeps records on uses of inputs and labour and production.

6.2 1992/93 SUMMER SEASON

6.2.1 Introduction

In contrast to the drought of the previous year, the 1992/93 summer season was marked by relatively good rains which can be a mixed blessing as far as gardening is concerned. On the plus side (and most importantly) it enabled the Collector Well to recharge due both to an increase in supply of water and a reduction in demand as the garden needed less irrigating; this also saved labour. However on the negative side the good rains promoted heavy infestations of pests, diseases and weed growth, waterlogging and a labour shortage as members worked on their rainfed crops. A task that was made more laborious by the shortage of draught animals which was a consequence of the number of animals that died during the drought.

Nevertheless 0.3 hectares was cropped with rape, tomatoes and maize and positive returns were earned.

6.2.2 Cropping operations

All 46 members sowed three and a half beds each of maize in October by dibbling with no land preparation necessary. Around the same time one nursery bed of tomato was sown; this was transplanted in early December and was sufficient to provide one bed for each of the 41 members who wanted them. At the same time, four nursery beds of rape were sown and transplanted at the beginning of January, also at one bed per member though by this time membership had increased to 48 members. Basal dressings of manure were applied at varying rates to the rape and tomatoes only.

The maize was irrigated once per week from the Collector Well during November at the rate of four buckets per bed (approximately 10 mm). By the time the rape and tomatoes had been transplanted, sufficient rain had fallen to enable the nearby stream to flow which was used to supplement the rainfall when necessary.

Spraying of tomatoes and rape against aphids was done at fortnightly intervals over the period 16 December to 10 February. However there was some dissatisfaction amongst members who felt that this should have been done more frequently but for the pre-occupation of the chairman (who supplied the sprayer and labour) with other activities notably construction of a small community dam. Instead the assistant secretary took over the spraying which he did free of charge but he was also constrained by other commitments. A consequence of this was that members purchased their own second-hand sprayer at the end of the season.

The maize received a top dressing of ammonium nitrate which members had received free as part of the drought relief effort.

Due to the demands of rainfed cropping and the wet weather, members only worked for half a day per week on the garden. The time was spent weeding, harvesting and irrigating from the stream when necessary.

6.2.3 Production

The maize was harvested green over the period late January to late March. The rape began bearing on 9 February and the tomatoes on 24 February but both were brought to a premature end when heavy rains in late February/early March caused severe waterlogging. Estimated total production and average yields are summarised in Table 37.

Table 37 Total production and average yields (1992/93 summer season)

Crop	Production (kg)			Area (ha)	Average yield kg/Ha
	Sold	Consumed	Total		
Rape	325	238	563	0.0576	9774
Tomatoes	233	328	561	0.0492	11402
Maize (grain)	327	468	795	0.1932	4115

6.2.4 Gross Margin analysis

Output	**Z$**	**Z$**
Rape	394	
Tomatoes	748	
Green Maize	1309	
Total Revenue		2451
Variable costs		
Seed	20	
Chemicals	43	
Total Variable Costs		63
Total Gross Margin		2388
Gross Margin per hectare		7965
Gross Margin per member		50
Family Labour	**Hours**	**Hours**
Land Preparation / transplanting	300	
Irrigation / weeding / picking	1900	
Total		2200
Average Gross Margin return to family labour		
$8.68 / day (8 hours)		

6.2.5 Comment

Considering the shortness of the season and the problems referred to above, the Gross margin figures are quite acceptable. Purchased inputs were kept to a minimum and all labour was supplied "free" by members and their families. Fixed costs were also minimal, being limited to $70 for purchase of a second hand sprayer or $1.46 per member, which is negligible when spread over a number of years. The Gross margin can therefore be interpreted as the reward to the members for the labour which they put into the garden. This worked out an average of $8.68 per day which compares favourably with wage labour (if available). In such a season as this, when the rains are good, it is probably lower than the returns from rainfed cropping (the "opportunity cost") which explains why members decided to allocate more of their labour to the rainfed crops rather than the garden at this time. However, rainfed cropping is a more risky undertaking as evidenced by last year's crop failure due to drought. Members therefore did not abandon the garden completely but kept it going during the rainy season at a lower level of intensity, partly as an insurance policy against such disasters.

A further factor to consider is that all output in the above analysis is valued at the prices charged by members for produce sold at the "garden gate". For rape and tomatoes, these were two to three times lower than retail prices at the nearest market centre of Ngundu at that time. If the members did not have the Collector Well garden then they might have had to purchase their own vegetable requirements at these market prices. If the value of the home consumed vegetables from the Collector Well garden are valued at the ruling market prices, then Total gross margin increases to $3154 ($66 per member) and $11.47 per day. This may further explain why members found it worthwhile to continue gardening during this time.

6.3 1993 WINTER SEASON

6.3.1 Cropping pattern

A slow start was made to the season as members faced a labour constraint. This arose because good rainfall during the summer of 1992-93 coupled with the continued absence of draught animals. Consequently garden members were busy headloading their bumper harvests of rainfed crops until well into May. An attempt was made to start a nursery for rape and cabbage during February however, many seedlings died due, it was said, to members of one kraal not pulling their weight. More rape was sown in the nursery during March but again there was high mortality, this time due to pests. Eventually it was not until the first of July that the garden was fully cropped at 0.4032 hectares. Table 38 summarises the dates of transplanting and the cropping pattern.

Table 38 *Dates of transplanting and cropping pattern*

Date	Crops transplanted (beds per member)	Notes
30 March	2 rape & 1 cabbage	
25 - 27 May	2 tomatoes	seedlings obtained free from members' private nurseries
24 - 28 June	1 rape	
1 July	1 cabbage	garden now fully cropped to replace 1 cabbage
12 July	1 onion	

6.3.2 Irrigation

Members were able to draw water for irrigation from the nearby stream until mid-April thus making a valuable saving on labour (pumping) and enabling the collector well to recharge. A further respite occurred during July when heavy rains meant that no irrigation was needed over a period of two weeks. Otherwise, irrigation continued to be on a twice weekly basis with members divided into four groups as for the previous seasons and the irrigation schedules set by the garden committee in terms of numbers of 20 litre buckets per bed. Based on the reported schedules, the Table 39 estimates the total amounts of irrigation water applied.

Table 39 *Estimated total irrigation water applications*

Crop	Duration	Wetted area * ha	Total water litres	Total water mm
Rape	30 Mar - 17 Sep	0.0768	526080	685
Rape	25 Jun - 17 Sep	0.0384	130560	340
Cabbage	30 Mar - 12 Jul	0.0384	147840	385
Cabbage	1 Jul - 2 Oct	0.0384	153600	400
Tomato	25 May - 2 Oct	0.0768	422400	550
Onion	17 Jul - 23 Oct	0.0384	130560	340
Nurseries			13600	
Total (30 March to 23 October)			1524640 of which:	
Abstracted from stream			141600	
Abstracted from collector well			1383040 (over 23 weeks)	
Average abstraction from well			8590 per day	

* excludes pathways

The above figures are plausible and the average daily abstraction rate from the well of 8 590 litres compares with meter readings from the garden pump only of 5 577 litres per day over the period 9 June to 23 October. However the latter does not include use of the domestic pump for irrigation when the garden pump was under repair. In addition 72 mm of rain fell during the period.

6.3.3 Plant protection

The whole garden was sprayed on a crop by crop basis by one man who was paid $5.28 per spraying (11 cents per member) using a second hand sprayer. This had been purchased by members after the previous season when it became evident that hiring of the personal sprayer of the garden chairman was proving both unreliable and expensive.

Use of the garden's own sprayer resulted in a relatively more consistent programme of plant protection with a total of 13 sprayings being carried out over the 23 week period from 24 February to 1 August. Nevertheless the tomato crop was severely affected by red spider mites and the cabbages by leaf eaters and Bagrada bugs. Wet weather in July also resulted in generally higher levels of pest infestations than are normally expected at this time of year.

6.3.4 Fertilisation

In the absence of cattle to provide manure and members' unwillingness to spend money on chemical fertilizers, there was a heavy reliance on use of leaves gathered from the surrounding hillsides and composted. All crops received two or three 20 litre tins at transplanting with some members also adding a top dressing. Some members substituted goat manure instead.

6.3.5 Production

Estimated production based on the numbers of harvested bundles is shown in Table 40.

Table 40 *Estimated production (1993 winter season)*

Crop	Production (kg)			Area * (Ha)	Average yield tonnes ha^{-1}
	Sold	Consumed	Total		
Rape	745	2221	2996	0.1728	17.16
Cabbage leaf;					
1st crop	429	856	1285	0.0576	22.31
2nd crop	-	484	484	0.0576	8.40
Tomato	-	452	484	0.1152	3.92
Onion	333	751	1084	0.0576	18.82

* Includes pathways
** Yields of all crops were reduced in comparison with the exceptionally high levels estimated for the same season last year.

The main reason was the higher incidence of pests following the good rains of 1992-93 compared with the absence of pests following the drought of 1991-92. The tomatoes and second cabbage crop were particularly badly affected since they were planted later in the season and suffered from renewed outbreaks of pests following the heavy rains during July.

A further consideration which became evident from August onwards was the lack of a market, particularly for the leaf vegetables. This was due to a glut in supplies as other community and private gardens came into full production. Again this situation had not arisen during the previous winter of 1992 since the drought had rendered many of the other gardens inoperable as the small dams and traditional wells on which they depended had dried up. As a result members sold 33 per cent of their production of rape and cabbage leaves this season compared with 57 per cent the previous year. It was in response to this situation that members decided to sow a late season crop of onions since they observed that this crop was less commonly grown by other gardens and highly priced. In any case, lack of a market should not necessarily be viewed as a problem since the original aim of the community garden was not to be a commercial enterprise but rather to provide a source of vegetables for members' families so as to improve nutrition. The unsold vegetables were not wasted but were dried and preserved for future use during the early part of the rainy season when fresh vegetables are normally scarce.

6.3.6 Gross Margin analysis (whole garden)

Output	**Kg**	**$Z**	**$Z**
Rape (fresh leaves)	2966	2042	
Cabbage (fresh leaves)	1769	1025	
Tomatoes	425	633	
Onions	1084	3925	
Total value of output			7625
Variable (cash) input costs			
Seed:			
Rape		5	
Cabbage		6	
Onion		9	
Total seed cost		20	
Chemicals:			
Carbaryl (1 kg)		78	
Thiodan (28 g)		3	
Karate (250 ml)		64	
Dimethoate (200 ml)		10	
Total chemical cost		155	
Hire of sprayer operator		58	
Total variable input costs			233
Gross Margin			7392
Average Gross Margin per hectare			18333
Average Gross Margin per member			154
Average labour inputs per member household			"Man"-hours
Clearing out old crops			4
Hoeing; 8 beds by 1 hour/bed			8
Transplanting; 8 beds by 2 hours/bed			16
Irrigation (including pumping) and weeding:			
- From the stream; 4 hours/week by 4 weeks			16
- From the well; 9 hours/week by 8 weeks			72
- During rains; 3 hours/week by 2 weeks			6
- From the well; 12 hours/week by 12 weeks			144
- From the well; 2 hours/week by 3 weeks			6
- Extra watering of new transplants; 8 beds by 1 hour / day x 5 days			40
Harvesting and marketing; 2 hours/day by 17 days			34
Total labour input per member household			346
Average Gross Margin return to labour $ per 8 hour day			3.56

Output is valued at the prices which were set by the garden members and includes both produce that was sold and that retained for home consumption. As can be seen from Section 6.3.8, the prices charged at the garden gate were approximately two to three times lower than the retail prices at the nearest market centre of Ngundu, so if anything there is an element of under-valuation. Tomatoes, which were not sold by the garden, are valued at $1.40 per kilogramme on the assumption that members would have otherwise had to purchase them at this price at Ngundu. The price at which members sold onions was slightly higher than the Ngundu price ($3.62 per kilogramme compared to a price at Ngundu of around $2.80 per kilogramme). However it is still felt justified to use the higher price since this is what members actually received from sales, while the value of home consumed onions are also valued at this price in order to take account of transport costs if members had to travel to Ngundu to purchase them.

Despite the problems with pests, the resulting Gross Margins are still attractive to the members since none have left the scheme and the garden continues to be cultivated. Although the average return to labour may seem low at $3.56 per day, it still represents a profitable use of that labour during the winter months when alternative income earning opportunities are scarce. Of the average Gross Margin per family of $154, approximately $40 was received in cash from sales and the balance of $114 represents the imputed value of home consumed produce.

Onions made a large contribution to the total value of output which was even greater if one takes account of the fact that they required no spraying and used less water and hence labour. Even higher returns might have been earned if they had been sown earlier since peak prices were fetched at the Ngundu market over the period June to August: From September they declined sharply while the community garden marketed their onions in October.

6.3.7 Economic performance of the Collector Well garden

Table 41 summarises the Total Gross Margins earned by the garden since its inception in 1991.

Table 41 *Total Gross Margins 1991-93*

Season	Total Gross Margin Z$:		
	Cash	Imputed	Total
June - Nov 1991	106	31	137
Dec 91 - Sep 92	6077	4051	10128
Oct 92 - Mar 93	1063	1325	2388
Mar - Nov 93	1920	5472	7392

From the above it can be seen that the garden earned a Total Gross Margin of approximately $Z10 000 for each of the two years of operation (1991-92 and 1992-93). Year one can be taken as 1990-91 during which time the site was identified, institutional arrangements sorted out, the well and garden were installed, and the first crops sown.

Due to "teething problems" this first crop earned negligible returns so it should be assumed that in year one a negative cash flow can be expected equal to the installation costs of the well and garden; the latter is estimated at $Z36 500. The cash flows for the first three years of the project completed to date are as summarised in Table 42.

Table 42 *Summary of cash flows (rounded) 1990-1993*

Year	Z$
1990 - 91 (1)	-36500
1991 - 92 (2)	+10000
1992 - 93 (3)	+10000

Assuming that these returns are maintained over a period of 10 years, then an Internal Rate of Return (IRR) of 23.21% would be earned. This is slightly below current commercial rates of interest in Zimbabwe. If the capital costs are amortised over 10 years at a commercial rate of 25 per cent then the project would face an Annual Capital Charge of Z$10 221 compared with an annual Gross Margin (income) of only $10 000. From a strictly **financial** point of view therefore the project is not yet commercially viable

Justification for the project therefore needs to be sought on **economic** grounds. The difference between financial and economic viability is that financial viability assumes that the project must be fully paid for at the commercial rate of interest by the beneficiaries (members of the community garden in this case). Economic viability considers the worth of the project from the point of view of the country as a whole as expressed through the Government's objectives and policies. The collector well and garden with its objectives of supplying clean water and improving family nutrition by enabling increased vegetable production was approved by the Government and so is presumably in line with its development objectives. Economic analysis does not necessarily assume that all capital costs associated with a project should be recovered directly from the beneficiaries as is the case with financial analysis. Rather the capital cost is borne by the country as a whole with Government deciding how exactly it should be financed. For example in the case of small-scale irrigation schemes participants are expected to pay for annual repairs and maintenance costs only while the capital costs are borne by Government though project beneficiaries may still contribute indirectly towards the capital costs through their payment of taxes. Shadow prices may be used where it is thought that the market values of certain inputs and/or outputs do not reflect their real value to society. For this project there is a case for using the Agricultural Finance Corporation interest rate of 13 per cent. This is the rate which is charged on loans to the smallholder sector and can be interpreted as the rate which is considered by the Government to be the appropriate yardstick for judging projects which are aimed at the smallholder sector.

From an **economic** point of view therefore the project is potentially viable since the Internal Rate of Return at 23 per cent is greater than the cost of borrowing (13 per cent). Or, looked at another way, the Annual Capital Cost of the project when amortised over 10 years at 13 per cent interest is $6 727 which is less than the annual Gross Margin of $10 000 (the net value of vegetables produced from the garden). The country as a whole is therefore making a "profit" on the project. Since in this case the project members are not expected to pay back the capital costs directly so they retain all the Gross Margin as the reward for the labour and management which they put into the project. Provided that the people are prepared to continue contributing their labour to the project for this reward then it can be assumed that the Gross Margin is greater than what could be earned from alternative uses of their labour (the "opportunity cost" of labour). Again therefore the project can be said to be economically viable.

The economic worth of the project could be further enhanced if a value is placed on drinking water taken from the well. This rises during drought years as other lower yielding water sources dry up. Further information on the *total economic value* of collector well garden schemes may be found in Waughray *et al* (1995).

The question which remains to be answered is whether a Collector Well is more or less economically viable than alternative sources of water. This is being addressed by the ODA TC-funded Collector Well Garden Pilot Project.

7. Ancillary studies

7.1 USE OF TIME DOMAIN REFLECTOMETRY TO MONITOR WATER USE EFFICIENCY ON OFF-STATION GARDENS

7.1.1 Introduction

Although metering of water from the Romwe Garden Collector Well has provided an estimate of the overall water use efficiency of the Romwe Garden, it was recognised in 1993 that there was no information on water use efficiency at the plot or bed scale on the Romwe Garden or on other farmer-managed gardens in the region. For this reason, a pilot experiment was set up with the following objectives:

i) To measure water use effectiveness at the plot or bed scale throughout a crop season on a typical farmer-managed garden;

ii) To compare water use effectiveness of beds irrigated using traditional flood irrigation with beds irrigated by subsurface pipe irrigation;

iii) To develop and evaluate techniques of using time domain reflectometry as a means of monitoring irrigation amount, irrigation frequency, effective rainfall and crop water use on farmer-managed gardens.

Time domain reflectometry (TDR) can be used to log the volumetric water content of soils at preset time intervals using multiplexed wave guides (Topp *et al.*, 1980). Wave guides can be different lengths, they can be installed in the soil either vertically or horizontally and they can be positioned either singly or as part of a one, two or three dimensional array. Compared to other methods of measuring soil water content, TDR has the following major advantages:

- no radioactive sources are used;
- once installed, labour requirements are low as soil moisture is logged automatically over periods of several weeks;
- once installed, wave guides are unobtrusive and farmers soon forget their presence;
- measurements can be made frequently enough to enable estimates to be made of irrigation frequency, irrigation amount and water use efficiency on most soil types;
- record keeping by farmers on irrigation amount or interval can either be minimised and/or checked independently.

It should be noted that at the time this experiment was carried out, reliable TDR equipment had only recently become commercially available. Despite the newness of TDR equipment, attempting this experiment was felt justified given the potential usefulness of the results and the success of previous experiments that used the insertion capacitance probes (Lovell *et al.*, 1992).

7.1.2 Materials and methods

Experimental design

The Romwe Garden, which is in Chivi Communal Area (20° 43'S, 30° 43'E, elevation 710 m), provided the location for the pilot experiment. Instrumentation was installed at the garden on 26th May 1993, prior to cultivation, within a single 6.5 m by 1.1 m plot (Figure 33). The TDR system used in the experiment was the Trase 1 system (Model 6050X1 Soil Moisture Equipment Corp., USA) with 28 (0.2 m length) buriable 3-wire stainless steel wave guides (Model 6005 Soil Moisture Equipment Corp., USA). The wave guides were installed horizontally into a vertical face that was trenched at one end of the plot. Installation was at 5 depths (0.05, 0.15, 0.25, 0.40 and 0.60 m) from the soil surface, and in 4 profiles (A, B, C and D) across half the plot (Fig. 33). Profiles E and F were installed in a similar way and in an equivalent position to profiles A and B further along the plot. They were however, inserted from the side of the plot so that although they were at the same depths, their orientation was perpendicular to the other wave guides. TDR logging intervals were initially half hourly which was increased to 2 hourly, then to 3 hourly, and finally set at 4 hourly.

Neutron probe (Didcot Instruments, UK) access tubes 1,2 and 3 were installed to a depth of approximately 1.0 m at the opposite end of the plot in equivalent positions to profiles A (& F), B and D. As the site was situated a 2 hour drive from the Chiredzi Research Station, readings with the probe were taken at the same depths as the TDR wave guides whenever downloading of the TDR processor unit was required.

Finally a profile of six manual manometer tensiometers (at depths of 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 m) were installed in the centre of the plot. These were in the equivalent central positions as TDR profiles A & F, and neutron probe access tube a. Tensiometer and neutron probe readings were taken at similar intervals. To obtain a detailed view of processes occurring during initial irrigations after transplanting, intensive tensiometer readings were also taken at 0600, 0900, 1200, 1500 and 1800 hrs daily from 26th June 1993 to 5th July 1993.

In addition it was requested from the villagers that a record be kept of irrigation events detailing the time and volumes of irrigation. Rainfall data were also recorded by villagers at the site using a simple manual rainguage.

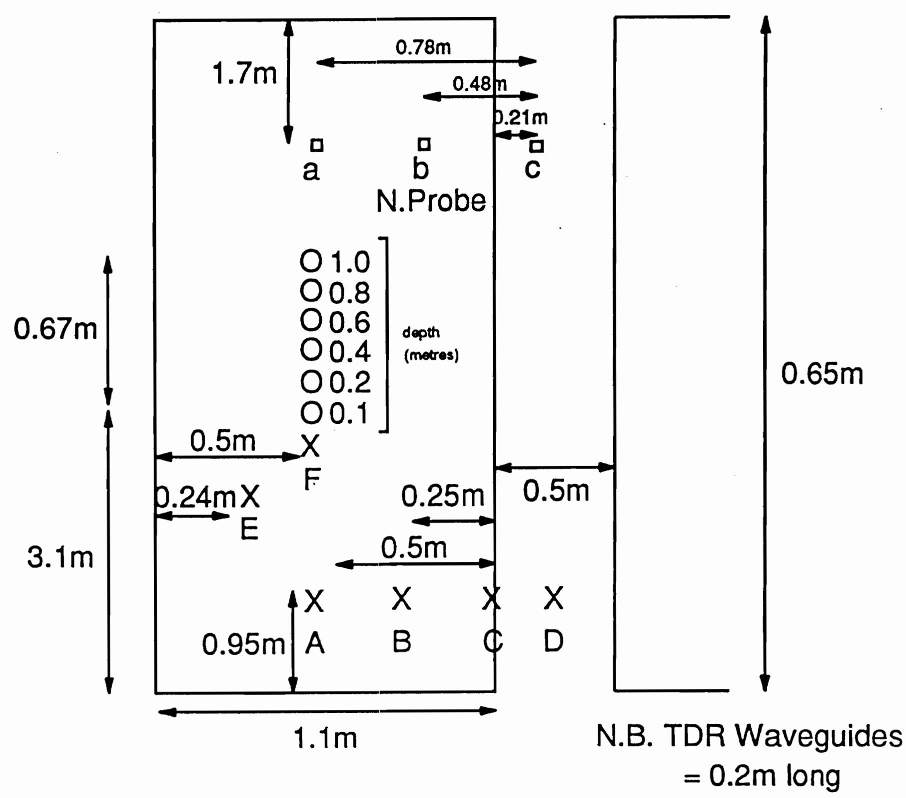
A rape crop was transplanted in 4 rows equally spaced across the plot, on 14th June 1993. The plot was flood irrigated twice weekly on average, although initially after transplantation water was applied at a greater rate in unrecorded quantities.

7.1.3 Results and discussion

The analysis of results is from data collected during the growing season of the rape crop, and covers a period of about four months from mid-June to mid-October 1993. Unlike the neutron probe data, TDR data for the initial two weeks after installation did not correspond with expected trends. It was thought that the erroneous TDR data may have been due to air gaps and compaction of soil around the wave guides created during their insertion. Over a period of about two weeks, however, correlation between TDR and neutron probe data improved possibly as a consequence of the wave guides "settling in" and air gaps around the wave guides becoming smaller.

TDR Installation at T.S.D. Kraal Garden

Plan View



Cross - section

Depth	A	B	C	D (Path)
0.05m	X	X	X	-
0.15m	X	X	X	X
0.25m	X	X	X	X
0.40m	X	X	X	X
0.60m	X	X	X	X

TDR waveguide at 0.05m not inserted under path in profile D

Key:
- □ Neutron Probe.
- O Tensiometers
- X TDR waveguides

Figure 33 *Design of on-farm water use experiment on Romwe Garden*

A further observation that gave rise to some concern was the considerable difference in water content measured by wave guides in corresponding positions. Although comparison of the results from the wave guides at 0.15 m in profile A with profile F produced relatively good 1:1 relationship, comparison of the 0.25 m wave guides of the same profiles produced a poor correlation. Data from the 0.25 m waveguide, profile F, appeared to be highly unreliable as many values obtained when the system did not completely fail were obviously still incorrect. 10 of the 28 wave guides (36%) provided data that was unreliable and which had to be discarded. An interesting observation was that all the wave guides at 0.6 m failed, 3/6 failed at 0.4 m and 1/6 failed at 0.25 m. The trend implies a failure rate consistent with some characteristic associated with depth, the most likely being an increase in clay content down the profile (Lovell *et al*, 1992). Inspection of the wave forms showed an attenuation of signal with increasing depth. A possible explanation of this attenuation is the ionic influences associated with specific clay minerals which conduct the signal away from the wave guide. Research since this experiment was carried out has shown that soil bulk density and mineralogy can have a strong influence on TDR measurements (e.g. Robinson *et al*, 1994.).

As there were obvious problems in the absolute values of soil water content measured by TDR and, to a lesser extent, by the neutron probe, analysis was carried out on soil water content change over time. Comparison of cumulative changes in water content between TDR and neutron probe measurements were found to be small. This suggests that although TDR may be inaccurate for establishing absolute values on this soil type, it can be used for looking at cumulative changes.

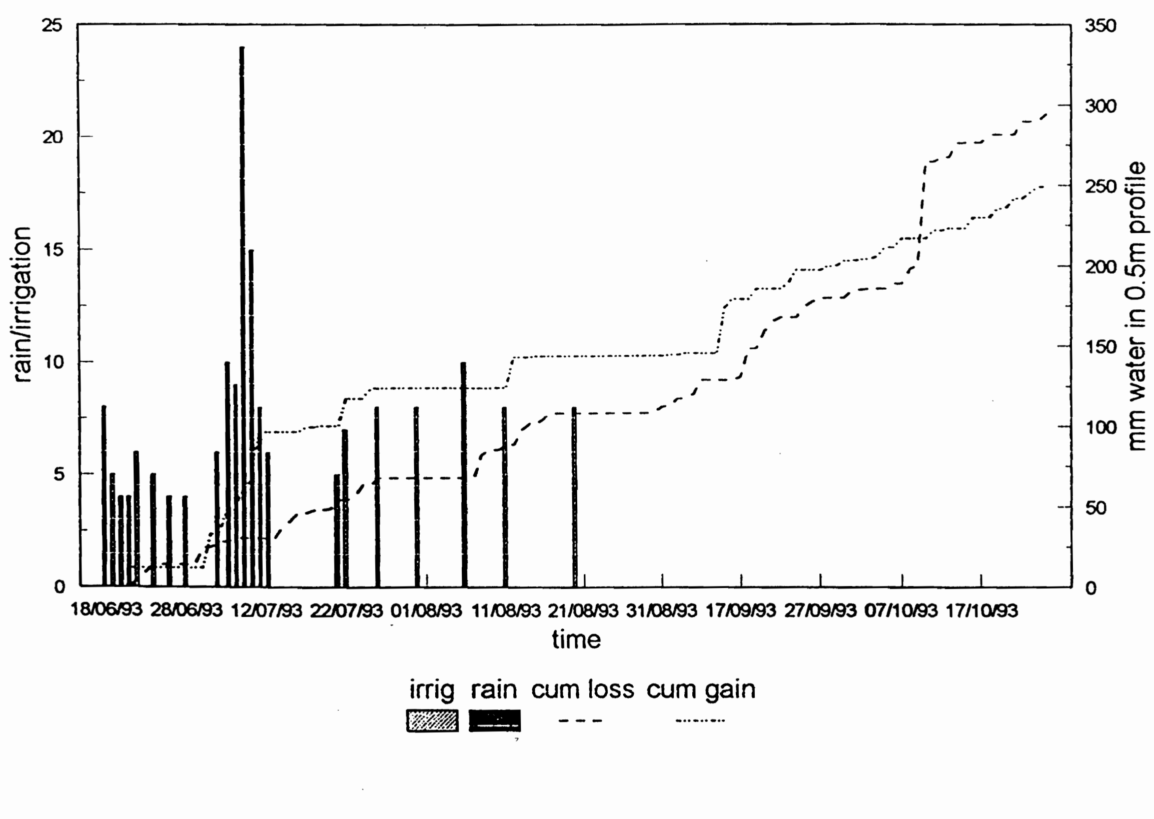


Figure 34 *Comparision of rainfall and irrigation with cumulative daily soil moisture gain and loss*

Figure 34 presents cumulative daily gains and losses in soil profile water content to a depth of 0.5 m. Assuming that drainage and lateral movement of water did not form a large component of the water balance, the cumulative loss of around 300 mm is a believable figure for seasonal water use of rape grown during the winter in southern Zimbabwe. However, a number of features in the figure are less believable. Irrigation appears to have ceased in mid-season. This is due to farmers halting their record keeping and not a true cessation in irrigation. The rapid loss of approximately 50 mm of soil water in 4 hours on 6th October 1993 still remains unexplained, but typifies the quirks in TDR data that were experienced in this soil type. The correlation between irrigation and soil moisture gain or loss appears to be quite poor at the beginning of the season, however, this was due to overirrigation and the soil remaining saturated for approximately 10 days.

The tensiometer data showed a rapid rise in soil water potential following the intensive irrigation at the beginning of the season. Saturation of the profile occurred throughout the profile to within 0.15 m of the surface for a period of approximately 10 days. Drainage would have been rapid under these conditions given that the saturated conductivity of this soil is of the order of 5 mm/day.

7.1.4 Conclusions

The following conclusions can be drawn from this pilot experiment:

i) TDR equipment of the specification used is unreliable and unsuited to the soil type found on the Romwe Garden;

ii) Record keeping by the farmers in participatory research of this type can be quite haphazard even when the farmers are very cooperative and involved;

iii) Despite the problems analysing the TDR data, the analysis and practical experience gained during this experiment confirmed that TDR equipment has enormous potential in any participatory irrigation research. As well as providing information on water use, irrigation interval, soil moisture deficits and water use efficiency, TDR data provides an independent verification of farmer's irrigation records.

iv) The objectives of this pilot experiment were not realised fully, however, it is recommended that this experiment be repeated on one of the collector well gardens that is not located on the same soil type as found at the Romwe Garden.

7.2 CROP WATER USE AND PRODUCTION MODELLING

7.2.1 Introduction

Modelling studies were undertaken to compare measured water balance, soil water distribution, crop growth, yield and water use efficiency (wue) with simulated output from soil and crop growth models. The aim of this work was to assess whether existing models can be used to generalise the results of the trials carried out at LVRS to other soil and crop types.

7.2.2 LEACHM-W Model

Work to date has included the validation of a soil water movement model, LEACH-W (Wagenet & Hutson, 1989). This model was chosen primarily because good results were being achieved with it in studies being carried out in the UK. Figures 35 and 36 compare the measured and simulated soil moisture distributions under two of the flood treatments of the Tomato Trial (Expt. 92/1) at 2, 8, 14 and 19 weeks after transplanting. Figure 35 demonstrates that agreement between measured and simulated for a treatment receiving full water requirements (T1) is quite good apart from a consistent overestimation by the model of soil moisture in the surface layers. In contrast, Figure 36 shows that agreement between measured and simulated is poorer for a treatment receiving less than full water requirements (T5). The main reason for this appears to be the model construction which does not permit the high evaporation rates that are encountered in semi-arid areas.

Figure 37 and 38 presents a comparison between measured and simulated total soil water content to a depth of 1.0 m for the whole season for the treatments considered in Figures 35 and 36 respectively. It can be seen that the simulated water content for both treatments was good at the beginning of the season. As the season progressed the agreement between measured and simulated became poorer. The model overestimated water content on the well irrigated treatment and underestimated water content on the treatment that received less than full water requirements.

Table 43 shows that the relative difference between treatments receiving full and less than full water requirements was maintained for estimated and simulated water use. Table 43 presents estimated and simulated water balance components for T1 (overirrigated) and T5 (relatively underirrigated) of the Okra Trial (Expt. 93/1). It can be seen that agreement between the water use estimates was good.

Table 43 *Expt 93/1 water use estimated by LEACH-W and by water balance method report in Section 3*

Estimation Method	Irrigation (mm)	Rainfall (mm)	Soil water content change (mm)	Estimated water use (mm)	Evaporation (mm)
T1 (water balance)	1026	74	34	1066	525
T1 (simulation)	1026	74	52	1047	463
T5 (water balance)	444	74	8	510	525
T5 (simulation)	444	74	44	473	437

7.2.3 PARCH Model

Some preliminary studies were carried out using the PARCH Model (Bradley & Crout, 1993), however, this work was not completed successfully for two reasons. Firstly, the model was not developed for the vegetable crops grown in the experiments reported here. Secondly, insufficient crop data were recorded during the experiments to run the model satisfactorily.

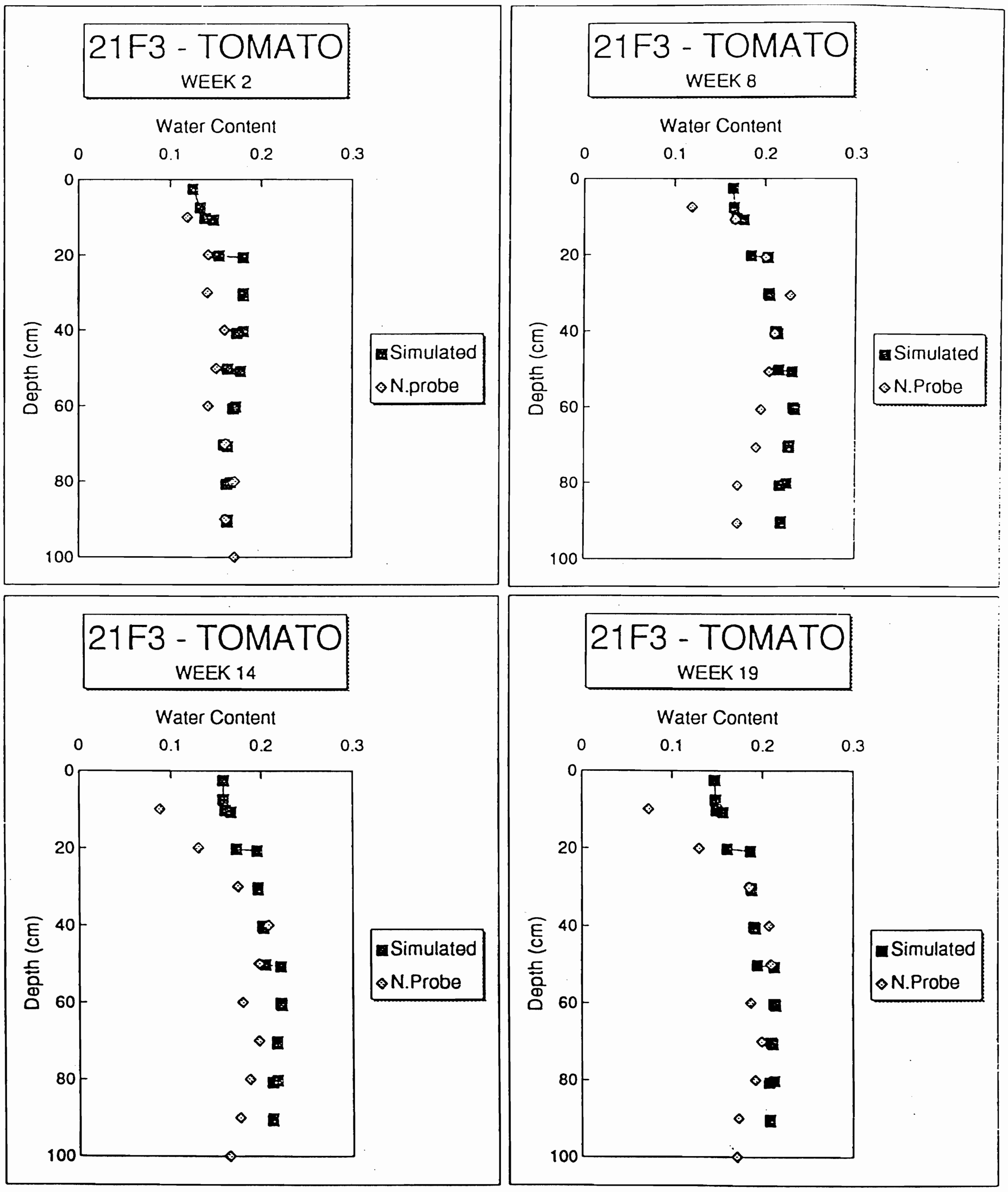


Figure 35 *Comparison of simulated and measured soil moisture content for Treatment 1 of Expt. 92/1*

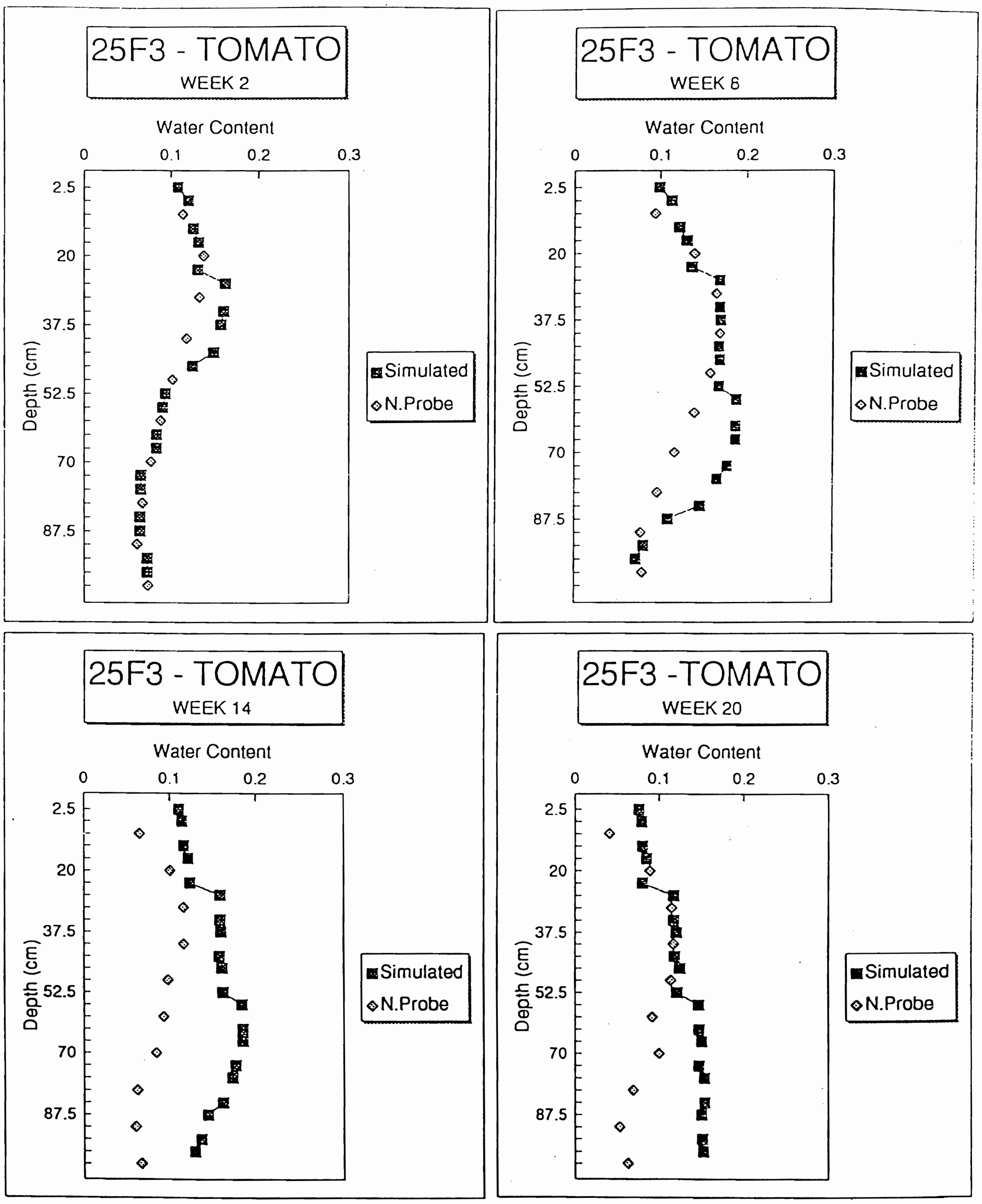


Figure 36 *Comparison of simulated and measured soil moisture content for Treatment 5 of Expt. 92/1*

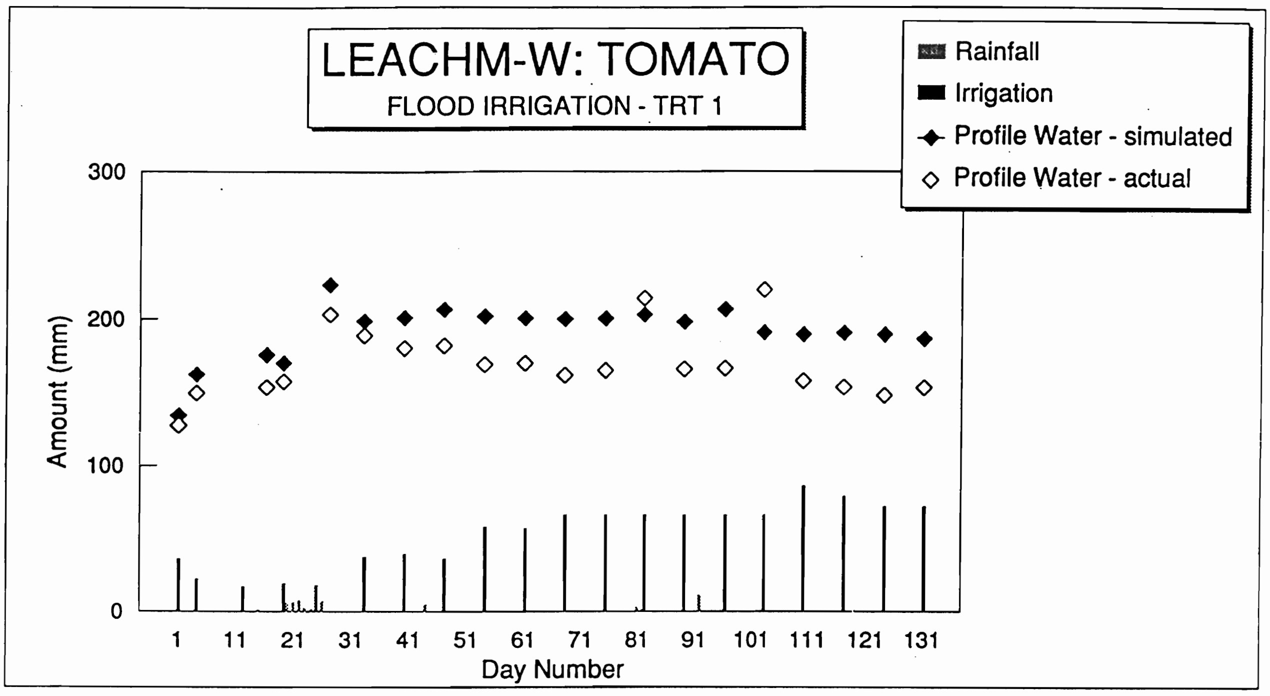


Figure 37 *Comparsion between simulated and measured total profile water content for Treatment 1 of Expt. 92/1*

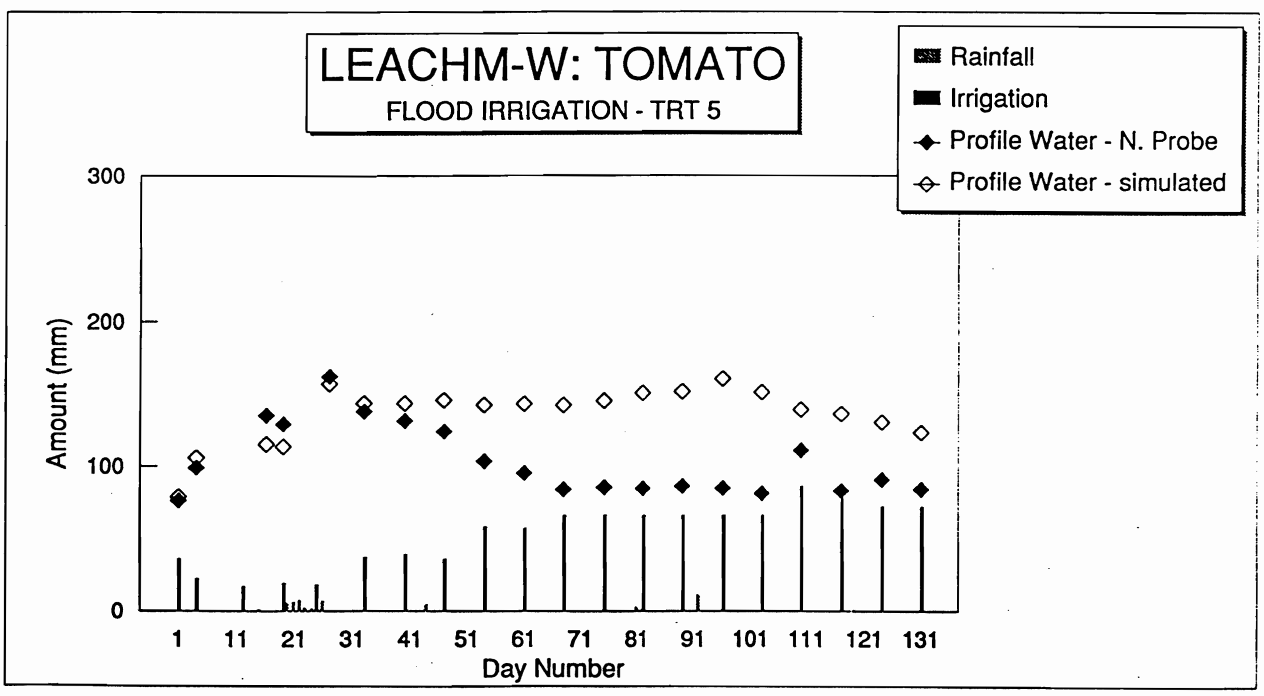


Figure 38 *Comparsion between simulated and measured total profile water content for Treatment 5 of Expt. 92/1*

8. Groundwater Resources in South-east Zimbabwe

8.1 INTRODUCTION

This section of the report considers the availability and sustainability of groundwater resources for developing irrigated gardens in south-east Zimbabwe. It is anticipated that more detailed information on groundwater resources of south-east Zimbabwe will become available as a result of two ODA-funded projects based in the Romwe Catchment (R5846 and R5551). These projects are studying the effects of land management on groundwater recharge and the sustainability of wells and boreholes in hard rock aquifers. The overall aims and objectives of these projects, which are being carried out by MLAWD in collaboration with IH and BGS, are discussed in Butterworth *et al.* (1995) and MacDonald *et al.* (1995).

8.2 REVIEW OF RECHARGE ESTIMATES

8.2.1 Recharge in Semi-arid Areas

Groundwater recharge in semi-arid areas is dominated by indirect recharge processes, this is in contrast to temperate areas where direct recharge processes predominate (Lloyd, 1986) (see Figure 39). Rates of recharge are extremely difficult to measure and any estimates of recharge are normally, and almost inevitably subject to large error (Foster, 1988). There are a range of different techniques that can be applied to the estimation of recharge. The applicability and usefulness of the different techniques is discussed by Lerner *et al.* (1990) and Foster (1988).

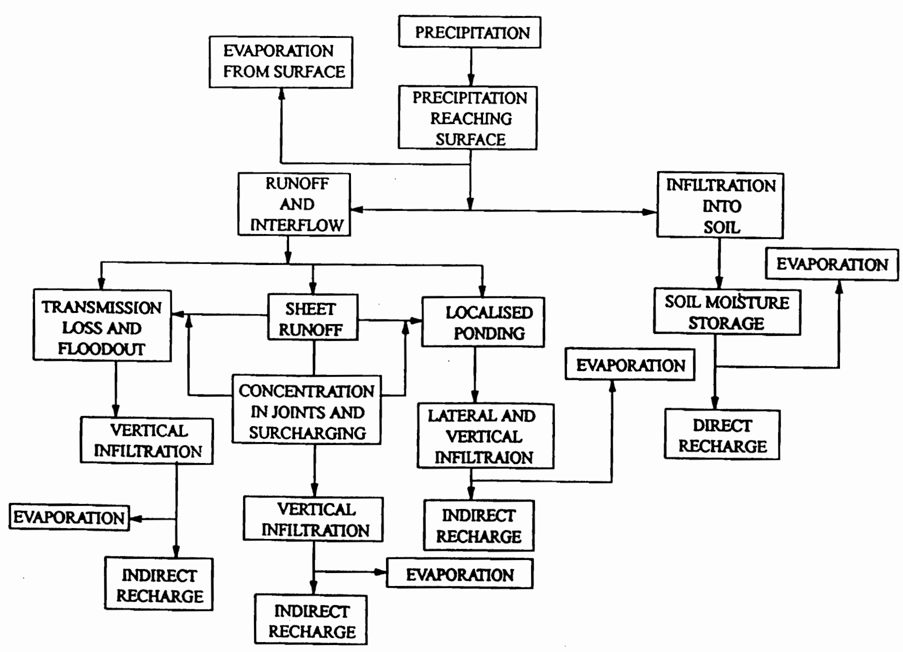


Figure 39 Schematic diagram of groundwater recharge in semi-arid areas (After Lloyd, 1986)

8.2.2 Recharge Estimates for South-east Zimbabwe

Houston (1988), estimated recharge for the Masvingo province of Zimbabwe using three independent methods; baseflow analysis, environmental tracer (chloride) and soil moisture budgets (based on a monthly recharge-runoff model). Data from 22 raingauges and 3 class 'A' evaporation pans were available for an area of 22000 km^2 roughly centred on Masvingo. Also flow data were available from the Chiredzi, Mzero, Musokwesi and Lundi rivers for periods ranging from 8 to 17 years. Houston estimated recharge throughout the Masvingo province to be 2-5% of rainfall, a range which was shown by all three methods. Houston further suggested that recharge was very dependent on annual average rainfall with low rainfall areas likely to have a recharge of 2% of annual rainfall. Based on an area receiving 500 mm annual average rainfall and a recharge rate of 2%, Houston calculated that an area of 65 ha was required to sustain a hand pump delivering 6500 m^3 annum.

Meigh (1988) made a first attempt at estimating recharge for the Lowveld region using two independent techniques based on a soil moisture budget model and two empirical models. The soil moisture model was a simplification of the Houston (1988) model but using meteorological data from the Lowveld Research Station and the airport at Buffalo Range. The empirical approach involved relationships developed for a number of catchments between annual average rainfall and runoff and base flow index (BFI) and soil type (Bullock, 1988). A second empirical approach used relationships for annual average rainfall and runoff and annual average rainfall and BFI developed by Meigh (1987). These methods gave recharge estimates of 0.5-6%, a range that encompasses that of Houston (1988).

8.2.3 Recharge Estimates for Other African Basement Areas

Wright (1992) reported estimates of recharge calculated by a number of methods for areas of Zimbabwe that generally have a higher rainfall than south-east Zimbabwe. Recharge calculations using base flow analysis demonstrated the importance of dambos and relief on base flow and hence on recharge. These relationships are also discussed by Farquharson and Bullock (1992). With rainfall in excess of 800 mm, groundwater recharge was estimated by Wright (1992) to be typically in the range 10-20% of mean annual rainfall which he considers to be substantially in excess of the demand of rural populations (1-3 mm). Estimates of recharge using chloride balance, again for an area with rainfall higher than normally experienced in south-east Zimbabwe, was 9-14% of mean annual rainfall.

Howard and Karundu (1992) estimated recharge for basement aquifers in south-west Uganda. Annual rainfall in this area is normally in the range 750 - 1000 mm. Using daily water balance techniques, mean recharge was estimated at 30 mm (3-4% mean annual rainfall) over an eight year period. However, median recharge for the same period was estimated at 17 mm (2% mean annual rainfall) and this value was considered to be more representative of annual recharge in the area. Howard *et al.* (1994) used water balance calculations and information from aerial photographs and LANDSAT images to assess the influence of land use change on groundwater recharge in south-west Uganda. Recharge estimates for the period 1954 to 1961 were found to be just over half those for the period 1988-91. The difference was attributed to large-scale deforestation during the intervening 30 years which has increased recharge by causing significant reductions in rates of actual evaporation.

8.3 AVAILABILITY AND SUSTAINABILITY OF GROUNDWATER RESOURCES IN SOUTH-EAST ZIMBABWE

8.3.1 Groundwater Resources

A review of the extent and availability of groundwater resources in Zimbabwe and other countries of southern and eastern Africa can be found in Anon (1989). Over the last decade, interest in shallow groundwaters of the regolith has gained considerable momentum with the recognition that the regolith in basement geologies may provide a more sustainable and less costly source of rural water supplies than the underlying bedrock fractures which have traditionally been exploited (Howard *et al.*, 1994). Despite this attention, many basic questions relating to the development and sustainability of shallow basement aquifers remain unresolved.

In principle a sustainable level of abstraction from an aquifer is one that does not exceed the recharge to groundwater. The exception to this is if the abstraction is very small compared to the storage of the aquifer, in which case the impact of the abstraction will be negligible, at least in the short term. Failure to match abstraction to recharge will result in a non-sustainable well field and will permanently reduce groundwater levels with consequent effects throughout the whole ecosystem. Even abstractions that are equal or less than recharge can have a deleterious impact; groundwater levels will not rise as much in response to seasonal rains and ephemeral rivers so caused will be reduced in volume or become extinct. Such rivers may be important water supplies for settlements and will certainly have an ecosystem dependent upon them. In summary, when considering the development of groundwater abstraction it is vital that estimates of recharge are made and the effects on surface waters and the environment as a whole are taken into account.

8.3.2 Land Use Change, Land Degradation and Groundwater Recharge

Wright (1992) stated that

> "the basement aquifers of this region (S.E. Zimbabwe) are distinctive in that their occurrence and characteristics are largely a consequence of the interaction of weathering processes related to recharge and groundwater throughflow. A close relationship exists therefore between groundwater occurrence and relief, surface water hydrology, soil and vegetation cover. Recharge is sensitive to certain land use changes, notably those associated with desertification. Improvements in the understanding of these relationships will be fundamental to the management and planning of groundwater resources in crystalline basement terrain."

The investigation of the relationships between hydrological phenomena and land use has normally been carried out within small experimental drainage basins or catchments. Results from such catchment studies, carried out in eastern and southern Africa, have been reviewed by Whitlow (1983) and Bullock (1994). These catchment studies have proved invaluable particularly in providing information on the impacts of afforestation and deforestation in sparsely populated upland areas. However, the critical water and soil resource problems throughout much of Africa occur in catchments that are heavily populated by subsistence farmers and their livestock (Pereira, 1981). With few exceptions, there is a paucity of data from such catchments (Whitlow, 1983).

In response, to growing populations, an increasing area of land is being taken over for crop production throughout Africa (Whitlow, 1983). Declining productivity of existing croplands has also promoted extension of cultivation often onto to more marginal terrain better suited to other less intensive forms of land use. Extension of cropland is often at the expense of grazing lands, thus placing even greater pressures on the remaining grazing land (Whitlow & Campbell, 1989). When critical levels are reached there is a serious risk that rural communities will become stuck in a "poverty trap" (Figure 40). The net result is reduction in vegetation cover, land degradation and changes to the water balance.

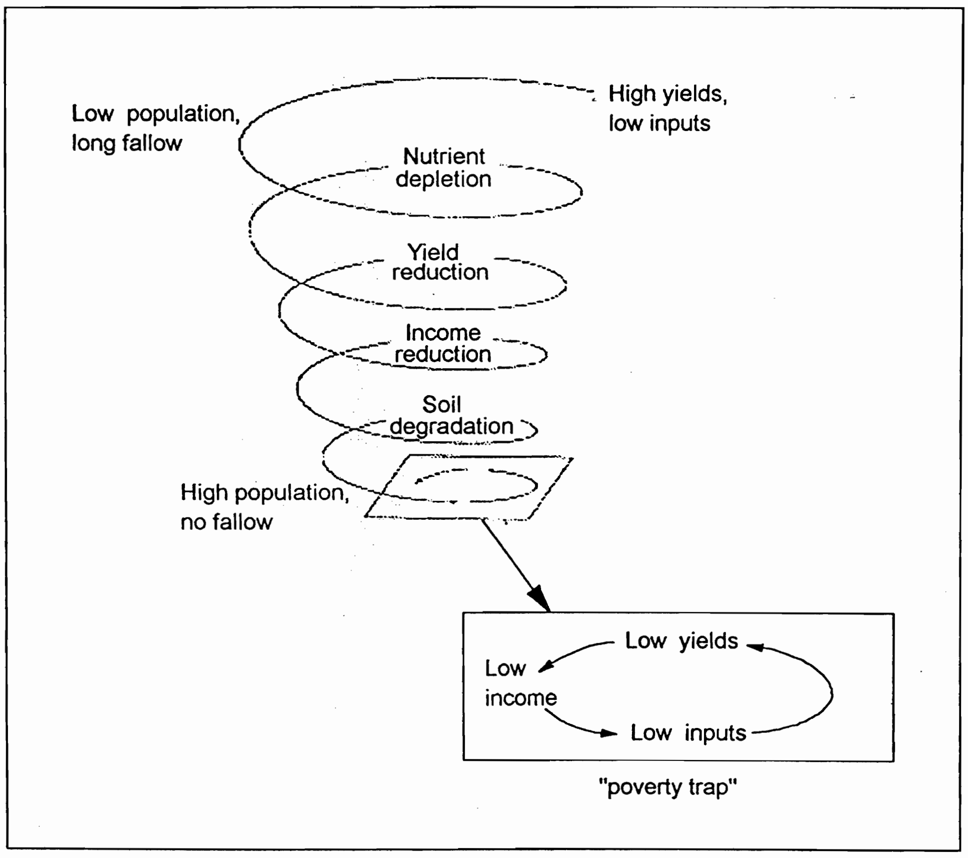


Figure 40 *Diagram the processes by which increasing populations and continuous cropping without inputs can lead to land degradation (After McCown & Jones, 1990)*

The extent of land degradation in south-east Zimbabwe has been described and discussed in a number of reports (e.g. Whitlow 1983; Whitlow & Campbell 1989; Abel & Blaikie, 1989; Campbell *et al.*, 1989; Tagwira, 1992; Scoones, 1992). It is clear that the fundamental causes of land degradation are various and complex involving a number of different combinations of social, institutional, political and physical determinants. It should be noted also that there is some disparity between reports on the extent and seriousness of land degradation in south-east Zimbabwe.

The mechanisms by which land degradation can influence different components of the water balance have been discussed by Whitlow (1983). Wallace (1994) provides an alternative framework for discussing the interactions between hydrological processes and land degradation. Wallace (1994) identifies four mechanisms that can lead to land degradation. Direct anthropogenic pressures resulting from poor or inappropriate land and resource management and leading to loss of vegetation as a consequence of such factors as over-grazing, soil erosion or deforestation (Mechanism 1). Loss of vegetation cover may trigger feedback mechanisms which can propagate further land degradation via the land surface-atmosphere feedback (Mechanism 2). This occurs when a decrease in evaporation and an increase in the amount of radiation reflected back to the atmosphere (albedo) reduce cloud formation and rainfall, causing a negative feedback, which may further reduce vegetation. A third possible mechanism contributing to dryland degradation is hydrological (Mechanism 3). This can occur when a decrease in ground cover associated with poor land management results in increased and more rapid run-off, decreased soil moisture storage and reduced groundwater recharge. In this situation, less of the rain that does fall on degraded land is available for plant growth, the risk of severe soil erosion is increased and less groundwater will be available either for deep-rooting trees or as a resource that can be used by rural communities. The hydrological feedback can also exist in the absence of any climatic change (the fourth mechanism in Fig. 2). Here, "external" influences stemming from sea-surface temperature anomalies, humid tropical deforestation and/or CO_2-induced climate change are thought to be associated with drought and degradation in arid zones such as the West Africa Sahel. Another example of a possible linkage between sea surface temperatures and rainfall is the connection between rainfall and crop yields in southern Africa and sea temperatures in the eastern equatorial Pacific Ocean (Cane *et al.*, 1994).

8.3.3 Reversing Land Degradation

Natural eco-systems in semi-arid areas commonly experience dramatic changes in character and biomass in response to natural climatic variations (Thomas & Middleton, 1994). These changes are often reversible as the ecosystems appear to be well adapted to cope with and respond to disturbance. Consequently, changes in vegetation cover as a result of human activities do not necessarily constitute land degradation unless they are associated with changes to the soil system (i.e. soil erosion or nutrient depletion). In practice, it is very difficult to distinguish between some of the impacts on the environment of human disturbance and natural fluctuations in moisture availability, though to do so is a vital component of successful management and implementation of viable remedies (Thomas & Middleton, 1994). When considering remedial measures it is also important to take account of the relative importance of and to distinguish between the essentially "local" human activities (i.e. overgrazing) and the "external" activities (i.e. CO_2-induced climate change) that might have been the original causes of the land degradation. In most cases, it will be simpler to obtain general agreement to modify or halt "local" activities than "external" activities.

From the historical perspective, the development of agriculture in much of south-east Zimbabwe is a recent phenomenon. Agriculture is obviously vital to the lives and well being of rural communities in this area, however, rapid agricultural development has had an enormous impact on the environment and the natural resources of the region. Resource depletion and land degradation is already extensive and it is probable that reversal of degradation processes may no longer be feasible in some of the most severely degraded areas. In the less severely degraded areas, however, it may be possible to halt and, possibly, reverse the processes of resource depletion and land degradation by adopting an integrated approach to resource management at the catchment scale.

An integrated approach to catchment has been adopted in the Murray-Darling Basin in Australia (Blackmore, 1994). Significant areas of the Murray-Darling Basin are degraded; with soil, land and water salinisation, soil acidification and eutrophication of water ways and lakes becoming increasingly common. In 1985 a programme was started *to promote effective planning and management for the equitable, efficient and sustainable use of water, land and environmental resources of the Basin.* The programme utilises an institutional structure that aims to encourage the participation of stakeholders from all levels in decision making and action programmes. The programmes also combines *knowledge-based activities*, which are principally involved with research and monitoring, with *onground works* which are developed primarily by various community groups.

Warren and Khogali (1992) suggest that drought demands short-term relief whereas desertification control or restoration of degraded dryland may require long-term planning and rehabilitation together with changes in land use practices. Integrated catchment management plans, such as the in Murray-Darling Basin, have been set up in the recognition that are no quick-fix solutions for the problems of dryland degradation. In Zimbabwe, there has been a growing awareness that action needs to be taken at a basin level. Campbell *et al.* (1989) make a range of recommendations for the Save Catchment that are aimed at solving the main social and agricultural problems in the catchment. In recognition, that tackling environmental problems separately from social and environmental problems will not be successful. Although there is yet to be any large scale integrated catchment management initiatives in Zimbabwe, it has to be hoped that work in the Romwe Catchment will lead to more action on the ground elsewhere in Zimbabwe.

8.4 IMPACT ON INCREASED GROUNDWATER DEVELOPMENT ON ENVIRONMENT

8.4.1 Groundwater Abstraction and Low Flows

Investigation of the factors which determine dry season river flow regimes reveals a dominant rainfall control, reflecting the relationship between groundwater base flow and rainfall (Farquharson & Bullock, 1992). Ephemeral rivers, such as many of the sand rivers of southern Africa, occur when the water tables in local aquifers rise to the surface as a result of seasonal rains. It is clear therefore that abstraction of water from the aquifers may effect both the duration and flow rate of rivers during dry seasons. In south-east Zimbabwe, dry season flows are used for irrigation and domestic consumption. It should be noted also that these low flows are very important to the ecology and biodiversity of the region.

It is possible that widespread use of wells for increased domestic use and garden irrigation may reduce water tables in the dry season to levels that can not be recovered in the wet season by anything less than an exceptionally high rainfall. Thus the local population and ecosystems that rely on the sand rivers will find that their water supply is more unreliable. The users of ground water will benefit at the expense of the river users with perhaps little net water resource benefit to the population of the whole water catchment.

The quantification of the effects of groundwater abstraction on river flows is complicated being a combination of aquifer recharge, aquifer properties (transmissivity and storage coefficient) and location and pumping rate of the wells. This complexity requires that mathematical models of the aquifer-river system are constructed in order that these interactions are accounted for fully. Such approaches have been attempted. Oakes and

Wilkinson (1972), for example, developed a model of a hypothetical aquifer-stream system and investigated the effects on stream flows for a range of abstraction regimes assuming different aquifer properties. A similar approach but based on a calibrated model of a specific catchment was undertaken by Clausen *et al.*, (1993). Both studies showed similar results, in particular that in the simplest case of a constant abstraction that, once equilibrium is reached, the river base flow is reduced by an amount equal to the pumping rate. The time to reach equilibrium depends on aquifer properties, a small aquifer with a high conductivity and a well close to the stream will reach equilibrium quickly, whereas the other extreme set of values for these factors will result in equilibrium taking several years to be achieved. Thus under intermittent abstraction regimes the effect on the rivers is less easy to characterize simply. Oakes and Wilkinson, (1972) showed that the effects of continuous abstraction could be diminished by the sequential operation of two groups of wells at different distances from the river, the nearer group being pumped in winter and the farther in summer.

It is anticipated that research being carried out in the Romwe Catchment will provide information on approaches to catchment management that are sustainable in terms of utilisation of resources both within the catchment and in areas outside the catchment that are influenced by activities within the catchment (Butterworth *et al.*, 1995).

9. General Conclusions

9.1 IRRIGATION TRIALS

9.1.1 Irrigation method

Table 44 summarises the yield and water use effectiveness (wue) results of all the water quality and water use efficiency trials that have compared traditional flood irrigation with subsurface pipe irrigation. Percentage yield and wue improvements were calculated for equivalent treatments in each trial. It can be seen that there is a clear trend of higher yields and wue on the subsurface treatments. The best yield improvements occurred on Expt. 91/4 which was a maize experiment that was influenced strongly by the hot dry conditions of the 1991/92 summer season. The results of Expt. 93/2 are not included in Table 44 because this experiment was affected badly by pests and diseases to such an extent that it was harvested early.

Table 44 *Percentage improvement in yield and wue for subsurface treatments as compared to equivalent flood treatments*

Expt.	Crop	Average Improvement		Best Improvement	
		Yield %	WUE %	Yield %	WUE %
91/4	Maize	64.4	64.2	94.3	95.6
92/1	Tomato	5.5	8.2	5.6	8.9
92/2	Rape	8.6	27.5	17.1	45.0
93/1	Okra	5.0	-1.1	17.8	8.6
93/2	Cabbage	-	-	-	-
93/3	Tomato	-0.9	4.8	9.7	10.9
93/4	Rape	8.6	14.0	22.2	43.7
Mean	-	15.2	19.6	27.8	35.5

Figures 41 and 42 are frequency plots that summarise the yield and wue improvements from the trials that compared traditional flood and subsurface irrigation. In this instance all treatments are presented. It can be seen that the yields and wue were consistently higher on subsurface treatments with only one exception. These results indicate that adoption of subsurface irrigation involves a relatively low risk. Poor management of subsurface irrigation is likely to result only in no improvement in yield, wue or crop quality. This is important because poor management of many other types of microirrigation can result in complete crop failure and/or catastrophic damage to the irrigation system itself.

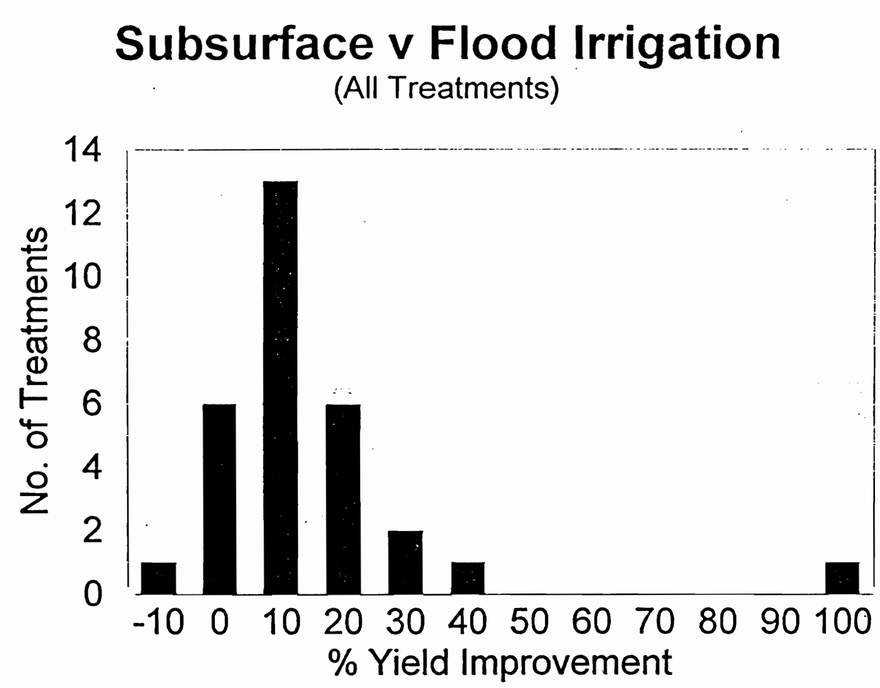


Figure 41 *Frequency plot showing improvements in yield of subsurface treatments compared to flood treatments for the six trials listed in Table 45*

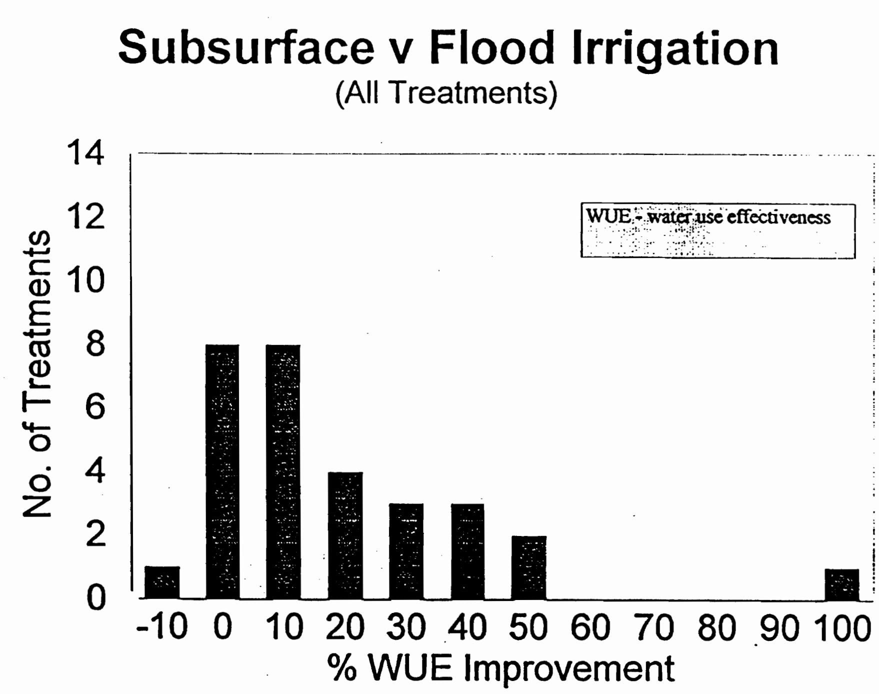


Figure 42 *Frequency plot showing improvements in water use effectiveness of subsurface treatments compared to flood treatments for the six trials listed in Table 45*

The relative advantages and disadvantages of a number of low-cost, high-efficiency irrigation methods has been summarised in Table 3. Table 3 shows that there are several options available to farmers wishing to improve yields, wue and crop quality. The option that will be most suitable for a given farmer will depend on a range of factors that will include: crop type, plot size, soil type, availability of water and labour, location of water source relative to the plot to be irrigated and the availability of materials to be used as mulches or clay for making pipes or pots. The general conclusion of the trials reported here is that the best options for improving yields, wue and crop quality on vegetable gardens are subsurface irrigation using clay pipes or improved flood irrigation using mulches.

9.1.2 Irrigation scheduling

Traditional irrigation scheduling practices were compared with other irrigation schedules. The conclusion from this work was that traditional schedules tend to lead to over-irrigation at the beginning of the crop season and under-irrigation in the middle and end of the crop seasons. Results from the trials also showed that subsurface irrigation can and, for many soil types probably, should be carried out at least twice a week. Unlike flood irrigation, subsurface irrigation can be practised frequently to create and maintain favourable soil moisture conditions without large quantities of water being lost to soil evaporation.

The indications from the trials reported here are that there is scope for improving irrigation scheduling on vegetable gardens particularly when using subsurface irrigation. In the next section a recommendation is made for a research project that looks specifically at irrigation scheduling on vegetable gardens in semi-arid areas.

9.1.3 Irrigation with poor quality water

Poor quality groundwater is very common in semi-arid areas. The trials showed that subsurface irrigation can be used effectively with poor quality groundwater and that, given appropriate land-forming practices, rainfall can be used to leach salts from the soil profile thereby preventing a critical build up of salts in the root zone.

9.1.4 On-farm trials

On-farm trials of subsurface irrigation have been carried out on a number of gardens that have included the Romwe Collector Well Garden and a community garden in Chiredzi. On-farm trials have also been carried out by the Intermediate Technology's Food Security Project in Chivi District. Murwira (1995) reported an uptake of subsurface irrigation by more than 400 households (see Section 3.5.4 for more details).

The attempts to monitor water use effectiveness on the Romwe Garden using time domain reflectometry (TDR) were only partially successful as a consequence of the Romwe Garden soil type (see Section 7). However, using TDR in participatory on-farm trials could provide very useful information on the performance of improved irrigation techniques. It should be noted that, although there has been a rapid uptake of subsurface irrigation in some areas of Zimbabwe, there is no information available on the wue of this method when used by farmers. It would be very interesting to know whether the wue achieved by farmers is similarly, or maybe even better, than was achieved on the research station.

The results of the experimental and on-farm trials presented here show that subsurface irrigation using clay pipes can be used as a practical means of improving yields, wue and crop quality. It has also been shown that subsurface irrigation is economically viable as well as being simple and adaptable. The technique can be incorporated easily into traditional gardening systems as part of a package of measures to improve water use efficiency and reduce risk of crop failure. These other measures should include land management practices that reduce run-off after rainfall, and improved irrigation scheduling, varietal selection, crop husbandry and pest management. A recommendation is made in the next section for a research project to study options for implementing subsurface irrigation as part of a package of measures aimed at improving vegetable production in semi-arid areas.

9.2 WATER RESOURCES

9.2.1 Collector wells

This project demonstrated successfully that collector wells can be used as a source of water for small irrigated gardens in semi-arid areas that are underlain by basement rocks. Many of the recommendations made in the earlier interim reports (Batchelor *et al.*, 1990; Lovell *et al.*, 1990; Lovell *et al.*, 1992) have been adopted by development projects in Zimbabwe. To date an additional eight collector well gardens have been implemented in south-east Zimbabwe and a further one hundred are planned. Considerable effort has been devoted to studying the socio-economic and institutional aspects of developing groundwater resources for garden irrigation in semi-arid areas (Lovell, 1993; Lovell *et al.*, 1993, 1994a, 1994b and 1995). This work has led to the development of decisions trees that can be used to identify groundwater resources, to select the most appropriate well design and to ensure community participation in the implementation of a given scheme.

9.2.2 Availability of groundwater resources

Research to date suggests that groundwater in much of semi-arid Africa constitutes a widespread and under-utilised resource, however, there are still many unresolved questions concerning the true availability and sustainability of groundwater resources in semi-arid areas. Section 8 of this report reviews the state of knowledge of groundwater recharge in basement areas and discusses some of the implications of increased groundwater abstraction on the hydrology of catchments and the environment as a whole. More information on groundwater recharge and the sustainability of aquifers in basement areas can be found in Butterworth *et al.* (1995) and MacDonald *et al.* (1995). It is clear that further research is needed particularly on the effects of increased and more efficient groundwater abstraction on dry season river flows.

9.3 IRRIGATED GARDENS

9.3.1 Socio-economic benefits

The rationale behind the project reported here was that irrigated gardens in semi-arid areas provide a source of vegetables for home consumption and for sale that is of enormous benefit, particularly to women and children, during dry seasons and periods of drought. Socio-economic monitoring of the Romwe Garden (see Section 6), which was funded by this project, and additional ODA TC-funded gardens have confirmed that vegetable gardens are economically viable and that they provide a range of benefits that are not quantified by conventional economic analysis. These include improved nutrition, reduced poverty, increased self-reliance and a source of income to pay for children's education and other household necessities.

9.3.2 Environmental benefits

When the project was planned it was hoped that the project would demonstrate that developing groundwater-based community gardens would reduce the need for communities in semi-arid areas to continue with unsustainable practices such as cropping and overgrazing of marginal lands. The evidence to date is that groundwater-based gardens have an important role to play in offering communities with an alternative to cultivating vegetables on stream banks.

Another major benefit of groundwater-based community gardens is that they provide a vital first step, or springboard, to other community-led activities aimed at reducing environmental degradation and promoting sustainable agricultural development. These activities can include improved livestock management, community woodlots and soil conservation measures. The community garden provides a stimulus in two ways. Firstly, once a community is benefiting from a garden, the community recognises the need to protect the groundwater-resource that supports the garden by taking measures that improve recharge and reduce degradation in the vicinity of the well. Secondly, the confidence and the organisational skills gained from implementing and managing the garden can be used to tackle some of the long-term environmental problems beset by communities in semi-arid areas. Figures 1 and 2 show schematically how feedback mechanisms lead to rapid degradation in semi-arid areas and how community gardening can be used to reverse these mechanisms. Although these schematic diagrams take an optimistic view of the potential for reversing land degradation in semi-arid areas, experience from this project indicates that groundwater-based gardening has an important role to play in any programme of catchment regeneration or integrated catchment management.

9.4 SCOPE OF WORK CARRIED OUT BY PROJECTS R5851 AND R5849

Table 45, which is a checklist that was used during the project (1988-1995) in prioritising the work carried out, gives an indication of the areas of research in which most effort and resources were concentrated. Table 45 also gives an indication of research topics that were not covered by the project.

Table 45 Checklist of research topics carried out under project

Research Topics	Effort Rating
1. Controlled Experiments at Lowveld Research Station	
1.1 Crop water use and water use effectiveness studies	C
1.2 Irrigation method studies	C
1.3 Irrigation scheduling studies	S
1.4 Integrated pest management studies	S
1.5 Studies of irrigation with poor quality water	C
1.6 Soil evaporation and mulching studies	C
1.7 Crop establishment studies	S
1.8 Planting configuration and relay cropping studies	S
1.9 Studies of tree and orchard crops	Z
1.10 Crop nutrition and soil fertility studies	Z
1.11 Economics of subsurface irrigation	
2. Regionalising and evaluating research recommendation	
2.1 On-farm trials	
2.1.1 Implementation of Romwe Collector Well Garden	C
2.1.2 Monitoring Romwe Garden total water use and yields	C
2.1.3 Monitoring bed water use using TDR	S
2.1.4 Subsurface demonstration plots on Romwe Garden	S
2.1.5 Institutional aspects of Romwe Garden implementation	C
2.1.6 Monitoring of gender issues	C
2.1.7 Socio-economic evaluation of research recommendations	C
2.2 Soil water balance modelling	C
2.3 Crop production modelling	S
2.4 Socio-economic modelling of collector well gardens	Z
2.5 Potential for gardening in integrated catchment management programmes	S
2.6 Development of combined socio-economic and hydrological catchment models	S
2.7 Rates of groundwater recharge in semi-arid basement areas	C
2.8 Environmental impact of increased abstraction from basement aquifers	S
2.9 Impact of collector well gardens on water quality	Z
2.10 Preparation of extension materials	C

Effort Rating C - considerable effort
S - some effort
Z - zero effort

10. Recommendations

10.1 DEVELOPMENT OF GARDEN IRRIGATION IN BASEMENT AREAS

The project reported here and subsequent ODA TC-funded projects have shown the enormous potential for widescale implementation community gardens in basement areas and the wide range of social, economic and environmental benefits that can accrue from such gardens in semi-arid areas. It is recommended that support be given by the Government of Zimbabwe and by donors for the proposed NGADI Project. The Ngadi Project aims to train and equip Provincial Units that are able to work with local institutions and local communities in the implementation of large numbers of community gardens throughout the semi-arid areas of Zimbabwe. It is also recommended that consideration be given to evaluating the potential for developing basement aquifers for community gardening elsewhere in the SADC Region and in other semi-arid areas of Africa.

10.2 IMPROVED GARDEN MANAGEMENT

There is an urgent need for a research project that takes a holistic approach to garden management whereby improved irrigation methods are evaluated at the same time as other measures of improving production and reducing the risk of crop failure. The measures that should be studies concurrently include different options for improving pest management, different options for improving crop nutrition and different cropping strategies so as to better serve market requirements. It is recommended that this project be carried by an interdisciplinary team with the participation of farmers on some of the existing and planned collector well gardens. The output from this project would a set of decision trees that would assist extension workers and gardeners wishing to improve the output and economic returns from vegetable gardening in semi-arid areas.

10.3 IRRIGATION SCHEDULING

Irrigation scheduling on vegetable gardens is generally very poor. Research into different aspects of irrigation scheduling has tended to concentrate on high-technology solutions that are only suitable for large commercial farms. On most gardens, rigid schedules are followed that take little account of crop water requirements or the moisture retention properties of the soil. Adoption of improved methods of irrigation such as subsurface irrigation gives scope for improving scheduling by such simple measures as varying the size of the subsurface pipes. As movement of water from the pipes to the soil is quite slow, pipes can be used to control the amount of water applied thereby reducing the risk of over-irrigation. It is proposed that a research project be set up with the participation of gardeners on collector well gardens using time domain reflectometry as a means of monitoring water use efficiency of beds being scheduled by a range of different methods.

10.4 IRRIGATION WITH POOR QUALITY GROUNDWATER

The trials reported here demonstrated that subsurface irrigation can be used successfully with poor quality irrigation water. Given the prevalence of poor quality groundwater in semi-arid areas, it is strongly recommended that these trials be continued for a range of crops and soil types. It is also recommended that participatory on-farm research be initiated in Zimbabwe on gardens that are currently flood irrigating using poor quality irrigation water.

10.5 MICROIRRIGATION DECISION SUPPORT SYSTEM

Competition for water between urban, industrial and agricultural users is increasing rapidly in south-east Zimbabwe and in other semi-arid areas. Recent droughts have only exacerbated an already critical state of affairs. There is an urgent need to improve the efficiency of irrigation, if agricultural production is to be maintained a current levels let alone increased to meet the requirements of an increasing population. Flood and sprinkler irrigation in Zimbabwe have efficiencies of 30-40% and 50-70% respectively. Serious consideration is now being given to increasing areas under microirrigation techniques such as drip irrigation. These systems have efficiencies in the order of 90%. Unfortunately many microirrigation techniques are expensive and difficult to manage. There are also a wide range of microirrigation techniques available. These range from the subsurface irrigation techniques reported here to computer-controlled drip systems. It is recommended that a project be set up there prepares decision trees that can be used by farmers to choose the most appropriate microirrigation system based on his or her holding size, soil type, crop type, managerial skills and economic status. This project should also look into the possibility of using subsurface irrigation as an intermediate step between flood irrigation and higher-technology microirrigation systems. Although subsurface pipe irrigation can only be used for irrigating small plots, it is much less sensitive to managerial mistakes that other microirrigation techniques. It should be noted that a proposal for such a project in Zimbabwe has already been prepared by AGRITEX.

Acknowledgements

Funding for the work reported here was provided by the British Overseas Development Administration and the Government of Zimbabwe. The authors wish also to acknowledge the advice and assistance of many colleagues and friends in Zimbabwe and the UK. Particular thanks should go to Mr Isiah Mharapara (Head of the Lowveld Research Stations) for his support throughout this project, Mr Stephen Mhlauri for his hard work and sensible suggestions during the trials and Ms Karen Sage for preparing figures for this report.

References

Abel, N.O.J. & Blaikie, P.M. 1989. Land degradation, stocking rates and conservation policies in the communal rangelands of Botswana and Zimbabwe. Land Degradation and Rehabilitation, 1, 101-123.

Andrews, A.J. & Bullock, A. 1994. Hydrological impact of afforestation in eastern Zimbabwe. IH Report ODA 94/5, Inst. of Hydrology, pp 133.

Anon. 1989. Ground water in Eastern, Central and Southern Africa. United Nations, Natural Res./Water Series No. 19, pp320.

Anon. 1994. Research and Development of collector well systems: Report of an evaluation study. ODA Eng. Div., ODA, London, pp36.

Batchelor, C.H. & Soopramanien, G.C. 1983. Drip irrigation in Mauritius: system selection and other considerations. Revue Agricole de l'Ile de Maurice, 62: 126-132.

Batchelor, C.H., Foster, M.W., Murata, M., Gunston, H. & Bell, J.P. 1990. Development of small-scale irrigation using limited groundwater resources: First Interim Report. IH report ODA 3/90, Institute of Hydrology, Wallingford, UK.

Batchelor, C.H., Lovell, C.J., Murata, M. & McGrath, S.P. 1994. Improving water use effectiveness by subsurface irrigation. Aspects of App. Biol., 38, 269-278.

Bradley, R.G. & Crout, N.M. 1993. The PARCH model for predicting arable resource capture in hostile environments. Tropical Crops Research Unit, Nottingham Univ., UK.

Butterworth, J.A., Lovell, C.J., Bromley, J., Hodnett, M.G., Batchelor, C.H., Mharapara, I., Mugabe, F. & Simmonds, L. 1995. Romwe Catchment Study: Effect of land management on groundwater recharge and implications for small-scale irrigation using groundwater. IH Report ODA 95/9, Institute of Hydrology, UK, pp 68.

Blackmore, D.J. 1994. Integrated Catchment Management- The Murray-Darling Basin Experience. Water Down Under Conf., Adelaide, Vol. 1, 1-7.

Bullock, A. 1988. Dambo process and discharge in central Zimbabwe, PhD thesis, University of Southampton.

Campbell, B., du Toit, R. & Attwell, C. 1988. relationships between the environment and basic needs and satisfaction in the Save Catchment. Univ. of Zimbabwe, Harare, pp119.

Cane, M.A., Eshel, G. & Buckland, R.W. 1994. Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea temperature. Nature, 370, 204-205.

Carruthers, R., Greenbaum, D., Jackson, P.D., Peart, R.J. & Shedlock, S.L. 1993. Geological and geophysical characterisation of lineaments in southeast Zimbabwe and implications for groundwater exploration.

Carter, R. 1992. Small-scale irrigation in sub-Saharan Africa: a balanced view. Proc. Conf. "Priorities for water resources allocation and management", Southampton, ODA, 103-116.

Chilton, P.J. & Talbot, J.C. 1992. Collector wells for small-scale irrigation: Construction and testing of a well at Tamwa/Sihambe/Dhobani Kraals and further work at Chiredzi. BGS Report WD/92/27, British Geological Survey.

Clausen, B., Young, A.R., Gustard, A. 1993. Modelling the Impact of Groundwater Abstraction on Low River Flows., In Proc. of the 2nd International Conference on FRIEND, Braunschweig, Germany, 11-15 October 1993.

Constable, G.A., Rochester, I.J. & Hodgson, A.S. 1990. A comparison of drip and furrow irrigated cotton on a cracking clay soil: 1. Growth and nitrogen uptake. Irrig. Sci., 11:137-142.

Constable, G.A. & Hodgson, A.S. 1990. A comparison of drip and furrow irrigated cotton on a cracking clay soil: 3. Yield and quality of four cultivars. Irrig. Sci, 11:149-153.

Doorenbos, J. & Pruitt, W.O. 1977. Crop water requirements. FAO Irrigation and Drainage Paper No. 24, Rome, pp144.

FAO. 1990. An international action programme on water and sustainable agricultural development: A strategy for the implementation of the Mar del Plata Action Plan for the 1990's. FAO, Rome.

Foster, S.S.D. 1988. Quantification of groundwater recharge in arid regions: A practical view for resource development and management. In: Simmers, I. (Ed.): "Estimation of natural groundwater recharge", D. Reidel, 323-338.

Gardner, W.R. 1967. Proc. Symp. FAO/IAEA, Istanbul, pp335.

Hodgson, A.S., Constable, G.A., Duddy, G.R. & Daniells, I.G. 1990. A comparison of drip and furrow irrigated cotton on a cracking clay soil: 2. Water use efficiency, waterlogging, root distribution and soil structure. Irrig. Sci., 11:143-148.

Howard, K.W.F. & Karundu, J. 1992. Constraints on the exploitation of basement aquifers in East Africa - water balance implications and the role of the regolith. J. Hydrol., 139, 183-196.

Howard, K.W.F., Taylor, R.G. & Salvatori, S.L. 1994. The dynamics of groundwater flow in the shallow regolith of Uganda. Proc. of "Water Down Under" Conf., Adelaide, Vol. I, 435-440.

Houston, J. 1988. Rainfall - runoff - recharge relationships in the basement rocks of Zimbabwe. In: Simmers, I. (Ed.): "Estimation of natural groundwater recharge", D Reidel, 349-365.

IIED, 1992. Environmental synopsis of Zimbabwe. IIED, London, UK, pp32.

IIED, 1992. Environmental synopsis of Zimbabwe. IIED, London, UK, pp32.

Institute of Hydrology. 1980. Low Flow Studies Report. Wallingford, UK.

Iremiren, G.O. & Okiy, D.A. 1986. Effects of sowing date on the growth, yield and quality of okra (Abelmoschus esculentus (L.) Moench) in southern Nigeria. J. Ag. Sci, 106, 21-6.

Lerner, D N, Issar, A S, Simmers I. 1990. Groundwater Recharge - A guide to understanding and estimating natural recharge, International Contributions to Hydrology, Volume 8, Hannover, Heise.

Lloyd, J.W. 1986. A review of aridity and groundwater. Hydrological Processes, 1, 63-78.

Lovell, C.J., Batchelor, C.H. & Murata, M. 1990. Development of small-scale irrigation using limited groundwater resources: Second Interim Report. IH Report ODA 11/90, Institute of Hydrology, Wallingford.

Lovell, C.J., Batchelor, C.H., Semple, A.J., Murata, M., Mazhangara, E. & Brown, M. 1992. Development of small-scale irrigation using limited groundwater resources: Third Interim Report. IH Report ODA 92/4, Institute of Hydrology, Wallingford, UK.

Lovell, C.J. 1993. Small-scale irrigation using collector wells pilot project: First progress report. IH ODA Report, Institute of Hydrology, UK, pp50.

Lovell, C.J., Batchelor, C.H., Brown, M.W., Chilton, P.J., Murata, M., Semple, A.J. & Thompson, D.M. 1993. Small-scale irrigation using collector wells pilot project: Second progress report. IH ODA Report 93/16, Institute of Hydrology, UK, pp120.

Lovell, C.J., Murata, M., Brown, M.W., Batchelor, C.H., Chilton, P.J., Semple, A.J., Thompson, D.M. & Dube, T. 1994a. Small-scale irrigation using collector wells pilot project: Third progress report. IH ODA Report 94/4, Institute of Hydrology, UK, pp58.

Lovell, C.J., Muarat, M., Brown, M.W., Batchelor, C.H., Thompson, D.M., Dube, T., Semple, A.J. & Chilton, P.J. 1994b. Small-scale irrigation using collector wells pilot project: Fourth progress report. IH ODA Report 94/9, Institute of Hydrology, UK, pp91.

Lovell, C.J., Mazhangara, E., Mtetwa, G., Dube, T., Thompson, D.M., MacDonald, D.M.J. & Batchelor, C.H. 1995. Small-scale irrigation using collector wells pilot project: Fifth progress report. IH ODA Report 95/6, Institute of Hydrology, UK, pp79.

MacDonald, D.J.M., Thompson, D.M & Herbert, R. 1995. Sustainability of yield from wells and boreholes in crystalline basement aquifers. BGS Report WC/95/50.

McCown, R.L. & Jones, R.K. 1990. Agriculture of semi-arid Eastern Kenya: problems and possibilities. ACIAR Procs. No. 41, Australia.

Meigh, J. 1987. Low flow analysis of selected catchments in Malawi and Zimbabwe, Unpublished report to British Geological Survey, Institute of Hydrology.

Meigh, J. 1988. A preliminary estimate of groundwater recharge in the Chiredzi area, Unpublished Report to ODA Engineering Division, Institute of Hydrology.

Murwira, K. 1994. Community-based sustainable development: The experiences of the Chivi Food Security Project. Proc. Int. Symp. on "Community Based Sustainable Development, Brighton, UK, Ref 211.

Murwira, K. 1995. Freedom to change - the Chivi experience. Waterlines, 13: 4, 23-25.

Oakes, D.B. & Wilkinson, W.B. 1972. Modelling of Groundwater and surface water systems, I - Theoretical relationships between groundwater abstraction and baseflow. Water Resources Board, UK, 1972.

Oster, J.D. 1994. Irrigation with poor quality water. Agric. Water Manag., 25, 271-297.

Pereira, H.C. 1961. Land use hydrology in Africa. Proc. Inter-African Conf. on Hydrology, CCTA, Nairobi, 45-50.

Phene, C.J., Bucks, D.A., Hutmacher, R.B., Ayars, J.E. 1993. Research successes, applications and needs of subsurface irrigation. Proc. Microirrigation Workshop, XV ICID Congress, The Hague, pp 249-267.

Purseglove, J.W. 1979. Tropical Crops: Dicotyledons. Longman, London, pp 719.

Rhoades, J.D., Kandiah, A. & Mashali, A.M. 1992. The use of saline waters for crop production. Irrigation and Drainage Paper 28, FAO, Rome, pp133.

Robinson, D.A., Bell, J.P. & Batchelor, C.H. 1995. Influence of iron and titanium on ater content determination by TDR. Danish Inst. of Plant and Soil Sci., SP Report 11, 63-70.

Sammis, T.W. & Wu, I.P. 1986. Fresh market tomato yields as affected by deficit irrigation using micro-irrigation system. Agric. Wat. Manage., 12, 117-126.

Scoones, I. 1992. Land degradation and livestock production in Zimbabwe's communal areas. Land Degradation and Rehabilitation, 3, 99-113.

Shalhevet, J. 1994. Using water of marginal quality for crop production: major issues. Agric. Water Manag., 25, 233-269.

Tagwira, F. 1992. Soil erosion and conservation techniques for sustainable crop production in Zimbabwe. J. Soil and Water Conservation, 47, 370-374.

Thomas, D.S.G. & Middleton, N.J. 1994. Desertification: Exploding the Myth. Wiley, Chichester, UK, pp194.

Topp, G.C., Davis, J.L. & Annan, A.P. 1980. Electromagnetic determination of soil water content: Measurement in coaxial transmission lines. Water Resour. Res., 16, 574-582.

Underhill, H.W. 1990. Small-scale irrigation in Africa in the context of rural Development. Cranfield Press, Bedford, UK.

Wagenet, R.J. & Hutson, J.L. 1989. LEACHM: Leaching estimation and chemistry model. Continuum Vol.2, Water Res. Inst., Cornell Univ., New York.

Wallace, J.S. 1994. Hydrological processes and dryland degradation. WMO Bull., 43, 1, 22-28.

Warren, A. & Khogali, M. 1992. Assessment of desertification and drought in the Sudano-Sahelian Region 1985-1991. U.N. Sudano-Sahelian Office, New York.

Waughray, D.N.K., Mazhangara, E., Mtetwa, G., Mtetwa, M., Dube, T., Lovell, C.J. & Batchelor, C.H. 1995. Collector Well Garden Project: Return to Households Survey Report. IH Report ODA 95/13, Institute of Hydrology, Wallingford, UK.

Whitlow, J.R. 1983. Hydrological implications of land use in Africa, with particular reference to Zimbabwe. Zimbabwe Agric. J., 80, 193-212.

Whitlow, J.R. & Campbell, B. 1989. Factors influencing erosion in Zimbabwe: a statistical analysis. J. of Environmental Management, 29, 17-29.

Wright, E.P. 1989. The Basement Aquifer Research Project, 1984-89: Final Report. British Geological Survey Report WD/89/15.

Wright, E.P. 1992. The hydrogeology of crystalline basement aquifers in Africa. In: Wright, E.P. & Burgess, W.G. (Eds): the Hydrogeology of Crystalline Basement Aquifers in Africa. Geological Soc., London, No. 66, 1-28.