Soil and Water Management in Spate Irrigation Systems in Eritrea

Mehreteab Tesfai Hadera

2001

Promotor: Prof. dr.ir. L. Stroosnijder
Hoogleraar in de erosie en bodem- en waterconservering

Samenstelling promotiecommissie:
Prof. dr. ir. E.M.A. Smaling (Wageningen Universiteit)
Prof. dr. ir. P.C. Struik (Wageningen Universiteit)
Prof. L. F. Vincent (Wageningen Universiteit)
Dr. ir. J. de Graaff (Wageningen Universiteit)

Soil and Water Management in Spate Irrigation Systems in Eritrea

Mehreteab Tesfai Hadera

Proefschrift

ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
Prof. dr. ir. L. Speelman
in het openbaar te verdedigen
op dinsdag 20 maart 2001
des namiddags te vier uur in de Aula

Wageningen University, ISBN 90-5808-388-8

Also published as Tropical Resource Management Papers, No. 36 (2001); ISSN 0926-9495

The completion of this PhD thesis was financially supported by NUFFIC/MHO project and Wageningen University.

Cover design
Piet Kostense and Mehreteab Tesfai

Cover photos
Mehreteab Tesfai

This work is dedicated to

- My family: Eminet, Senai and Samson and

- My parents

Abstract

This thesis is about spate irrigation in Eritrea with special reference to soil and water management practises. Eritrea's coastal zone has been identified as area of substantial development potential for spate irrigation. Research was carried out in Sheeb spate irrigation area (as a case study) with the objectives of describing the processes and functioning of the spate irrigation system, determining its development potential and constraints and recommending possible improved soil and water management techniques. A farming system survey revealed that the main problem of spate irrigation system is water shortage mainly caused by irregular rainfall in the highlands of Eritrea and the breaching of the irrigation structures ('agims' and 'misghas') by destructive big floods. The dominant types of soils in Sheeb area are the Fluvisols (spate irrigated soils) which are high in available phosphorus and available potassium but relatively low in total nitrogen and organic matter content. Nutrients are eroded from the highlands, transported by seasonal streams (wadis) and eventually deposited on spate irrigated fields via sedimentation. This annual sedimentation on the fields enabled the farmers to harvest a crop without application of fertilisers since the last 100 years of spate irrigation practises. A nutrient balance study has revealed no soil mining. However, to improve the nitrogen and organic matter contents of the spate soils, farmers should use the manure that is produced by their livestock. With better levelling, farmers can maintain a uniform water distribution over their fields. Of the total area of Sheeb (8,000 ha), about 3,160 ha of land was classified as highly and moderately suitable for spate irrigation. When the flood diversion structures (at wadis Laba and Maiule) are made more permanent an additional 2,000 ha of land can be irrigated. In general, the spate irrigation production system is a relatively 'cost effective' system provided that the irrigation structures are properly maintained at low cost and the fields receive enough water and nutrients.

Acknowledgements

In February 1996, a team of professors from (then) Wageningen Agricultural University, The Netherlands came to visit Eritrea to carry out a sector survey of the College of Agriculture and Aquatic Sciences (CAAS) of the University of Asmara (UoA) in accord with the linkage programme established between the Netherlands government and the government of Eritrea. After a field visit to Sheeb spate irrigation area (the research site), the spate irrigation system was identified as an important research subject in the course of discussion with my supervisor, Prof. Dr. Ir. Leo Stroosnijder. Many thanks for his initiatives to involve me in this interesting subject and also for his invaluable and endless support in supervising the research. I also highly appreciate his intellectual guidance and suggestions, which helped me to produce this thesis in its present form.

I would like to express my deepest gratitude to the Netherlands Universities Foundation For International Co-operation (NUFFIC) for financing my research in Eritrea and training costs at Wageningen University. I gratefully acknowledge also the UoA and CAAS for granting me the scholarship and for co-ordinating this sandwich research programme.

I am grateful to all staff members of Erosion, Soil and Water Conservation (ESWC) Group of Wageningen University, particularly to Jan de Graaff and Geert Sterk for critically reviewing some of the manuscripts and for their constructive comments and suggestions. And also to Dirk, Helena, Emiel, Max, Wim, and many others, and to the secretaries for their hospitality and assistance during my stay in The Netherlands.

I am indebted to all staff of Eastern Lowlands Wadi Development Project (ELWDP) of the Ministry of Agriculture (MoA) in Eritrea for the assistance given to make use of aerial photographs, maps and reports of the project and also for providing me accommodation in Sheeb and also to the staff of the soil science laboratory of the Research department in the MoA for the analysis of some of the soils samples.

My special thanks goes to Mr. Tekle Yemane in the Water Resources Department of the Ministry of Water, Land and Environment, who assisted me in processing and analysis of the geo-reference data using the Arc/INFO and Arc/view, Geographic Information System (GIS) to produce the soil and land use digital maps of the Sheeb area.

I can not conclude without thanking the Sheeb community as a whole, in particular farmers like Ahmed Saleh Tekrurai from Bises village, Mohammed Dirar Meselem from Sheebkhetin village, and Ibrahim Suleman Bedir from Dimnadige village for their endless co-operation in organising farmers for interview, providing land for experimentation and their warm hospitality right from the onset of this project.

Finally, I wish to thank my parents for their support during my school life and love to my wife Eminet and our children, Senai and Samson for their endurance and patience whenever I was away.

Wageningen, December 2000

Table of contents

Chapter 1

General introduction

1.1 Spate irrigation

Food shortages are common phenomena in large parts of sub-Saharan Africa (SSA) where the rate of population growth is 3% per year (FAOSTAT 1998), the highest in the world. To meet the food demand of the population of SSA, which is estimated to be 560 million as reported by FAO (1997), agricultural production should be increased either by expanding the area of cultivated land (extensification) or increasing the number of crops grown on a particular area of land or by increasing the yield per unit of individual crops or both (intensification).

Spate irrigation can be defined as a pre-planting system of irrigation where use is made of seasonal rivers (wadis) producing flash floods (with very short duration) from highlands and mountainous areas. These floods are diverted by structures to irrigate land in the lowlands (Peter 1987; Tesfai and Stroosnijder 2000). Spate irrigation is practised traditionally in arid and semi-arid areas of the world where rainfall is too low for rainfed production such as in the Middle East, Yemen, Pakistan, Northern Africa, Sudan, Somalia, Eritrea, etc. The areas under spate irrigation in some countries of the world are shown in Table 1.1. Accordingly, the total irrigated land under spate irrigation is estimated at about 2.2 million ha of land.

Table 1.1. Total irrigated land versus spate irrigated area in some countries of the world.

Country	Total irrigated area † (,000 ha)	Spate irrigated area ‡ (,000 ha)	Spate irrigation as % of total irrigation
Pakistan	17580	1450	8.2
Sudan	1946	280	14.4
Morocco	1258	165	13.1
Algeria	560	70	12.5
Yemen	485	193	39.8
Libya	470	53	11.3
Tunisia	380	10	2.6
Somalia	200	2	1.1
Eritrea	28	14 §	50.0
Total	22907	2237	9.8

† Source: FAO (1997)
‡ Source: UNDP/FAO (1987)
§ Source: IFAD (1995)

At present, spate irrigation covers about 50% of the total irrigated land in Eritrea (Table 1.1). There are about 11 spate irrigation schemes which all are located in the coastal plains of the country. The floods that reach the coastal plains of Eritrea precede the growing season in the plains. Therefore, farmers wet their soils with so much water that a crop can grow using the water stored in the soil profile (residual water). With enough floods and deep soils, farmers are able to 'harvest' enough water to grow two or even three crops in sequence, all on residual moisture since rainfall in the growing season is marginal and erratic (i.e. 200 mm annual average).

The spate irrigation system (SIS) in Eritrea has many advantages. (1) spate irrigation provides water for one or more crops in arid areas in the coastal plains of Eritrea where rainfed agriculture is totally unthinkable; (2) at present about 350,000 people (10% of the population of Eritrea) makes a livelihood on spate irrigated agriculture; (3) the traditional spate irrigation structures locally called 'agims' (diversion), 'misghas' (canals) and bunds are constructed from locally available materials and can be repaired by local people; (4) the 'agims' are effective to divert small to medium-sized floods to the irrigable fields; (5) spate irrigation build up land by depositing fertile soils on irrigable fields; (6) spate irrigation leaches the soluble salts deep into the soil profile and therefore controls the development of salt-affected soils and (7) the distribution of floodwater in the fields is simple and no input of energy is required since the water flows by gravity from field to field.

Nonetheless, the spate irrigation system suffers from unpredictability and irregularity of the rainfall in the highlands of Eritrea (where the source of water comes from). Moreover, big floods often breach the diversion and canal structures and huge resources of labour and large number of trees are required to repair them. Large amount of sediments (in the form of boulders, gravel and coarse sediments) are deposited on the canal beds, which block the passage of water and decrease the life span of the irrigation structures. The sedimentation inside the spate irrigated fields' raises the level of soil surface every year. This makes adjustment of the heights of the bunds needed so as to impound the diverted floodwater to infiltrate into the soils and to prevent overflow and breaching of the bunds.

The two basic requirements for installing new spate irrigation systems are: the topography and climatic conditions must be appropriate for directing the floods to an irrigable site and for harvesting water inside the fields. Furthermore, the arable soils must be capable of storing sufficient water during the flood season in order to ensure an ample moisture supply for the crops after flooding is over. In other words, the existence of deep soils with adequate water holding capacity is an essential condition to establish new spate irrigation systems in a given area.

1.2 Why studying soil and water management?

The government of Eritrea is committed to assure food security in the country by introducing integrated farming methods (i.e. mechanised farming) in rainfed crop production systems in the south western lowlands and in parts of central highlands and by rehabilitating existing spate irrigation schemes (intensification) as well as by constructing new schemes in the coastal plains of the country (area enlargement). For example in 1996, the government has launched a project called Eastern Lowlands Wadi Development Project (ELWDP) funded by IFAD at two spate irrigation pilot areas namely Sheeb and at Wadi-Labka (30 km north of Sheeb). One of the main objectives of the project was to improve the traditional spate irrigation system through construction of permanent flood diversion structures at the main wadis Laba, Maiule and Labka. Based on the experience gained on these wadis, it was hoped that local staff could be capable to construct similar structures in other spate irrigation areas of Eritrea. However, there is a lack of knowledge and experience on spate irrigation system especially with regards to soil and water management.

Soil and water management includes all farming practises applied on land through which soils and water are conserved and utilised with minimum wastage for sustained agricultural production. Under spate irrigation system, where water and soils are one of the two most important natural resources, studying either soils or water will not give a complete understanding of the system, since soil and water management practises are complementary. Cook and Ellis (1992) argued that water and soil management plans must be closely linked, one without the other leads to disaster. The question that could be raised is how should we manage the soil and water resources of Eritrean spate irrigation systems to obtain maximum agricultural yield at a minimum cost while preserving the quality of the environment? To answer this question, the elements of the spate irrigation system in particular the soils and water; their characteristics, interrelationships and their interaction with the other elements of the system and its environment as a whole were studied.

1.3 Research objectives and questions

The general objective of this thesis is to understand and to describe the functioning of the Eritrean spate irrigation system from the socio economic as well as from the technical point of view with respect to soil and water management. This includes the farming community, the farm household, soil formation, sedimentation, the nutrient balance, the water balance and land suitability for spate irrigation systems in eastern Eritrea.

In order to achieve this general objective, detailed studies were performed in a representative irrigation scheme, i.e. the Sheeb area. For this area, the specific objectives were:

1. To describe the principles and practises of the spate irrigation system,
2. To identify farmers' production constraints and opportunities and to analyse farm household income and expenditures,

3. To characterise the soils and to identify problems of soils,
4. To measure the sedimentation rate on spate irrigated fields and to assess the impact of sedimentation on the soils,
5. To determine the size of inputs and outputs of nutrients and water to and from the spate irrigated fields,
6. To determine the land use potential and its limitations for spate irrigation development and
7. To recommend possible soil and water management techniques and future research subjects in spate irrigation systems.

Table 1.2. Summary of research questions addressed in the Sheeb spate irrigation system, Eritrea.

Research scale	Research questions
1. Regional (Eastern Eritrea)	• What are the principles and the practises of spate irrigation system in Eritrea?
2. Village (Sheeb area)	• Which factors are considered as production constraints to spate irrigation and their solutions from farmers' perspectives?
3. Village (Sheeb area)	• What are the characteristics of the soils? • How much area of land do each soil types cover? • What are the main problems of soils and their possible solutions?
4. Village (Sheeb area)	• How much area of land is suitable for the use of spate irrigation? • What are the possible land use management practises for sustainable spate irrigation system?
5. Farm (household)	• What is the average farm household resources and their management practises? • What is the average farm household income and expenditures?
6. Field/Plot	• How much is the sedimentation rate and what is the effect of sedimentation on the spate-irrigated soils?
7. Field /Plot	• How much is the size of input and output of nutrients? • How much are the crop water requirements and the crop evapotranspiration rates?
8. Plot to Regional/National	• Which subjects deserve future research on spate irrigation systems?

The research questions are presented in Table 1.2, which are arranged systematically in order to understand and to describe how the spate irrigation system functions at various scales of study in the Sheeb area.

1.4 The systems approach

A systems approach is defined as studying a system as an entity made up of all its components and their interrelationships, and including relationships between the system and its environment (Stroosnijder and van Rheenen 1991). The systems approach is considered a research approach because it is a way of doing things and thinking about things and it includes specific methods and techniques. The central idea in the systems approach is that one must clearly define the system boundaries, i.e. what is in and what is not in the system (Spedding 1988).

The systems approach was used in the case study of the Sheeb area (Figure 2.2, Chapter 2) to achieve the research objectives mentioned earlier and to answer the research questions addressed in Table 1.2. The Sheeb area is representative for other spate irrigation areas in Eritrea in terms of climate, soils, water, topography and biotic factors. Furthermore, the accessibility of the area, involvement of various development projects such as ELWDP and presence of research center of the Ministry of Agriculture are some of the important factors for carrying out this research in the area.

Table 1.3. The elements of the spate irrigation system in Sheeb area versus the catchments of Sheeb.

Elements	Sheeb area (Lowland system)	Sheeb catchment (Highland system)
Agroecological zone	Coastal plains	Eastern escarpment & CHZ †
Climate	Hot and arid	Cool and sub humid
Hydrology	Flash floods (wadis Laba, Mai-ule)	Wadi Laba & Maiule basin
Rainfall (annual)	< 200 mm	550-800 mm
Agriculture	Spate irrigation	Rainfed agriculture
Topography	Alluvial plains with flat slopes	Mountainous with steep slopes
Altitude, (a.s.l)	165-275 m	2000-2625 m
Geology	Alluvial sediments	Precambrian basement complex
Soils	Transported soils	Residual and weathered soils
Tillage	Oxen drawn implements ‡	Oxen drawn implements
Cereals (dominant)	Sorghum, maize, millets	Wheat, barely
Vegetables & fruits	Watermelons, tomatoes	Potatoes, citrus, coffee
Livestock (dominant)	Camel, goats	Equines, sheep
Vegetation	Scattered bushes and scrubs	Disturbed high forest
Household	Agro-pastoralists, transhumance	Sedentary farmers

† Includes part of the Central Highland Zone
‡ Oxen drawn implements fitted with plough tip and its accessories (see descriptions in Chapter 2.2)

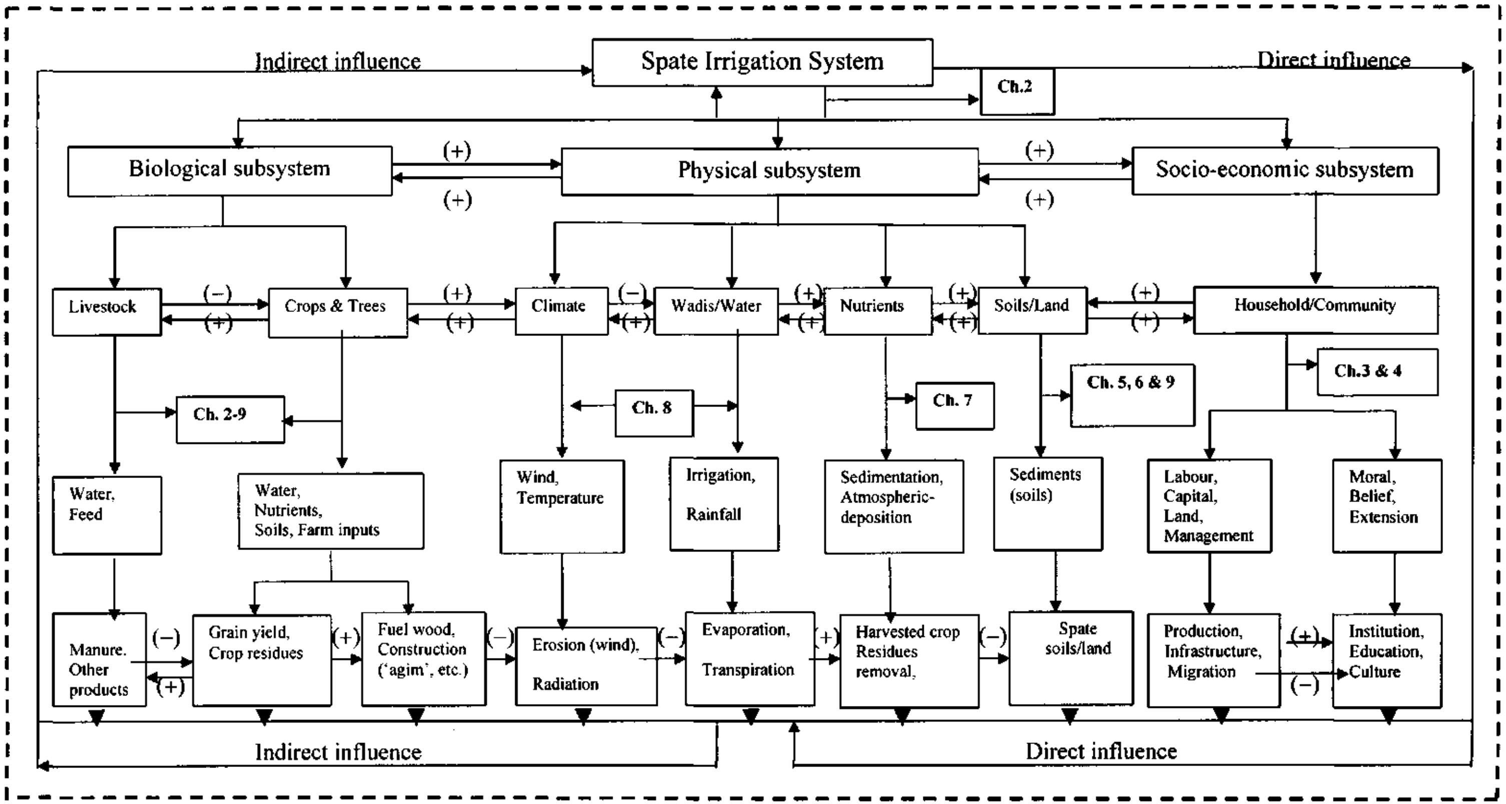


Figure 1.1. The spate irrigation system research (in Sheeb area) dealt per chapter and its structural flow diagram. (+) positive feed back and (–) negative feed back.

– – – – – The spate irrigation system boundary

The spate irrigation system in Sheeb consists of input and output variables dynamically changing in time and space. For example, if there are small rains in the highland catchments of Sheeb, less water will be available for spate irrigation in the lowlands of Sheeb area, resulting to lower yield and eventually decreasing the productivity of the spate irrigation system as a whole. What is found in the spate irrigation system in the Sheeb area and in the Sheeb catchment are listed in Table 1.3.

Except for tillage implements, all other elements are different between the lowlands of Sheeb and the highlands of Sheeb catchment. The spate irrigation system is only practised in the lowlands and not in the highlands because of the topography and climatic conditions (in the highland) are not conducive to establish the system. However, relationships exist between the lowland and the highland of Sheeb catchment. For instance, the lowlands system of spate irrigation entirely depends on the resources of the highlands. Any change in the highlands (such as rainfall, erosion) has a direct impact on the spate irrigation system in the lowlands of Sheeb area.

1.5 Outline of the thesis

This thesis is the result of research carried out on socio-economic and technical aspects of soil and water management in the spate irrigation system in Sheeb area in eastern Eritrea. Figure 1.1 depicts the spate irrigation system research as dealt per Chapter and its structural flow diagram. Before describing the technicalities of spate irrigation system, the natural resources of the system, its limitations and the socio-economic conditions are primarily identified and described through Chapters 2 to 4. Chapter 2 discusses the principles and practises of the Eritrean spate irrigation system in general and in particular the Sheeb area. The main wadis Laba and Maiule, which drew their supply of water from the highland catchments of Sheeb (used for spate irrigation and drinking water) are explained in this Chapter.

How the spate irrigation system operates spatially, temporally and socially at community scale is explained in Chapter 3. Farmers' production constraints and their possible solutions are identified and ranked using a Participatory Rural Appraisal (PRA) approach. The qualitative data gathered during the PRA process are quantified at household level, which is described in Chapter 4. Furthermore, the farm household economy (crop and livestock budgets) and balance of income and expenditures are analysed.

In Chapter 5, the soil formation processes; the soil characteristics and the types of soils in Sheeb area are described. Soil management problems are also identified and their possible solutions are discussed. The rate of sedimentation on spate irrigated fields is determined and the impact on soil physical properties is discussed in Chapter 6. Subsequently in Chapters 7 and 8, the quantity of inputs and outputs of nutrients and water in the spate-irrigated fields are determined. The nutrient harvesting impacts on chemical properties of soils inside and outside the irrigated fields are explained. Alternative nutrient management practises such as nutrient saving and/or adding techniques are discussed. Farmers' techniques to decrease water losses via soil evaporation are described in Chapter 8.

A land suitability system for spate irrigation is designed in Chapter 9 by incorporating the biophysical and socio-economic data analysed in the preceding Chapters. The expansion of the SIS in Sheeb area is determined and possibilities of land use management practises are recommended under this chapter.

In the general discussion in Chapter 10, the major constraints and opportunities of the spate irrigation system are thoroughly discussed. Future research subjects in the field of spate irrigation are also forwarded in this last chapter.

1.6 References

Cook, Ray. L. and Ellis Boyd. G., 1992. Soil management: A worldview of conservation and production: Krieger publishing company, Malabar, Florida, USA, pp. 23-45.

FAO, 1997. Production year book, Vol. 51. FAO statistics series no. 142, FAO, Rome, 239 pp.

FAOSTAT, 1998. Agricultural database. In: FAO, 1999. Soil fertility initiative for Sub-Saharan Africa, world soil resources reports No.85. Proceedings of the SFI/FAO consultation, 19-20 November 1998, Rome, Italy.

IFAD, 1995. Appraisal report on Eastern lowlands wadi development project, Eritrea, 52 pp.

Peter, H.S., 1987. Small scale irrigation: A manual of low-cost water technology. Intermediate technology, London, UK, 80 pp.

Spedding, C.R. W., 1988. An introduction to agricultural systems, 2nd edition, Elsevier applied science publishers, London, 189 pp.

Stroosnijder, L. and van Rheenen T., 1991. Making farming systems analysis a more objective and quantitative research tool. In: F.W.T. Penning de Vries (eds.), Systems approaches for agricultural development, Kluwer academic publishers, pp. 341-353.

Tesfai, M. and Stroosnijder, L., 2000. The Eritrean spate irrigation system. Agricultural water management (In Press).

UNDP/FAO, 1987. Spate irrigation: Proceedings of the sub regional expert consultation on wadi development for agriculture in Yemen, Aden, PDR, 180 pp.

Chapter 2

The Eritrean Spate Irrigation System

Tesfai, M. and Stroosnijder, L., 2000. The Eritrean Spate Irrigation System. Agricultural Water Management (In press).

Abstract

Eritrea's coastal zone has been identified as an area of substantial development potential. About 14,000 ha of this 5 million ha area (i.e. less than 0.3 %) has already been developed under a form of spate irrigation known locally as 'jeriff'. This is a water diversion and spreading technique in which wadis (ephemeral streams), springing from Eritrea's Central Highlands are diverted to irrigate land in the coastal plains. The system as it is applied in Sheeb, an area north-east of Asmara, characterised by agro-pastoral spate irrigation, is described. Under spate irrigation, crop growth is entirely dependent on the residual soil moisture stored in the soil profile. If the field bunds are flooded adequately, the resulting residual soil moisture is sufficient for two or sometimes three crop harvests. The spate irrigation system builds up land by depositing rich sediment on the fields, but the elevation of the irrigated lands rises every year. Moreover, the system requires huge numbers of trees annually for constructing diversion structures which are subsequently often washed away by heavy floods. In general, the overall irrigation efficiencies of spate schemes are only about 20% because of the difficulty of controlling floods and because water is lost by percolation and evaporation. Suggestions are made to improve the system and make it more sustainable: permanent flood diversion and distribution structures should be built to effectively divert the floods and to reduce water loss through percolation and the fields should be properly levelled to distribute the floodwater uniformly over the entire field.

2.1 Introduction

Eritrea is located in north-eastern Africa between 12° to 18° N and 36° to 43° E and has a tropical arid to semi-arid climate. It covers about 125,700 km^2 (DoE 1997) and consists of three main agro-ecological regions: the western zone (40%), the central highlands (20%) and the coastal plains zone (40%). The low and erratic rainfall in the coastal zone makes agricultural production impossible without irrigation. Because this flat alluvial coastal zone receives abundant water from the Central highlands, the government of Eritrea has identified it as an area for substantial agricultural development via spate irrigation (IFAD 1995).

Spate irrigation is practised traditionally in many parts of the Middle East, notably in the south and east of the Arabian Peninsula, in Northern Africa, in the Sudan and in Eritrea (Peter 1987). The indigenous irrigation technique already used in the coastal plains zone of Eritrea is known as spate irrigation, locally also called 'jeriff'. The practise of spate irrigation in Eritrea was started more than 100 years ago and is said to have first been established in the Zula area (south of Massawa: port city of Eritrea). It is believed to have been introduced by Yemenis from across the Red Sea (Tesfai and de Graaff 2000).

At present, only about 14,000 ha of the 5 million ha coastal land area (i.e. less than 0.3 %) has been developed under spate irrigation. The total potential area of spate irrigable land in the coastal plains of Eritrea has been variously reported as 90,945 ha (IFAD 1995) and 60,135 ha (NRCE 1996).

2.2 Principles of spate irrigation in Eritrea

Although spate irrigation is quite common in many parts of the Middle East and Northern Africa, remarkably little has been published in English on this type of irrigation (except UNDP/FAO 1987). Spate irrigation is a water diversion and spreading technique making use of seasonally heavy floods of short duration. These floods which spring from highland and mountainous areas are diverted to irrigate adjacent land in the lowlands, using diversion structures. In Eritrea, water is diverted before the planting season as a collective community action. Arable fields which are surrounded by bunds are flooded using several spates. The water soaks deep into the soil profile and provides residual moisture for crops to grow. Several floods and soakings are necessary before a cumulative amount of about 1000 mm of water has infiltrated into the soil.

Under a spate irrigation system, the fields are flooded to saturation and all the macro and micro pores in the soil become completely filled with water. In the Sheeb area, which (as explained in section 2.3.1) is the area on which our description is based, the total porosity of the spate irrigated soils is about 57% taking into account a dry bulk density of 1.13 g cm^{-3} and a particle density of 2.65 g cm^{-3}. The volumetric water content of the soils in this area varies from 40 to 44% at field capacity (Chapter 5). Therefore, with an average field capacity 42%, the wetting depth of the soil profile could reach to about 2.4 m. Note that sorghum varieties root to a depth of about 2 m. If the fields are flooded adequately, the residual moisture is sufficient to collect two or sometimes even three crop harvests using the traditional farming practises. Fields are planted after the flooding has subsided.

2.2.1 Water diversion and spreading

The elements and mechanisms of water diversion and spreading will be described here with the help of Figure 2.1.

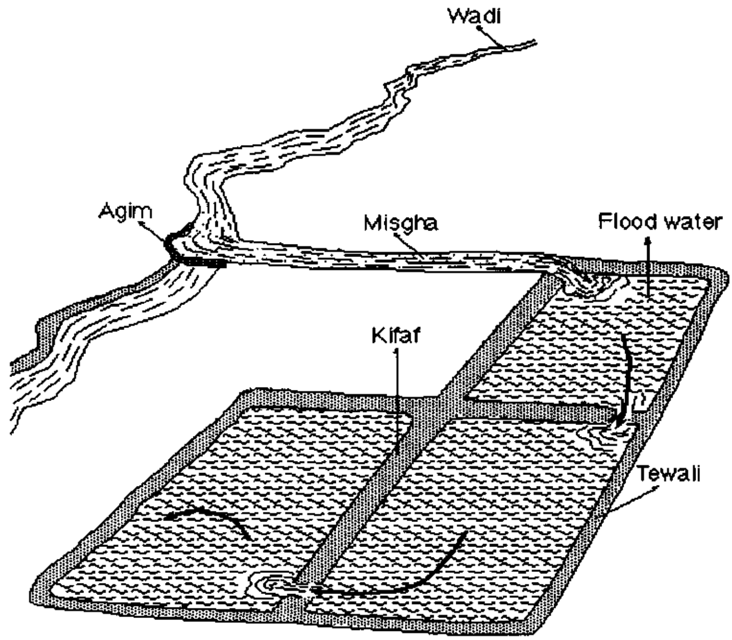


Figure 2.1. The spate irrigation system in Eritrea.

'Agim' is Arabic word which means diversion of river. An 'agim' is a temporary diversion structure erected at a low flow side of the wadi. After the wadi has discharged its torrential floods from the escarpment that separates the central highland from the coastal plains, the water slows down quickly after having flowed about 200 m over this plain. An 'agim' is made from brushwood trees, stones and/or boulders. Large tree branches are placed vertically in the river bed, with stones or boulders at their base to anchor the branches and secure them against heavy floods. Usually, the 'agim' is semi-circular, with the convex side facing the direction of the wadi flow to ease the diversion of floodwater. The purpose of 'agim' construction is to divert a large part of the flow of the wadi during a spate flow (flooding) to adjacent agricultural fields. The height of an 'agim' ranges from 3 to 4 m and its base width varies between 5 m for small wadi beds and 10 m for large wadi beds.

'Misgha' also derived from Arabic, is the term for the primary distribution canal. This is an earth embankment built at the end of 'agims' to distribute the flow into two or more smaller canals as it reaches the irrigable area. The 'misgha' has a large capacity in relation to the irrigated area because of the short duration of the spate flows. Normally, the widths of 'misgha' vary from 3 to 5 m, depending upon the area of irrigated land.

'Kifaf' is an interior earthen bund for steering the direction of the floodwater (often zig-zag over the field). In one field, a farmer will construct two or more 'kifafs' about 1 m high to irrigate the fields plot by plot and to slow down the flow to allow the sediments to settle.

'Tewali' is an exterior earthen bund constructed around the edges of individual spate fields. This bund could be as high as 1.5 m and its purpose is to keep the floodwater from flowing to adjacent farm blocks. It forms a basin in which the water can infiltrate into the soil. The size of the field varies from 0.5 to 1.0 ha and it is often rectangular.

The irrigated fields are designed so that water flows into the individual fields easily under the influence of gravity. The bunds around each field are constructed so that one side of the field is higher than the other side, to impound the floodwater. The floodwater enters the field at the low bund side and flows towards the side with the higher bund. By the time the water reaches this higher side, the whole field will be adequately flooded to a depth of about 0.5 to 1.0 m or to a wetting depth of about 2.0 to 2.4 m in the soil profile. At this point in time, the farmer will breach one of the high basin bunds and the water will flow into the lower bund side of the next downstream field. The whole process continues in this manner from one field to the other field until the total command area is flooded.

2.2.2 Construction and maintenance

In the spate irrigation system practised in Eritrea, farmers use oxen (sometimes called the tractors of the lowland) to help construct and repair the irrigation structures. An animal-drawn implement locally called a 'mehar' is used to scoop out soil to construct field embankments such as the 'kifaf' and 'tewali'. The 'mehar' is pulled by a pair of oxen and operated by one person who has to keep a firm grip on the tail of the animal while pressing the 'mehar' with his leg. When the blade of the 'mehar' is full of soil, the soil is transported over a short distance and tipped out at the appropriate site of the embankment. This device is also used for constructing 'agim' and 'misghas'.

Although the traditional spate irrigation structures described above seem to be elementary, they provide considerable advantages. They are constructed and repaired by farmers from locally available materials and are effective in diverting small to medium-sized floods. But during a large spate, as there is no provision for an emergency spillway, the 'agim' is either breached deliberately or it is overtopped as the flood rises. On such occasions a major section of the 'agim' is washed away, just before its command area could have been watered. Then, water cannot be diverted to the fields again until the 'agim' has been repaired. Usually this laborious task is done communally. Yearly repair and maintenance of the 'agim' are essential to keep the elements of the water diversion system functioning.

Table 2.1. Summary of indigenous spate irrigation techniques, purpose and problems in Sheeb area.

Local name	Purpose	Problems
'Agim'	A temporary diversion structure used to divert the entire flow channel of the wadi to 'misghas' (primary canals).	1. Washed away by heavy floods 2. Must be repaired every year 3. Trees are cut and used for 'agim' constructions 4. Labour intensive 5. Construction is time consuming
'Misgha'	A primary canal to convey the floodwater to secondary canals.	1. Washed away by heavy floods 2. Sedimentation in the canals
'Kifaf'	An interior field bund used to impound the floodwater and allow the fine sediments to settle.	1. Erosion in the fields caused by strong floods 2. The level of the land rises annually 3. Stratified soils are created
'Tewali'	An exterior field bund to prevent the floodwater from overflowing and to help the water infiltrate into the soil.	1. Bund heights have to be raised yearly 2. Stratified soils are created
'Mehar'	An animal-drawn implement used to scoop soil for construction of bunds	1. The implement has difficulty scooping heavy soils 2. The implement breaks in heavy soils
'Mekemet'	A type of soil tillage used to conserve the stored soil moisture and to reduce evaporation losses from the soil surface.	1. Could cause compaction in heavy clay soils 2. Reduces hydraulic conductivity and infiltration rate
'Jeleb'	A hollow tube used to sow seeds in rows.	1. No proper spacing between and within the rows
'Zeriba'	Places where animals are tethered and fed with a cut-and-carry feeding system.	1. Manure is not dropped in the fields 2. Requires labour to feed the animals

Towards the end of the flooding season, when farmers do not expect more floods, a type of soil tillage locally called 'mekemet' is practised in the flooded fields. They plough the fields about 0.15 m deep to create a tilth soil. The purpose of 'mekemet' tillage, also called conservation tillage is, to create a water vapour barrier to conserve the stored moisture in the soil profile by reducing the evaporation losses from the soil surface until sowing time. The interval between sowing and the last flooding is about 10 days.

The indigenous practises described above and the problems that local farmers face were identified during a Participatory Rural Appraisal (Tesfai and de Graaff 2000) and are summarised in Table 2.1.

2.3 Spate irrigation as a System

A system has been defined as 'a limited part of reality that contains interacting components, operating together for a common purpose, capable of reacting as a whole to external stimuli' (Spedding 1988). The indigenous spate irrigation practise will be considered here as an open and dynamic system having input and output variables dynamically changing in space and time.

2.3.1 Description of the area studied

The Sheeb area which is about 10 km^2 in extent, is a district in the northern Red sea zone of Eritrean at 15° 52′ N and 39° 0′ E (see Figure 2.2). It is in the eastern lowlands, about 110 km north-east of Asmara (capital of Eritrea). Here, the landscape is formed of flat to almost flat alluvial plains with an average elevation of 225 m a.s.l. The alluvial plains of the Sheeb area are part of the Red Sea basin drainage system and are cut through by numerous wadis which eventually discharge into the Red Sea.

The surface geology of the Sheeb area is Quaternary to recent alluvial deposits and aeolian sands (NRCE 1996). The climate is hot and arid, with more than 2000 mm mean annual potential evapotranspiration and a mean annual rainfall of less than 200 mm. Mean monthly air temperature ranges from 25°C in January and February to 36°C in July and August (Halcrow 1997).

The Sheeb area receives water mainly from two adjacent catchments: Laba and the smaller Mai-Ule. Wadi Laba is the biggest and most important wadi in the Sheeb area. During the rainy season in the highlands, this wadi contains water to a depth of about 1 m. The spates account for about 65% of the volume of annual flow in the wadi. The mean annual flood discharge is estimated to be 150 m^3 sec^{-1} (Table 2.2). In a good flooding season, about 15 floods (large and small) occur in wadi Laba, but in a dry year only 5 to 8 floods occur. On average, the floods flow for about 6 hours, with a recession flow lasting for 48 hours. About three-quarters of the irrigated land in the Sheeb area is watered by wadi Laba.

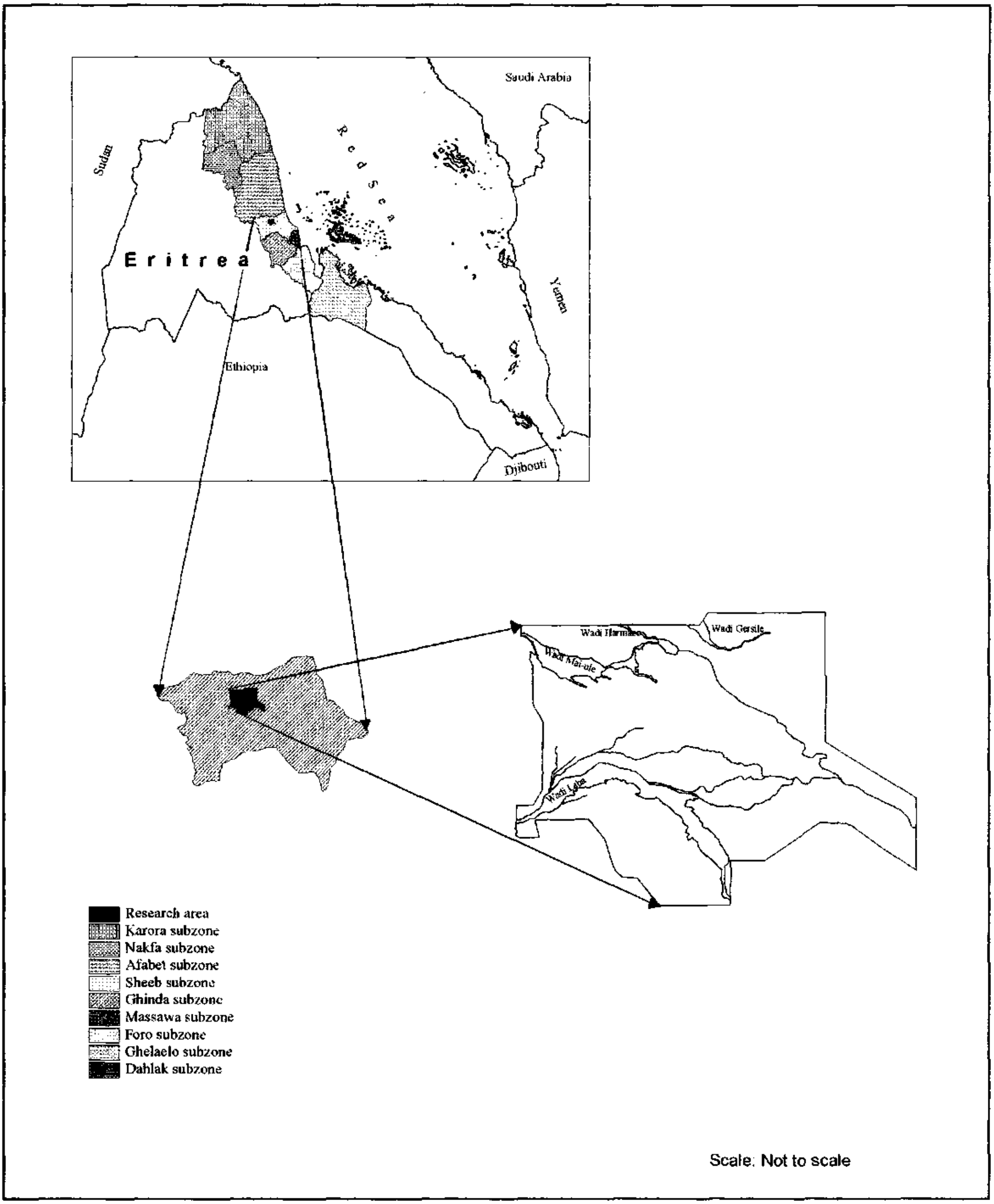


Figure 2.2. Location of Eritrea and the Sheeb research area in Northern Red Sea zone.

Table 2.2. Basic hydrological and irrigation data estimates for the Sheeb area and its catchments †.

Data	Wadi Laba	Wadi Mai-Ule	Total
Catchment characteristics			
(1) Catchment area, km^2	640	165	805.0
(2) Length of the wadi, km	56	35	-
(3) Average width of catchment, km	24	8	-
(4) Highest point (elevation a.s.l), m	2625	2000	-
(5) Elevation at diversion site, m	258.5	279	-
Catchment rainfall			
(6) Mean annual rainfall, mm	800	550	-
(7) Mean annual rainfall volume, Mm^3 (#1 × #6)	512	90.8	-
Peak flows			
(8) Mean annual flow volume, Mm^3	51.2	9.08	-
(9) Mean annual runoff coefficient (# 8 ÷ # 7)	0.10	0.10	-
(10) Mean annual flood, $m^3 s^{-1}$	150	35	-
(11) 5-year flood, $m^3 s^{-1}$	230	65	-
(12) 10-year flood, $m^3 s^{-1}$	410	90	-
(13) 20-year flood, $m^3 s^{-1}$	500	120	-
(14) 50-year flood, $m^3 s^{-1}$	690	170	-
Diversion & irrigation efficiency with improvements			
(15) Diversion efficiency, % ‡	80	80	-
(16) Conveyance/distribution efficiency, %	50	50	-
(17) Field application efficiency, %	50	50	-
(18) Overall spate irrigation efficiency, % §	25	25	-
Irrigable areas with improvements			
(19) Command areas, ha	2850	850	3700
(20) Average gross irrigation requirement, $m^3 ha^{-1}$ ¶	14200	14200	-
(21) Average annual area irrigable, ha	2648	676	3324
(22) Additional average annual area irrigable, ha	1456	395	1891

† **Source**: Adapted from Halcrow (1997).

‡ The diversion efficiency is the percentage of the annual spate flows that can be diverted for irrigation, the remainder being wadi seepage losses and flows passing through the sediment sluiceway and over the spillweir to downstream users or to the Red Sea.

§ The overall spate irrigation efficiency is the conveyance or distribution efficiency multiplied by the field application efficiency, averaged for the whole area commanded by the diversion headworks.

¶ The average gross spate irrigation requirement is the average net irrigation requirement estimated as 3,550 $m^3 ha^{-1}$ divided by the overall spate irrigation efficiency.

Wadi Mai-Ule is small in terms of its size and the number of its spates. Its mean annual flood discharge is 35 $m^3 sec^{-1}$. The wadi only flows after torrential rains in the highlands (July-September). The wadi command area accounts for about one quarter of the total spate irrigated land in the Sheeb area. IFAD (1995) reported an EC (Electrical Conductivity) of surface water in Laba and Mai-Ule of about 0.6 d S m^{-1} (about 400 mg l^{-1}). According to Landon's (1991) ratings, this indicates good quality water for irrigation. The probable reason is that the chemistry of the surface rock and the rainwater in the highlands is relatively free from salts.

Halcrow (1997) estimated the overall spate irrigation efficiency at wadis Laba and Mai-Ule schemes to be around 20%. That report suggested that with improvements of the traditional spate irrigation system, this efficiency could be increased to 25% (Table 2.2). In general, the irrigation efficiencies of spate schemes in both wadis are low. The main reason for this is the difficulty of controlling large amounts of water in a short period of time (and often at night). A second reason is the loss to deep percolation during flooding of the fields and a third reason is the seepage loss in the canal systems, particularly for the downstream areas far from the diversion points.

The traditional spate irrigation system in the Sheeb area consumes huge numbers of trees annually for the construction of diversion structures like 'agims'. The 'agims' do not last long; they are frequently washed away by big floods, which creates a great demand for wood.

Most of the spate-irrigated soils in this area are loams to silt loams. They have been accumulated as a result of the build-up of sediment over the years, and now often exceed a depth of 3 m. They are presumed to be fertile with good water-holding capacity and are well drained. The irrigated soils are non-saline, because the deep flooding form of irrigation that is characteristic of spate irrigation leaches the soluble salts to below a depth of 2 m, which is beyond the root zone of sorghum.

2.3.2 History of irrigation in Sheeb

Spate irrigation was introduced to the Sheeb area by Besisian tribes (Yemenis) from the Zula area. The first spate diversion structures were established at wadi Laba (upstream) where canals locally called Gebel, Mia, Sita, Halfa, Kurfotat and Futum were constructed by the Yemenis at the beginning of the last century. Later in the 1920s, the local farmers copied the spate irrigation method and built canals like Erem, Gelit, Emdenai and Ide-Eket at sites further downstream (Halcrow 1997).

2.3.3 The farming system

The farming system of the Sheeb area depends on agro-pastoral spate irrigation and features transhumance, which is a seasonal movement of both people and livestock between the central highlands and the coastal plain. During the hot summer season from May to

September, the people of Sheeb move to their highland areas with their livestock in search of grass and water. They return to their villages in mid September to October to grow crops and to feed their livestock until the end of April.

The system of water rights in the Sheeb area is long established with water being diverted through the various 'agims' in sequence, the order depending on their position in wadi. According to the water rights, the upstream lands receive water first. Downstream areas are only irrigated after the upper lands have received a sufficient supply of water.

Cropping subsystem

The main crop grown in the area is sorghum (Sorghum bicolor, L.var. 'hijeri') followed by maize. Minor crops include pearl millet, sesame, groundnut and some vegetables. The variety of sorghum widely grown in the Sheeb area called 'hijeri', was introduced from Sudan. This sorghum is well adapted to the local climate because it has a well-branched root system and is very efficient at extracting residual moisture from the soil.

The crops are usually sown from mid September, after the flooding of the fields has subsided. They are entirely dependent on the residual soil moisture in the soil profile for their growth. To sow the seed in rows, the farmers use a tube called 'jeleb', which is tied to the plough. The 'jeleb' is a hollow tube of wood, plastic or metal into which the plough operator drops two or more seeds every few seconds while ploughing the field. Seeding depth is about 0.15 m. The spacing between rows in sorghum fields has been reported by Natarajan (1999) as 0.30 m, while within the row, the seeding rate is very dense and irregularly spaced.

In the spate-irrigated areas of Sheeb, the farmers do not apply chemical fertilisers or manure neither do they incorporate crop residues into the soils. They believe that the nutrient requirement of their crops is sufficiently satisfied by the fertile sediments brought by flooding.

Livestock subsystem

The most common type of livestock reared are camels and goats. Oxen are kept to construct and maintain temporary diversion structures and field embankments and to till the land. There is a shortage of animal feed in Sheeb area, as the surrounding area is semi-desert. During the dry season, crop residues such as maize and sorghum stalks are removed from the fields and fed to the livestock. During the cropping season, the livestock is kept tethered and is fed with grass cut in the fields. This system, known locally as 'zeriba', prevents the livestock from trampling and grazing on young growing plants.

2.4 Making the spate irrigation system more sustainable

The spate irrigation system in Eritrea has many advantages. It provides water for one or more crops; it builds up land by depositing fertile soils on the fields adjacent to the overflowing river, etc. However, spate irrigation also has a number of drawbacks. One is that it deposits boulders, gravel and coarse sediments that obstruct the canals, making it necessary for the irrigation structures ('agim' and 'misgha') to be frequently maintained. Another drawback is that spate irrigation also raises the ground level of spate-irrigated fields a certain amount every flood season, by sedimentation. As a result, the height of bunds ('kifaf' and 'tewali') has to be readjusted. Due to this process, traditional spate irrigation is not a permanent system but adjusts its structure and even its location over time. This adjustment has two aspects: water intake and location of the fields. If the elevation of the fields becomes too high with respect to the water intake structure, the 'agim' can be moved higher upstream in the wadi. However, the closer the intake comes to the escarpment, the wilder the flow in the wadi becomes. This increases the risk of washing away the 'agim'. An alternative is to leave the agim at its original site but to move the fields in effect, to create new fields further downstream. There are limitations to this option too, since the main canal ('misgha') cannot be too long because of the large percolation losses in the permeable alluvial bed of the unlined canal.

In view of the above, the best option to make the system more sustainable would be to build permanent flood diversion structures at the head of the wadis. Such structures would have four advantages: they could withstand the force of heavy floods and divert the water effectively; they would eliminate the need to cut trees; they would reduce the expenditure of human and animal labour; and finally, they would increase farmers' productivity. Lining the main canals with cements (at an affordable cost) would reduce the loss of water by percolation and seepage, and properly levelling the basin fields would distribute the floodwater uniformly over the entire field.

2.5 References

DoE, 1997. National report on the implementation of Article 6 of the Convention on Biological Diversity (CBD). Department of environment of the Ministry of land, water and environment, Asmara, Eritrea, 104 pp.

Halcrow, W., 1997. Inception report, Eastern lowlands wadi development project, MoA, Asmara, Eritrea, 50 pp.

IFAD, 1995. Appraisal report on Eastern lowlands wadi development project, Eritrea, 52 pp.

Landon, J. R., 1991. Booker Tropical Soil Manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London,UK., pp 167-173.

Natarajan, M., 1999. Report on production and farming systems agronomy; strengthening the agricultural research and extension in Eritrea, GCP/ERI/001/ITA, FAO branch, Asmara, Eritrea, 50pp.

NRCE, 1996. Final report on the reconnaissance study of water-based agricultural development potential in Eastern Eritrea, Asmara, Eritrea, 202 pp.

Peter, H.S., 1987. Smallscale irrigation: A manual of low-cost water technology. Intermediate technology, London, UK, 80 pp.

Spedding, C.R. W., 1988. An introduction to agricultural systems, 2nd edition, Elsevier Applied science publishers, London, 189 pp.

Tesfai, M. and Graaff, J. de, 2000. Participatory rural appraisal of spate irrigation system in eastern Eritrea. Journal of agriculture and human values (In Press).

UNDP/FAO, 1987. Spate irrigation: Proceedings of the sub regional expert consultation on wadi development for agriculture in Yemen, Aden, 180 pp.

Chapter 3

Participatory Rural Appraisal of Spate Irrigation System

Tesfai, M. and J. de Graaff, 2000. Participatory rural appraisal of spate irrigation systems in eastern Eritrea. Agriculture and Human Values 17:359-370.

Abstract

In the Sheeb area, in eastern Eritrea a Participatory Rural Appraisal (PRA) was carried out in two villages, one upstream and one downstream of the ephemeral rivers Laba and Mai-ule. The objectives of the study were to obtain a better understanding of farmer-managed spate irrigation systems and to enable the local people to perform their own farming system analysis. This paper describes the various PRA activities, such as mapping, diagramming and ranking of problems, that were undertaken with the participation of local people. The resource mapping revealed that lack of water and not scarcity of land is the main constraint affecting the development of the spate irrigation system in the Sheeb area. When there is a lack of rainfall in the nearby highlands of Eritrea, there are only few floods per year in the Sheeb area. The development trend diagrams showed that the number of floods, the food production and the prevalence of pests vary considerably over time. The livelihood diagrams indicated that food, fodder and water were only available during part of the year. In search of these resources, the farmers have developed a livelihood strategy of seasonal migration to the highlands of Eritrea. The PRA data collected in the two villages appeared to be very useful for the preparation of community action plans in the entire Sheeb area.

3.1 Introduction

Spate irrigation is a pre-planting method of irrigation practised in semi-arid zones, whereby use is made of flash floods from highland areas, that through structures are diverted to irrigate land in the lowlands (Peter 1987). During the rainy season in the highlands of Eritrea, floods are produced in the form of runoff that flow towards the lowland parts of the country such as the Sheeb area. The runoff with its sediments is diverted by means of temporary irrigation structures called locally as 'agims' and conveyed by distribution canals called 'misghas'. Eventually, the runoff is collected in the fields that are surrounded by bunds. The water infiltrates deep into the soil profile while the sediments and nutrients are deposited on the soil. Crop production is sustained on residual soil moisture under this irrigation system. To fully investigate this farming system at the farm level, a formal survey was undertaken. Before carrying out this formal farm survey, there was a need for a community wide analysis of the spate irrigation system (SIS) in Sheeb area in Eritrea, by means of an informal survey. Byerlee and Collinson (1980) first introduced the informal survey concept and Hildebrand (1981) and Rhoades (1982) elaborated the concept. Hildebrand called it 'sondeo'. An informal survey is a field based methodology in which farmer interviews, direct observations and measurements are used to acquire an understanding of farming systems constraints and potentials (Fresco et al.

1990). The informal survey differs from the formal survey, in that it is not based on a statistically adequate sample with which conclusions can be drawn about the total population (Valk and de Graaff 1995).

Various rural development project personnel in Africa, Latin America and Asia have further developed these informal rural surveys. Chambers (1981) introduced the Rapid Rural Appraisal (RRA) method and this was in the early 1990s (Chambers 1992) followed by Participatory Rural Appraisal (PRA). According to Conway et al. (1987), PRA is a systematic yet semi-structured data gathering activity of rural life carried out in the field by a multi-disciplinary team intended to enable local people to conduct their own analysis, to prepare a plan and to take action. This reflects the increased emphasis on farmer participation (Mutsaers et al. 1997).

Although RRA usually involves some participation by the farmers and rural poor, it is primarily focused on learning by outsiders. PRA distinguishes itself from RRA, by its less pronounced concern for rapidity and its greater emphasis on involving farmers as partners, rather than mere subjects, in the appraisal process (Gosselink and Thompson 1997).

The objectives of this research were to develop a better understanding of farmer managed spate irrigation system and to enable the local people to do their own farming system analysis. To achieve these objectives, a Participatory Rural Appraisal (PRA) approach was undertaken. By using the PRA approach, advantage could be taken of various features of this approach, such as its emphasis on the understanding of rural problems, on participation of farmers, on developing better linkages between local people and outsiders and on the use of community resources.

The Sheeb area is located in the district of Sheeb in the northern Red Sea province of Eritrea. It is about 110 km north east of the Eritrean capital, Asmara. The area lies at 15°52' N; 39°01' E on an altitude of about 225 m above sea level. The climate of the area is hot and arid, with an estimated mean annual potential evapotranspiration of more than 2000 mm and mean annual rainfall less than 200 mm (Halcrow 1997). In the study area, agriculture is practiced using a spate irrigation system. The major crops grown are sorghum followed by maize, millets and some vegetables.

According to the Ministry of Local Government (1998), the total area of Sheeb district is about 2,321 km^2 and the population density is about 18 person per km^2. Whereas, the Sheeb area is about 10 km^2 and consists of six villages, of which three are located upstream and three downstream of the main wadis or ephemeral rivers Laba and Mai-ule. Daniel (1997) reported that the average population of Sheeb area is about 18,810 during the cropping season and lowers in the rest of the year, when the people migrate to the highlands of Eritrea in search of food and water. In this paper, the terms upstream and downstream are defined on the basis of the proximity to the wadis. Hence, upstream villages or fields are found near to the diversion sites of the wadis, while downstream villages or fields are found quite far from these sites.

3.2 PRA techniques

The Participatory Rural Appraisal was conducted in Sheeb area during the 1997 cropping season, from November to December. The PRA team was composed of eight persons: two from the organizing group of the University of Asmara, two from the Ministry of Agriculture (MoA) technical extension office and four from the community leaders, including both men and women. The organizing group gave a two day training in PRA principles and techniques to the team members, which was supplemented by a practical in the field and by a manual.

Before the rural appraisal, a preliminary visit to the area was made in September 1997 by the PRA team to explain the principles and purposes of PRA to the community and to select representative villages. In the selection of the two villages use was made of a PRA procedure. Dimnadige village was selected in the downstream area and Bises village in the area upstream of the Laba and Mai-ule wadis. Because of the different location and distance to the wadis, it was assumed that there would also be differences in resources and in the use of soil and water between these two villages.

For the field data collection, use was made of the PRA guidelines by Francis et al. (1995a and 1995b), with a few modifications where necessary. The PRA comprised three different categories of techniques:

- Techniques directed towards the spatial aspects of resource use in the spate irrigation system (spatial);
- Techniques that focus on resource use over time in the spate irrigation system (temporal);
- Techniques that look at resource availability and resource use by different social groups in the system and at problems encountered by these groups (social). The first two focus on the use of physical resources and the latter on the effects thereof on the various groups of people.

3.2.1 Techniques focusing on spatial aspects of the SIS

Village resource mapping

The PRA team and community members tried first to get an overview of each of the two villages, by overlooking them from the highest point. Thereafter, the community members drew their village maps on the ground using sticks and they placed different colours of pebbles to indicate the position of houses, farms, roads, wells, irrigation structures and gully sites in their territory (Photo 3.1). This exercise was done in order to understand the spatial variability of land and water resource use in the villages and differences between the two villages.

Transects

The PRA team undertook transects for one day during the cropping season to assess how the spate irrigation system operates in the field and to identify problems and opportunities of the system. Using the village drawings on the ground, the team selected two transects routes, crossing various land use types (irrigated and non-irrigated) and assigned two small teams in each village to carry out the transects. During these systematic walks in the field, team members made observations on soil conditions, soil and water conservation, irrigation, crop, livestock, socio-economic conditions, problems and opportunities. Casual interviews were also carried out about practises and problems of the spate irrigation system.

3.2.2 Techniques focusing on development trends (temporal)

Historical profiles

Historical profile diagramming was undertaken in the two villages to obtain insight in the events that occurred since the onset of the spate irrigation system. The PRA team selected young and old people from the community to trace back past and current trends, and to identify major problems and achievements. The team asked the participants to use major historical events in the country, such as the Italian occupation, Independence year, etc., as a reference point, and forwarded questions to the participants in chronological order, starting from the earliest times. For instance when did settlement begin and when did spate irrigation start? Group discussions were used to encourage dialogue among the villagers.

Trend lines

To understand the development of natural resource use in the villages, trend diagramming was undertaken during the cropping season. The PRA team explained the group involved, how to draw simple graphs on the ground whereby the horizontal axis indicated the years and the vertical line expressed the resource status in terms of low, moderate and high, written in local language. One participant drew the graph on the ground and indicated the status of a particular resource by placing pebbles at the year specified on the horizontal line. This exercise was continued for the following years. By connecting all the points on the ground a trend line was drawn. This was repeated for all major resource issues mentioned by the community.

Seasonal calendar

The seasonal diagramming was carried out to assess at which time of the year farmers undertake the various farming activities (e.g. period of cropping, tillage, conservation practises, labour demand, etc.). Sketches were made on the ground on loose sand, with a time scale in months on the horizontal axis, and with the type of the activities and the duration within the year on the vertical axis of the chart. The participants placed pebbles of different colours for the various activities on the chart at the relevant month(s).

3.2.3 Techniques to analyse social features of the SIS (social)

Interviews

Semi-structured household interviews were carried out with checklists to collect data on crops, livestock, vegetation, water resources and health, and to identify problems and their solutions from the farmer's point of view. A sample of rich and poor farmers was selected for interviews: 26 heads of households in each of the two villages. Female-headed households were only found among the poor households.

Livelihood mapping

Villagers comprising young and old, men and women, listed all the resources they considered very important for their livelihood like food, clothing, and shelter items. The PRA team drew a large circle representing the community boundary on the ground. Then, members placed all the resources available within the community inside the circle, those resources that were only partially available on the border of the circle and those completely unavailable outside the circle.

Ranking of problems

The PRA team and the community members developed a list of problems of the spate irrigation system on the basis of the field survey, the interviews and the discussions. A pair-wise ranking matrix approach was used for problem ranking and scoring, after the PRA team had explained the principles of this method to the community members.

The list of problems was written both on the top and on the left side of the matrix. The problems were weighed in pairs each at a time and the dominant one was written in the matrix. If there was no consensus, the community members voted by raising their hands. This was repeated for each pair until the entire matrix was completed. The final ranking was done simply by counting the number of times the particular problem dominated the others and this number was written on the chart.

3.3 The PRA findings and discussion

3.3.1 Spatial aspects of the spate irrigation system

The sketch maps drawn by the community members in the two villages (Photo 3.1) showed the location of resources and features like wadis, irrigation channels, cropland, buildings, roads and village boundaries, and the transects routes. The approximate size of irrigated land was 200 and 250 ha in Bises and Dimnadige, respectively. While, the total area of these two villages was 2.0 and 2.5 km^2. The potential areas (in terms of fertile soils) and the limitations (such as gullies and water shortage areas) for spate irrigation development were also indicated on these maps. Table 3.1 shows the differences in resource availability between the two villages. The upstream village, Bises had more water because of its proximity to the Laba and Mai-ule wadis. The downstream village, Dimnadige had on the other hand more irrigable land, which is however not yet used for spate irrigation because of a lack of water. This is due to the low rainfall in the highlands, to the weak structures to divert the big floods and to the water law for Sheeb area. This law prescribes that upstream fields should be irrigated first, and that downstream fields are only irrigated when the upstream fields have received enough water. Sometimes downstream fields do not get any floods at all. The upstream village had a high population density, many livestock and only few trees. The downstream village had relatively rich soils, a low population density and only few livestock.

Photo 3.1 "Handing over the stick"- Farmers in Dimnadige village drawing their village map on the ground using a stick.

During the transect walks, the teams observed in the downstream fields among others water shortage, gully erosion, bird damage and many weedy shrubs *(Cappris decidua)* locally called 'sorob'. In the upstream fields, the team observed breached irrigation structures ('agims' and 'misghas') and pest infestations. Pests also affected the poorly equipped grain stores.

Table 3.1. Comparative resource availability in the villages of Bises and Dimnadige.

Resources	Upstream village (Bises)	Downstream village (Dimnadige)
Irrigable land	less land	more land
Soils	silt to sandy soils	clayey to loamy soils
Water	more water	less water
Crops	sorghum, maize	sorghum, maize and pearl millet
Livestock	large number of livestock	small number of livestock
Trees	few, scattered trees	many trees, dominated by *Cappris sp.*
Population density	high	low

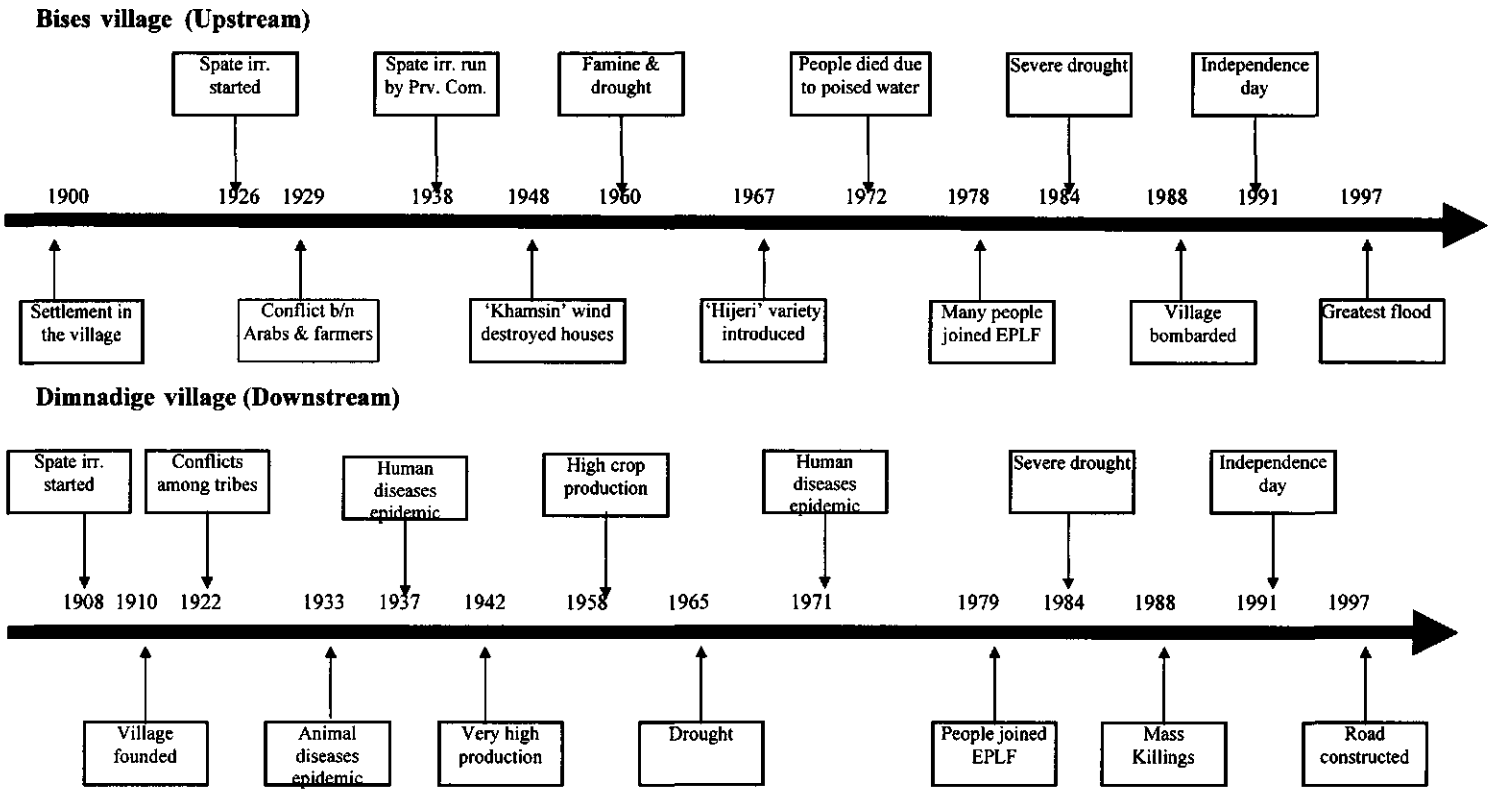


Figure 3.1. Historical profiles illustrating major historical changes in Sheeb area. (EPLF: Eritrea's' People Liberation Front).

3.3.2 Development trends in spate irrigation system

Figure 3.1 shows what the communities in the two villages considered as historical events, in the form of major problems or achievements. This concerns in particular the establishment of spate irrigation in 1908 in Dimnadige village and in 1926 in Bises village. This finding is in agreement with Halcrow (1997), who reported that spate irrigation started in downstream areas and gradually spread towards the upstream sites of the wadis. The practise of spate irrigation is believed to be introduced by the Yemenis who came from across the Red Sea. It was apparently first established in the Zula area (south of the coastal town of Massawa) and then to the Sheeb area. Before the introduction of spate irrigation, farmers were growing crops along the wadi beds by using simple digging implements, locally called as 'suluka' (Ibrahim, W. personal communication 1997).

The historical profile diagramming revealed that there were severe droughts in Sheeb area in the 1960s and in the 1980s. The number of livestock decreased between 1950 and 1990 due to these droughts, to the liberation war and to the inadequate disease control measures.

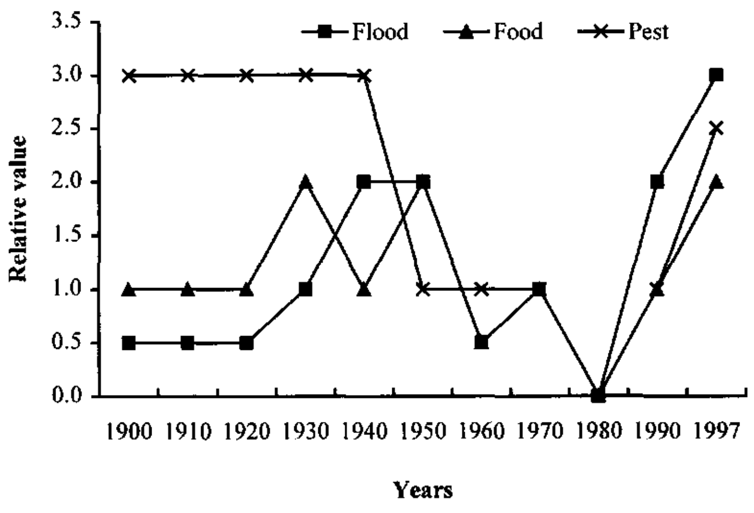


Figure 3.2: Trend lines for floods, food production and the occurrence of pests in Sheeb area. The relative values express respectively, very low (= 0.5); low (= 1); medium (= 2) and high (=3) values.

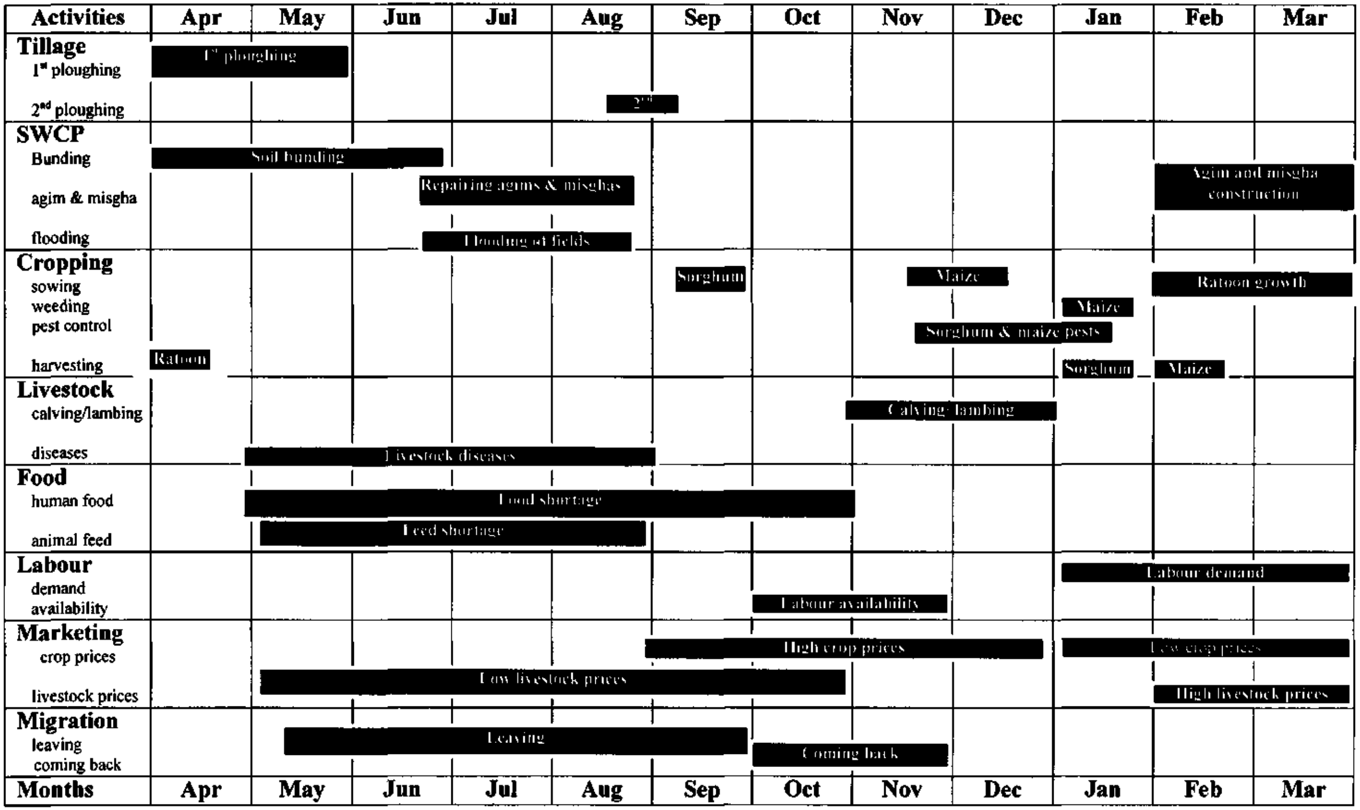


Figure 3.3. Complete spate irrigation calendar in Sheeb area. SWCP: Soil and water conservation practices

The trend diagram in Figure 3.2 indicates that the number of floods was very low in the 1960s and that there was no flood at all in 1984. This caused droughts, as a result of which food production was very low in these periods. The diagram shows that there were many pests before 1950, when there were no control measures yet, and that there were also many pests in the 1990s, when inadequate control measures were undertaken.

Figure 3.3 shows the spate irrigation calendar. The farmers are fully engaged in crop cultivation and livestock husbandry from September to March. From February to June, they construct flood diversion and distribution structures ('agims' and 'misghas') and soil bunds and they also plough their fields in that period. From July to September, the fields are flooded and the structures are repaired, whenever needed. The seasonal calendar also indicates that the peak labor period is from January to March, which is the time of crop harvesting and construction of diversion structures.

3.3.3 Social aspects of spate irrigation system

The interviews with the farmers gave insight into crop and livestock production, water and firewood supply and into the problems encountered by different social groups in the community.

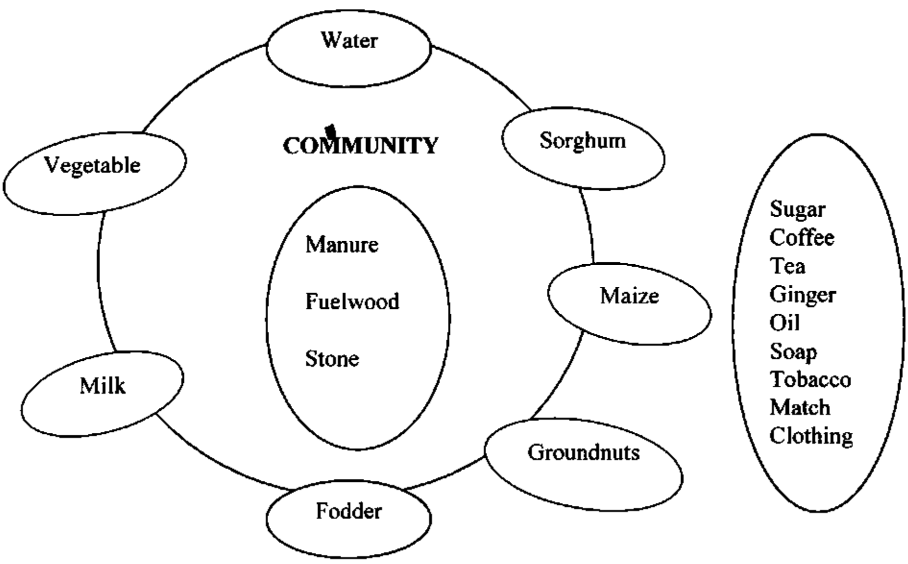


Figure 3.4. Availability of resources and products in Sheeb community. Note that products in circle are available, on borderline partially available and outside the circle not available in the community.

Figure 3.4 presents the results of the livelihood diagramming, and shows the availability of resources and products in Sheeb area. Manure is available all year round, but it is not used to fertilize the soil because farmers assume that the spate soils have a high nutrient content. They realize that the floods carry fertile topsoil eroded from the highland and deposit this on their fields. Some farmers use manure for house wall construction and as fuel. As a result of the rainfall pattern water, food and grass are only available during the cropping season, and are scarce in the rest of the year.

The Sheeb farmers have developed a specific livelihood strategy to combat these shortages of water, food and animal feed. Some farmers do earn their living by selling firewood or engaging in off-farm activities. The rest of the people migrate with their livestock to the highland areas in search of these resources (a kind of transhumance) and to escape from the harsh climate of the year. Only the men remain behind temporarily to divert the floods in July and August and to sow the seeds in mid September. This system of migration has negatively affected (partly) the life of the community. Some agricultural activities, such as the repair of irrigation structures, the sowing and the weeding, are not undertaken at the right time. Besides, the migration hinders the infrastructural development in the community.

With regard to the basic needs of the community, food items such as sugar, coffee, tea, etc. are not produced in Eritrea, except for some coffee in the highlands. Raw materials for clothes are also not much produced locally. Since the demand for these items is high, they are imported in large amounts.

3.3.4 Ranking of problems in the spate irrigation system

Figure 3.5 shows a listing and ranking of the major problems in the downstream village (Dimnadige) and a comparison with the ranking of problems by the farmers in the upstream village (Bises). The most important problem (rank = 1) in both villages consisted of the breaching up of irrigation structures ('agims' and 'misghas'), because of their weak construction. Shortage of water (for drinking and irrigation) is the second most important problem in the downstream village, while drinking water is only a slight problem in the upstream village, thanks to the proximity of the wadis.

The upstream farmers ranked health and pests as severe problems (rank = 2) whereas the downstream farmers considered these only slight problems. The probable reason might be that the wadis create favorable conditions for the multiplication of pests and waterborne diseases in upstream villagers. The farmers in both villages indicated that a lack of capital (rank = 4) did affect their spate irrigation system. These farmers do not have access to credit and jobs, and therefore usually encounter a serious cash deficit. They are obliged to sell their produce at low prices to traders, from whom they borrow money or products.

The PRA team finally developed a list of farmers' problems, their causes, coping strategies and opportunities (Table 3.2). The farmers in Sheeb area tackle the problem of breaching of irrigation structures by repairing them with dry acacia trees and earth fills; shortage of water, food and feed by migrating to highlands; pest infestations by changing sowing dates; and the lack of capital by borrowing money from friends or obtaining remittances from abroad. They use local treatments to heal sick people and livestock. Some farmers' store grains and fodder in good years to reduce migration. Moreover, there are various other opportunities to solve the problems of spate irrigation system, as described in Table 3.2.

3.3.5 Strengths and limitations of PRA

The application of PRA in the spate irrigation system has some limitations. Firstly, PRA can only be carried out during the cropping season when the villagers are present and when the climate is conducive to work. Secondly, PRA involves different social groups, and it is sometimes difficult to find the right resource people, such as old people who are able to trace back past events and recall the changes of resources in the community. Thirdly, the PRA techniques generate more qualitative data, which are difficult to countercheck unless followed by a formal farm survey.

Nonetheless, by using PRA it was possible to understand the changes of resources over space and time and their use by the local people and also to identify the problems of the spate irrigation system. Moreover, the PRA techniques helped the researcher to strengthen his communication with local farmers and staff and to build up confidence for work on other research activities. For this type of farming system research, most of the research materials were locally available (e.g. loose sand, pebbles, sticks to draw sketches and diagrams) and there was hardly any dependence on outside inputs.

Problems	Is	Wa	Jo	Ca	Ma	Ai	Fs	Ed	Si	Sa	He	Pe	Fu	Score †	Rank	
															Downstream	Upstream
Irrig. structures (Is)	**X**	Is	Is	Is	Is	Is	Is	Is	Is	Is	Is	Is	Is	12	1	1
Water (Wa)		**X**	Jo	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	10	2	10 ‡
Jobs (Jo)			**X**	Jo	Jo	Ai	Jo	Jo	Jo	Jo	Jo	Jo	Jo	10	2	11
Capital (Ca)				**X**	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	9	4	4
Marketing (Ma)					**X**	Ma	Fs	Ma	Ma	Ma	Ma	Ma	Ma	7	5	5
Agr. Inputs (Ai)						**X**	Ai	Ed	Ai	Ai	Ai	Ai	Ai	7	5	7
Food shortage (Fs)							**X**	Fs	Fs	Fs	Fs	Fs	Fs	7	5	7
Education (Ed)								**X**	Ed	Sa	Ed	Pe	Ed	4	8	np
Shrub infest. (Si)									**X**	Si	He	Si	Si	3	9	np
Salinity (Sa)										**X**	He	Sa	Sa	3	9	np
Health (He)											**X**	Pe	He	3	9	2
Pests (Pe)												**X**	Fu	2	12	2
Fuelw. Lack (Fu)													**X**	1	13	np
Migration (Mi)														-	np	5
Land shortage (Ls)														-	np	9

Figure 3.5. Ranking of problems in downstream village (Dimnadige) using pair wise ranking matrix (in last column comparison with upstream village (Bises).

† Scores represent 9-12: severe problem, 6-8: moderate problem and 1-5: slight problem.

‡ Water for drinking

np: Problem not indicated.

Table 3.2. Summary of farmers' major production constraints; causes; coping strategies and opportunities in Sheeb area.

Constraints	Causes	Coping strategies	Opportunities
• Breaching of irrigation structures (Is)	• Weak temporary structures	• Repairing & maintaining the temporary irrigation structures	• Construction of permanent flood diversion structures
• Scarcity of water (Wa)	• Lack of rainfall in the highlands • Drought	• Migrating to highlands	• Well digging
• Pests infestation (Pe)	• The wadis favor the pest to multiply • Poor storage facilities • Less control measures to pests	• Drainage excess water • Constructing grain storage houses • Changing sowing date	• Maintaining drainage channels • Application of pesticides • Treatment of wadis and wells
• Shortage of food and animal feed (Fs)	• Not enough floods • Low crop yield	• Migrating to highlands • Planting forage plants • Off-farm work	• Changing food habit • Improving farming practises
• Poor health of humans and livestock (He)	• Poor clinic facilities • Lack of adequate veterinary extension services • Water borne diseases in the wadis	• Walk long distance to health center of Mensheeb (town of Sheeb area) • Use of local treatment	• Improved access to clinic services • Vaccination services • Treatment of wadis and wells
• Lack of capital (Ca)	• Lack of job opportunity • No access to credit facilities	• Borrowing money from friends or traders • Remittance	• Creating credit institutions • Distribution of draught animal and insecticides on credit basis
• Migration (Mi)	• Shortage of food, grass and water • Culture inherited • Harsh climate	• Storing grains and fodder (during good year)	• Increasing crop yields • Planting forage plants along the wadi beds • Well digging • Improving local infrastructure

3.4 Conclusions

The spatial aspects of the spate irrigation system revealed a resource variation of land and water availability between the upstream (Bises) and downstream (Dimnadige) villages. There is more land for development of spate irrigation in downstream villages. However, this can only be achieved if the floods are controlled by constructing permanent diversion structures at the head of the wadis and some improvements in the water law that will lead to a more equitable distribution of water among the users. The water resources in the spate irrigation system of Sheeb area depend on the water resources in the nearby highlands of Eritrea. In other words, if there are good rains in the highlands, more runoff is produced and more water becomes available for spate irrigation and drinking water in the lowlands of Sheeb area.

The development trends in the spate irrigation system showed that the number of floods, food production, pest prevalence and diseases vary considerably over time in the Sheeb community. The livelihood diagrams indicated that manure, fuel wood and stones were available all year round in the community. Water, food and fodder were only available during the cropping season but are scarce in others periods of the year. Shortage of water and not scarcity of land is the main constraint affecting the development of spate irrigation system in the Sheeb area and in particular for the downstream area. Halcrow (1997) and Natarajan (1999) have also reported that water and not land is the main problem in the Sheeb spate irrigation system. The main reasons for water shortage are the lack of rainfall in the nearby highlands of Eritrea and the breaching of diversion structures by destructive big floods.

The farmers in Sheeb area have developed various livelihood strategies to combat the problems of spate irrigation. For example during the dry season, the people migrate to the highlands in search of food, water and grass. Some of the problems, like the breaching of the diversion structures, are beyond the control of the farmers. Therefore, the local government or other development agencies should support the farmers to utilize the opportunities available at hand.

Farmers in Bises and Dimnadige villages suggested that the information collected on the spate irrigation system could be used to teach school students and the Sheeb community. The PRA data collected in these two villages are also useful to prepare community action plans for spate irrigation development in the Sheeb area.

Acknowledgements

The authors gratefully acknowledge the financial support of the Netherlands Universities Foundation For International Co-operation (NUFFIC) to undertake this farming system research, and of they thank the College of Agriculture and Aquatic Sciences of the University of Asmara for co-ordinating the work. Special thanks are also due to the Sheeb community and in particular to the PRA team members and local staff who devoted their time for successful completion of this project. The authors like also to thank two anonymous reviewers for their very useful comments.

3.5 References

Byerlee, D. and M.P. Collinson (eds.), 1980. Planning technologies appropriate to farmers; concepts and procedures. CIMMYT, Mexico. 71pp.

Chambers, R., 1981. Rapid rural appraisal: rationale and repertoire. Public administration and development, Vol. 1, pp 95-106.

Chambers, R., 1992. Rural appraisal; rapid, relaxed and participatory. Discussion paper 311. Institute of development studies, UK.

Conway, G. R., J.A. Macracken, and J.N. Pretty, 1987. Training notes for agroecosystem analysis and rapid rural appraisal. Sustainable agriculture programme, IIED, London.

Daniel, A.M., 1997. A preliminary report on a pre-project Sheeb-Wadi Labka socio-economic study: A strategy for rural development Vol. 1 (a) and (b), MoA, Asmara, Eritrea.

Fresco, L., H., Huizing, H. van Keulen, H. Luning and R. Schipper, 1990. Land evaluation and farming system analysis for land use planning. FAO guidelines: Working document. FAO, Rome.

Gosselink, P., and Thompson, J., 1997. Application of participatory rural appraisal methods for action research on water management. Short report series on locally managed irrigation, No.18, International irrigation management institute, Sri Lanka 29 pp.

Halcrow, W., 1997. Inception report, Eastern lowlands wadi development project. Ministry of agriculture, Asmara, Eritrea, 50 pp.

Hildebrand, P.E. 1981. Combining disciplines in rapid appraisal: the Sondeo approach: Agricultural administration Vol. 8, pp. 423-432.

Ministry of Local Government, 1998. Annual report. Asmara, Eritrea.

Mutsaers, H. J., W.G. K. Weber, P. Walker and N.M. Fischer, 1997. A field guide for on-farm experimentation, IITA/ CTA/ ISNAR, pp 18-35.

Natajaran, M., 1999. Report on production and farming systems agronomy; strengthening the agricultural research and extension in Eritrea. Project GCP/ERI/001/ITA, FAO branch, Asmara, Eritrea, 50 pp.

Peter, H.S., 1987. Small scale irrigation: A manual of low-cost water technology. Intermediate technology, London, UK, 80 pp.

PRA programme, Egerton University, 1995a. PRA field handbook for participatory rural appraisal practitioners. Egerton University, Njoro, Kenya.

PRA programme, Egerton University, 1995b. Participatory rural appraisal: A case study of Gilgil Sub-location, Nakuru district. Egerton University, Njoro, Kenya.

Rhoades, R.E., 1982. The art of the informal agricultural survey. Training document 1982-2. Social sciences department, International Potato Center, Lima, Peru.

Valk, W. and J. de Graaff, 1995. Social and economic aspects of soil and water conservation. Lecture notes. Agricultural University, Wageningen, The Netherlands.

Chapter 4

Farm-household Survey of Spate Irrigation System

Abstract

A farm-household survey was carried out in Sheeb area in eastern Eritrea to obtain quantitative data on farm household resources and to analyse the average income for small farmers operating under spate irrigation system. Formal interviews were held with 53 heads of household comprising poor and rich farmers from six villages in Sheeb area. Nearly 57% of farmers interviewed mentioned that breaching of spate irrigation structures, lack of water and insect pests are the major constraints to crop production. While lack of feed, prevalence of diseases and drought posed problems to livestock production as mentioned by 69% of the interviewed farmers. About 83% of the farmers interviewed practise a transhumance system (called locally as 'sebek-sagim') to the highlands of Eritrea in search of food, water and grass. The standard of living of the majority of farmers is low and their income is solely dependent on crop and livestock production. During the 1997/98 good year, the average household earnings amounted to US $520 per year, which is similar to small farmers elsewhere in sub-Saharan African countries. In general, it can be concluded that the contribution of the small farm households to spate irrigation development and food security in the Sheeb area is considerable and to the region at large is not small at times of good flood seasons. The spate irrigation production system is 'cost effective' if the irrigation structures are properly maintained at low cost and if the fields receive enough water and nutrients.

4.1 Introduction

The majority of farmers in the developing countries of Africa, Asia, and Latin-America are smallholders. These farmers are responsible for the bulk of food production in their respective countries (Dillon and Hardaker 1993). It is estimated that 70-80% of the population of Eritrea (3.5 million) makes a livelihood on the production of crops, livestock and fisheries as small scale farmers living at subsistence level (World Bank 1994; FAO 1997). The agricultural sector contributes about 26% of the country's gross domestic product (GDP) as reported by Bereket and John (1999). Therefore, any attempt at boosting agricultural production needs to focus on improving the productivity of these small-scale farmers.

The government of Eritrea has placed food security as a major goal in its macro-policy. In 1997, the government has introduced integrated farming methods (IFM) i.e. mechanised farming in potential crop production areas such as in the south-western lowlands, in parts of central highlands and in the spate irrigated areas in the eastern lowlands of the country. Because of the good rains and the intervention of IFM, there was a bumper harvest in 1998 and in 1999, which Eritrea has never obtained before. For example in production year 1997/98, the country has produced 472,193 tonnes of cereal grains (Ministry of Agriculture 2000). This amount of production has fulfilled about 84% of the country's annual cereal food requirements (560,000 tonnes) which could be accounted as a greatest achievement in terms of food security.

The use of seasonal rivers (wadis) which spring from the highlands of Eritrea to irrigate land in the lowlands where rainfall is insufficient for crop cultivation is known as spate irrigation. During the rainy season in the highlands of Eritrea, floods are produced in the form of runoff that flow towards the lowland parts of the country such as the Sheeb area. The runoff with its sediments and nutrients is transported by wadis notably Laba and Maiule. In the lowlands, the runoff is diverted to adjacent irrigable lands (by means of temporary irrigation structures called locally 'agims') and it is conveyed by distribution canals called 'misghas' to the series of fields that are surrounded by bunds made of earthen material. In the fields, the water infiltrates into the deep soil profile while the sediments and nutrients are deposited on the soil. Seeds are sown in these fields and crop production is sustained on residual soil moisture under this irrigation system.

In the system of spate irrigation, the farm household is a subsystem, which usually consists of three inter-linked and interactive elements. These are: the household as the decision making unit, the farm with its crop and livestock activities and an off-farm component involving one or more income earning or social activities (Figure 4.1).

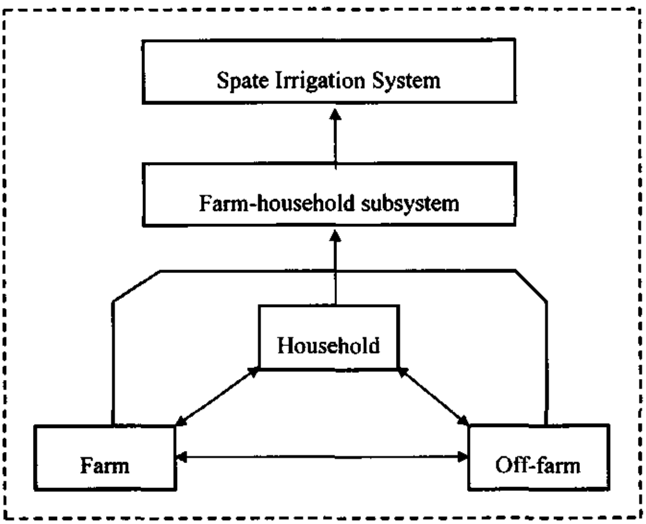


Figure 4.1. Schematic structure of a farm household in spate irrigation systems in Eritrea.

According to Huijsman (1986), a farm-household is defined as an organised social and economic unit, the members of which undertake agricultural and non-agricultural activities (either communally or complementarily) aimed at the satisfaction of material needs of the group and at the creation of material conditions to fulfill non-material needs. The economic unit constitutes of land, labour, capital and management, while social units are moral, belief and services, etc. provided to the household. In this paper, a household is defined as a person or group of persons normally living together in the same house or compound and sharing their resources and their income as well. The male-headed household could have more than one wife with children who live in different compounds.

The qualitative data gathered on the spatial, temporal and social features of the spate irrigation system in Sheeb community using the participatory rural appraisal approach (Chapter 3) should be quantified to determine the contributions of the small farm household to spate irrigation development and food security. It was therefore decided to carry out a formal household survey among the small farmers in spate irrigation system. The objectives of the survey were twofold: (i) to obtain quantitative data on farm household resources in the spate irrigation system and (ii) to analyse the average income for small farmers operating under this system.

4.2 Survey methodology

4.2.1 The study area

The state of Eritrea is divided into six administrative regions (equivalent to provinces). The northern Red Sea region is one of the administrative regions, which includes among others the Sheeb sub-region, (equivalent to a district). The Sheeb district (Figure 2.2, Chapter 2) comprises five village administrative units locally called as 'kebabi mimihedar'. These are (a) Tiluk, (b) Mensheeb, (c) Wekiro, (d) Ghediged and (e) Shellshela.

The study area i.e. Sheeb area is located about 110 km north-east of the Eritrean capital, Asmara. The area is administrated under the Sheeb district and it covers only the first two village administrative units (Tiluk and Mensheeb). It includes six villages namely Bises, Sheebkhetin, Tiluk, Ghineab, Mensheeb, and Dimnadige. The Sheeb area was selected because it is representative for the spate irrigation zone in terms of socio-economic, physical and biotic resources. In addition, it has a good accessibility and encompasses a large population. Secondary data sources (such as archival documents and reports) were used to describe the population of the Sheeb area.

4.2.2 Sampling

A farm-household survey was conducted in six villages of Sheeb area during the 1997-98 cropping season, that is from September 1997 until January 1998. Formal structured household questionnaires were prepared in line with the objectives of the farm survey. A pilot survey was first undertaken in selected villages of the study area in order to test out the questionnaire.

Table 4.1. Selection criteria used for household survey in Sheeb area.

Criteria	Resource-rich household (n = 20)	Resource-poor household (n = 34)
Oxen and ploughing implements	≥ 1 oxen & 1 set of implements	non owners
Dairy cattle number	> 1 dairy cattle	none

The sampling methods employed were cluster sampling and stratified random sampling. The population is the number of households in six different villages of Sheeb area. The population was divided into two main groups of rich and poor households. The basis of this classification was ownership of oxen with ploughing implements and number of dairy cattle (Table 4.1). Physical assets such as land holdings and conditions of the house were not used as criteria since they do not differ much, and are related to the above criteria. A sampling frame was prepared from which a sample of farmers was selected randomly from each group in each village.

Table 4.2. Characteristics of selected villages in the household survey.

Village name	Position to the wadis (Laba and Mai-ule)	Sample size	Farm households	
			Rich	Poor
Bises	Upstream	9	3	6
Sheebkhetin	Upstream	9	3	6
Tiluk	Upstream	9	4	5
Ghineab	Downstream	9	3	6
Mensheeb	Downstream	9	3	6
Dimnadige	Downstream	8†	4	4†
Total	-	53	20	33

† One poor farmer did eventually not contribute to the survey.

Norman, et al. (1995) pointed out that the appropriate sample size depends on the variability in the population and not on the size of the population. On the other hand, Shaner et al. (1982) suggested a minimum sample size of 20 from each sampling category when the variability within the categories is low. The variability of the farming population in Sheeb area is relatively 'low' and large parts of the population are poor farmers. Hence, a total of 53 households from the six villages (Table 4.2) were interviewed: three villages were located at upstream and three at downstream sites of the main wadis, (Laba and Mai-ule). The sample size was composed of 20 resource-rich male households and 33 resource-poor households divided into 17 male and 16 female households. In all cases, the head of the household was interviewed.

4.2.3 Data collection and analysis

The data collection on farm household resources and resource use was carried out using a formal structured questionnaire and field surveys. The questionnaire (Annex A) comprised of an inventory of the farm family (population, labour and women activities); an inventory of farm household resource endowments and resource uses (land, water, crop, livestock, farm tools and farm houses); inputs and outputs of crops and livestock production and issues on food security. The types of questions consisted of closed-ended with codified answers, open-ended, tabular and dichotomous questions (Annex A). Enumerators who speak the local language were recruited to interview the farmers. The enumerators were trained how to approach respondents, how to explain questions in the questionnaire and how to fill in the forms.

After completing the formal interview process, the researcher and the enumerators cross-checked the information given by the respondents. Cross checking was undertaken through direct observation and ground truth measurements in selected fields e.g. crop yields through crop cutting and by measuring field size using a tape.

The data on crop and livestock inputs and outputs, household expenditures, food consumption and requirements were processed and analysed using Excel 97 software program.

4.3 The farm-household: resources, resources use and analysis

4.3.1 Farm household resources

The population

The population size of Sheeb area is difficult to determine, since the families move from place to place in certain seasons. Population levels are highest between October and May, when most of the families are present and lowest during June to September when most of the women and children have migrated to the highlands of Eritrea.

The most common seasonal movement of people and livestock in Sheeb area can be described as a transhumance system locally called 'sebek-sagim'. This is practised mainly to search for food, water and grass; to escape from the extreme high temperatures (40-45°C) and the strong dusty winds called locally 'khamsin'. About 83% of the interviewed farmers migrate annually to the highlands of Eritrea, such as Gheleb, Gizgiza, Afabet, etc., which are about 70 to 90 km from Sheeb. This migration involves the movement of women, children and livestock, but the head of these households, usually the men, remain behind to divert the floods, to irrigate the fields and to repair the irrigation structures ('agims', 'misghas' and bunds).

The transhumance system has affected the livelihood of the Sheeb community both in positive and negative ways. The positive side is that it exploits different agro-ecological zones (for example food, water and grass are available in the highlands when these resources are scarce in the lowlands of Sheeb area). But, the need to rebuild the temporary houses (locally called 'agnet') year after year is a drain on labour and capital resources. The 'agnet' is usually constructed from branch of trees, plastic sheets and clothes that are easily destroyed by the strong wind storms and intense sun heat in the summer. Moreover, the migration sometimes hinders agricultural activities (e.g. repairing of irrigation structures, flooding of fields, sowing of seeds are not performed at the right time) and also the development of infrastructures (such as roads, buildings, etc.) in the Sheeb community is impeded by the migration of the people.

Table 4.3. Population statistics by village in Sheeb area. †

Village name	Households number	Household heads male	Household heads female	Population number ‡
Bises	261	184	77	1,566
Sheebkhetin	759	700	59	4,554
Tiluk	650	600	50	3,900
Ghineab	250	215	35	1,500
Mensheeb	968	891	77	5,808
Dimnadige	247	210	37	1,482
Total	3,135	2,800	335	18,810

† Adapted from Daniel (1997).
‡ estimated.

Table 4.3 gives the estimated population of Sheeb area and the number of households by sex in each village. Of the total household number (3,135 households), the female-headed households constitute about 10%. The family size of a single household is most often between 5 to 7 persons as shown in Figure 4.2. This is as large as elsewhere in rural areas of Eritrea. Using the average of 6 persons per household, the population of Sheeb area would be 18,810 during the cropping season and lower in the rest of the year. The population density of Sheeb district is around 18 persons per km^2 and the population growth is 2.9% per year, which is also the national average (Ministry of Local Government 1998).

A large part of the households in Sheeb area are ethnic of Tigre and originate from ten different clans namely Regibat, Aflanda, Bete-Aseghed, Zagir, Asfada, Bete-Lailit, Dobait, Ade-Temariam, Deg-deg and Ade-Moalim and some ethnic Rashaidas. Nearly all of them are Muslims and the main local languages spoken in the area are Tigre and Arabic.

The majority of the population in the Sheeb area are illiterate, apart from a small proportion that can read and/or write the local languages and a few who got the chance to attend primary education. A small percentage of this group has access to higher education. The majority interrupts their schooling, mainly due to the poverty of their parents and other associated cultural problems such as early marriage in the case of girls. The high illiteracy rate is mainly because there were no educational institutions established in the area before Eritrea was liberated (in 1991).

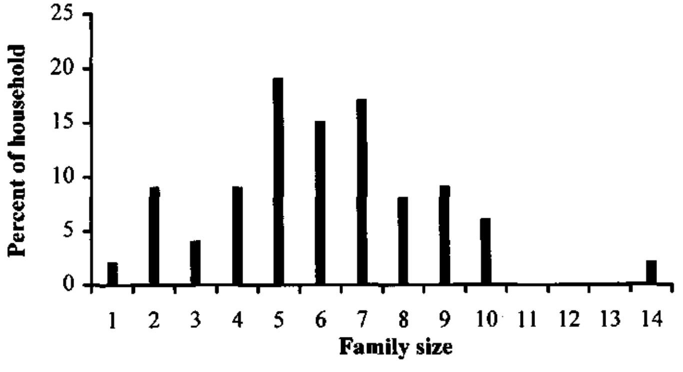


Figure 4.2. Family size distribution per household in Sheeb area. (Source: field survey 1998).

Most of the female respondents were widows who lost their husbands during the war for liberation. Over 90% of the adult male respondents were married to one wife and few were polygamists. The male to female proportion in the villages of Sheeb area is 51 to 49 for every hundred inhabitants of the area. In other words, the male is about equal to the female population, despite the loss of lives during the war.

Around 58% of the population are young males and females under the age of 20 years, while about 3% of the population are 66 years and above. The school age group under 10 years old constitutes around 31%. The active population group falls between 20 and 66 years old and constitutes about 39% of the total population in Sheeb area. Daniel (1997) reported that in the rural settings of Africa and the rest of the developing world, children become already economically active from 15 to 20 years old. This holds also true in most rural areas of Eritrea, which would mean that the economically active population is higher than the 39%, mentioned above.

Labour

The traditional spate irrigation system is labour intensive. The peak labour periods are at the time when the irrigation structures are constructed and repaired communally (March-May); when fields are ploughed (May-June); during sowing of seeds (September) and during harvesting and threshing of grains (January for the main crop sorghum and April for ratoon crops). The slack periods are during flooding of fields (July and August) and between sowing and harvesting (October-December). In addition to the family labour used (husband, wife, adult boys and girls), many farmers (>50%) hire labour at the time of crop harvesting and threshing grains. Labourers are available within the community by hiring especially those farmers whose fields have not been flooded or sometimes people from the highlands come down to work for wages at the rate of 12 'nakfa'[1] (about US $1.7) per day.

In the Sheeb area, during the hot summer and dust storms (April-August), the working time consists of only 4 hours but in the rest of the year it is 7 to 8 hours. The farmers in Sheeb area are not working full time on their fields. They are idle particularly between the period of planting and harvesting, while cultivation, weeding, thinning and other crop management practises are not properly practised. During these idle months, off farm employment opportunities that could have supplemented their farm income, are rare.

Women labour profile

About 77% of the farmers interviewed reported that women are engaged primarily in agricultural activities such as harvesting, threshing, and transporting grains and straw. The women working in the fields are mostly divorced or widowed women and young girls. The second area, in which women are active, is in trade. A small proportion of adult women is involved in petty trade, mainly in selling handicraft products such as mats and baskets. A few sell vegetables and some operate a shop.

[1] Nakfa is a local currency of Eritrea. In 1997/98 the exchange rate was US $1 = 7.20 nakfa.

The third area of activity for women is in community affairs like members of the village 'Baito'[2], and as participants in community development programs and politics. The government of Eritrea has passed legislation that at least 15% of the seats of village 'Baito'[2] must be occupied by women. The National Union of Eritrean Women (NUEW) is also encouraging women to take full part in the national development. As a result, around 33% of the total adult female population in Sheeb area are involved in 'Baito'[2], community development programs and politics.

However, the general attitude of male residents in the area towards this untraditional women activity is negative. More than 50% of the male respondents rejected the activities of women outside the house, because they believe that this is interfering with their cultural norms.

Land and water

In Eritrea, land is under the domain of the state. In Sheeb area, there are two traditional land tenure systems locally known as 'awlet' and 'sawahil', which are practised in the highlands and in the lowlands, respectively. The 'awlet' system refers to few farmers who own small farmland in the highlands through inheritance from their forefathers. The majority of the farmers in Sheeb area are under the 'sawahil' system, which confers the right to use the spate irrigable land continuously.

The total land area of Sheeb is approximately 10 km^2. Out of this, about 5,000 ha of land is potentially spate irrigable land for crop production. At present, only between 2,500 to 3,000 ha of land is irrigated annually (Chapter 9), mainly due to a lack of water. In 1980, when the Eritrean Peoples' Liberation Front (EPLF, the ruling party now in the country) took over the Sheeb area, land was redistributed equitably to all inhabitants. At the time of redistribution, each household consisting of husband, wife and children were given 4 'tsimidi'[3]. Divorced men and women, single adults of 18 years or more, and orphans who were less than 18 years old were given 2 'tsimidi'[3]. According to the household survey, about 80% of the interviewed farmers owned on average 4 'tsimidi'[3]. Of the interviewed farmers, about 90% own land and the rest are landless farmers who live on share cropping or by renting land. The main reason for not owning land is the large farming population in the area.

Most of the spate-irrigated soils in the Sheeb area are loams to silt loams. These soils have been accumulated as a result of the build up of sediments over the years, and now often exceed a depth of 3 m. The soils are presumed to be fertile with good water-holding capacity and are well

[2] Baito is people's assembly, which is community based and forms the link with the local village and administration.

[3] 'Tsimidi' is a local measurement unit, which is equal to 0.25 ha of land.

drained. Salinity is not a problem for most farmers (87%) because of flooding of the fields, which leaches the soluble salts deep into the soils.

Most farmers (87%) have observed an increase of soil depth in their spate-irrigated fields because of sedimentation. Of the farmers that reported sedimentation on their fields, 61% indicated that the average sediment layer thickness increases by 3 to 5 cm per year. This response is in agreement with the IFAD's staff appraisal report (1995) which estimated that the sediment layer thickness in spate irrigated fields' increases with 3 cm per year. About 78% of the farmers attach a positive value to the sedimentation on their fields as it adds fertility to the soil and increases crop yields and 22% said sedimentation increases the arable land. Lawrence (1996) has also reported that the fine sediments, which settle on the fields, are needed by the farmers to build up soil depths and to maintain fertility.

The arable lands of Sheeb area receive floods mainly from the wadis Laba and Maiule. Two other smaller wadis called Harmazo and Gersile are also used to irrigate the fields located in Ghineab and Dimnadige villages. The main floods usually occur in the period between July to September, which is the time of the heavy rains in the highlands. As rainfall is important for highland farmers so are floods for lowland farmers in Sheeb. A good flood season has 15 or more floods, a moderate season between 10 and 15 floods, and when less than 10 floods occur, the season is considered as bad. But, the exact size and frequency of the floods in Sheeb area are unknown and thus, uncertainty is an inherent characteristic of the spate irrigation system. According to the farmers, the number of floods in the 1997 flood season was about 20 (big and small) floods, which is classified as a good year.

Of the farmers interviewed, 68% responded that they encounter a lack of water for drinking and for irrigating their fields. The causes for water shortage are mainly a lack of rainfall in the highlands and the weakness of the diversion structures especially in diverting the big floods. Access to water varies among the upstream, midstream and downstream villages. According to the water rights adopted in the area, fields located in upstream villages always get water first. While, fields in downstream villages are irrigated only after the upper fields have received enough water.

In the system of spate irrigation, water, and not land, is the major limiting resource (Halcrow 1997; Tesfai and de Graaff 2000). Other problems recognised by many farmers (60%) were the breaching of irrigation structures by destructive big floods and soil crusting. Farmers appeared to know the techniques to reduce the above problems by repairing the irrigation structures with dry acacia trees or earth fills and by breaking down the crusted soils while they are still moist.

Table 4.4. Average farm resources of rich and poor households in the Sheeb area.

Resources	Unit	Rich households	Poor households	Average
Farmland size	'tsimidi'	4.0	3.6	3.8
Family size	number	7.3	4.1	5.7
Family labour force †	number	3.5	3.3	3.4
Dairy cattle	number	2.7	1.5	2.1
Draught animals	number	2	1	1.5
Farm tools ‡	'nakfa'	221	89	155
Farm house §	'nakfa'	562	342	452

† Economically active labour force (15-66 years old).
‡ Estimated present value of hand tools such as spade, sickle, axes, winnower, etc.
§ Estimated present value of multi purpose housing, made of wood and grasses.
Source: field survey, 1998.

Table 4.4 presents some of the major farm household resources by rich and poor farmers in the Sheeb area. Accordingly, a typical farm household on average possess 3.8 'tsimidi' (0.9 ha) of farmland, an economically active labour force of 3 persons, 2 dairy cattle and 2 draught animals. The poor households have small capital assets in the form of farm tools and houses and their family size is lower than that of resource rich households.

4.3.2 Resource utilisation

Crop production

The farming system in Sheeb area is characterised by an agro-pastoral spate irrigation system. The farmers in this area are engaged in small-scale subsistence farming employing simple traditional farming implements. The main crops grown are sorghum [*Sorghum bicolor, (L) var.hijeri]* followed by maize, which is sown when there are enough floods. Other minor crops grown include pearl millet, sesame, groundnut, and some vegetables, which are all grown using the residual moisture in the soil profiles.

The sorghum variety mostly preferred by the local farmers is called 'hijeri' (a white type of local sorghum). According to most of the respondents, this variety is chosen because it is high yielding, dwarf (easy for harvesting), fast maturing and palatable. When the spate-irrigated fields are flooded three to four times to the height of the bunds (about 0.5 m), sorghum can produce after the main crop, a first ratoon crop with grain yield and even a second ratoon but with forage only with out addition of fertilisers into the soils. Some of the major pests attacking the sorghum and maize plants are green stinkbug, stalk borer, earhead bug, aphids and termites. Birds also damage the crops in the downstream villages where they find shrubs to perch. Spraying of pesticides when pests break out and changing of sowing dates are some of the control measures undertaken by farmers and local extension agents.

In 1997/98 production year, the average grain yield of sorghum was in the range of 1,200 to 1,500 kg ha^{-1} for the main crop and 700 to 1,000 kg ha^{-1} for the ratoon crop. All farmers collect the straw of crops from their fields after harvest. This implies that there is no replenishment of fertility into the soils except from the deposition of sediments by the floods. The straw of sorghum, maize and millets is mostly used for feeding livestock and temporarily for roofing of dwellings. Those farmers who do not own animals sell the straw. Many farmers sell more than 10% of their crop produce to buy some household items. The main reason for not selling grains in some years is because of a poor harvest. Farmers mentioned that shortage of water and pest infestations are the main constraints to crop production in the study area (Table 4.5).

Table 4. 5. Crop production constraints in Sheeb area (n = 53), by order of importance.

Constraints	Contribution
	%
Shortage of water	31
Insect pests	26
Lack of capital	15
Marketing	14
Lack of agricultural inputs	14
Total	100

Source: Field survey 1998.

In 1997/98 production year, the average prices of sorghum and maize lied between 2.60 to 2.70 nakfa per kg before harvesting. After harvest, the prices of these crops dropped to 1.20 to 1.35 nakfa per kg as the supply exceeded the local demand, which is usual. Most of the farmers sell their crop produce immediately after harvest. However, a few well-to-do farmers sell their produce later when prices are higher and therefore they earn up to 1.40 nakfa per kg more. About 62% of the farmers interviewed mentioned that low prices, absence of markets, and the inability to settle debts are the major constraints faced in marketing their agricultural products. Virtually, the farmers do not save money and also no seeds at times of poor harvest.

Almost 53% of the interviewed farmers do not have access to credit facilities. The remaining 47% get credit from friends, relatives and local money lenders. The main purpose of taking credit is to adjust food shortages and to buy seeds and draft animals. They repay the credit in the form of grain or in cash. Many farmers mentioned that they encounter serious cash deficits during the months of May to September when most of the people migrate to the highlands. Lack of agricultural inputs (such as improved seeds, draught animals, chemicals and farm implements) are also constraints to crop production which are caused by a lack of capital and non-availability in the case of improved seeds.

Livestock production

Livestock is one of the integral components of the farm household spate irrigation production system in the Sheeb area. The dominant types of livestock are oxen, cows, camels, goats, sheep, donkeys and chickens. The oxen are used for the construction of the irrigation structures and for tilling the land. The cows, goats, sheep and chickens are a source of food and income for the household. The camels and donkeys are used to transport the crop produce and crop residues to homesteads or markets and also for transporting people. In addition, donkeys are the primary means of transport for fetching water.

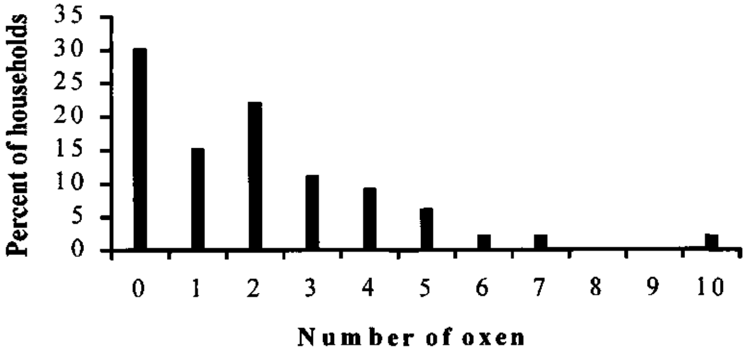


Figure 4.3. Distribution of oxen among the 53 households in Sheeb area. (Source: field survey 1998)

The household survey revealed that about 92% of the farmers own animals. Most of them possess a small number of animals and only a few farmers have more than ten animals. However, nearly 30% of the farmers do not own oxen (Figure 4.3). These farmers rent or share oxen with their relatives or friends to plough their fields and to construct and repair the field bunds. A pair of oxen and an operator can be hired for 42 nakfa (about US $6) per day to plough the fields and to repair the bunds. The main reasons for not owning oxen are the high mortality rate during the liberation war, and the lack of capital. According to Daniel (1997), the total livestock population in the five villages (excluding village Sheebkhetin) was 5,519 goats; 1,875 cattle; 1,168 sheep; 1,007 oxen; 813 donkeys; 803 chickens and 375 camels.

The livestock products are mainly milk, butter, meat and eggs that often serve as a buffer against low crop yields during the years of drought. Milk, butter and eggs are sold at any time of the year but live animals are sold mostly during the dry season from May to September. The main reasons for selling animals are to repay loans and to buy food items. In Sheeb area, there is no grazing land allocated for livestock. Livestock is tethered and fed by a cut-and-carry feeding system on green matter during the cropping season and on dry straw during the dry season. Crop residues such as sorghum and maize stalks are the major feed items.

The spate irrigation farmers encounter a critical shortage of feed and drinking water during the months of May to September. During this period, most of the farmers (83%) have adopted a risk coping strategy i.e. to migrate to the highland areas of Eritrea where they can get grass and water. Those who remain in the lowland feed their livestock with crop residues stored since the previous season or purchase some fodder from the market. Introducing agroforestry in the spate irrigation system such as growing leguminous trees (that are adaptable to the Sheeb area) along the field bunds or planting forage plants in the wadi courses could alleviate the shortage of livestock feed (Chapter 7).

Table 4.6. Constraints to livestock production according to the farmers (n = 53), by order of importance.

Constraints	Contribution
	%
Lack of feed	30
Diseases	20
Drought	19
Lack of grazing land	16
Shortage of water	10
Lack of capital	5
Total	100

Source: Field survey 1998.

Next to animal feed, diseases form the second major constraint to livestock production in the Sheeb area (Table 4.6). The common diseases found in the area are locally called 'chincha' (Trypanosomes), 'anisa' (foot and mouth), 'lalishe' (heart water) and 'abek' (pox). The main control measure for the above diseases is vaccinating the animals in veterinary centres. Most farmers (69%) vaccinate their animals annually, but for 31% the vaccination centre is too far from their villages. Drought periods form the third most important constraint to livestock production in the Sheeb area (Table 4.6).

4.3.3 Food security issues

Food security in its most basic form is defined as the access of all people to the food needed for a healthy life at all times (FAO and WHO 1992). The staple food crops in Sheeb area are sorghum, maize and pearl millet. The people eat often a type of pan-cake locally called 'kicha' with milk during breakfast. At lunch and dinner, almost all people eat porridge made of sorghum or maize flour or traditional foods locally called 'tendur' and 'injera' (sometimes) with sauce. The local people consume much grain but not much meat and vegetables, which means that they get enough carbohydrates but probably not enough proteins and vitamins. On average, each person in Sheeb area consumes about 156 kg of grains per year or 13 kg of grains per month, which is close to the World Bank (1994) estimate of 160 kg per year. The per capita food consumption is even less in large families, which is probably associated with the communal eating habit. Both men and women consume frequently much coffee and tea with much sugar.

Table 4.7. Estimates of cereal food production and requirements in Sheeb area versus national level.

Food production/requirement	Unit	Sheeb area		National level
		1996/97†	1997/98‡	1997/98§
Food production	Tonnes	2,246	6,700	472,193
Food requirements	Tonnes	2,740	2,934	560,000
Deficit/surplus	Tonnes	– 494	+3,766	-87,807
Food production as % of food requirements	%	82	228	84

Source: Field survey 1998
† Bad year with estimated population = 17,564 and irrigated area = 2,246 ha
‡ Good year with estimated population = 18,810 and irrigated area = 2,680 ha
§ Good year, Ministry of Agriculture annual report (2000).

Table 4.7 gives the estimated food production and food requirements in Sheeb area and compares it with the national level. In 1996/97, the food production was lower than the basic food requirements of the population. As a result, there was food insecurity in Sheeb area, which was mainly caused by insufficient floods. Indeed, 90% of the farmers evaluated the 1996/97 production season as a bad year. During this year of food deficit, the Sheeb area still produced 82% of its food requirements. Whereas in 1997/98, the food production was better than in 1996/97 because of a high number of floods. The production was then enough to feed the inhabitants of Sheeb area and to provide a surplus to other parts of Eritrea where there was a food deficit. At national level, even in a good harvest year, a food deficit of about 87,807 tonnes of cereals was shown in the country (Table 4.7). This implies that food security remains a major threat to the economic development of Eritrea. Therefore, intensification of agriculture in the potential crop production zones (such as the spate-irrigated areas, currently estimated at 14,000 ha by Tesfai and Stroosnijder, 2000) could contribute much to the country's food requirements.

Most farmers mentioned that during very bad years their crop production could satisfy food consumption for not more than 3 months but during good years it is enough for the whole year. In an average year, less than 40% of the households produce enough food for the whole year. In other words, many of the people in Sheeb area are threatened by food insufficiency and food insecurity. To combat these food shortages, the Sheeb farmers have developed a livelihood strategy of seasonal migration to the highlands of Eritrea where they eat cactus fruits as food supplements and some farmers cultivate small farmland inherited from their forefathers.

4.3.4 Crop budget analysis

In this and the following two sections, a typical farm household budget is drawn up for 1 ha spate irrigated farm including the crop and livestock yields and the cost of production during bad year (1996/97) and a good year (1997/98). Subsequently, the household farm income and expenditures are calculated and the balance budget sheets are shown.

The possibility of harvesting two times, sometimes even three times, from a single sorghum plant within a year is one of the benefits of the spate irrigation production system. Crop budget analysis was calculated for the sorghum main crop and ratoon crop separately because the main crop produced ratoons during the 1997/98 good year.

Table 4.8 shows a budget analysis for a 1 ha spate irrigated sorghum main crop during a bad year (1996/97) and good year (1997/98). According to the table, the crop production value was greater than the cost of production and thus a net return of about 1,000 nakfa (about US $139) per ha was obtained in 1997/98. This was attributed due to the good rains in the nearby highlands which resulted to good flood season in the Sheeb area. During this time of the year, most of the spate-irrigated fields were flooded 3 to 4 times and the residual moisture was enough to produce ratoon crops. Whereas in 1996/97, the production value was lower almost by 33% and the net return per ha was almost three times lower than that of 1997/98 due to shortage of floods. In spate irrigation system, the cost of production is similar in bad or good years because a large proportion of the labour and animal power costs (for repairing the irrigation structures and ploughing) are already incurred before flooding of fields.

Table 4.8. Crop budget analysis for sorghum crop at 1 ha spate-irrigated field, 1996/97-1997/98 (n= 53).

		Quantity per ha.		Total value (nakfa)	
Input/output	Price (nakfa)	1996/97	1997/98	1996/97	1997/98
Output (mean)					
Grain yield (kg)	1.20	1,000	1,500	1,200	1,800
Straw yield (kg)	0.17	1,000	1,500	170	255
Subtotal outputs	-	2,000	3,000	1,370	2,055
Inputs (mean)					
Material cost † (nakfa)	-	-		75	75
Labour cost (mandays)					
Repairing irr. structures	12.00	15	15	180	180
Ploughing	12.00	4	4	48	48
Flooding	12.00	2	4	24	48
Planting	12.00	5	5	60	60
Harvesting & threshing	12.00	8	12	96	144
Animal power cost ‡ (nakfa)	-	-	-	500	500
Subtotal inputs (nakfa)	-	-	-	983	1,055
Gross margin per ha (nakfa)	-	-		387	1,000
Net return per ha (nakfa)	-	-		387	1,000
Net return man-d^{-1} § (nakfa)	-	-		12	18
Input/output ratio	-	-		0.72	0.51

Source: Field survey 1998.

† It includes costs of seeds and pesticide chemicals.

‡ The draft animal power cost includes: repairing of 'agims', 'misghas' and bunds, ploughing and transporting the produce.

§ Average annual working hours = 6

In 1997/98, the production costs of the ratoon crop (including material, labour and power costs) were much lower than that of the main crop. For example, in the case of labour cost, a total of 40 man-days were involved in the production of the main crop but only 18 man-days were needed for the ratoon crop since this does not needs tillage and sowing activities anymore. Hence, the net return per ha was higher in the ratoon crop than in the main crop. Moreover, the net return per mandays was almost two times greater in the ratoon crop than in the main sorghum crop (Table 4.8).

In 1996/97, most of the spate irrigated fields were insufficiently irrigated as a result of shortage of rainfall in the highlands of Eritrea, and thus no ratoon crop production occurred. Normally, a spate-irrigated field should be flooded (to the brim of the bunds height i.e. about 0.5 m) at least three to four times to produce ratoon crops.

Table 4. 9. Crop budget analysis for sorghum ratoon crop at 1 ha spate irrigated field, 1997/98 (n = 53).

Input/output	Quantity per ha.	Price (nakfa)	Total value (nakfa)
Output (mean)			
Grain yield (kg)	1,000	1.80	1,800
Straw yield (kg)	800	0.14	112
Subtotal outputs	1,800	-	1,912
Inputs (mean)			
Material cost † (nakfa)	-	-	38
Labour cost (mandays ‡)			
Harvesting	8	12.00	96
Threshing	10	12.00	120
Animal power cost § (nakfa)	-	-	97
Subtotal inputs (nakfa)	-	-	351
Gross margin per ha (nakfa)	-	-	1,561
Net return per ha (nakfa)	-	-	1,561
Net return per man-days (nakfa)	-	-	33
Input/output ratio	-	-	0.18

Source: Field survey 1998.

† It includes costs of pesticide chemicals.

‡ The mandays = 4 working hours due to the harsh climate (hot temperature and dust storms) prevailing at harvesting and threshing (April)

§ The draft animal power cost include transporting the produce.

In a good year such as 1997/98, a typical household in Sheeb area has earned a total of nakfa 2,561 (about US $355) from the main crop sorghum plus from the ratoon crop production. This positive balance was largely contributed (61%) by the production of ratoon crops which is accounted as a double bonus. Moreover, the overall cost of labour invested in sorghum production was small because normally cultivation and weeding are not practised in sorghum fields and no tillage and sowing is undertaken in the case of ratoon crops. The total production values in sorghum main crop and ratoon crops were more or less similar despite the yield difference between the two crops. This may be explained by the fact that the price of grain sorghum was high at the time of ratoon harvest.

4.3.5 Livestock budget analysis

The main livestock products (milk, butter, meat and eggs) are used for subsistence and are mostly consumed by the members of the household. For the livestock budget analysis in Table 4.10, the livestock production and its costs are considered for a household with a 'typical' number of livestock: 2 cows/oxen, 2 goats, 1 sheep, 1 donkey, and 1 chicken. Although budget analysis is usually worked out for one type of animal, here the budget is calculated together for a livestock unit.

In both years (1996/97 and 1997/98) the cost of production was less than the production value obtained (Table 4.10). However, the production value in 1997/98 (good year) was more than twice as high as that of 1996/97 (bad year) probably because the quality of livestock feed and the health of livestock was better off. During bad years, most of the animals are easily susceptible to diseases and thus farmers expense on veterinary drugs increases.

Table 4.10. Livestock budget analysis in Sheeb spate irrigation area, 1996/97 and 1997/98 (n = 53).

		Quantity per household †		Total value(nakfa)	
Input/output	Price(nakfa)	1996/97	1997/98	1996/97	1997/98
Output (mean)					
Milk yield (liter)	2.00	312	625.0	624	1,250
Butter yield (kg)	30.00	9	18.0	270	540
Eggs yield (number)	0.25	65	130.0	16	32
Live animal (number)	100.00	-	1	-	100
Subtotal outputs (nakfa)				910	1,922
Inputs (mean)					
Materials ‡ (nakfa)	-	-	-	500	344
Labour cost § (hours)					
Feeding	1.50	160	160	240	240
Milking	1.50	52	104	78	156
Subtotal inputs (nakfa)				818	740
Gross margin per unit (nakfa)	-	-	-	92	1,182
Net return per unit (nakfa)	-	-	-	92	1,182
Net return per man d^{-1}(nakfa)	-	-		8	24
Input/output ratio		-	-	0.90	0.38

Source: Field survey 1998.

† Average household possesses about 2 cattle (cow and /or oxen), 2 goats, 1 sheep, 1 donkey and 1 chicken.

‡ The material cost includes fodder and veterinary drugs.

§ The labour cost includes the family labour used for feeding and milking. Herding is insignificant because the animals are tethered in a place called locally 'zeriba'.

¶ Average annual working hours = 6

In 1997/98 good year, the input/output ratios were 0.51 in the main crop, 0.18 in the ratoon crop and 0.38 in the livestock production, implying that the income from the farm was enough to cover the cost of production on crops and livestock. During this year, the net return per man-day in crop and livestock productions were above the local wage rate (12 'nakfa') because demand for labour rise up. Conversely, in bad year (1996/97) the net return per man-day was below the wage rate in the case of livestock production and lower than recorded in a good year in crop production. This is maybe attributed due to a low production, which consequently slows down the labour activity in the area.

4.3.6 Whole farm analysis

Table 4.11 compares the average income and expenditures of a typical farm household in Sheeb area during a good year 1997/98 versus a bad year 1996/97. The average household income was estimated looking at the two main sources of farm household incomes i.e. crop production and livestock production. Off farm income was not included because only a small number of farmers (16%) are engaged in off-farm work such as trading, handicrafts and services. Nearly 84% of the household income depends solely on crop and livestock productions.

Table 4.11. Estimated income & expenditures of a typical farm household in Sheeb area (n = 53).

Summary	1996/97 †		1997/98		Average	
	(nakfa)	(%)	(nakfa)	(%)	nakfa	(%)
Income						
Crop gross margin	671	88	2,561	68	1,616	72
Livestock gross margin	92	12	1,182	32	637	28
Total net farm income	**763**	100	**3,743**	100	**2,253**	100
Expenditures						
Food items	ns	-	4,233	84	ns	-
Household essentials & services	ns	-	791	16	ns	-
Total expenditures	**1,888**	-	**5,024**	100	**3,456**	-
Balance	**– 1125**	-	**– 1,281**	-	**–1,203**	-
Balance as % of total income	–147	-	–34	-	–53	-
Expenditure/ income ratio	2.5	-	1.3	-	1.5	-

Source: Field survey 1998.
ns: not specified.
† During this time of the year, most of the people of Sheeb depend on food aid.

In 1997/98, the income from crop production contributed the greater percentage (68%) to the total household income and the remaining 32% were derived from livestock production. The total household income amounted to 3,743 'nakfa' (about US $520) per year. With an average family size of 6 persons in the Sheeb area, the family earnings were about US $86 per person a year, which is below the poverty line suggested by the World Bank (1990). The total household income refers to the majority of Sheeb farmers, since few well-to-do farmers could earn more than the amount shown in Table 4.11.

In 1996/97 the income and expenditures balance was even worst, and showed a negative balance of about 147%. However, during such year, the farm household took risk diffusion measures such as reducing expenditures. Although most of the people depend on food aid, expenses on luxurious food items (such as tobacco, beverages, etc.) are reduced. Other household services (like repairing houses, weddings, etc.) are postponed.

Like any other consumer, the farmer buys some essential items from the market, which he can not produce, or only produces, in small quantities. These are food items including cereals, meat, coffee, tea, sugar, salt, edible oil, etc. The farmer also spends money on household essentials and services such as household utensils, clothes, education, medication, repairing temporary houses ('agnet') and so forth.

In surveys, farmers often exaggerate expenditures and under estimate their income. The average total household expenditure was 53% higher than the household income (Table 4.11). Thus, a negative balance was shown in the farm household budget analysis. However, it is worthwhile to mention that this does not mean that all households have experienced such a balance of income and expenditures. The balance sheet refers to the majority of Sheeb farmers.

The household analysis also showed that (during a good year) a large percentage (84%) of the farmers' expenses were spent on the purchase of food items including coffee, sugar, edible oil, butter, etc., which are not at all or not much produced in the area. This is may be explained by the fact that the type of food style adopted in the area requires much oily ingredients and cereals grain, for example when preparing the traditional food 'tendur'. In a recent farm survey, Natarajan (1999) reported that the Sheeb community gives an impression of being less thrifty and probably living beyond their means in terms of commodities they buy, such as clothing, coffee, and sugar.

4.4 Conclusions

The household survey of spate irrigation system in Sheeb area has quantified the farm household resources (human, land, water, crops, livestock, farm tools and farm houses) and described how the small farmers tackle the production problems. At last, the survey has also analysed the inputs and outputs of crop and livestock production during a bad year as well as good year and calculated the average household income and expenditures.

The standard of living of the majority of farmers in Sheeb area is low and their income depends solely on crop and livestock productions. For many households the income was lower than their expenditures, resulting in a negative balance on their farm budget. This was largely due to high expenses incurred on food items (coffee, sugar, edible oil, butter, etc.) which are not produced or not much produced locally and also to a lack of off farm employment opportunities. It would be appropriate, therefore, to advise poor households with a negative balance to reduce their expenses on items not produced in the region.

Alternatively, the farmers could apply organic fertilisers (e.g. manure, where possible and crop residues) and practise weeding, thinning and introducing intercropping and crop rotations in the cropping system to increase their farm productivity. Growing leguminous trees (that are adaptable to the Sheeb area) along the field bunds or planting forage plants in the wadi courses could alleviate the shortage of livestock feed (Chapter 7). Moreover, the local government and other development agencies should assist the farmers to construct permanent flood diversion structures to divert the floods efficiently and also to generate off farm employment opportunities to the small famers in Sheeb area.

In general, it can be concluded that the contribution of the small farm households to spate irrigation development and food security in the Sheeb area is great and to Eritrea at large is not small at times of good flood season (Table 4.7). The spate irrigation production system is 'cost effective' if the irrigation structures are properly maintained at low cost and if the irrigated fields receive enough water and nutrients (Tables 4.8, 4.9 and 4.10).

Acknowledgements

The author acknowledges the financial support by the Netherlands Universities Foundation For International Co-operation (NUFFIC). Special thanks are extended to the Sheeb community in general and to the respondent farmers and enumerators in particular. The author also thanks to Jan de Graaff for his constructive comments and suggestions on the manuscript.

4.5 References

Bereket Araya and John Asefu Adjaye, 1999. Returns to farm level soil conservation on tropical steep slopes: The case of the Eritrean highlands. Journal of agricultural economics, Vol. 50, no.3, 589-605.

Daniel, A.M., 1997. A preliminary report on a pre-project Sheeb-Wadi Labka socio-economic study: A strategy for rural development, Vol. 1(a) and (b). MoA, Asmara, Eritrea 185 pp.

Dillon, J., and Hardaker, J.B., 1993. "Farm management research for small farmer development'. Farm systems management series 6, 291 pp.

FAO and WHO, 1992. Protecting consumers through improved food quality and safety. In: ICN, major issues for nutrition strategies, FAO and WHO, theme paper no. 2. Rome, Italy.

FAO. 1997. Production year book, Vol. 51. FAO statistics series No. 142. FAO, Rome, 239 pp.

Halcrow, W., 1997. Inception report, Eastern lowlands wadi development project. MoA, Asmara, Eritrea, 50 pp.

Huijsman, A., 1986. Choice and uncertainty in a semi-subsistence economy: A study of decision making in a Philippine village, Ph.D. thesis. WAU, The Netherlands, pp. 71-118.

IFAD, 1995. Appraisal report on Eastern lowlands of wadi development project. Asmara, Eritrea, 52 pp.

Lawrence, P., 1996. Sediment management, ELWDP, working paper No.2. Asmara, Eritrea pp.1-10.

Ministry of local government of Eritrea, 1998. Annual report. Asmara, Eritrea.

Ministry of agriculture of Eritrea, 2000. Annual report. Asmara, Eritrea.

Natarajan, M., 1999. Report on production and farming systems agronomy; strengthening the agricultural research and extension in Eritrea, GCP/ERI/001/ITA. FAO branch, Asmara, Eritrea, 50 pp.

Norman, D.W., Worman, F. D., Siebert, J. D. and Modiagotia, E.,1995. Farming systems approach to development and appropriate technology generation. FAO, farm systems management series, no.10. Rome, Italy, pp.91-207.

Shaner, W.W., Philipp, P.F. and Schmeal, W.R., 1982. Farming systems research and development: Guidelines for developing countries. In: Norman, D.W., Worman, F. D., Siebert, J. D. and Modiagotia, E.,1995. Farming systems approach to development and appropriate technology generation. FAO, farm systems management series, no.10. Rome, pp.111-117.

Tesfai, M. and de Graaff J., 2000. Participatory rural appraisal of spate irrigation system in eastern Eritrea. Journal of agriculture and human values. (In Press).

Tesfai, M and Stroosnijder L., 2000. The Eritrean spate irrigation system. Agricultural water management. (In Press).

World Bank, 1990. World development report. Oxford University press, pp. 24-38.

World Bank report, 1994. Eritrea, options and strategies for growth: Vol II, report no.12930 ER. Eritrea, Washington D.C., USA, pp.59-89.

Chapter 5

Soil Resources of Spate Irrigation Schemes

Abstract

The aim of this study was basically to characterise the soils found in spate irrigation schemes at Sheeb area in eastern lowlands of Eritrea. Soil descriptions and soil analyses were conducted in the field and in the laboratory, respectively. The dominant factors that influence the formation of soils in the Sheeb area were the effects of human activities, the floods and the kind of parent material. The major types of soil in the study area were Fluvisols (spate-irrigated soils) and Arenosols (non-irrigated soils). About 4,550 ha of land was covered by Fluvisols and 3,450 ha of land by Arenosols. In general, the Fluvisols vary both in physical and chemical characteristics from the Arenosols. The Fluvisols had good water holding capacity (414 mm m^{-1} depth) and the average basic infiltration rates of the soils were 3.9 cm h^{-1} and the saturated hydraulic conductivity was 0.58 m d^{-1}, which are moderate and suitable for spate irrigation. The Fluvisols were low in total nitrogen (0.013%) and organic matter contents (0.9%) but were high in available phosphorus (18 mg kg^{-1}) and moderately high in available potassium (164 mg kg^{-1}) in the topsoils and lower in the subsoils. Except for currently non-irrigated soils, the soils were also non-saline because of flooding which leaches the soluble salts in the soil profile. On the other hand, the Arenosols showed salinity in the topsoils and were very low in physical and chemical fertility except for phosphorus (12 mg kg^{-1}) and potassium (285 mg kg^{-1}).

5.1 Introduction

Soil is one of the most important natural resources in a country like Eritrea where agriculture forms the main source of income and employment for the vast majority of the population (70-80%). Nonetheless, there is very limited information available so far on the nature and properties of the soils of Eritrea in general and in spate-irrigated areas of the country in particular. Spate irrigation is a pre-planting irrigation system that makes use of flash floods (from highlands of Eritrea) which are diverted by structures to irrigate fields in the lowlands. During the rainy season in the highlands of Eritrea, floods are produced in the form of runoff that are transported by seasonal rivers (wadis) which flow towards the lowland parts of the country such as the Sheeb spate irrigation area. The runoff with its sediments and nutrients is diverted to the nearby irrigable fields by means of temporary irrigation structures locally called 'agims', and conveyed by distribution canals called 'misghas'. Eventually, the runoff is collected in the fields that are surrounded by earthen bunds. The water infiltrates into the deep soils while the sediments and nutrients are deposited on the soil surface. Crop production is sustained on residual soil moisture under this irrigation system.

According to IFAD (1995), in parts of Sheeb area, it was thought possible to develop an area of shallow and stony soils into suitable spate soils (in a few years) by simply passing spate flows over the land. However, the proposed development appeared to be unviable. Because, with an estimated increment of sediment thickness layer i.e. 0.03 m per year (IFAD 1995), it will take about 70 years to develop a soil profile with 2 m depth that could store enough water and nutrients for crops to grow under spate irrigation. In order to avoid such failures in development, soil investigations through soil surveys are very essential to identify the suitable soils for spate irrigation system. FAO (1979) has also strongly recommended a systematic soil survey that distinguish and characterize soils in terms of all important surface and subsurface characteristics should form part of any irrigation studies.

Hence, a soil survey was carried out in the Sheeb area at spate irrigation schemes of wadi Laba and Mai-ule to find answers for the following set of research questions:

1) Which soil forming factors play a significant role in the formation of the Sheeb soils?
2) What are the characteristics of the soils; what types of soils are found in Sheeb area and how much is the area coverage by each soil types? and
3) What are the main problems of the soils of Sheeb area?

It is believed that, this study would (1) contribute towards the understanding of the genesis and characteristics of the soils suitable for spate irrigation, (2) recommend possible soil management practises in spate irrigation system, (3) provide basic soil physical and chemical data for the subsequent studies on sedimentation rate, nutrient balance, water balance and land suitability evaluation in this thesis and last but not least (3) the findings from this study will serve as a soil reference for spate irrigation areas in Eritrea.

5.2 Methods and techniques

5.2.1 Field survey

A systematic detailed soil survey of Sheeb area (10 km^2) in the eastern lowlands of Eritrea was carried out on a scale of 1:10,000 from July 1997 until April 1998. Prior to conducting the field work, all available information regarding the environment of the Sheeb area and materials such as aerial photographs, orthophotomaps, topographic maps and other related-maps covering the area were collected, compiled and studied.

Accordingly, five orthophotomaps and five topographic maps (Sheeb 540-535, Sheeb 496-530, Sheeb 504-525, Sheeb 504-530 and Sheeb 496-525 on a scale of 1:10,000) were acquired from the Easter Lowlands Wadi Development Project (ELWDP) of the Ministry of Agriculture (MoA) in Eritrea. The maps were produced from aerial photographs flown in March 1997 by Maps Geo-systems, United Arab Emirates with contours spaced at 1 m vertical intervals. Land features such as land forms, rock-out crops, eroded fields; water features like wadis, irrigation structures ('agims', 'misghas' and field bunds), and land use types (irrigated and non-irrigated lands) were identified and delineated on the photomaps.

Preliminary soil mapping units were defined based on the recorded features and the interpretations were transferred to a base map. A base map of Sheeb area on a scale of 1:10,000 was produced from the orthophotomaps and topographic maps. Field traverses were made across the wadi Laba and Mai-Ule spate irrigation schemes to verify the boundaries of the mapping units on the base map and to select sampling sites for soil descriptions and soil analysis. Profile pits and auger hole sites were selected and their positions were located on the UTM (Universal Transverse Mercator) grid using the Global Positioning System (GPS-Magellan 4000). Afterwards, the locations of the pits and auger holes were transferred to the base map.

Because of a uniform flat terrain and a great homogeneity of the soils, the observations were made at an overall density of 1 per 400 ha of land. In total, 15 profile pits and a few auger holes were dug and prepared for descriptions and analysis of soils. The dimensions of the soil pits were 2 meter deep and 1.5 meter long. Exposed sites such as wadi banks and gully walls were also used to study the morphology of spate irrigated soils.

The soils were described according to the international standards laid down by FAO: Guidelines for soil profile descriptions (FAO 1990). General information on the characteristics of the profile sites as well as information related to the identification and soil horizon descriptions was recorded on standard soil description forms conform to the FAO-ISRIC (1989) soil coding sheet.

Some soil properties were determined in the field, e.g. soil texture by feeling method and soil colour by comparison with Munsell soil color charts (Munsell 1994). The calcium carbonate contents of soils were tested by adding 10% diluted HCl to the soil material. A total of 35 soil samples were collected from all profiles and augerings from topsoils and subsoils depth for laboratory analysis. The samples were sent to the soil science research laboratory of the MoA for further soil physical and chemical analysis so as to complement the field observations.

5.2.2 Laboratory analysis

Before analysis, the soil samples were air-dried, crushed in a porcelain mortar and passed through a 2 mm sieve. The method of analysis used for each of the determined soil properties is described in Table 5.1.

Table 5.1. Soil physical and chemical analysis methods used in this study. †

Soil property	Method of analyses
Particle size analysis (φ)	Bouyoucos Hydrometer
Soil texture (class)	USDA textural triangle
Bulk density of soils (g cm^{-3})	Core method
Moisture content at field capacity (%)	Gravemetric method
Infiltration rate (cm h^{-1})	Double ring infiltrometer
Saturated hydraulic conductivity (m d^{-1})	Inverse auger hole method
Soil reaction, pH (H_2O)	pH meter, soil: water (1:2.5)
Electrical conductivity (d S m^{-1})	EC meter, soil: water (1:5)
Organic carbon (%)	Walkey-Black titration with ferrous ammonium sulphate
Total Nitrogen (%)	Macro Kjeldahl digestion
Available P (mg kg^{-1})	Olsen's method by 0.5M sodium bicarbonate extraction
Available K^+ (mg kg^{-1})	Flame emission Photometer
Exchangeable Na^+ (meq $100g^{-1}$)	Flame emission Photometer
Exchangeable cations of Ca^{2+} and Mg^{2+}(meq $100g^{-1}$)	EDTA titration of 1M ammonium acetate extract (NH_4OAC)
Cation exchange capacity (meq $100g^{-1}$)	Flame emission Photometer of 1M sodium acetate trihydrated extract

† (Klute 1986; John, et al. 1996)

5.2.3 Soil classification and mapping

The soils of the Sheeb area were classified on the basis of their morphological, physical and chemical properties using the FAO/Unesco (1988) soil classification system. Some of these properties were observed or estimated in the field while others depend on the results of laboratory analysis. The soils were also correlated to USDA soil taxonomic system (USDA 1985).

Soil mapping units (SMUs)

A soil-mapping unit is a soil unit delineated on the soil map indicated by a certain mapping symbol (Figure 5.1). The boundaries of each SMUs (identified in this study) were digitised using a digitizer. Geo-reference data (UTM co-ordinates) were entered into the database of Geographic Information System (GIS) of ARC/INFO program. Then, all attributes data were processed and analysed by ARC/View GIS-version 3.1. Finally a digital soil map of Sheeb area was produced on a scale of 1:10,000 (see Map 5.1). The soil mapping units are classified and designated according to the revised FAO-Unseco (1988) map legend. Since the study area has relatively homogenous topography, slope classes have not been considered in the map legend. The elements of the legend used are major soil groups, soil units, soil sub-units and soil textural classes.

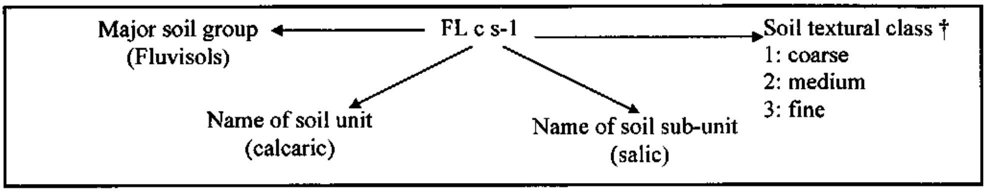


Figure 5.1. Explanation of the soil mapping unit symbols used in this study.

† Coarse texture: < 15% clay and > 65% sand; medium texture: < 35% clay and < 70% sand and fine texture: > 35% clay (Landon 1991).

The major soil group is mentioned first, followed by the soil unit and sub-unit. The textural class figure follows the soil sub-unit symbol, separated from it by a dash. It refers to the texture of the upper 0.25 m of the soil, which is important for tillage and water retention (FAO/Unesco 1988).

In this paper, the term upstream, midstream and downstream is defined on the basis of proximity of the fields to the diversion sites of the wadis Laba and Mai-ule. Thus, upstream fields are located near (in the range of 0.2 to 2 km) the flood diversion sites of the wadis. While, downstream fields are found at approximately 5 to 8 km from the diversion sites and the midstream fields are in between these two. The term topsoil in this paper refers to the top 0.25 m depth (the plough layer) and the subsoil is that part of the soil profile below the topsoil.

5.3 Soils of the Sheeb area

5.3.1 Soil formation factors (SFFs)

The physical and socio-economic settings of the Sheeb area have already been described in Chapters 2 through 4 of this thesis. However, some of the physical settings are described here as factors of soil formation.

Studies of soils throughout the world have shown that, soil formation processes are largely determined by six major SFFs (Brady 1990). These are human activity, climate, parent material, vegetation, relief and relative time. The soils of Sheeb area are a function of these interdependent factors.

Human activity

The influence of man on soil formation in the Sheeb area is evident from the following activities. For over 100 years, the Sheeb farmers have harvested floodwater, sediments and nutrients in their fields by constructing flood diversion structures ('agims') at the head of the main wadis Laba and Maiule, which divert the floods to nearby irrigable fields. The diverted floodwater is conveyed by canals ('misghas') to the series of fields that are surrounded by bunds made of earthen material. The water infiltrates into the deep soils and at the same time the sediments and nutrients are deposited on the soil surface. In such a way, the local farmers have developed irrigable soils whereby crop production could be realised under residual soil moisture on originally dry sandy soils. Therefore, human activities have changed the land use in the study area (i.e. from non-irrigated land into irrigable land).

Climate

The climate of Sheeb area is arid (annual rainfall < 200 mm) and hot (mean annual temperature 25-36°C), which limits weathering processes in the soils. Out of the elements of climate, the floodwater plays an important role in the processes of transportation and deposition of soils. Annually, the topsoils are eroded from different areas of the Sheeb catchment; transported by the wadis and deposited on the irrigated lands of Sheeb area. Thus, the irrigated lands have developed very deep soils (often >3 m) with irregular compositions of textures and nutrients. On the other hand, when big floods breach the diversion structures, the wadis change their courses and erode the agricultural fields thereby forming gullies particularly in downstream areas of Sheeb.

The other climatic factor is wind, which creates heavy dust storms (locally called 'khamsin') during the summer months (July-September) when the temperature is very hot (40-45°C) and when the soils are bare of crops. These dust storms deposit very fine sands eastwards and create sand dunes in the non-irrigated lands of the study area.

Parent material

The Sheeb irrigated soils are developed on alluvial parent materials derived from Precambrain basement complex of the highlands catchments which consists of chlorite schist and granite intrusions (Halcrow 1997). These parent materials have been transported (from the highland catchments by wadis Laba and Maiule) to the Sheeb spate irrigation area. Since the soils in the spate irrigated fields are transported and deposited by water, they are generally classified as alluvial soils. Whereas, the original soils of Sheeb area (i.e. the non-irrigated soils) are developed in the weathering products of parent rock, which are broadly classified as residual (in-situ) soils.

The surface geology of the Sheeb area consists of Quaternary to recent alluvial sediments and aeolian sands with tertiary evaporites, shales, sandstones and limestones (NRCE 1996).

Vegetation

The Sheeb area is characterised as semi desert, almost devoid of natural vegetation except a few scattered thorny scrubs found on the nearby hills and few Tamarix tree species along the wadi courses. Therefore, the impact of vegetation (in the Sheeb area) on the formation of soils is small. But, the vegetation in the highland catchments could have a greater influence on soil formation in the Sheeb area. For instance, the river basin of Laba is partly found in the sub-humid ecoclimatic zone with more disturbed high forests than the Mai-ule basin (FAO 1997). Therefore, soils deposited on the Laba command areas are likely to be higher in organic matter and nitrogen contents than soils deposited by wadi Mai-Ule. In the same way, the source of runoff also determines the type of sediments (soils) to harvest in the Sheeb spate irrigated area. When the runoff is originating from the nearby hills and mountains (which are sparsely covered by vegetation), the soils are poor in nutrients, whereas runoff from the agricultural fields in the highlands (where the land is covered by crops and grasses) consists of organic matter and plant nutrients.

Relief

The topography of the Sheeb area is almost flat to flat alluvial plain. It lies between an altitude of 275 to 165 m (above sea level) in the upstream and downstream site of the wadis, respectively. The average slope gradient is 1-2% downward stretching from the foot of the escarpments in the west across the irrigated fields to the sand dunes in the east. Owing to the uniformity of the topography, the soil types are rather conditioned by the distance from the diversion sites of the wadis Laba and Maiule. For instance, heavier sediment particles settled out near the wadis, and are often deposited in the upstream fields forming coarse sandy soils. While, finer sediments are transported a long distance and are deposited at downstream fields.

Time

As the soil materials are deposited by floodwater regularly, there is not sufficient time for weathering and pedogenetic processes to take place in the soil profile. Soil development and soil horizon differentiation are at their initial stages. Thus, the spate-irrigated soils are young in age and development. Apparently, there is a clear stratification of soil layers with irregular textures and different nutrient contents with depth. Time could function only as a yardstick on soil age. For instance, IFAD (1995) estimated the sediment layer thickness in the spate-irrigated fields' increases with 0.03 m per year. Taking the current average soil depth as 3 m, we could say that the age of spate irrigated soils is not more than 100 years. This crude estimation corresponds to the response made by farmers during the participatory rural appraisal in the Sheeb area (Tesfai and de Graaff 2000).

In general, the human activities in the Sheeb area, the climate (wadis and floodwater), the nature and properties of the parent material (chemical and mineralogical compositions) and vegetation (distribution, type and species composition) in the highland catchments profoundly influence the formation and distributions of soil types in the Sheeb area. But, it is worthwhile to mention here that the formation of soils in the Sheeb area is a product of the interaction of all the six soil-forming factors described earlier.

5.3.2 The soil mapping units (their properties and classification)

The Sheeb area soils are broadly classified into two main soil mapping units. These are soils developed on irrigated lands and non-irrigated lands, designated broadly as SMU-A and SMU-B, respectively (see profile descriptions in Annex B). The soils developed on irrigated lands (SMU-A) are all soils being used for spate irrigation crop production and/or all soils cultivated in the past but not utilised currently. The other groups (SMU-B) are all soils that have never been used for spate irrigation, i.e. the original soils of the Sheeb area.

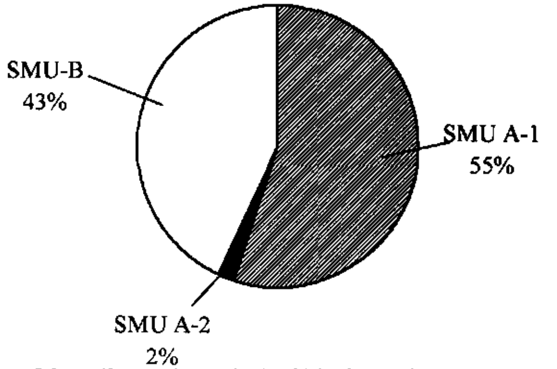


Figure 5.2. Area coverage of the soil mapping units by % in the study area.

The SMU-A soils (spate-irrigated soils)

The soils of map unit-A are found in the upstream, midstream and downstream fields that are irrigated by canals locally called Idi-Abai, Dibret, Erem, Sheebkhetin, Emdenai, Bises, etc. (see Map 6.1, Chapter 6). These are spate-irrigated soils that receive water from the diversion of wadi

Laba and Maiule and two other smaller wadis known as, Harmazo and Gersile. The SMU-A soils cover around 4,550 ha of irrigable land.

The SMU-A soils are developed on the flat alluvial plains through the recurrent deposition of sediments brought by the wadis from the highland areas of Eritrea. One of the diagnostic properties of these soils is that they have fluvial properties, which show a strong stratification of textures within the top 1.25 m of the surface. Soil horizon development is at its initial stage except for the Ap horizon (the plough layer), which is well developed in the arable fields. The time factor has not been sufficient enough to develop soil horizons in these soil units. In other words, they are genetically young soils with little or no horizon development. Hence, the soils have depositional rather than pedogenetic profiles.

In general terms, the soils of SMU-A are characterised as very deep, often deeper than 3 meters with irregular textural compositions, light yellowish brown to brownish and with stratified structures of a weakly platy type. On the basis of the diagnostic properties and chemical characteristics, the soils have been differentiated into two soil units: SMU A-1 and SMU A-2 soils.

a) The SMU A-1 soils (currently spate-irrigated soils)

The SMU A-1 soil unit is the most predominant soil type in the Sheeb area (Photo 5.1).

Photo 5.1. The profiles of a typical spate irrigated soil (SMU A-1) taken from the bank of wadi Laba. Note the parallel lines showing thin laminated layers of sediments. The land use above the profile is a spate-irrigated field.

This soil unit is found in the upstream, midstream and downstream fields. Mapping unit A-1 covers about 4,400 ha irrigable land or 55% of the Sheeb area (Figure 5.2).

Physical properties of the soils

Soil texture and colour

Texture is a basic property of soils, which affects many other soil properties such as infiltration rate, water-holding capacity, fertility, etc. (FAO 1979). The particles size distribution and colour of the soils are presented in Table 5.2. The difference in textural compositions of the soils among the upstream, midstream and downstream fields is very small. Most of mapping unit A-1 soils are silt loams with on average 52% silt and 27% sand and 21% clay (Table 5.2).

The soil colour for most of the studied profiles had similar hue 10YR, high value between 4 to 6 and high chroma 4 in the topsoils. The average colours of the soils are dark yellowish brown (10YR 4/4, moist) and light yellowish brown (10YR 6/4, dry), which clearly indicates that the soils are low in organic matter (OM) content. Usually, the soil colour is a good indicator for fertility and drainage conditions of soils (Landon 1991).

Similar or different types of textures are often deposited at various depths in the soil profile by the floodwater. For example, layers of silt loams were found at 1 m interval in the profile P5 (see Annex C). Particle size sorting with depth often reflects the deposition of sediments of different origin over time. Since the texture of soils is variable with depth and in time in this mapping unit, so are the other soil physical and chemical properties.

Table 5.2. Particle size distribution and colour of topsoils (0-0.25m) in mapping unit A-1.

Profile/auger	Sand	Silt	Clay	Soil texture	Soil colour Munsell	
no. & position		%		class	moist	dry
P1†, ms	32	42	26	loam	10YR 6/4	10YR 6/4
P3, ds	16	59	25	silt loam	10YR 4/4	10YR 6/4
P5, us	9	65	26	silt loam	10YR 5/4	10YR 6/4
P6, us	28	57	15	silt loam	10YR 6/4	10YR 6/4
P7, us	23	66	11	silt loam	2.5YR 3/3	2.5YR 6/4
P8, us	nd	nd	nd	nd	2.5YR 5/2	2.5YR 6/2
P9, us	nd	nd	nd	nd	2.5Y 4/2	2.5Y 6/4
P11, ms	25	53	22	silt loam	10YR 3/2	10YR 5/4
P13, ds	32	43	25	loam	10YR 4/4	2.5Y 6/4
P14, us	16	63	21	silt loam	10YR 4/4	10YR 5/4
P15, ds	32	48	20	loam	10YR 4/3	10YR 6/4
A2‡, ds	55	26	19	sandy loam	nd	10YR 5/4
Mean	27	52	21	silt loam	10YR 4/4	10YR 6/4

†: Profile pit no.
‡: Auger no.
us: upstream, ms: midstream and ds: downstream sites. nd: not determined.

Soil structure

The topsoils of SMU A-1 have weakly developed platy types of structures though tillage and cultivation effects on the soils. The soils does not have well-developed aggregates probably because the recurrent deposition of fresh soil materials by the floodwater. The soils are slightly hard when dry and slightly sticky when wet. The subsoils have weak, moderate fine to medium angular and sub angular structures. Where the soils contain more silt in the upstream sites, they are structureless singled grains. For example, profile pit P7 was collapsed so many times at the time of soil descriptions because of the unstable structure of the soils.

Crusting

Surface crusting in the form of depositional crust (Photo 5.2) was observed during the flood season (July-September) in the spate irrigated fields. Soils found in the downstream fields showed thin to medium crusts (2-5 mm thickness) with hard consistency. The crusts finally develop cracks after the topsoil dries out. In these fields, the average width of the cracks was about 0.1 m, which is wide and the cracks penetrate to a depth of about 0.15 m. Jacobson et al. (2000) have found silt deposit forming cracks more than 0.1 m thick with polygonal plates up to 0.5 m across in alluvial deposited soils by ephemeral rivers in Namib desert.

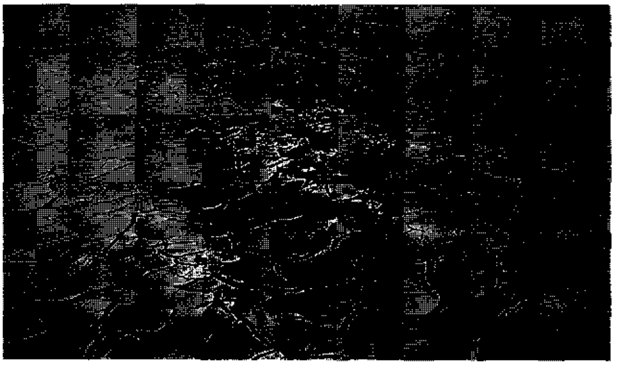


Photo 5.2. Surface crust with cracks in spate irrigated fields of Sheeb area.

The cause for crusting is the deposition of silt on the spate-irrigated fields by sedimentation from the floodwater. In addition, the low organic matter content of the soils (Table 5.6) and the soil surface being left bare of crops (after harvest) exacerbates the problem of crusting. Crusting was also reported in Tihama spate irrigated fields in Yemen as a result of low organic matter and high silt contents (USAID 1983). At the time of sowing, the Sheeb farmers break down the crusts using animal drawn implements while the soils are still moist.

Bulk density and porosity

The bulk density (BD) of the unit A-1 soils was measured with three replications at three different positions (i.e. upper, middle and lower parts) of a spate-irrigated plot in the topsoil and subsoil depth using the core method. The plot was located at midstream fields of Sheeb area. The bulk density of the soils increased with depth in the upper, middle and lower parts of the plot (Figure 5.3). The increase of BD with depth might be associated with lower OM content of the subsoils than that of the topsoils. Landon (1991) also reported that there is very often a tendency for bulk density values to increase with depth, as effects of cultivation and OM content decrease. The mean value of the bulk density of the topsoils was 1.13 g cm^{-3}, which is common for agricultural soils. The total porosity of most of the topsoils was 57% (assuming average value of particle density as 2.65 g cm^{-3}) which indicates that risk of compaction is not likely to occur.

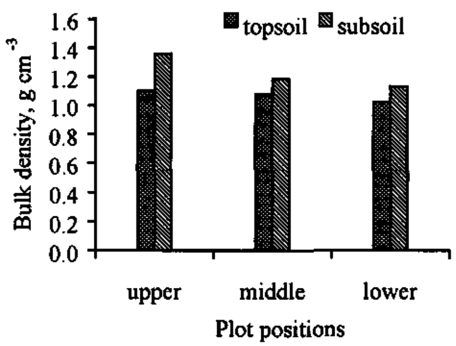


Figure 5.3. Bulk density of mapping unit A-1 soils at three different positions of a plot in Sheeb area.

Drainage and soil moisture

Most of the SMU A-1 soils (in the upstream and midstream fields) showed no signs of mottling in their profile. Thus, the soil profiles drainage class can be categorized as well drained (drainage class 4) with the exception of profiles P5 and P8 which are imperfectly drained (drainage class 2) in the subsoil layers showing mottles in the soil matrix. The profiles (P3, P13, P15) in the downstream fields were also imperfectly drained.

The water content of the spate-irrigated soils at field capacity (FC) was measured in-situ using the gravimetric method. The moisture content (MC) by weight was converted into a volume basis as follows:

$$\text{MC (\% by weight w/w)} \times \text{BD} = \text{MC (\% by volume v/v)} \qquad [1]$$

The mean soil water content at FC was about 414 mm per meter of soil depth (Table 5.3), which indicates that the spate irrigated soils have a high water holding capacity according to Landon (1991) ratings. This is one of the most important soil qualities that enable spate irrigated crops to grow under residual soil moisture.

Table 5.3. Water holding at field capacity (FC) of mapping unit A-1 soils † in Sheeb area.

Soil depth	Upper plot	Middle plot	Lower plot	Mean †	σ	CV
		% v/v				
cm					-	%
0-25	36.83	45.05	38.71	40.20	4.31	10.71
25-50	41.14	42.80	47.19	43.71	3.13	7.15
50-75	35.10	40.72	43.42	39.75	4.24	10.68
75-100	42.05	62.68	21.52	42.08	20.58	48.90
Total (%)	155.12	191.25	150.85	165.74	-	-
Total ($mm\ m^{-1}$)‡	387.8	478.1	377.1	414.35	-	-

† average of three replications.
‡ total ($mm\ m^{-1}$) = total % by v/v × 250 mm
σ: standard deviation, CV: coefficient of variation.

Infiltration and hydraulic conductivity

The infiltration rate of the soils was measured using a double ring infiltrometer with three replications at upper, middle and lower part of a spate irrigated plot. The average basic infiltration rate of the soils was 3.9 $cm\ h^{-1}$, which according to the classification suggested by Landon (1991) is moderate and adequate for spate irrigation. Similar results of infiltration rate (4 $cm\ h^{-1}$) were obtained also on spate irrigated soils in Yemen (UNDP/FAO 1987).

Saturated hydraulic conductivity of the spate-irrigated soils was tested in the field with three replications following the inverse auger hole method also known as the Porchet method. The method consists of boring a hole to a given depth, filling it with water and measuring the rate of fall of the water level (Landon 1991). This method was used because the ground water table in Sheeb area is very deep (often >10 m) both in dry and wet seasons.

The hydraulic conductivity was calculated as follows:

$$k = \frac{1.15 \times r \log[h(t_i) + r/2] - \log[h(t_n) + r/2]}{t_n - t_i} \times 864 \qquad [2]$$

where, k is saturated hydraulic conductivity ($m\ d^{-1}$), r is radius of the auger hole (cm), $h(t_i)$ is the water level in hole at initial time t_i (cm), $h(t_n)$ is the water level in hole at final time t_n (cm) and 864 is used to convert into $m\ d^{-1}$.

The mean k value was 0.58 m per day (Table 5.4), which is a moderate conductivity class according to the classification of Landon (1991). This result corresponds to the value of indicative hydraulic conductivity for silt loams soils.

Table 5.4. Saturated hydraulic conductivity values of mapping unit A-1 soils in Sheeb area.

Plot position	k	
	$cm\ h^{-1}$†	$m\ d^{-1}$
Upper part (replication 1)	2.1	0.50
Middle part(replication 2)	3.2	0.77
Lower part (replication 3)	1.9	0.46
Mean	2.4	0.58

†: k value calculated by equation [2]

Chemical properties of the soils

Soil reaction (pH), salinity and carbonates

The soil reaction (pH), electrical conductivity (EC) values and exchangeable calcium ions (Ca^{2+}) for topsoil and subsoils are given in Table 5.5. The pH of most topsoils was 7.93 and the subsoils was 7.76 which could be classified as slightly alkaline except for profiles P3 and P7 that have a pH 8.1 at a deeper subsoils (1.1 to 1.6 m) and (0.8 to 1.8 m), respectively.

Table 5.5. pH, EC values and exchangeable Ca^{2+} for topsoil and subsoils of mapping unit A-1.

Profile/ auger no.	pH (H_2O) 1:2.5		ECe, † $d\ S\ m^{-1}$		Exchangeable Ca^{2+} meq 100 g^{-1}	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
P1	8.04	7.93	15.3	3.3	17.0	29.8
P3	7.90	8.10	0.8	0.8	30.5	11.0
P5	7.90	7.71	3.2	1.0	33.8	40.4
P6	7.89	nd	2.9	nd	29.4	nd
P7	7.94	8.10	1.0	1.2	33.0	24.0
P8	nd	7.80	nd	2.9	nd	45.3
P9	nd	7.15	nd	4.7	nd	34.4
P11	7.88	7.76	2.6	3.4	36.8	nd
P13	7.95	7.83	1.7	1.7	36.5	37.0
P14	7.97	7.68	0.7	3.7	24.5	31.5
P15	7.91	7.60	0.7	6.5	30.5	43.8
A2	7.88	7.67	0.7	0.6	32.3	49.5
Mean	7.93	7.76	3.0	2.7	30.4	34.7
σ	0.1	0.3	4.5	1.9	5.6	10.8
CV (%)	0.64	3.4	150.4	68.4	18.5	31.1

† $ECe = 6.4 \times EC_{1:5}$ (Talsma 1968; Loveday et al. 1972)

All of the topsoils and subsoils measured between pH 7.6 and 8.1. This indicates the presence of free calcium carbonates in the soil matrix. From the fertility point of view, the pH values are in the optimum range for the growth of spate irrigated field crops such as sorghum.

Most of the analysed topsoils and subsoils measured an EC less than 4 d S m^{-1} which are considered as non-saline according to the interpretation of EC values suggested by Landon (1991). Only Profile P1 from the bank of the wadi Laba had an EC of about 15 d S m^{-1}, which is classified as strongly saline. At a depth of 0.7-1.3 m, Profiles P9 and P15 measured an EC of 4.7 and 6.5 d S m^{-1}, respectively and both are slightly saline. In general, salinity is not a problem in most of this soil unit due to the fact that the floodwater leaches the soluble salts deep into the soil profiles. This result agrees with the report made by Halcrow (1997) that the deep flooding form of irrigation, which is characteristics of spate irrigation, would tend to induce good leaching of salts. As sorghum is moderately tolerant to salinity, its growth will not be hampered at salinity levels of 3.0 d S m^{-1} (FAO 1985).

In the upper 0.2 to 0.5 m of all profiles studied, the soils showed moderate to strong effervescence, when 10% HCl diluted solution was added to the matrix. This suggests more than 2% $CaCO_3$ equivalent according to Hodgson (1974). The measured exchangeable Ca^{2+} ions were very high in the topsoils (30.4 meq 100 g^{-1}) as well as in the subsoils (34.7 meq 100 g^{-1}). The high exchangeable Ca^{2+} ions may be explained by the fact that divalent cations such as calcium are easily leached from the catchment areas of Sheeb and transported by the wadis along with the floodwater and deposited on the spate irrigated fields. This increases the concentrations of calcium and other divalent cations in the spate irrigated soils and water.

Organic matter, Nitrogen, Phosphorus and Potassium

Table 5.6 gives the organic matter, total N, available P and K contents in the top 0.25 m and subsoil. Organic matter is one of the major sources of soil fertility particularly for nitrogen and phosphorus. All soils analysed for OM showed low to very low contents that are on average of 0.86% for topsoils and 0.77% for subsoils. The low OM content of the soils in Sheeb is probably because first, a large part of the catchment is covered by sparse natural vegetation presumably caused by erosion and deforestation. Second, the small amount of OM available is mineralized rapidly by the prevailing high temperatures in the area. Niemejer (1993) and Mokwunye et al. (1996) argued that soils in hot dry areas, generally have a low organic matter content because of the low biomass production and rapid rate of decomposition. Third, in Sheeb area crop residues are not incorporated into the soils and manure is not applied. The crop residues are rather used for livestock feeding and temporarily for roofing of the houses.

The average total N content was 0.013% in both the topsoils and the subsoils (Table 5.6). The total N content of the topsoils and subsoils are very low, some are nil. The reasons explained for low organic matter content holds also for the low level of nitrogen in the soils. According to UNDP/FAO (1987), the OM content of spate irrigated soils in Yemen does not exceed 1% and the mean nitrogen content is 0.07% which is similar with the OM and N levels in Sheeb soils.

The average P-Olsen content in the topsoil was around 18 mg kg^{-1} and 15 mg kg^{-1}in the subsoils, which are high and moderate, respectively according to the interpretation of available phosphorus by Landon (1991). But, the high levels of Ca^{2+} ions in the soils and their high affinity for phosphates may indicate that P availability for plant uptake could be a problem in this soil unit.

The available K was about 164 mg kg^{-1} for topsoils and 167 mg kg^{-1} for the subsoils (Table 5.6). Accordingly, the levels of available potassium in both soil depths are moderately high. This is might be attributed to chemical compositions of the parent materials in the catchments which consists of K-bearing minerals such as micas derived from chlorite schists (Halcrow 1997).

Table 5. 6. Organic matter, total N, available P & K contents of mapping unit A-1 soils.

Profile/ auger no.	OM †		Total N		P-Olsen		K- available	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
	%				mg kg^{-1}			
P1	0.70	0.40	0.02	nl	26.0	14.8	175.4	228.0
P3	0.76	0.10	0.01	nl	12.7	3.3	175.4	122.8
P5	1.38	2.06	0.01	nl	11.1	28.6	140.3	157.8
P6	0.89	nd	nl	nd	24.9	nd	140.3	nd
P7	1.31	0.50	0.01	0.01	16.3	15.7	140.3	121.9
P8	nd	1.29	nd	0.01	nd	30.5	nd	174.1
P9	nd	0.44	nd	0.02	nd	13.6	nd	104.5
P11	1.42	0.84	0.01	0.01	25.3	20.6	208.9	139.3
P13	0.56	0.73	0.02	0.02	10.3	7.5	156.7	191.5
P14	0.59	0.72	nl	nl	26.4	13.2	139.3	156.7
P15	0.54	0.77	0.01	0.01	12.2	7.7	174.1	262.4
A2	0.48	0.62	nl	nl	12.2	9.8	192.5	175.0
Mean	0.86	0.77	0.013	0.013	17.7	15.0	164.3	166.7
σ	0.4	0.5	0.01	0.01	7.0	8.6	24.8	47.3
CV (%)	42.9	67.9	37.9	38.7	39.4	57.1	15.1	28.4

† (% OM = % C × 100/58)
nl: nil

The cation exchange capacity (CEC) of the SMU A-1 unit in the topsoil varied from 6.1 to 14.0 meq per 100 g of soil, which was low according to rating of CEC results for topsoils by Landon (1991). The low amount of CEC might be attributed to low contents of clay (Table 5.2) and low OM (Table 5.6) in the soils. Landon (1991) has mentioned that CEC is essentially a property of the colloidal fraction of soil, derived mainly from the clay and OM fractions. However, minimum values of CEC in the topsoil for satisfactory irrigated cropping are considered to be 4 meq 100 g^{-1}

of soil provided that other factors are favourable (Dent and Young 1980).

Soil classification

It has been mentioned earlier that the unit A-1 soils are deep, recently deposited alluvial soils and show fluvial properties. In addition, the average OM content of the soils remains between 0.35 – 0.86%; the profiles show fine stratification having a silt loam texture in most of the topsoils; the profiles receive new fresh materials at regular intervals and the soils are occurring on nearly flat irrigated land.

On account of the above characteristics, the soils of mapping unit A-1 are classified as Fluvisols. Most of the profiles contain high exchangeable Ca^{2+}ions and more than 2% $CaCO_3$ equivalent and they show calcaric properties. The soils are thus classified as calcaric Fluvisols (FLc-2) and are correlated as calcic Fluvents according to USDA soil taxonomy system (1985).

b) The SMU A-2 soils (currently, not irrigated spate soils)

The mapping unit A-2 (photo 5.3) is found in the middle part of the Sheeb area including the Dige site where the MoA research centre is proposed to be stationed.

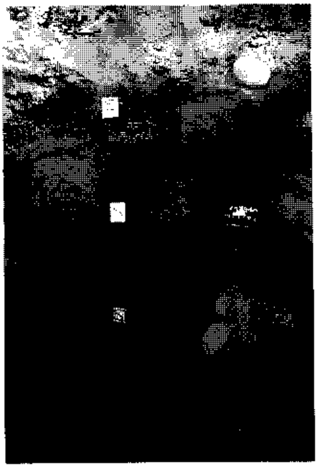


Photo 5.3. The profile of SMU A-2 showing buried spate irrigated soil layers, where the trowel is inserted. Note the top two soil layers (S1 and S2) which are dry because of no irrigation.

This soil unit covers land that is not currently irrigated but once was used for spate irrigation crop production. From 1950s to 1990s, this area was used as a settlement for the Sheeb community. But in 1993, the inhabitants were moved to a new place called Mensheeb (an administrative town of Sheeb district) and since then, the land has not yet been utilised for spate irrigation. The mapping unit A-2 soils cover about 150 ha of irrigable land (Table 5.8) or 2% (Figure 5.2) of the study area.

Physical and chemical properties of the soils

The physical and chemical characteristics of A-2 unit soil profile (P10) are more or less similar with those of soil mapping unit A-1 except for higher EC values. The entire topsoil of this unit measured about 25 d S m^{-1} that is classified as strongly saline. The probable reason for the high amount of salts is that, this land has not been irrigated for about 50 years. In this time, salts have accumulated on top of the soil surface through upward movement of saline ground water originating from parent materials, which contain salts like evaporites and limestones (NRCE 1996). Moreover, wind blown salt particles from the Red Sea coast (which is about 40 km from Sheeb area) and waste disposals by human and animals might have also contributed to the development of salts in this soil unit.

The pH of topsoil was 7.7 and the subsoil pH was 8.4, which is classified as slightly alkaline and moderately alkaline, respectively. The soils showed distinct effervescence (>2% $CaCO_3$ equivalent) when tested with 10% HCL solution. The average OM was 1.4% and total nitrogen was 0.04% in the topsoils. The contents of available P measured about 7 mg kg^{-1} and 164 mg per kg of K^+ in the topsoils. The topsoils are rated as low in OM and nitrogen but moderate in phosphorus and moderately high in potassium and very high in exchangeable Ca^{2+} ions (31.3 meq 100 $g^{-1}$of soil).

Soil classification

The mapping unit A-2 soils showed both fluvic and calcaric properties. In addition, they have salic properties where the ECe value is greater than 15 d Sm^{-1} within 0.3 m of the surface. Most of the topsoils are loams with medium textured. Therefore, the soil-mapping unit A-2 is classified as sali-calcaric Fluvisols (Flcs-2) because of intergrades of calcaric and salic units. The soils are correlated to salic-calcic Fluvents in USDA soil taxonomy system (1985).

c) The SMU-B soils (non-irrigated soils)

The soils of mapping unit-B (profiles P2, P4 and P12 and auger A1) are found on flat non-irrigated lands under natural conditions including land covered by thorny scrubs, rock-out crops, wadi courses, canal beds and settlement sites (villages). For example, the fields south of village

Sheebkhetin and hamlet Idi-Eket (more downstream) have soil bunds but have never been irrigated because of floods does not reach the area. The area covered by this soil unit is about 3,450 ha of land (Table 5.8) or 43% (Figure 5.2) of the study area.

Physical properties of the soils

The topsoils and subsoils of mapping unit-B contain more than 50% sand and less than 15% clay (Table 5.7) in the fine earth fraction. The texture of the topsoils and subsoils are classified as sandy loam and loamy sand, respectively. The sandy character of the soils testifies that the soils are formed in parent rock weathering. They are the original soils of the Sheeb area and are confined to non-irrigated flat lands. Weathering and soil formation processes are slow mainly due to a lack of water. The topsoils are dry for almost all the year.

The depth of soils is about 1.5 m and the colour of the topsoils is mostly brownish yellow and the subsoils are yellowish brown to brownish yellow at dry conditions. The topsoils are single grained and structureless. Consistency of the topsoil at dry conditions is slightly hard, at wet conditions is slightly sticky. Due to the large proportion of the sandy particles and because of no mottling is observed in the profiles, the soils are classified as somewhat excessively drained (drainage class 5). The moisture retaining ability of the soils is very low; while infiltration of water is likely to be rapid.

Chemical properties of the soils

Both the topsoils and subsoils showed a pH of 7.9 and are classified as moderately alkaline. The soils are saline having an EC range of about 5 to 7 d S m^{-1} (Table 5.7). When tested with a 10% HCL solution, the soils showed distinct effervescence at 0.2 to 0.5 m depth, which suggests more than 2% $CaCO_3$ equivalent according to Hodgson (1974). The exchangeable Ca^{2+} ions were very high (Table 5.7) in the topsoil as well as in the subsoil. The reasons for high amount of soluble salts and high Ca contents in this soil unit is as explained for mapping unit A-2 soils.

The average OM contents of the soils are less than 0.5% (Table 5.7) which is low due to the reasons explained elsewhere in this text and in addition there is no input of OM and plant nutrients in the form of sediments unlike the spate irrigated soil units (SMU A-1 and A-2). The total N content follows the same pattern (as the other mapping units) that is very low in the topsoils and nil in the subsoils. The available phosphorus content is moderate in the topsoils but low in the subsoil. But, the high pH plus high exchangeable Ca^{2+} ions might decrease the availability of phosphorus in the soils. The average potassium level of the topsoils is high and in the subsoils as moderately high probably because of the high compositions of sands, derived from annual potassium-rich aeolian deposits and parent sedimentary rocks that consist of minerals such as shales (NRCE 1996).

Table 5.7. Physico-chemical characteristics of mapping unit-B soils.

Soil characteristics	Average †	
	Topsoil	Subsoil
Sand (%)	51	70
Silt (%)	38	27
Clay (%)	13	3
Soil colour (Munsell notation)	10YR 6/6	10YR 5.5/6
PH-H_2O (1:2.5)	7.92	7.90
ECe (d S m^{-1})	6.65	4.65
Organic matter (%)	0.45	0.45
Total N (%)	0.01	nl
P-Olsen (mg kg^{-1})	11.7	6.4
Available K (mg kg^{-1})	285.5	169.1
Exchangeable Ca (meq $100g^{-1}$)	33.9	31.7

† Average of three profiles and one auger samples.

Soil classification

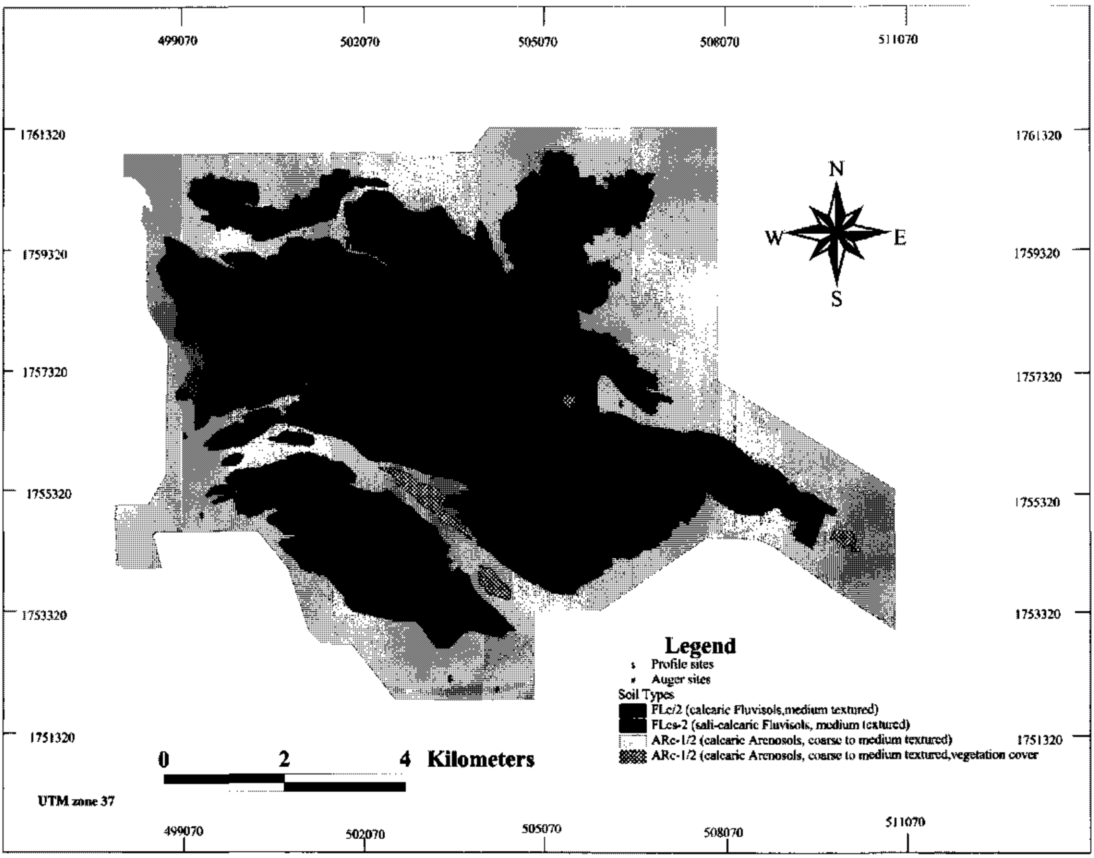
As described earlier, this mapping unit is characterised by deep sandy soils containing more than 50% sand particles and less than 15% clay; weakly developed soils; structureless surface horizons; very low amount of OM and total N; excessively drained soils; dry soils; brownish yellow soils; high chroma and value (soil colour >5) and non sticky to slightly sticky.

On the basis of the characteristics mentioned above, these soils are classified as Arenosols. Furthermore, the soils show calcaric properties within 1.25 m of the surface and salic properties within 0.3 m of the soil surface, and thus are classified as sali-calcaric Arenosols (ARcs-1/2) correlated to salic-calcic Psamments according to USDA soil taxonomic system (1985).

5.3.3 Problems of soils of Sheeb area

The major soil problems in the Sheeb area are listed in Table 5.8. In general, the soils of Sheeb area are low in OM and total nitrogen contents. The levels of P and K seem to be adequate in the topsoils and subsoils depth. But the high pH and high exchangeable Ca^{2+} ions in the soils may decrease the availability of P and increase the liability of deficiency of some micronutrients (Fe, Mn, Zn, Cu, Co).

Surface crusting posed problems in spate-irrigated fields of Sheeb area. Stroosnijder and Eppink (1995) have mentioned that the key to the solution of the problem with crusted soils is to increase soil organic matter. Therefore, by applying manure and incorporating crop residues (where possible), the OM content of the spate-irrigated soils could be increased. Consequently, the OM will improve the aggregate stability of the soils and reduce crust formation.



Map 5.1. Soil map of Sheeb area

Table 5.8. Summary of the major problems of soils in the Sheeb area.

Soil mapping units	Major soil groups & soil units	Area coverage ha	Problems description
SMU A-1	calcaric Fluvisols (FLc-2)	4,400	• low nitrogen and low OM content • soil crusting • soils prone to erosion by heavy floods
SMU A-2	salic-calcaric Fluvisols (FLcs-2)	150	• soil salinity in the top soils • low availability of plant nutrients and OM
SMU-B	salic-calcaric Arenosols (ARcs-1/2)	3,450	• very low in plant nutrients and OM • soil salinity in the top soils • poor physical fertility • dry soils and coarse sandy textured
Total	-	8,000	-

Breaching of the temporary irrigation structures ('agims' and 'misghas') by heavy floods often causes the wadis to change their courses and create erosion particularly in downstream irrigated fields. The permanent flood diversion structures, which would be constructed (at wadi Laba and Maiule) by ELWDP could mitigate the flood hazards and erosion problems in the Sheeb spate irrigation area. Besides, these structures increase the availability water for spate irrigation in the area.

Developing spate irrigation in SMU A-2 and SMU-B soil units could alleviate the problem of salinity in the soils. Moreover, the spate irrigation practises will improve the physical and chemical fertility of these soil units.

5.4 Conclusions

The soil survey in the Sheeb area has characterised, classified and mapped the type of soils found and their distribution in the area. In addition, the survey has identified the major soil problems and their possible solutions to sustain agricultural production in the spate irrigation system.

Results from the survey have revealed that human activities on the land, the floods and the kinds of parent materials are the three major soil forming factors that influence the genesis, characteristics and distribution of the soils in the Sheeb area. The spate-irrigated soils vary both in physical and chemical properties from that of the non-irrigated soils.

On the basis of morphological, chemical and physical characteristics, the soils of Sheeb area are broadly classified into two major soil mapping units namely SMU-A (the Fluvisols: irrigated soils) and SMU-B (the Arenosols: non-irrigated soils). The spate-irrigated soils cover large area of land (i.e. 57% of the Sheeb area). High water holding capacity and non-salinity of the spate-irrigated soils are one of the two most important soil qualities which makes agricultural production possible in arid climate of Sheeb area. It would be useful to characterise also the soils found in the highland catchment of Sheeb in order to complement the findings of this soil survey.

5.5 References

Brady, N.C., 1990. The nature and properties of soils, tenth edition, Collier Macmillan publishers, London, U.K 621 pp.

Dent, D. and Young, A., 1981. Soil survey and land evaluation. George Allen & Unwin Inc., London, UK, 278 pp.

FAO, 1979. Soil survey investigations for irrigation, FAO soils bulletin 42, FAO, Rome, Italy, 134 pp.

FAO, 1985. Water quality for agriculture, FAO irrigation and drainage paper no. 29 Rev.1, FAO, Rome, Italy, 174 pp.

FAO, 1988. Salt-affected soils and their management. FAO soils bulletin 39, Rome, Italy, 131pp.

FAO-Unesco, 1988: Soil map of the World, Revised legend with corrections. World soil resources report 60. FAO, Rome, Italy, 140 pp.

FAO-ISRIC. 1989. FAO-ISRIC soil database (SDB), In. FAO, 1990. Guidelines for soil profile description, third edition. FAO, Rome, Italy, 70 pp.

FAO, 1990. Guidelines for soil profile description, third edition. FAO, Rome, Italy, 70 pp.

FAO, 1997. Support to forestry and wildlife sub-sector, pre-investment study report TCP/ERI/6712 (F). Annex 5: Afforestation in Eritrea, FAO, Eritrea.

Halcrow W. 1997. Inception report, Eastern lowlands wadi development project, Ministry of agriculture, Asmara, Eritrea, 50 pp.

Hodgson, J.M., 1974. Soil survey field handbook, Soil survey technical monograph 5, Rothamsted, Harpenden soil survey, In: Dent, D. and Young, A.1981. Soil survey and land evaluation. George Allen & Union, London, UK, 78 pp.

IFAD, 1995. Staff appraisal report on Eastern lowlands wadi development project, Asmara, Eritrea, 52 pp.

Jacobson, P.J., K.M. Jacobson, P.L., P.L. Angermeier and D.S. Cherry. 2000. Hydrologic influences on soil properties along ephemeral rivers in the Namib desert. Journal of arid environments, 45: 21-34.

John Ryan, Sonia Garabet, Karl Harmsen and Abdul Rashid, 1996. A soil and plant analysis: Manual adapted for the West Asia and North Africa region, ICARDA, Aleppo, Syria.

Klute, A. (Ed), 1986. Methods of soil analysis: Physical and mineralogical properties of soils, Agronomy no.9 (Part 1) Am. Soc. of Agronomy, Madison, Wisconsin, 1188 pp.

Landon, J. R., 1991. Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London, UK, 474 pp.

Loveday J. Beatty, H. J. and Norris J.M. 1972. Comparison of current methods for evaluating irrigation soils. In: Landon, J.R., 1991. Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London,UK., pp. 157-177.

Mokwunye, A.U., Jager, A.de. and Smaling, E.M.A. (ed.), 1996. Restoring and maintaining the productivity of West African soils: In Mateete,A. Bekunda, Andre Bationo and Henry Ssali. Soil fertility management in Africa: A review of selected research trials. A special publication no.51, of the Soil Science Society of America (SSSA). Proceedings of an international symposium cosponsored by ICRAF. SSSA, Madison, Wisconsin, USA. pp. 63-79.

Munsell., 1994. Munsell soil colour Charts. Revised edition, NewYork, U.S.A.

Niemejer D., 1993. Indigenous runoff farming in a hanging environment: The case of Kassala's Border area, Sudan. area, Sudan.Volume 1 and 2 , landscape environment research group, University of Amsterdam &. Department of Irrigation and Soil Water Conservation, Wageningen Agricultural University, The Netherlands, 209 pp.

Stroosnijder, L. and Eppink, L., 1995. Lecture notes on processes and models in soil and water conservation, Department of Irrigation and Soil & Water Conservation, Wageningen Agricultural University, Wageningen, The Netherlands.

Talsma. T., 1968. Environmental studies of the Coleambally irrigation area and surrounding districts. In: Landon, J.R., Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London,UK. 474 pp.

Tesfai, M. and Jan de Graaff, 2000. Participatory rural appraisal of spate irrigation system in eastern Eritrea. Journal of agriculture and human values (In Press).

UNDP/FAO, 1987. Spate irrigation: Proceedings of the sub-regional expert consultation on wadi development for agriculture in the Natural Yemen, Aden, 180 pp.

USAID, 1983. Soil survey of the Yemen Arab Republic, final report (contract no. AID/NE-C-1665), Washington DC pp.141-145.

USDA, 1985. Keys to soil taxonomy. Soil management support service, Technical monograph no. 6, USDA, Washington DC.USA, 244 pp.

Chapter 6

Sedimentation Rate on Spate Irrigated Fields

Tesfai, M. and Sterk G., 2001. Sedimentation Rate on Spate Irrigated Fields in Sheeb area, Eastern Eritrea. Journal of Arid Environments (Submitted).

Abstract

Annual sedimentation in Sheeb area in eastern Eritrea, enables the farmers to harvest a crop without application of fertilisers, but on the other hand, the sedimentation increases the surface level of spate irrigated fields, which often requires raising the field bunds. This study was conducted to determine the sedimentation rate inside spate irrigated fields and to assess the impact of sedimentation on the physical characteristics of the soils. The thickness of deposited sediment layers on the fields was measured using sediment pins. Twenty-seven sediment pins were installed at three plots in Sheeb area on a fine, loamy, calcaric Fluvisol. The measured sedimentation rates ranged from 8.3 to 31.6, 6.0 to 18.0, and 5.2 to 8.6 mm y^{-1} in upstream, midstream and downstream sedimentation plots, respectively. These rates corresponded with an average sedimentation of 143 tons ha^{-1} in the three plots. The impact of sedimentation on soil depth, water retention capacity, infiltration, etc. is positive except for soil horizon development. In general, it can be concluded that, the sedimentation has noticeably improved the physical characteristics of irrigated soils for agricultural production from that of non-irrigated soils adjacent to the fields.

6.1 Introduction

Soil erosion in Eritrea is severe, particularly during the rainy season when soils are tremendously eroded in the highland zones (FAO 1994). The on-site erosion processes in the highlands are detachment and transport of soil particles. Apart from sediments, runoff is produced in the highlands and is transported downward by ephemeral streams (wadis). In the lowland zones of the country sedimentation occurs, which is defined as deposition of sediments on the surface of the ground by water (Bergsma 1996).

In the lowlands, which are characterised by an arid environment, agriculture is practised using a spate irrigation system. Spate irrigation, locally called 'Jeriff', is a type of runoff farming that makes use of flash floods produced in highlands, which are diverted by temporary irrigation structures to irrigate fields in the lowlands. The spate irrigation practises among others includes techniques to harvest runoff, sediments, and nutrients.

One of the main spate irrigation areas in Eritrea is located in Sheeb, which is a district in the northern Red Sea region. Runoff, sediments and nutrients are transported from an altitude over 2000 m in the highlands to around 200 m in the lowlands by the main wadis Laba and Maiule. The runoff in these wadis is diverted to nearby irrigable fields by 'agims', temporary diversion structures, and conveyed to the fields by 'misghas', the distribution canals. Eventually, the runoff is collected in the fields surrounded by bunds, locally called 'kifaf' and 'tewali' (interior and exterior bunds, respectively). The purpose of these structures is to let the runoff infiltrate into the deep soil layers and at the same time to allow deposition of sediments and nutrients.

In Sheeb area, the main flooding season begins in early July and ends in early September, which is also the rainy season in the Central highlands of Eritrea. But the area also gets few floods during the winter rains in the nearby highlands (called locally 'Semenawi Bahari') from mid September until February. During this period, fields that did not received floods (in the main season) will get water.

When farmers in Sheeb observe a cloudy sky in the mountains during the rainy season, they expect a flood and are prepared to irrigate their fields. In the highlands, it often rains in the late afternoon and the runoff produced reaches the lowlands after about two hours. Most of the time, the big floods reach in the evening and produce an enormous noise. When the farmers hear the sound, they rush into their fields to divert the floods and to irrigate the fields. In other words, diversion of floods and irrigation of fields are mostly practised in the evening.

Spate irrigation has been practised for over a century in Sheeb area, and has resulted in advantages and disadvantages. The sedimentation in the area has increased the original soil depth by at least 3 meters. The soils inside the spate-irrigated fields are very deep which is evident from the depth of soil profiles along the canals and from the elevation of the irrigated fields.

The sedimentation also enables the farmers to harvest a crop without application of fertilisers on the soils. This is due to the fact that the sediments contain plant nutrients, which enrich the soil. A farmer from Sheeb area has indicated that "No sedimentation means no fertile soils", which implies that without spate irrigation agricultural production would not be feasible in the area. But with sedimentation, two to three harvests from a single sorghum plant is possible during a good flooding season.

The physical characteristics of soils inside the spate-irrigated fields are better than outside the fields because the sediments contain organic matter. Furthermore, the sedimentation expands the irrigable land by developing deep alluvial soils with good water holding capacity on originally dry infertile sandy soils (Chapter 5).

On the other hand, the high sediment loads carried by the wadis Laba and Maiule have an adverse effect of blocking the 'agims' and 'misghas' by depositing gravel on these structures (FAO 1994; Halcrow 1997). The 'agims' are effective to divert the small to medium-sized floods, but are not strong enough to divert the big floods and thus are often washed away. Until the structures are repaired, a number of floods may flow into the Red Sea without being diverted to the fields, which finally results in lack of water, sediments and nutrients. The big floods also cause the wadis to change their courses, often bypassing the diversion structures and finally damaging the bunds in the fields. Therefore, construction and maintenance of the 'agims', 'misghas' and the bunds are routine works in the spate irrigation system of Sheeb area.

According to Halcrow (1997), the total sediment yield for wadi Laba is estimated to be 1.4 million tons y^{-1}. Only about 35% of the total load are estimated to be diverted to the irrigated fields along with the diverted water, which increases the height of the fields by almost 16 mm y^{-1}. About 0.9 million tons of bed load material will settle in the wadi and canal networks every year. Mace (1997) found that the mean suspended sediment concentrations for six floods in wadi Laba to be about 61.4 g l^{-1}, which is a high concentration according to the rating of UNDP/FAO (1987).

Because of the sedimentation, the surface level of irrigated fields is rising every year. Therefore, adjustments of the bund heights with respect to the elevation of the 'misghas' are needed to prevent overflow and breaching of the bunds. In the long term, farmers may even have to abandon their fields if the elevation has become too high due to the annual sedimentation. For instance, Niemeijer (1993) has reported for eastern Sudan that farmers left their spate-irrigated fields after 50 years of cultivation because of the excessive rise in field levels, and started to cultivate new land.

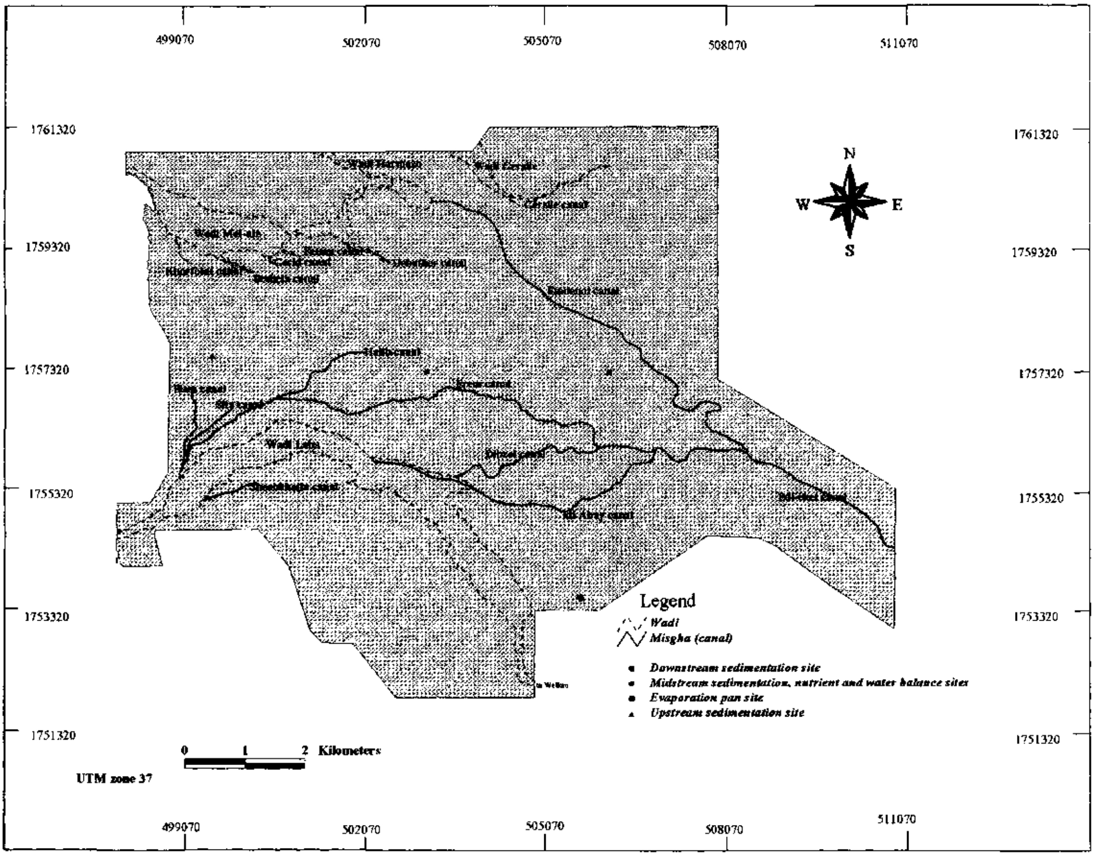
Generally speaking, there is a dearth of English literature on spate irrigation system apart from the proceedings by UNDP/FAO (1987). The information presented in this paper is a result from a research project on spate irrigation system in Sheeb area. The objectives of this study were (1) to measure the sedimentation rates inside spate irrigated fields in Sheeb area, and (2) to assess the impact of this sedimentation on the physical characteristics of the soils.

6.2 Materials and methods

6.2.1 Site characteristics

A field experiment was conducted in the lowlands of Sheeb area (15°52'N; 39°01'E) during 1998 and 1999 flooding seasons. The Sheeb area is located about 110 km north-east of the Eritrean capital, Asmara. It has an arid climate with a mean temperature of 36°C in the main flooding season (July to September) and 25°C in the cropping season (October to February). The mean annual potential evapotranspiration is estimated to be more than 2000 mm and annual rainfall is less than 200 mm (Halcrow 1997). Most of the runoff at wadis Laba and Maiule is derived from rainfall in the highlands between the months of July to September.

Three sedimentation plots (see Map 6.1), each with a size of 40 m by 20 m, were selected in spate irrigated fields at an elevation of 256 m (upstream), at 216 m (midstream) and at 200 m (downstream), respectively. In this paper, the term upstream, midstream and downstream is defined on the basis of proximity to the wadis and elevation difference among the sedimentation plots. Thus, upstream plots are located nearer to the wadis (about 200 m) and have a higher elevation.



Map 6.1. Site locations of sedimentation, nutrient and water balance

Whereas downstream plots are found at approximately 6 km from the wadis and have lower elevations. The midstream plots are in between these two. Each experimental plot represents the population of soils along the cross section of upstream, midstream and downstream sites in the area, which are separated by distances of approximately 3 km.

The plots have a flat topography with 1-2% slope downward from west to east. The spate-irrigated fields have homogenous alluvial soils with on average 27% sand, 52% silt, and 21% clay in the topsoil layer (0-0.25 m). The soils are classified as calcaric Fluvisols according to FAO-Unesco soil classification system (FAO 1988), and as Fluvents in the USDA soil taxonomic system (USDA 1985).

6.2.2 Measuring sedimentation rate

The sedimentation rates in the three plots were measured using the pin method. This method (Figure 6.1) consists of pushing a pin into the soil so that the top of the pin gives a datum from which changes in the soil surface level can be measured in one dimension at a point (Haigh 1977). The sediment pins are measuring the rise of the surface level from the ground, whereas erosion pins operate the opposite way. Hudson (1993) recommended to use pins with a small diameter as thicker pins could interfere with the surface flow and cause scour. In this study, sediment pins made of iron rod (9 mm diameter) and sharpened at the end were used.

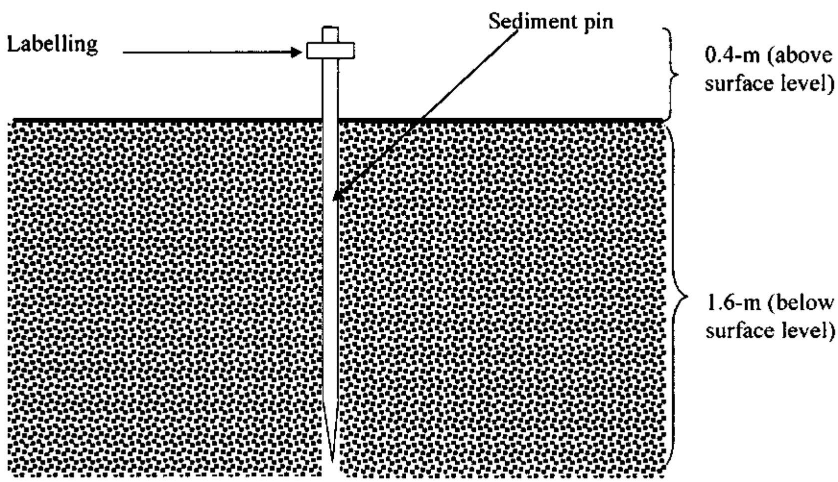


Figure 6.1. Sedimentation pins to measure change in surface level inside spate irrigated fields in Sheeb area.

The sedimentation plots were levelled uniformly prior to installing the sediment pins. Nine pins were installed in each plot before the onset of floods in 1998. The length of the pins was

2 m, and they were pushed into the soil to a depth of 1.6 m to make them stable. The positions of the nine pins in each plot (Figure 6.2) were three at the upper part (Row 1), three at the middle (Row 2) and three at the lower part (Row 3). Distances between pins were 7 m in east-west direction and 16 m in north-south direction. The spacing of the pins to the east-west direction was narrower than in the north-south direction because the floodwater flows towards the east. Robert and Bryanl (1993) reported that best results are obtained when pins are used in short rows. The sediment pins were installed 4 m far from the border of the plots in all directions to exclude boundary effects.

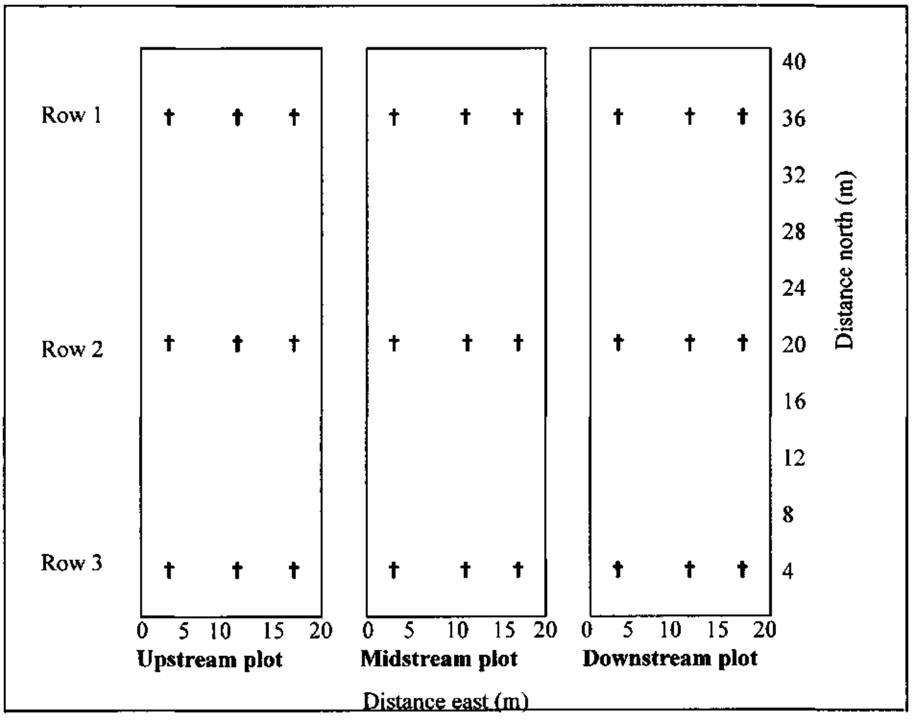


Figure 6.2. Positions of 27 sediment pins in upstream, midstream and downstream plots in Sheeb spate irrigation area.
†: Sediment pins.

The top of all pins were 0.4 m above the surface of the ground (Figure 6.1), and were used as the reference points ($h = 0$) for the measurements, with positive values of h upwards and negative values downward. The initial height of the soil surface, $\bar{h}_i$ (= 0.40 m) was measured at t_i (July 1998) before flooding occurred. The final height of the soil surface, h_n was measured just after the 1999 flood season was over ($t = t_n$). Additional measurements were also taken after the first and during the two flooding seasons.

The average annual rise of the soil surface ($\bar{S}$ in mm y^{-1}), in other words the change in thickness of the sediment layer in each plot per year was calculated as follows:

$$\bar{S} = \frac{\Delta \bar{h}}{\Delta t} = \frac{\bar{h}_n - \bar{h}_i}{t_n - t_i} \qquad [1]$$

The change in sediment layer in terms of thickness was converted into the sedimentation rate, which has mass units (ton ha^{-1}) using the dry bulk density $\rho_b{}^d$, that was determined in each plot (see hereafter).

6.2.3 Soil physical analysis

Sediment samples were collected in each sedimentation plot at the time of removal of the pins after the second flooding season (1999). Samples from the deposited layer (0-0.05 m) were taken very close to the installed sediment pins in a 100 cm^{-3} ring using a core sampler. The dry bulk density of each sample was determined using the core method (Klute 1986).

Soil physical analyses were conducted on soil samples from the midstream spate irrigated field at three locations (upper, middle and lower parts of the field) to assess the impact of sedimentation on the soil characteristics. Particle size analysis of the soils were determined by the hydrometer method (Klute 1986), soil moisture content by the gravimeteric method, infiltration rate using a double ring infiltrometer and penetration resistance by a penetrologger in the field.

In addition to the field measurements and observations, farmers were interviewed on their perception of the floods and sedimentation in the spate irrigation system. The results of these surveys has been reported elsewhere (Chapters 3 and 4), but part of the information is repeated here. Also, the farmers monitored the frequency and the size of the floods occurring during the 1997, 1998 and 1999 flooding seasons. The rainfall data were collected from rain-gauge stations at Merara and Aditeklezan, which are found in the highland catchments of Sheeb.

6.3 Results and discussion

The nature and properties of floods in Sheeb area influence both the quantity and quality of sediments harvested inside the spate irrigated fields. The floods are irregular and unpredictable in nature and are heavily dependent on the occurrence and intensity of rains in the highlands of Eritrea. The rainfall pattern in highland zones of Eritrea is often erratic and torrential in behaviour (FAO 1994). Therefore, there are usually good and bad flooding seasons in

Sheeb area.

Table 6.1. Summary of catchment rainfall and flood records for wadi Laba at Sheeb area.

Date	Catchment rainfall, mm	Frequency and size of floods			Rating of flood season §
		Small †	Big ‡	Total	
1997 July	na	8	1	9	
1997 August	na	7	4	11	Good
1998 July	99.0	0	2	2	
1998 August	187.0	7	0	7	Bad
1999 July	196.6	7	5	12	
1999 August	204.3	7	3	10	Good
Mean per season	343.5	12	5	17	Good

† Small flood, i.e. when flow depth in the canal is < 0.75 m

‡ Big flood, i.e. when flow depth in the canal is > 0.75 m

§ Good flood season is > 15 floods and bad flood season is < 10 floods.

na: not available.

Farmers recorded all the floods during the three flooding seasons (1997-1999) and the seasons were classified as good or bad. This classification was based on the frequency of floods indicated by the interviewed farmers (Chapter 4). A good season has 15 or more floods, a moderate season between 10 and 15 floods, and when less than 10 floods occur the season is considered as bad. The size of the floods was described in qualitative terms, which means big and small floods. Farmers described a flood as big when people or animals could not cross the wadi or when the flow depth in the distribution canal is greater than 0.75 m. During a small flood, people or animals could cross the wadi, or the flow depth in the canal is less than 0.75 m. The flooding seasons of 1997 and 1999 were classified as good seasons, while the 1998 season was considered bad (Table 6.1).

The land and water resources in the highlands influence the spate irrigation system in the lowlands. When there are good rains and much runoff in the highlands, large amounts of sediments are harvested in the spate-irrigated fields. The quality of sediments harvested in the spate-irrigated fields also depends on the source of the runoff. The Sheeb farmers are usually able to identify the origin of a runoff by observing the type of sediment deposited on their fields. When the runoff is originating from the nearby hills and mountains, which are devoid of vegetation cover, the sediments consist largely of coarse sand particles that are poor in nutrients. While, runoff from the agricultural fields in the highlands consists mainly of clay and organic matter that supply nutrients for crop growth.

6.3.1 Sedimentation rate

The measured values of sediment layer thickness (S) are shown in Table 6.2. A few outliers were excluded from the calculations of sedimentation rates. The coefficients of variation in all plots were below 50%, indicating a low variation among the pins with in the plot. The main reason for this low spatial variation is that similar sediment sizes and density were deposited over a horizontal distance in the plot by the floodwater. Coarse sand and silt particles with higher density often settle first in the upstream fields, while fine silt and clay particles deposit in the downstream fields (Chapter 5).

The means of the three sedimentation plots were highly significant ($p \leq 0.01$). In other words, the sediment layer thickness is affected by the positions of the plot and thus has a great variation among them. This may be explained by the high variability of (the frequency and size) floods received and the difference in sediment size as well as density deposited in each plot. According to the water law adopted in the Sheeb area and due to the field to field system of gravitational irrigation, the upstream fields receive water always first. These fields receive more floods than the midstream and downstream fields even in the bad seasons. Downstream areas are only irrigated after the upstream fields have received a sufficient quantity of water and sometimes may not even get a single flood at all.

Table 6.2. Summary statistics of sediment layer thickness † during two seasons at Sheeb spate irrigated fields.

	1998			1999		
Sedimentation plots	S‡	σ	CV	S‡	σ	CV
	—— mm y^{-1} ——		%	—— mm y^{-1} ——		%
Upstream	8.3	4.0	47.6	31.6	9.4	29.9
Midstream	6.0	2.9	48.6	18.0	6.7	37.2
Downstream	5.2	2.5	48.6	8.6	4.0	47.2
Total	6.5	-	-	19.4	-	-

† Rate calculated by equation [1]

‡ S = average sediment layer thickness; σ = standard deviation; CV = coefficient of variation.

The average sediment layer thickness for the three plots in the 1999 flooding season was about 19 mm y^{-1} (Table 6.2), which was more than twice the rate of 1998 (7 mm y^{-1}). The probable reason could be the number of floods and their sizes in 1999 (Table 6.1), which were two times higher than those occurred in 1998. Furthermore, the intensity of rainfall in the highland areas was greater in 1999 (Table 6.1); characterised by torrential rains, which brought huge amounts of surface runoff to the Sheeb area.

The measured average sediment layer thickness ($\bar{S}$) in the upstream plot was about 20 mm y^{-1} (Figure 6.3) which is 1.7 times higher than the midstream (12 mm y^{-1}) and almost three times higher than the downstream plot (7 mm y^{-1}). The difference in the thickness of sediments among the plots gives rise to elevation differences from one site to another, which is easily observed in the field.

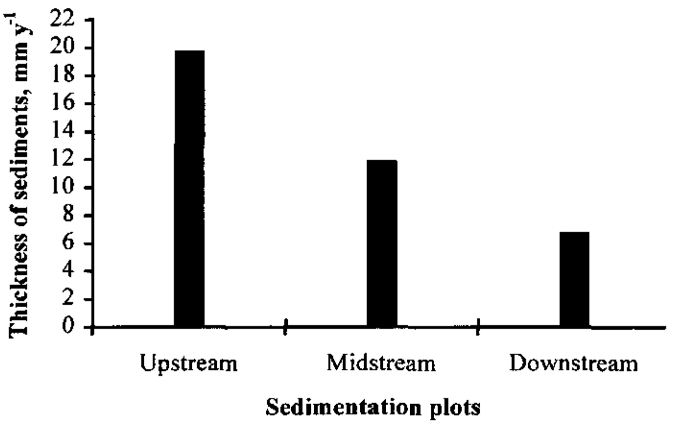


Figure 6.3. The average sediment layer thickness at three plots in Sheeb spate irrigated fields.

Although only two seasons have been measured, it is concluded that the current increase in sediment layer thickness is about 13 mm y^{-1}, which is the average sediment layer thickness for the three plots and the two seasons (Table 6.3). This result is comparable with that of Halcrow (1997), who estimated that the level of spate irrigated fields in Sheeb area rises by almost 16 mm y^{-1}. Niemeijer (1993) in eastern Sudan has also estimated that the maximum sediment layer thickness varies from 9.5 to 39 mm y^{-1} in the spate irrigated fields.

The average depth of the soil that was deposited by the spate irrigation practises is about 3 m. According to the farmers in Sheeb area, spate irrigation was introduced at the beginning of the 20th century (Tesfai and de Graaff 2000). This implies that the average increase in sediment layer thickness was about 30 mm y^{-1} (IFAD 1995). The measured sediment layer in this study (13 mm y^{-1}) is well below the estimated sediment layer (30 mm y^{-1}) probably because most of the soils in the adjacent highlands have been eroded away and are left now with shallow soils. Thus, the runoff volumes are still high but the sediment concentrations on the fields have decreased.

Table 6.3 shows that the mass of sediments in upstream plot was greater than the other plots during the two flooding seasons because of a higher bulk density and a higher thickness of sediments deposited on the plot. Whereas, the sedimentation rates (mass and volume) in the downstream plots were lower since fine sediments with low bulk density often settled out in the fields and very few floods reached the site.

With a mean bulk density of 1.13 t m^{-3}, in an average year about 143 tonnes of sediment ha^{-1} (Table 6.3) is deposited on spate irrigated fields in Sheeb area. On volume basis, an average of 129 m^3 of sediment ha^{-1} is harvested in the fields. As a whole, the total sediment volume harvested in the Sheeb spate irrigated area (4,550 ha) amounts to 586,950 m^3 y^{-1}.

Table 6.3. Mass, thickness and volume of sediments deposited on spate irrigated fields in Sheeb area.

Sedimentation plots	Average (1998 and 1999)			
	ρ_b^d †	S	SV	SM
	t m^{-3}	m	m^3 ha^{-1}	t ha^{-1}
Upstream plot	1.20	0.0199	199.0	238.8
Midstream plot	1.01	0.0120	120.0	121.2
Downstream plot	1.01	0.0069	69.0	69.7
Total mean	1.13	0.0129	129.3	143.2

† ρ_b^d : dry bulk density, S: average sediment layer thickness, SV: sediment volume and SM: sediment mass.

6.3.2 Strengths and limitations of the pin method

The use of the pin method on spate-irrigated fields has some limitations. First, various detritus (plant and animal remains) and trash materials brought by floods are deposited around the pins, which frequently requires removal. Second, some scouring around the pins is inevitable due to the flow of the floodwater in the fields. Third, the pin method is only applicable for relatively homogenous alluvial soils where pins can easily be pushed deep into the soil. Fourth, daily monitoring of the pins is required because they could easily be stolen, and the method requires intensive sampling for larger areas.

Despite the above shortcomings, the sediment pins are simple made from locally available materials, cheap and user-friendly. In addition, the installation of pins and the measurement of sedimentation could be carried out by local people. The pin measurements give accurate data on sedimentation rates in one dimension at a point but only if the pins are made firm at their position.

6.3.3 Sediment harvesting impacts

Because of sedimentation, the spate-irrigated fields have developed deep alluvial soils (on average 3 m deep) accumulated by many years of sediments brought by floods from the highlands. The spate-irrigated soils have been developed at the expense of erosion in the highlands. The soil profiles show stratification of layers of textures with irregular moisture retention and nutrient status as a result of sedimentation. The sedimentation rate is higher than the rate of soil formation (with regard to differentiation of horizons) because of the frequent deposition of sediments by floods. In other words, the recurrent sedimentation and deposition of fresh sediments brought by floods retarded the differentiation of soil horizons. Thus, the spate-irrigated fields are covered by young soils that have little profile development.

Table 6.4. Average soil physical properties in the top 0.25 m layer inside versus outside spate irrigated fields.

Property	Inside fields	Outside fields
Sand, %	27.0	70.0
Silt, %	52.0	27.0
Clay, %	21.0	3.0
Soil depth, m	3.0	1.5
Soil colour, Munsell notation	10YR 4/4	10YR 6/6
Bulk density (dry), g cm^{-3}	1.1	1.8
Water holding field capacity, mm m^{-1}	414.0	206.0
Infiltration rate, cm hr^{-1}	3.9	5.0
Water stable aggregates	62.9	16.5
Penetration resistance †, Mpa	0.58-1.36	nd

† measurement from 0-0.7 m soil depth.

nd: not determined.

Table 6.4 compares the average soil physical characteristics inside versus and outside spate irrigated fields. Soils inside spate irrigated fields have medium to fine textured topsoils and a low bulk density. They are well-drained soils with good water holding capacity. While, the soils outside spate irrigated fields are coarse textured with greater bulk density and very low water holding capacity because of their high content of coarse sands. The water stable aggregates outside spate irrigated fields are also low due to very low organic matter content of the soils (Chapter 5). The penetration resistance of spate irrigated soils are in the range of 0.58 to 1.36 MPa to a depth of 0.70 m, rated as low to moderate. The soils are thus not compacted by the effect of sedimentation till the depth of subsoils. Non-compacted soils with low bulk density have high porosity, which allows for good aeration and high available water capacity (Niemeijer 1993).

6.4 Conclusions

The on-site erosion effects in the adjacent highlands are characterised by a net loss of sediment, water and nutrients from the catchment. Whereas, the off-site effects of sedimentation on the spate irrigated fields in Sheeb are building up of soil depth and gaining of sediments, water and nutrients.

As far as sedimentation within the spate irrigation system is concerned, on average almost 13 mm of layer of sediment thickness per year corresponding to 143 tonnes of sediments per ha per year are harvested in the irrigated fields. Sediment harvesting technique must be regarded as an important aspect of indigenous spate irrigation practises from the standpoint of building up of soil depth and soil physical characteristics. In general, the soils inside spate irrigated fields have better physical characteristics than fields without spate irrigation. Thus, the impact of sedimentation on physical characteristics of spate irrigated soils is positive except for soil horizon development.

From the magnitude of the measured sediment input, the risk of too much sedimentation on the spate-irrigated fields is low at the present time. Even in the long term, the sedimentation in Sheeb area will not cause the farmers to give up their fields and it will not lead to the destruction of the traditional spate irrigation system at all. However, at the flood diversion sites the sedimentation has negatively affected the spate irrigation system by depositing large amounts of sediment loads, which often damages the 'agims' and 'misghas' structures. This problem could be reduced by constructing permanent flood diversion structures at the head of wadis Laba and Maiule and distribution structures at the lower reaches of the wadis.

We can conclude that, the sedimentation has noticeably improved the physical characteristics of irrigated soils for agricultural production from that of non-irrigated soils adjacent to the fields. One good example is that a farmer from Sheeb has strongly stated that 'No sedimentation means no fertile soils", which implies that without spate irrigation, agricultural production would not be feasible in the area.

6.5 References

Bergsma, E., 1996. Terminology for soil erosion and conservation. Prepared for the sub-commission soil and water conservation of the International Society of Soil Science. ISSS/ITC/ISRIC, pp. 217-218.

FAO-Unesco, 1988: Soil map of the world, revised legend with corrections. World soil resources report 60. FAO, Rome, Italy, 140 pp.

FAO, 1994. Eritrea agricultural sector review and project identification, Annex 5, Rome, Italy, pp. 3-4.

Haigh, M. J., 1977. The use of erosion pins in the study of slope evolution, In: Hudson, N., 1995. Soil conservation. Fully revised and updated, third edition, London, UK, pp. 158-159.

Halcrow, W., 1997. Inception report, Eastern lowlands wadi development project, MoA, Asmara, Eritrea, 50 pp.

Hudson, N.W., 1993. Field measurement of soil erosion and runoff. FAO soils bulletin no.68, FAO, Rome, Italy, pp. 13-23.

IFAD, 1995. Appraisal report on Eastern lowlands wadi development project, Eritrea, 52 pp.

Klute, A. (Ed), 1986. Methods of soil analysis: Physical and mineralogical properties of soils, Agronomy no.9 Am. Soc. of Agron., Madison, Wisconsin, pp. 363-411.

Niemeijer, D., 1993. Indigenous runoff farming in a hanging environment: The case of Kassala's Border area, Sudan. Vol.1 and 2, landscape environment research group, University of Amsterdam and Department of Irrigation and Soil and Water Conservation, Wageningen Agricultural University, The Netherlands. 209 pp.

Robert, J. L. and Bryan, L.C., 1993. The identification of catchment sediment sources. In: Foster, I.D.L., A.M. Gurnell and B.W. Webb. (ed.) Sediment and water quality in river catchment, ©1995 John Wiley and sons ltd., UK. pp. 189-205.

Tesfai, M. and Graaff, J. de, 2000. Participatory rural appraisal of spate irrigation system in eastern Eritrea. Journal of agriculture and human values. (In Press).

UNDP/FAO, 1987. Spate irrigation: Proceedings of the sub-regional expert consultation on wadi development for agriculture in the Natural Yemen, Aden, 180 pp.

USDA, 1985. Keys to soil taxonomy. Soil management support service, technical monograph no. 6, USDA, Washington DC.USA, 244 pp.

Chapter 7

The Soil Nutrient Balance in Spate Irrigated Fields

Abstract

A macronutrient balance study in the spate-irrigated fields of Sheeb area in eastern Eritrea was carried out to determine the size of inputs and outputs of total N, P and K and to assess the impact of nutrient harvesting on chemical properties of spate irrigated soils. Nutrient inputs by sedimentation (IN5) and atmospheric deposition in dust (IN3) and nutrient outputs by crop harvest (OUT1) and crop residues removal (OUT2) were quantified. The average of the two input factors minus the average of the two output factors rendered the values of +137 kg total N, +68 kg total P, and +1,378 kg total K per ha per year. The positive balances for N, P and K were attributed mainly by higher input of nutrients via sedimentation (IN5). The organic matter, total N and available P contents were relatively higher inside spate irrigated fields than the outside fields due to nutrient harvesting effects. However, the average nutrient contents of the soils (in the top 0.25 m depth) were low for total N and organic matter but high in available P and available K. Hence, the farmers in Sheeb area should adopt integrated nutrient management practises in order to add and/or save nutrients thereby to improve soil organic matter and N contents in spate irrigated fields.

7.1 Introduction

Spate irrigated fields in the Red Sea coastal zone of Eritrea exist for about 100 years. The question how sustainable the spate irrigation system is can be looked at from different view points. This Chapter will discuss soil fertility aspects of the system.

Food shortages are common phenomena in large parts of sub-Saharan African countries mainly caused by drought, increased population growth (i.e. rate of 3%) and decline of soil fertility which results to nutrient depletion and imbalance of soil nutrients (FAOSTAT 1998). According to Stoorvogel and Smaling (1990) soil nutrient depletion is quite severe in sub-Saharan Africa (SSA). In all of the 38 SSA countries studied, more than 10 kg N, 4 kg P_2O_5 and 10 kg K_2O ha^{-1} y^{-1} are lost from the topsoil. Macronutrient depletion rates were even highest in East Africa, exceeding 40 kg N, 6.6 kg P_2O_5 and 33.2 kg K_2O ha^{-1} y^{-1} (Ahenkorah et al. 1995; Smaling et al. 1997).

Spate irrigation (called locally 'jeriff') is a pre-planting irrigation system that makes use of flash floods (from highland areas of Eritrea) that are diverted by structures to irrigate fields in the lowlands of the country. During the rainy season (July-September) in the highlands, ephemeral streams (wadis) notably Laba and Mai-ule transport large amounts of runoff with sediments to the lowlands of Sheeb area. The farmers in this area divert the runoff into adjacent arable fields by temporary irrigation structures locally called 'agims'. The diverted runoff with its sediments is conveyed by canals (called 'misghas') and collected in the fields that are surrounded by earthen bunds. The sediments settled out and finally deposited in the fields while the diverted water infiltrates into the deep soils. Seeds are sown on these fields and are grown using the residual moisture in the soils. The sediments contain, amongst others, plant nutrients and organic matter that enriches the nutrient stocks of spate irrigated soils. The soil nutrient stock is defined by de Jagre et al. (1998) as the total amount of nutrients present (i.e. nutrients in the organic matter fraction, nutrients adsorbed to the solid phase and dissolved nutrients in the soil solution) in the top 0.25 m of the soil profile.

Table 7.1 compares the chemical properties of soils inside spate-irrigated fields (with sedimentation) versus outside fields (without sedimentation). The nutrient contents of total N, organic carbon and available P inside the spate-irrigated fields were 1.3 to 1.8 times higher than outside the fields. However, the level of N and organic carbon inside as well as outside fields was low to very low, respectively. This is explained by the fact that the catchments of Sheeb is covered with little natural vegetation and low biomass production, presumably caused by human-induced degradation such as deforestation and erosion (FAO 1994). The area outside the spate-irrigated fields is almost devoid of natural vegetation cover except for a few shrubs and thorny scrubs scattered in some places. The available P-content inside fields were higher than outside fields probably because the parent materials in the catchments are relatively rich in apatites, ($Ca_5(F,Cl)(PO_4)$. Whereas, the available K was greater in outside fields due to the high composition of sands, derived from the aeolian sands that consists of soil minerals such as micas, $K(Mg,Fe^{2+})_3(AlSi_3)O_{10}(OH,F)_2$. In similar systems (in runoff farming systems in eastern Sudan), Niemeijer (1993) also mentioned that micas are most prominent in the medium to coarse sand fractions (250 to 2000μm).

Table 7.1. Average soil chemical properties in the top 0.25 m inside versus outside spate irrigated fields (n = 4).

Property	Inside fields	Outside fields	Inside divided by outside
C-organic (g kg^{-1})	9.0	5.0	1.8
N-total (g kg^{-1})	1.3	1.0	1.3
P-Olsen (mg kg^{-1})	19.2	11.7	1.6
K-available (mg kg^{-1})	169.0	285.5	0.6
pH (H_2O)	7.93	7.92	1.0
ECe (d S m^{-1})	1.8	6.6	0.3

The soils inside spate irrigated fields measure an ECe of 1.8 d S m^{-1}, which is non-saline according to the general interpretation of ECe values by Landon (1991). The practise of spate irrigation leaches the soluble salts out of the root zone of crops. This is one of the most important properties of spate-irrigated soils that make agriculture possible in arid environments like the Sheeb area. The level of ECe outside spate irrigated fields was more than three times greater than the inside field. The pH values in both fields were suitable to plant growth.

Spate irrigation has been practised in the Sheeb area since the beginning of the 20th century (Tesfai and de Graaff 2000). The farmers in this area have harvested crops without addition of inorganic or organic fertilisers into the soils using only the nutrients deposited in their fields. However, the nutrient harvesting techniques made the Sheeb farmers to be reluctant from applying fertilisers (organic or inorganic) or from adopting other soil management practises that could improve the fertility of the soils. The farmers believe that the soils are rich in nutrients because the topsoils from the highland areas are eroded and deposited on the irrigated fields by floods year after year.

From the above evidence, we believe that there is no mining of soil nutrients as it occurs in so many other tropical (agricultural) production systems (Stoorvogel and Smaling 1990; Van der Pol 1992). The reasons are:

1. The system is in use for about 100 years without the addition of fertilisers (organic or inorganic) into the soils.
2. The average grain yield of harvested product of sorghum in spate irrigated fields was 1500 kg ha^{-1} in 1998 and 2000 kg ha^{-1} in 1999. Whereas under rainfed condition, FAO (1997) estimated the national average yield of sorghum to be 615 kg ha^{-1}.
3. The spate irrigation farmer's believe that soil nutrients are available in abundance.
4. The soil fertility of the spate-irrigated fields is considerably higher than the non-irrigated fields.

A common tool to judge a production system on its sustainability with respect to soil nutrient is the Nutrient Balance Approach (NBA). It is of interest to compare the observation of no soil mining (empirical evidence) with the more scientific NBA method. Since the nutrient input via the deposited sediment is the major nutrient source, a field experiment was carried out to quantify this amount.

7.2 Methods and approach

7.2.1 Experimental site

The study was carried out in Sheeb spate irrigation area (15°52'N; 39°01'E) during the cropping seasons of 1998 and 1999. The Sheeb area is located about 110 km east of the Eritrean capital, Asmara, at an altitude of about 225 m above sea level. The total catchment area of Sheeb (including wadis Laba and Maiule) is about 805 km^2. The catchment covers the northern part of the eastern escarpment called locally 'Semenawi-bahari' and part of the central highlands of Eritrea. The geology of the Sheeb catchment is characterised by Precambrian chlorite schist and granite intrusions (Halcrow 1997).

The Sheeb spate irrigation area has a flat topography with slope 1 to 2% downward from west-east. The surface geology of the area consists of Quaternary to recent alluvial sediments and aeolian sands (NRCE 1996). The spate-irrigated soils are developed on alluvial parent materials derived from Precambrain basement complex of the highlands. The average soil particle size is 27% sand, 52% silt and 21% clay in the topsoils. According to FAO/Unseco (1988) soil classification system, the soils inside spate irrigated fields are grouped under calcaric Fluvisols and outside fields as calcaric Arenosols (Chapter 5).

The climate of Sheeb area is hot and arid with mean annual potential evapotranspiration estimated to be more than 2000 mm and annual rainfall (long-term record) less than 200 mm (Halcrow 1997). Mean monthly air temperature ranges from 25°C in January and February (during the cropping season) to 36°C in July and August (during the flooding season). In the study area, the major crops grown are sorghum followed by maize, millet and some vegetables. Crop growth is achieved using residual soil moisture in the soil profiles. The cropping subsystem in Sheeb area is characterised by monocropping of sorghum at a subsistence level of production using traditional farming methods.

7.2.2 Field experiment

A plot size of 20 m by 40 m (Figure 7.1) was selected at the spate-irrigated fields of Sheeb area, and was located in the midstream of wadi Laba and Maiule (see Map 6.1, Chapter 6). The plot was divided into grids occupying a size of 5 m by 4 m. Before soil sampling, three auger holes (at the upper, middle and lower parts of the plot) and one profile pit were examined inside and outside of spate irrigated fields.

Soil samples were collected from a depth of 0-0.25 m of each grid (see black dots in Figure 7.1). The sampling was done within the topsoil layer because the maximum sediment layer thickness inside the spate-irrigated fields does not exceed 0.25 m y^{-1} (Chapter 6). The soil samples were spread on a clean polythene sheet, mixed thoroughly and approximately 1 kg subsample (mixture of 4 sample points) recovered from each row in the plot. In total 10 samples were collected from the entire plot to determine the size of nutrients input via sedimentation. Compared to plant analysis, the primary advantage of soil analysis is its ability to determine the nutrient contents of the soil before the crop is planted (Tisdale et al. 1993).

After sampling, the whole field was sown with sorghum [*Sorghum bicolor, L. var. hijeri*]. The same sample procedure was repeated at the time of harvesting to determine the size of nutrients stocks in the soils. Soil sampling and soil chemical analysis were carried out for two consecutive years (1998 and 1999).

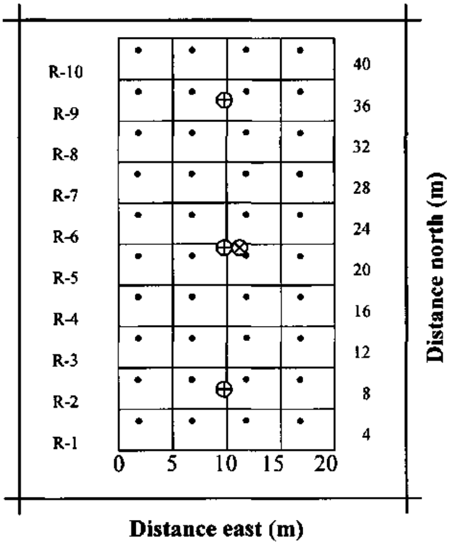


Figure 7.1. Experimental plot layout for nutrient balance measurements in Sheeb spate irrigated fields. R: row, • Sample points, ⊕ Auger holes and ⊗ Soil profile pit.

The soil samples were air-dried, crushed in a porcelain mortar and passed through a 2 mm sieve. The samples were analysed at soil science laboratory of the Ministry of Agriculture in Eritrea (1998), while the 1999 samples were sent to Wageningen University for nutrient analysis. Smaling and Braun (1996) recommended to measure total nitrogen, total phosphorus and total potassium contents in deposited sediments. The soils were thus analysed for total nitrogen (N), phosphorus (P), potassium (K) as these elements are also the most widespread limiting nutrients to food production in Africa (Bekunda et al. 1997; Sanchez et al. 1997). The total N was determined by micro-Kjeldahl digestion method, total P was analysed by spectrophotometer manually, total K by flame emission spectrophotometer. Organic carbon was determined according to Kurmies (spectro-photometric) method as explained by Houba et al. (1995). Soil pH was determined in a 1:2.5 of soil:water suspension and electrical conductivity (EC) in a soil:water ratio of (1:5). The $EC_{1:5}$ values were later multiplied by 6.4 to convert into ECe, according to Talsma (1968) and Loveday et al. (1972). Apart from chemical soil analysis and observations made on crops, farmers were interviewed about their perception on soil fertility management in spate irrigation system.

7.2.3 Nutrient Balance Approach (NBA)

The nutrient balance is defined as the difference between the amount of plant nutrients exported from arable fields and those added (imported) into the fields. Export processes of nutrients include removal of harvested crop (OUT1) and crop residues (OUT2), solute leaching (OUT3), gaseous losses (OUT4) and water erosion (OUT5). Nutrients are imported via application of mineral fertilisers (IN1), organic fertilisers (IN2), atmospheric deposition in rain and dust (IN3), biological nitrogen fixation (IN4), and sedimentation (IN5) by natural flooding and irrigation water (Van der Pol 1992; Smaling et al. 1997). In this study, the nutrient balance approach after Smaling et al. (1997) was adopted with minor modifications to fit to the conditions of the spate irrigation system in the Sheeb area.

In spate irrigation system, the major input of nutrient is sedimentation (IN5) followed by atmospheric depositions in dust (IN3). There are no inputs of nutrients either by application of mineral fertilisers (IN1) or organic fertilisers (IN2) because application of mineral fertilisers, organic manuring and incorporation of crop residues into the soils are not practised in the system. Biological nitrogen fixation (IN4) is hardly found because the system is mainly characterised by a continuous monocropping of sorghum.

Factors considered in the output of nutrients were crop uptake (OUT1) and removal of crop residues from the fields (OUT2). In this study, losses of nutrients by leaching (OUT3) was not considered because the nutrients imported (IN3 and IN5) are largely present in the form of solid inorganic and organic particles. Moreover, under spate irrigation system, normally irrigation is not applied after sowing of seeds. Therefore, the deposited nutrients are unlikely to be washed away from the root zone of crops (e.g.1.8 m for sorghum). Elias et al. (1998) argued that gaseous losses of N can be caused by volatilisation of ammonia and burning in arid climates where volatilisation can be important in feedlots, intensively grazed areas and in manure heaps. In the study area, crop residues are intensively used as feed and are not burnt in the fields. Hence, nutrient loss through volatilisation was assumed to be negligible. The loss of nutrients by water erosion (OUT5) was disregarded because of the flat topography of the study area. Stoorvogel and Smaling (1990) reported that the loss of nutrients by erosion in naturally flooded or irrigated land/water class to be 0 kg ha^{-1} y^{-1}.

The nutrient budget of a spate-irrigated field is a balance sheet showing the magnitude of different processes of nutrient inputs and outputs during a cropping season. A positive nutrient budget means nutrient accumulation in the soils. Whereas, a negative nutrient budget indicates that the soils are degraded through mining of nutrients. For sustainable development, however, it is necessary that the nutrient budgets be near equilibrium (Reuler and Prins 1993).

To calculate the total nutrient balance, P_2O_5 was converted into elemental P by multiplying with 0.44 and K_2O into K by 0.83 (Landon 1991). The total nutrient balance (TNB) for each macronutrient were calculated as follows:

$$\text{TNB (kg ha}^{-1}\text{ y}^{-1}) = (\text{IN3} + \text{IN5}) - (\text{OUT1} + \text{OUT2}) \qquad [1]$$

7.3 Results

7.3.1 Field experiment

Table 7.2 shows the nutrient contents of total N, P and K in the sampled soils at the time of sowing and harvesting of sorghum in 1998 and 1999 (organic carbon also analysed). Results of the chemical analyses in 1998 are not consistent and not used in the further analysis. However, since the amount of sedimentation in 1998 differed much from that in 1999, it is of interest to show the effect of this difference on the nutrient balance. For that reason, results of the 1999 chemical analysis were also used in the calculations for 1998.

Table 7.2. Nutrient contents (g kg^{-1}) at time of sowing and harvesting of sorghum in spate irrigated fields.

	Sample †	R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10	Mean	σ	CV
							Year 1998							
sowing	N	0.09	0.08	0.57	0.18	0.14	0.07	0.14	0.09	0.26	0.11	0.18	0.151	85.6
	P	0.24	0.24	0.25	0.25	0.32	0.35	0.35	0.25	0.28	0.27	0.28	0.04	15.2
	K	21.8	21.3	19.5	19.0	20.0	21.3	19.5	19.0	16.4	17.7	19.6	1.7	8.6
harvesting	N	1.10	0.88	0.69	0.92	0.66	0.67	0.78	0.71	0.88	0.78	0.81	0.1	17.2
	P	0.302	0.296	0.290	0.283	0.294	0.286	0.289	0.304	0.272	0.259	0.26	0.01	4.8
	K	16.32	14.03	15.43	14.03	14.03	14.03	14.03	16.32	14.91	11.68	14.5	1.4	9.4
							Year 1999							
sowing	N	1.55	1.50	1.52	1.58	1.56	1.56	1.52	1.42	1.41	1.41	1.50	0.07	4.4
	C	15.5	15.4	16.1	17.6	17.0	16.1	16.0	15.3	15.4	15.7	16.0	0.75	4.7
	P	0.68	0.69	0.71	0.71	0.73	0.71	0.70	0.69	0.68	0.68	0.70	0.02	2.4
	K	10.52	10.62	10.87	10.98	10.99	10.68	10.64	10.56	9.70	10.37	10.59	0.37	3.5
harvesting	N	1.29	1.42	1.42	1.49	1.46	1.46	1.41	1.34	1.29	1.36	1.39	0.07	5.1
	C	15.4	16.9	15.9	17.0	16.7	16.2	16.2	15.5	14.8	15.8	16.0	0.70	4.4
	P	0.67	0.70	0.68	0.70	0.68	0.67	0.66	0.68	0.62	0.64	0.68	0.02	3.7
	K	10.27	10.37	10.65	10.78	10.62	10.31	10.39	10.42	10.02	10.14	10.40	0.23	2.3

† R1-R3 samples were located at lower, R4-R7 at the middle and R8-R10 at the upper parts of the plot.
σ: Standard deviation.
CV: Coefficient of Variation (%).

In 1999, the mean nutrient contents of total nitrogen (1.39 g kg^{-1}), organic carbon (16.0 g per kg ~ 2.7% organic matter) were low, but total phosphorus (0.68 g kg^{-1}) was moderate and the total potassium (10.4 g kg^{-1}) was moderately high at crop harvest according to the fertility ratings of ILACO (1989) and Landon (1991). The coefficient of variation ranged from 2.3% to 5.1% at harvest and 2.4% to 4.7% at sowing, implying that the variations of soil nutrient contents at time of sowing and harvesting were low. However, the nutrient inputs were relatively greater in the lower parts of the plot (R1-R3) than in the upper parts (R8-R10). This could be explained by the large amount of sediments settled out often at the lower part of the plot. The floodwater flows by gravity from field to field in the system of spate irrigation.

7.3.2 Quantification of inputs

Atmospheric deposition in dust (IN3)

During the flooding season, the hot temperature, high evaporation rates as well as the fields being bare of crops favours windy conditions to prevail in the Sheeb area. Thus, dust storms locally called 'Khamsin' winds are often produced, which blow day and night. The amount of nutrients added by dust deposition was calculated using the multiple regression equation developed by Stroorvogel and Smaling (1990) for areas outside the Harmattan influence (Table 7.3).

Sedimentation (IN5)

During the rainy season, the runoff produced in the highlands is diverted to the lowlands of Sheeb spate-irrigated fields using the irrigation structures ('agims' and 'misghas'). Apart from water, the runoff contains plant nutrients and sediments, which all are deposited on the irrigated fields by sedimentation. Seeds are sown on these fields in mid-September without addition of fertilisers. The crops absorb nutrients from the deposited sediments and water from the residual moisture in the soil profiles.

For simplicity, the nutrient inputs of total elements of N, P and K by sedimentation (IN5) in the deposited sediment layer were converted into kg ha^{-1} y^{-1} as follows:

$$IN5\ (\text{kg ha}^{-1}\ \text{y}^{-1}) = \left\{ (\rho_b^{d} \times NC) \times \bar{S} \right\} \times 0.01 \qquad [2]$$

where, ρ_b^{d} is the dry bulk density of the deposited sediments (kg m^{-3}), NC is nutrient contents of soils (mg kg^{-1}), $\bar{S}$ is the average sediment layer thickness (m y^{-1}) and 0.01 used to convert into hectare. The mean values for total N, P and K contents were taken respectively, as 1.5, 0.7 and 10.6 g kg^{-1} (Table 7.2) for both 1998 and 1999.

7.3.3 Quantification of outputs

Harvested crop (OUT1)

In the system of spate irrigation, the sorghum crop and its residues are 100% removed from the field after harvest. The farm household consumes the harvested grains and the crop residues are mainly used for livestock feed. The livestock are kept tethered outside the fields in a place called locally 'zeriba'. During the cropping season, the livestock are fed grass and crop residues cut in the fields in order to prevent them from trampling and grazing on the growing plants. During the off season (May to September), the people of Sheeb with their livestock migrate to the highlands of Eritrea in search of food, water and grass. This indicates that potential sources of soil organic matter (i.e. crop residues, manure and urine) are not recycled in the spate irrigated fields of Sheeb area.

The crop removal for N, P_2O_5, K_2O was considered as 14.5, 12.6 and 4.5 g per kg of harvested product, respectively. Other such as Hengsdijk et al. (1996) suggested the minimum nutrient concentrations of 10.9 N, 1.3 P_2O_5 and 2.5 g K_2O per kg harvested grain of sorghum with correction factors 1.2 for semi-intensive and 1.4 for intensive production levels.

Residues removal (OUT2)

The average yield of crop residues of sorghum was taken as 1500 and 2000 kg ha^{-1} in 1998 and 1999, respectively from field observation made during harvest and farmers interview. Normally, the ratoon crop gives half of the yield of the seeded crop. Since the crop residues are not incorporated into the soils after removal, the maximum content of nutrients for above-ground crop residues (i.e. 13.5 N kg, 13.2 P_2O_5 kg and 39.5 K_2O harvest) was used because of the low level of management in the Sheeb spate irrigation system. On the other hand, a minimum nutrient concentrations of 10.0 N, 0.7 P_2O_5 and 18.0 g K_2O per kg harvested residues (with correction factors 1.3 and 1.7 for semi-intensive and intensive production levels, respectively) was reported by Hengsdijk et al. (1996).

7.3.4 The nutrient balance

Using equation [1], nutrient balances for N, P and K were calculated. The total nutrient stock in the topsoil (0-0.25 m) for each macronutrient was computed by multiplying the soil bulk density with the content of each soil nutrient. Table 7.3. summarises the nutrient balance calculation methods used in this study.

Table 7.3. Nutrient balance (kg ha^{-1} y^{-1}) calculation methods in Sheeb spate irrigated fields.

Input/ Output	Calculation methods
IN3: Atmospheric deposition in dust	Multiple regression analysis (Stoorvogel and Smaling 1990) IN3 (Total N) = 0.14 × $(Rainfall)^{1/2}$† IN3 (P_2O_5) = 0.053 × $(Rainfall)^{1/2}$† IN3 (K_2O) = 0.11 × $(Rainfall)^{1/2}$†
IN5: Sedimentation	Soil analysis (nutrient contents at sowing time using Eq. [2])
OUT1: Harvested crop	Total N, P_2O_5 and K_2O contents of harvested product (Stoorvogel and Smaling 1990) × Yield (field measurement)
OUT2: Crop residues	Total N, P_2O_5 and K_2O contents of crop residues (Stoorvogel and Smaling 1990) × *Yield* ‡

† Mean annual rainfall of Sheeb area was about 200 mm in 1998 and 230 mm in 1999.
‡ Field observations and farmers interview

Table 7.4 gives the total nutrient budgets and balances in spate-irrigated fields for the years of 1998 and 1999. According to the table, the balance of N was increasing from +42.4 kg ha^{-1} in 1998 to +231.6 kg ha^{-1} in 1999. For P, the balance also increases from +23.4 to +113.1 and K from +649.7 to +2107.6 kg ha^{-1} in 1998 and 1999, respectively.

Table 7.4. Total nutrient budgets (kg ha^{-1} y^{-1}) and balances at Sheeb spate irrigated fields.

	1998			1999		
Input/output	N	P	K	N	P	K
Mineral fertilisers, IN1	0.0	0.0	0.0	0.0	0.0	0.0
Organic manure, IN2	0.0	0.0	0.0	0.0	0.0	0.0
Atmospheric deposition, IN3	2.0	0.8	1.6	2.1	0.8	1.7
Biological N fixation, IN4	0.0	0.0	0.0	0.0	0.0	0.0
Sedimentation, IN5 †	103.4	48.2	730.3	313.5	146.3	2215.4
Total input	**105.4**	**49.0**	**731.9**	**315.6**	**147.1**	**2217.1**
Harvested crop, OUT1	32.6	12.5	8.4	43.5	16.6	11.2
Residue removal, OUT2	30.4	13.1	73.8	40.5	17.4	98.3
Leaching, OUT3	0.0	0.0	0.0	0.0	0.0	0.0
Volatilisation, OUT4	0.0	0.0	0.0	0.0	0.0	0.0
Erosion, OUT5	0.0	0.0	0.0	0.0	0.0	0.0
Total output	**63.0**	**25.6**	**82.2**	**84.0**	**34.0**	**109.5**
Total Nutrient Balance	**+42.4**	**+23.4**	**+649.7**	**+231.6**	**+113.1**	**+2107.6**

† Calculated using Eq. [2] taking ($\rho_b{}^d$ = 1,060 kg m^{-3} and $\bar{S}$ = 7 mm for 1998) and ($\rho_b{}^d$ = 1,100 kg m^{-3} and $\bar{S}$ = 19 mm for 1999).

7.4 Discussion

7.4.1 Comparing of practise and theory

Figure 7.2 depicts the average values of nutrient inputs and outputs of total N, P and K. The total inputs of K were much higher than the outputs mainly because of the very high positive nutrient contribution by sedimentation. For total N and P, the average inputs are also moderately higher than the outputs.

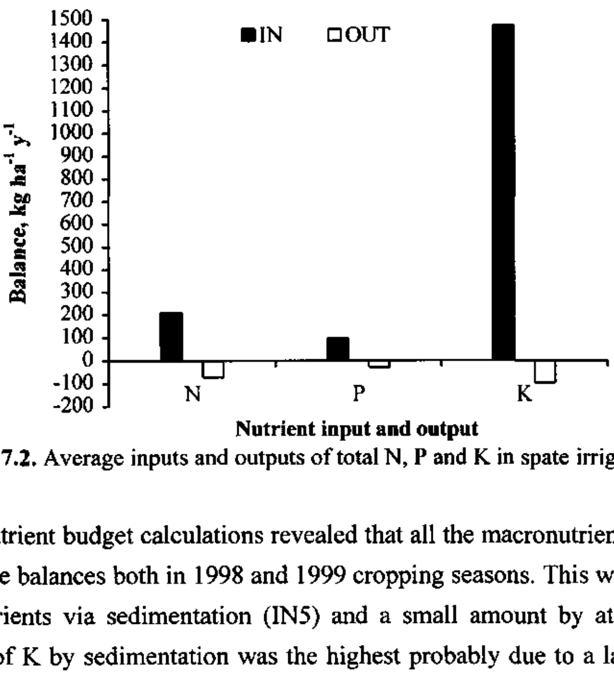


Figure 7.2. Average inputs and outputs of total N, P and K in spate irrigated fields, (1998 & 1999).

The nutrient budget calculations revealed that all the macronutrients (total N, P and K) showed positive balances both in 1998 and 1999 cropping seasons. This was accounted by a great input of nutrients via sedimentation (IN5) and a small amount by atmospheric deposition (IN3). Input of K by sedimentation was the highest probably due to a large amount of K-containing mica derived clay minerals such as chlorites (Halcrow 1997) are weathered from the Sheeb catchments. The size of total P inputs and outputs were the lowest among the macronutrients.

The average nutrient balance i.e. the average of the two input factors minus the average of the two output factors rendered the values +137 kg total N, +68 kg total P, and +1,378 kg total K per ha per year. This indicates that all the nutrients (total N, P and K) are accumulating in the soils. In other words, total elements of N, P and K are not depleted from the soil pool.

The total nutrient budget in Table 7.4 can be converted into available forms of nutrients in order to assess the contribution of atmospheric deposition (IN3) and sedimentation (IN5) to the soil fertility and soil productivity in the spate irrigation system. In most soils, the amount of phosphorus and potassium in the available forms at any one time is very low, seldom exceeding about 0.01% and 1-2% of the total phosphorus and potassium in the soil, respectively (Brady 1991). Hence, the average total P and K balance (Table 7.4) would be equivalent to +0.68 kg ha^{-1} of available P and +20.7 kg ha^{-1} of available K. These amount of available nutrients might have a small contribution to improve soil fertility and productivity of spate irrigation system.

The average nutrient stocks in the soils were 3.8 tons of total N, 1.9 tons of total P and 28.6 tons of total K ha^{-1}, taking the nutrient contents of the soils in 1999 (Table 7.2), and the mass of topsoil as 2.75×10^6 kg ha^{-1}. Assuming an annual mineralisation rate of 2% nitrogen (Niemeijer 1998), about 76 kg N ha^{-1} becomes available for crop uptake. This is more than the annual N output through harvested crops and residues in 1998 (63.0 kg N ha^{-1}) but slightly less than in 1999 (84.0 kg N ha^{-1}) (see Table 7.4).

In general, the results of nutrient balance and budgets suggest that the spate irrigation system may be sustainable with regard to N, P and K.

7.4.2 Strengths and weaknesses of NBA

The application of the nutrient balance approach in spate irrigated fields has some weaknesses. Firstly, the nutrient balance study quantified the inputs and outputs of nutrients to and from the spate irrigated fields using primary data, transfer functions and a number of assumptions. Secondly, the use of regression analysis to calculate atmospheric deposition (IN3) and data on crop nutrient contents (Stoorvogel and Smaling 1990) are less reliable for lower scales (plot/field) because the model is more relevant to supranational and continental scales of study. Thirdly, the nutrient inputs (IN3 and IN5) largely consists of nutrients not immediately available to crop uptake because the elements are present in the form of solid organic and inorganic particles except to minor flow of dissolved available nutrients via infiltrating water. Last but not least this study could not carry out plant and water analysis (because of a lack of facilities). Hence, the result obtained herein on nutrient balance and budget should be interpreted with caution, when discussing the sustainability of the spate irrigation system in relation to soil nutrients.

Despite these shortcomings, the concept of NBA has a wide range of applications from plot/field to continental and global scales. The nutrient balance calculations is straightforward i.e. the sum of inputs minus the sum of outputs, though some of the factors are difficult to measure. The balance includes all possible nutrient inflows and outflows in the soil and plant systems. It indicates whether the balance is negative (nutrient depletion) or positive (nutrient accumulation) or zero (steady state) and shows the general trend of nutrient status in the soils and gives a signal if measures are required to maintain the nutrient stocks in the soils in the long-term. In general, nutrient balance provides information on the long-term fate of the land and not just the next crop. Van der Pol (1992) argued that nutrient balance constitute an important diagnostic tool, with the power to demystify the consequence of farming on soils by describing them in a transparent manner.

7.4.3 Improving soil fertility

The average grain yield of sorghum (OUT1) at times of good season varies between 1,500-2,000 and 800-1,000 kg ha^{-1} for the seeded and for the ratoon crop, respectively. These yields are fairly high compared to other rainfed sorghum production areas in Eritrea (Natarajan 1999). But, there seems to be still possibilities of increasing crop production (↑OUT1) by about 50% using improved farming practises such as application of inorganic fertilisers, proper plant density, weeding, pest control, etc. Field experiments in spate irrigated areas in Yemen have shown that crop yields of sorghum were increased by 30-50% with the application of nitrogen fertilisers and other improved farming practises (UNDP/FAO 1987). Table 7.5 gives the average crop yields under traditional versus improved spate irrigation practices. The total cropping intensity in the Sheeb area is 165% (>100%) in a good year, implying that double or triple cropping is not uncommon practise in spate irrigation crop production system.

Table 7.5. Estimated average crop yields under traditional versus improved spate irrigation farming.

Crop	Cropping intensity †	Traditional farming	Improved farming	Increment by
	%	Kg ha^{-1}		%
Sorghum	65	1500-2000	3000-4000	50
Ratoon crop	40	800-1000	1500-2000	50
Maize	25	1000-1500	2000-3000	50
Millet	20	500-800	1000-1500	50
Others	15	nd	nd	nd
Total	165	-	-	-

† Adapted from IFAD (1995)
nd: not determined.

There are several options at hand to improve the fertility status of the spate-irrigated soils in Sheeb area. The farmers can easily adopt integrated nutrient management practises such as those listed in Table 7.6. Integrated nutrient management is defined as the 'judicious' manipulation of nutrient inputs, outputs and flows in the farm in a way that leads to 'satisfactory' and sustained production from both environmental, economical and social standpoints (Smaling and Braun 1996). Nutrient management practises (Table 7.6) would not so much decrease the losses of nutrients from the spate-irrigated fields but add new nutrient supplies to the fields.

Organic fertilisers such as manure (where possible) and crop residues can be incorporated into the soils of Sheeb spate irrigated fields. The addition of organic fertilisers increases soil organic matter content which, in turn, results to an increase in water storage and nutrient retention capacity of the soils and prevents nutrients from leaching (Smaling 1993; Zacchea et al. 1997). However, incorporation of crop residues into the soils is only practicable when developing other means of providing feed for livestock. The possible options to alleviate the problem of feed could be to grow forage plants along the wadi beds or to plant leguminous tree species (that are adaptable to the Sheeb area) along the field bunds. These trees besides used as sources of fodder, enrich the soil with nitrogen through fixation (↑IN4) and serve as windbreak and shelter. Further, the trees also intercept leaching of nutrients (↓OUT3) during flooding and pump up nutrients from deep soil layers, which are inaccessible to roots of annual crops.

Table 7.6. Major constraints and possible solutions to improve soil fertility in Sheeb spate irrigation system.

Constraints	Possible solutions
No inputs of organic fertilisers	Application of manure (↑IN2) and restitution of crop residues (↓OUT2)
No input of nutrients by biological fixation	Growing leguminous crops (↑IN4) such as ground-nuts, cowpea, soybeans, etc. and introduction of agroforestry in the spate irrigation system
Continuous cropping of sorghum and maize	Diversification of crops by practising intercropping and crop rotations (legumes with sorghum or maize)

Other options to improve the fertility of spate irrigated soils are growing leguminous crops (↑IN4) and introducing intercropping and crop rotations in the cropping system. In addition, planting trees along the hillsides in the catchments of Sheeb would regenerate the vegetation growth and increases the biomass production, which in turn, improve the fertility of the soils in the highlands and eventually improve fertility of the spate irrigated soils in the Sheeb area.

The reasons put forward by Sheeb farmers for not applying fertilisers in the spate-irrigated fields are (1) the farmers believe that the spate irrigated soils are sufficiently rich in nutrients, (2) the floods will wash off the applied mineral and organic fertilisers, and (3) the mineral fertilisers and manure will burn the crops.

The chemical analysis revealed that the nutrient content of total N and organic matter is relatively low but available P and K are high for the reasons explained elsewhere in this text. Therefore, the first assumption of farmers that the soils are rich in nutrients did not prove to be correct with regards to total N and organic matter. The second and third famers' concern can be avoided by broadcasting manure just after flooding of fields is over but before sowing of seeds. Such method of application would retain the fertilisers in the soil and it gives sufficient time for the manure to decompose and to dissolve so that the germinating seeds do not get burnt. But, with regard to the applications of inorganic fertilisers, fertiliser research should be conducted first that takes into consideration the technical aspects (kind, dosage, timing and placement of fertilisers) and the social and economic effects of fertiliser applications on spate irrigation system in the Sheeb area.

7.5 Concluding remarks

The macronutrient balance calculations for spate irrigated fields in Sheeb area were quantified using primary data, transfer functions and assumptions. The average inputs of total N, P and K showed a positive balance in both years (1998 and 1999) due to a high input of nutrients by sedimentation. This implies that the spate-irrigated soils are not depleted in total elements of N, P and K. Hence the spate irrigation system may be sustainable with respect to these macronutrients. But, the total nutrient balance data should be interpreted with caution. It should be emphasised that positive balance in this study does not necessarily mean that fertiliser applications are not required. The balance indicates that nutrients are not mined. It must be remembered that, this study quantified only some, although, the major inputs and outputs of nutrients to and from the spate irrigated fields.

The soils inside spate irrigated fields (with sedimentation) showed better nutrient status than outside the fields (without sedimentation). The difference is likely to be attributed by nutrient harvesting effects. However, the fertility class of spate irrigated soils with regards to total N and organic matter remains to be low. Research in Yemen indicates that there is still room for yield improvement with better management practises. It is still remains to be seen whether, for Sheeb conditions this should be in the water (Chapter 8) or in the nutrient sphere. This chapter suggests that nutrients are not a production limiting factors for spate irrigation system. If this conclusion becomes not (fully) correct, farmers can easily improve the fertility status of spate irrigated soils in Sheeb area by adopting integrated nutrient management practises such as applying organic fertilisers; incorporation of crop residues; growing leguminous crops and practising crop rotations.

7.6 References

Ahenkorah, Y., Owusu-Bennoah, and Dowuona, G.N.N. (ed.), 1995. Sustaining soil productivity in intensive African agriculture, seminar proceedings, November,1993, Accra, Ghana.

Bekunda, Mateete.A., Andre Bationo, and Henry Ssali, 1997. Soil fertility management in Africa: A review of selected research trials: A special publication No.51, of the Soil Science Society of America (SSSA), Madison, Wisconsin, USA, pp. 63-80.

De Jager, A., Nandwa, S.M., and Okoth, P.F., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON) I. Concepts and methodologies. Agriculture, ecosystems and environment 71 (1998) pp. 37-48.

Elias, E., Morse, S., and Belshaw, D.G.R., 1998. Nitrogen and phosphorous balance of Kindokoisha farms in southern Ethiopia, Agriculture, ecosystem and environment 71, pp. 93-113.

FAO/Unesco, 1988: Soil map of the world, revised legend with corrections. World soil resources report 60. FAO, Rome, Italy, 140pp.

FAO, 1994. Eritrea agricultural sector review and project identification, Annex 5, Rome, Italy, 3-4 pp.

FAO, 1997, FAO production year book, Vol.51, 1997. FAO statistics series no. 142. FAO, Rome, pp 239.

FAOSTAT, 1998. FAO Agricultural database. In: FAO. 1999. Soil fertility initiative for sub-Saharan Africa, world soil resources reports No.85. Proceedings of the SFI/FAO consultation, 20 November 1998, Rome, Italy.

Halcrow, W., 1997. Inception report, Eastern lowlands wadi development project, MoA, Asmara, Eritrea, 50 pp.

Hengsdijk, H., Quak, W., Bakker, E. J., and Ketelaars J.J.M.H., 1996. A technical coefficient generator for land use activities in the Koutiala region of South Mali, DLV-Report no.5, Wageningen, The Netherlands, 96 pp.

Houba, V.J.G., Van der Lee, J.J. and Novozamsky, I., 1995. Soil analysis procedures and other procedures (Soil and plant analysis, Part 5B), Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, The Netherlands, pp 41-44 and pp.121-128.

IFAD, 1995. Appraisal report on Eastern lowlands wadi development project, Vol.I Main report and Annexes Eritrea, 52 pp.

ILACO, BV., 1989. Agricultural compendium for rural development in the tropics and subtropics. Elsevier, Amsterdam, pp. 51-195.

Landon, J. R., 1991. Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London, UK.474 pp

Loveday J. Beatty, H. J. and Norris J.M., 1972. Comparison of current methods for evaluating irrigation soils. In: Landon, J. R., 1991. Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London, UK., pp.157-177.

Natarajan, M., 1999. Report on production and farming systems agronomy; strengthening the agricultural research and extension in Eritrea, GCP/ERI/001/ITA, FAO branch, Asmara, Eritrea, 50 pp.

Niemeijer, D., 1998. Soil nutrient harvesting in indigenous 'teras' water harvesting in eastern Sudan. Land degradation and development, 9: 323-330.

NRCE, 1996. Final report on the reconnaissance study of water-based agricultural development potential in Eastern Eritrea, Asmara, Eritrea, 202 pp.

Reuler van H. and Prins, W.H., 1993. The role of plant nutrients for sustainable food crop production in sub-Saharan Africa, Dutch Association of Fertiliser Producers (VKP) Wageningen, The Netherlands, 232 pp

Sanchez A.Pedro, Keith D.Shepherd, Meredith J. Soule, Frank M. Place, Roland J. Buresh, Anne-Marie N. Izac, A. Uzo Mokwunye, Fred R.Kwesiga, Cyrus G.Ndiritu, and Paul L. Woomer., 1997. Soil fertility replenishment in Africa: An investment in natural resource capital: A special publication no.51, of the Soil Science Society of America (SSSA), Madison, Wisconsin, USA pp.1-46.

Smaling, E.M.A., 1993. An agro-ecological framework for integrated nutrient management with special reference to Kenya. Ph.D. thesis, 250 pp.

Smaling, E.M.A. and Braun, A.R., 1996. Soil fertility research in sub-Saharan Africa: New dimensions, new challenges. Commun. Soil Sci. Plant Anal. 27: 365-386.

Smaling, E.M.A., Stephen M. Nandwa and Bent H. Janssen., 1997. Soil fertility is at stake. A special publication no.51, of the Soil Science Society of America (SSSA), Madison, Wisconsin, USA. pp 47-61.

Stoorvogel, J.J. and Smaling, E.M.A., 1990. Assessment of soil nutrients depletion in sub-Saharan Africa: Volume I–IV, Report 28, The WINAND Staring Centre, (SC-DLO), Wageningen, The Netherlands.

Talsma. T., 1968. Environmental studies of the Coleambally irrigation area and surrounding districts. In: Landon,J.R., Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London,UK., 474 pp.

Tesfai, M. and de Graaff J., 2000. Participatory rural appraisal of spate irrigation system in Eritrea. Journal of agriculture and human values (In Press).

Tisdale, S.L., Nelson, W.L. Beaton,J.D. and Havlin, J.L., 1993. Soil fertility and fertilisers. 5th edition, Macmillan publishing company, NewYork, USA, pp. 405-461.

Van der Pol, F., 1992. Soil mining: An unseen contributor to farm income in southern Mali Royal Tropical Institute, bulletin 325, Amsterdam, The Netherlands, 47 pp.

UNDP/FAO, 1987. Spate irrigation. Proceedings of the sub-regional expert consultation on wadi development for agriculture in the Natural Yemen, Aden, 180 pp.

Zaccheo, P.,Genevini,P. and Ambrosini, D., 1997. The role of manure in the management of phosphorus resources at an Italian crop-livestock production farm. In: Smaling, E.M.A., O.Oenema and L.O.Fresco. 1999. Nutrient disequilibria in agroecosystem: Concepts and case studies. CABI publishing, U.K., pp. 99-117.

Chapter 8

Soil Water Balance in Spate Irrigated Sorghum Fields

Abstract

A field experiment was conducted to quantify the various components of the water balance on sorghum [*Sorghum bicolor (L.) var.hijeri*] grown in arid climate of Sheeb, eastern Eritrea in spate irrigated fields. The main contributors to addition of water (irrigation and rainfall) and withdrawal of water (evaporation and transpiration) to and from the crop root zone, respectively, were considered in the calculation of the soil water balance. The crop evapotranspiration (ETc) was estimated using reference evapotranspiration and Penman-Monteith methods and the actual ET (ETa) was measured as the change in soil moisture contents (in the root zone) with Time Domain Reflectrometry (TDR). The estimated values of the crop coefficient at the four growth stages (initial, development, mid-season and late season) were 0.25, 0.62, 1.1 and 0.77-0.84, respectively. In 1999 (wet year), the ETa amounted to 420 mm during the total growing period which was slightly greater than the ETc (411 mm) but less than the ETc (465 mm) in 1998 dry year. On the other hand, the total water added (720 mm) to the crop root zone was greater than the total water lost (420 mm) from the root zone. Hence, a positive water balance of 300 mm moisture was achieved in the root zone of sorghum. To satisfy an average crop water requirement of about 440 mm and evaporation loss (60 mm) with effective rainfall contributing about 100 mm, a total amount of 400 mm water is needed for the main crop sorghum and more water with ratooning. The irrigation depth (0.75 m) estimated in this study falls within the upper limit of farmers' field application depth (0.5-1.0 m). The causes of water shortage (in most of the years) in the spate fields appeared to be not the depth of irrigation water but the number of irrigations applied to the fields and the uneven distribution of water over the fields.

8.1 Introduction

Lack of adequate water supply is one of the principal constraints to crop production in arid regions of the world (Lal 1991). In these regions, crop production is possible only when additional water is made available for cultivation. For instance, in the eastern lowlands of Eritrea where the mean annual rainfall is very low (< 200 mm y^{-1}), farmers are producing crops by the system of spate irrigation. Spate irrigation is a unique form of irrigation predominately found in arid regions whereby flash floods (with very short duration) from highland areas are diverted to irrigate fields in the lowlands (UNDP/FAO 1987).

During the rainy season (July-September) in the highlands of Eritrea, runoff causes floods that turn out into seasonal rivers (wadis) which flow towards the Red Sea, crossing the eastern lowlands of the country (such as the Sheeb area). In the lowlands, the floods with their sediments are diverted by means of temporary irrigation structures locally called 'agims', and conveyed by distribution canals called 'misghas' to a series of arable fields. Eventually, the water is collected in the fields that are surrounded by earthen bunds of 0.5-1.0 m high. The diverted water infiltrates into the deep soil profiles, while sediment that includes plant nutrients and organic matter are deposited on the soil surface. Seeds are sown on these fields and crop production is sustained under residual moisture in the soil profile.

During the flood season (July-September) in the lowlands, the spate irrigation farmers in Sheeb area divert a certain amount of floodwater to their fields. In case there are very few floods during the season the farmers might face water shortage during the cropping season (September-January) when there are no more floods to divert and no other means of water supply, except from little rainfall.

The spate irrigation farmers rely on empirical evidence and traditional knowledge for their irrigation practises. Therefore, it is of interest to quantify the various components of the water balance (irrigation, rainfall, evaporation, transpiration, etc.) and water uptake; application and distribution in the soil in scientific terms. This helps to judge the adequacy of the farmers' irrigation practises. Moreover, it allows an estimate of the development potential of the spate irrigation system and of the possible expansion of the system into new areas.

8.2 The approach

The most commonly used soil water balance equation for the root zone is given by (Hillel 1980; Lal 1991) as follows:

$$\Delta S = P + I + CR - RO - DP - (E + T) \qquad [1]$$

where ΔS is the change in soil moisture in the soil profile during crop growth; P is rainfall; I is irrigation; CR is capillary rise; RO is surface runoff; DP is deep percolation; E is evaporation from the soil surface and T is transpiration from plants. All terms of Eq.[1] are expressed in mm of water. The first three factors (P, I, CR) add water to the root zone, while the last four factors (RO, DP, E and T) remove water from the root zone.

In spate irrigated fields of Sheeb area, the water input to the fields is mainly by irrigation (I) i.e. through flooding and in smaller amounts by rainfall (P). The upward flow of ground water by capillary rise (CR) towards the root zone is assumed to be negligible due to deep ground water levels (often >10 m) during the cropping season. Capillary rise can normally be assumed to be zero when the water table is more than 1 m below the bottom of the root zone (Dastane 1979; Allen et al. 1998).

On the output side, the major losses of water are evaporation (E) from the soil surface and transpiration by crops (T). In this study, the loss of water by deep percolation (DP) is assumed to be zero. Normally there is no irrigation after sowing under the system of spate irrigation. The little rainfall during the cropping season is also assumed to be effective in the crop root zone. This implies that during the crop-growing period, the soils would hardly drain and thus DP = 0. Surface runoff (RO) is also considered to be zero due to the flat topography of the spate irrigated fields.

Spate irrigation systems are characterised by a separation of the period in which irrigation (I) takes place and where evapotranspiration (ET) takes place. We can now simplify Eq. [1] in to:

$$\Delta S = P - ET \qquad [2]$$

in which ΔS is change in soil moisture (mm) in the root zone of sorghum (0-1.8 m) from date of sowing until harvest and ET is the evapotranspiration (mm). With a relative simple measurement of P, we can obtain ET values by determining ΔS. The latter will be done by frequent measurements of the total amount of water in the root zone.

In order to judge the adequacy of the farmers' irrigation practises, we will compare the actual ET (ETa) with the crop ET (ETc), i.e. the value of ET when the crop grows without moisture stress. ETc will be estimated in a two-step procedure. Firstly, a reference ET (ETo) will be determined. Secondly, ETc will be obtained by multiplying ETo with a so-called crop coefficient (k_c) (Allen et al. 1998). The latter varies over the cropping season (mainly due to a difference in leaf area index) and can be obtained from literature.

8.3 The method

8.3.1 Experimental site and crop characteristics

The study was conducted in the eastern lowlands of Eritrea in Sheeb spate irrigated fields from September to January for two consecutive years (1998 and 1999). The Sheeb area (15°52'N; 39°01'E, 225 m a.s.l,) is located about 60 km north-west of the Eritrean Red Sea port, Massawa. The area has a flat topography with a slope of 1 to 2% from west to east. The soils of the experimental fields are regarded as 'homogenous' alluvial soils of loamy texture. In general, the soils are fertile with good water holding capacity and are well drained (Chapter 5).

The climate of Sheeb area is hot and arid with mean annual ETo of more than 2000 mm and mean annual rainfall less than 200 mm (long-term data) falling mainly in the period October to January. Mean monthly air temperature ranges from about 25°C in January and February to about 36°C in July and August, but with maximum temperatures exceeding 40°C. The mean relative humidity is often below 50% during the summer but reaches 88% in January. The mean sunshine hours range between 11 to 13 hours per day in the cropping season and off-season, respectively. The annual solar radiation varies from 22-29 MJ m^{-2} d^{-1}. During the summer, strong windstorms locally called 'Khamsin' are often produced in the Sheeb area, which blow day and night (IFAD 1995; Halcrow 1997).

In Sheeb area, the major crops grown are sorghum followed by maize, millet and some vegetables. The sorghum crop [*Sorghum bicolor (L.)*] is planted in mid-September and harvested after 90-120 days. The crop is well adapted to the arid climate of Sheeb area because of its well-branched and deep root system, which could extract residual moisture from the deep soil layers. Sorghum is sometimes locally called a 'camel crop' because it can grow well under low moisture regime.

When the residual soil moisture levels permit, the sorghum crop is ratooned and a second harvest of grain is taken from the original plants. In some years, it is also possible to harvest a second ratoon but for forage only, which is used as livestock feed. Ratooning behaviour of sorghum has many advantages. First, by the time the main crop matures, the remaining moisture in the soil profile is deep. New seeded plants do not have a chance to grow because they are unable to reach and use the deep water. But, the ratoon crop could extract this residual moisture and give yields. Second, a ratoon crop avoids land preparation, seeding and problems of establishing a good stand from seed, which therefore reduces material and labour costs (Chapter 4). Last but not least, the period between sprouting and harvesting is always shorter (70-80 days) in a ratoon crop than in a seeded crop (Doggett 1988).

8.3.2 Measurement of actual evapotranspiration (ETa)

A field experiment was conducted in a plot of 20 × 40 m situated in the midstream of wadi Laba and Maiule spate irrigated fields (see Map 6.1, Chapter 6). The purpose was to determine the ETa rate by measuring the change in soil moisture content over a certain period of time. Owing to the 'homogeneity' of the soils in the experimental plots, three sampling sites were selected within the plot. The plot was subdivided into upper, middle and lower subplots, each with a size of approximately 20 × 13 m.

Prior to sowing of seeds, three boreholes were dug to 2 m depth at the three subplots using an Edelman auger with extension rods. Afterwards, three plastic access tubes (each length 2.0 m) were installed in the monitored boreholes to a depth of 1.8 m. Access tubes were sealed by top-caps, closed with rubber stoppers at the lower end and were left in the soil until harvest. A few days after installing the access tubes, the whole field was sown with sorghum, local variety 'hijeri'.

The change in soil moisture contents in the root zone (i.e. the soil moisture depletion) was measured with Time Domain Reflectometry (TRIME–FM). TDR measures soil moisture contents near the surface as well as at various depths in the soil profile (Wegehenkel 1998).

TDR relates volumetric soil water content (cm^3 H_2O cm^{-3} soil) to the apparent dielectric constant of the soil (Topp et al. 1980). The moisture content (%) was later converted into mm of depth of water to conform to the standard unit of ET measurements and crop water requirement data.

The initial soil moisture content (θ_I) measurement was made at sowing date of sorghum on 19 September 1998 and 30 September 1999 to determine the amount of soil moisture stored in the root zone. Thereafter, measurements were carried out at approximately fortnight intervals from day 0 until day 108 (in 1998) and until day 91 (in 1999) after sowing. During this period, soil moisture readings were taken at 0.2 m intervals from the soil surface to a depth of 1.8 m. Dogett (1988) reported a maximum rooting depth of 2.0 m for sorghum.

The final soil moisture content (θ_F) was measured at crop harvest on 4 January 1999 and 30 December 1999. The change in soil moisture content from sowing to harvesting of sorghum within the rooting depth plus the rainfall within this period gives the actual water loss from the soil and from the crop.

$$\sum ET_a = \sum_{i=1}^{i=n} (\theta_I - \theta_F) \Delta D_i + P \qquad [3]$$

where ΣET_a is in mm per cropping season, n is the number of layers to the rooting depth, θ_I is the initial soil moisture (%) at sowing, θ_F is the final soil moisture (%) at harvesting, ΔD_i is the thickness of each layer in mm, P is the rainfall in mm, measured with a raingauge.

In addition to the field measurements, discussions on farm water management issues were held with spate irrigation farmers in the Sheeb area.

8.3.3 Estimation of reference evapotranspiration (ETo)

The reference ET (called ETo, hereafter) was determined using the pan evaporation method as well as using the Penman-Monteith approach. A Class-A evaporation pan was installed at Sheeb automatic meteorological station, located at a distance of about 100 m open fetch to the east of spate-irrigated crop fields (see Map 6.1, Chapter 6). The pan was sited in the station on bare dry soils surrounded by spate irrigated cropped fields, which have an average wind speed of < 2 m s^{-1} and relative humidity $> 70\%$. The evaporation pan was covered with screen made of fine galvanised wire, 1 mm in diameter by 50 mm mesh to protect birds from drinking the water. Thin wired screens mounted over the pan reduce pan evaporation by 10% in (semi-) arid environments (Howell et al. 1983; Allen et al. 1998).

The evaporation pan measurements were done daily in the morning at 07:00 hours from the seeding date (19/9/98 and 30/9/99) until harvest date (04/01/99 and 30/12/99). ETo was calculated according to Doorenbos & Pruitt (1977) and Allen et al. (1998) with minor adjustment to fit the local conditions.

$$\text{ETo} = K_{pan} \times (E_{pan} + 0.1 E_{pan}) \qquad [4]$$

where ETo is reference-crop ET (mm per day), K_{pan} pan coefficient (-) taken from Table 5 of Allen et al. (1998) and E_{pan} is pan evaporation (mm per day). When calculating ETo, 10% of the Epan was added in order to compensate the screening effect on the pan evaporation.

Parameters such as air temperature, relative humidity, wind speed and radiation were collected from the meteorological station at Sheeb to compute the ETo using the Penman-Monteith method (CROPWAT program, version 5.7 by Smith 1992). However, the ETo was calculated only for 1998 because of missing and doubtful climate data in 1999.

8.3.4 Estimation of crop evapotranspiration (ETc)

To account for the effect of the crop characteristics on crop water requirements, the crop coefficients (k_c) approach was used. Crop coefficients at various phenological stages of crop growth (initial, developmental, mid-season and late season) were calculated following the equation as given by Allen et al. (1998) with few adjustments to fit the local climatic conditions (see Table 8.1). The crop-ET was computed (Doorenbos & Pruitt 1977; Allen et al. 1998) using the formula:

$$\text{ETc} = k_c \times \text{ETo} \qquad [5]$$

in which ETc is crop ET (mm per day). The k_c-values obtained from Allen et al. (1998) should be combined with ETo-values estimated as described in Allen et al. (1998). The latter estimate of ETo is based on the Penman-Monteith approach, which is the same as used by Smith (1992) in the CROPWAT-program. Therefore, it seems that a combination of k_c according to Allen et al. (1998) with ETo according to Smith (1992) gives appropriate values for ETc.

Table 8.1. Calculation methods of crop coefficients (k_C) by growth stages used in this study.

Growth stages	k_C equations and sources
Initial	$k_{C\,ini}$ derived from (Figure 30b of Allen et al. 1998)
Development	$k_{C\,dev.}$ developed from constructed k_C curve (Figure 8.3)
Mid-season	$k_{C\,mid} = kc_{\,mid}(Tab)† + [0.04 (U_2‡ - 2) - 0.004 (RH_{min}\,§ - 45)]\{¶\,h/3\}^{0.3}$
Late season	$k_{Cend} = k_{C\,end} (Tab)† + [0.04 (U_2‡ - 2) - 0.004 (RH_{min}\,§ - 45)]\{¶\,h/3\}^{0.3}$

† $kc_{\,mid}$ (Tab) and $kc_{\,end}$ (Tab) are 1.05 and 0.55 values, respectively taken from Table 12 of Allen et al. (1998).

‡ Mean U_2 (daily wind speed) at 2 m height during mid-season (1.6 m s^{-1}) and end of the late season stage (1.52 m s^{-1}).

§ Mean RH_{min} (daily minimum relative humidity) during mid-season (27.5%) and end of the late season stage (48.6%).

¶ Mean h (plant height) during the mid-season and end of the late season stage (2 m).

8.4 Results and discussion

8.4.1 The measured ETa of sorghum

Under field conditions, the ETa of a crop is a function of ETc and the soil moisture depletion in the root zone. Because of technical problems encountered in installing the access tubes in 1998, ETa was analysed only for the 1999 cropping season.

Table 8.2. Soil moisture, ΔS, and ΣETa (mm) in sorghum spate-irrigated field, 1999.

Crop stage	SO	GE	CD†	CD‡	FL	R & H	ΔS	ΣP	ΣETa
DAS	0	14	28	51	76	91	-	-	-
P	0.0	17.6	12.7	25.0	24.5	24.5	-	104.3	-
Upper	597.0	543.2	492.4	408.0	308.0	299.4	297.6	104.3	401.9
Middle	538.8	533.4	433.6	409.6	306.8	281.2	257.6	104.3	361.9
Lower	716.4	715.6	640.2	427.4	375.6	324.8	391.6	104.3	495.9
Mean	617.4	597.4	522.2	415.0	330.2	301.8	315.6	104.3	419.9

DAS: days after sowing, SO: sowing, GE: germination, CD: crop development, FL: flowering, R & H: ripening & harvesting and P: rainfall (mm) per stage.

† 0.20 m crop height (mean).

‡ 1.0 m crop height (mean).

Soil moisture, ΔS and ΣETa at upper, middle and lower subplots are presented in Table 8.2. The soil moisture at the lower subplot was higher than at the middle and upper subplots throughout the entire crop growth stages. This may be attributed to accumulation of water caused by improper land levelling. The soil moisture in all three subplots gradually decreased from sowing to harvesting because of increasing moisture depletion by the sorghum crop. After 91 days of sowing, the total soil moisture depletions were about 298, 258 and 392 mm in the upper, middle and lower subplots, respectively within the root zone (0-1.8 m). The highest moisture depletion (182 mm) was measured during crop development stage and the lowest moisture depletion (20 and 28 mm) during germination and from ripening to harvesting stage, respectively.

A total of about 104 mm of rain was captured between the date of sowing and harvest (Table 8.2) and the depth of rains varied from 0.5 to 25 mm. All irrigation and rainfall were assumed to be effective up to the field capacity of the average spate soils (about 400 mm m^{-1}, Chapter 5).

Figure 8.1 depicts the change of soil moisture profiles between sowing and harvesting at upper, middle and lower subplots in spate-irrigated sorghum fields. It can be observed from the figure that, the soil moisture was decreasing with depth as well with time (from the time of sowing to harvesting) in all three subplots. The moisture depletion rates were greater in the deep subsoil layers between the depth of 1.0-1.6 m than in the top 0.8 m. In other words, the crop water uptake in all the three subplots was larger in the deep subsoil layers. This is probably due to the well-branched and deep rooting development of sorghum towards the late stage of crop growth.

The soil moisture profile in the average subplots clearly shows that the root distribution of sorghum expands laterally in the deep subsoil layers (Figure 8.1.). At crop harvest about 300 mm, 280 mm and 325 mm moisture remained (in the root zone) in the upper, middle and lower subplots, respectively. The average moisture of the plots (i.e. about 300 mm) in the root zone could be used for growing a ratoon crop.

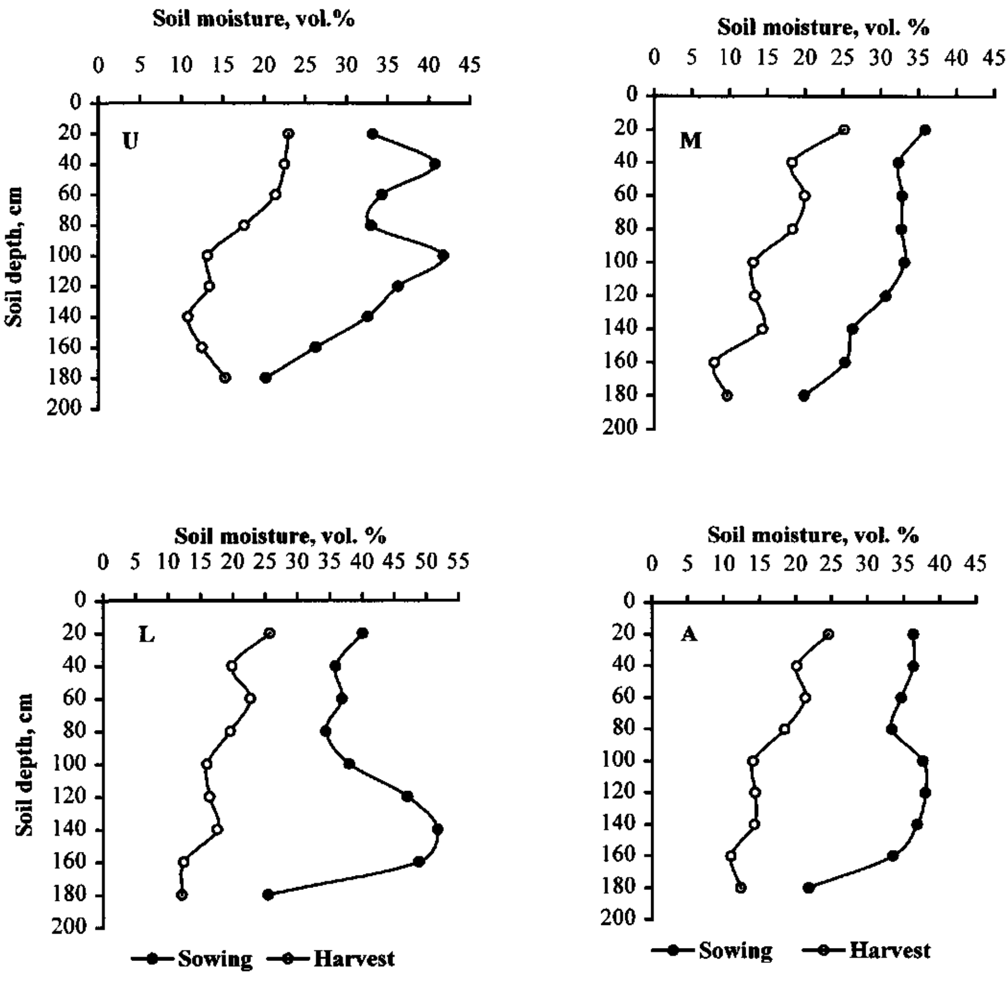


Figure 8.1. The soil moisture profiles between sowing and harvesting at **U**: upper; **M**: middle; **L**: lower subplots and **A**: average for all subplots in a spate irrigated sorghum field, 1999.

8.4.2 Estimated ETo

The mean monthly climate data of Sheeb spate irrigation area during the cropping seasons of 1995-98 is given in Table 8.3. The last three columns of the table compare the value of ETo using the Class-A pan method versus the Penman-Monteith. Accordingly, the estimated mean ETo (4.8 mm d^{-1}) using pan evaporation gave very close value to the mean ETo (4.9 mm d^{-1}) calculated by Penman-Monteith method using a long-term (1970-1997) climate data of Massawa, but it was lower than the 1998 data of Sheeb (5.8 mm d^{-1}) by Penman-Monteith. ETo decreased from the months of September (6.0-6.9 mm d^{-1}) to January (3.7-4.6 mm d^{-1}). This is due to the decrease of air temperature, wind speed, wind run and solar radiation. Whereas, relative humidity increased from 54% in September to 88% in January. ETo (pan) in Sheeb is about 20% lower than ETo (Penman-Monteith in Sheeb). Pan data can easily be converted into approximate Penman-Monteith values by using slightly (20%) higher values for Kpan as used in Table 8.4.

Table 8.3. Mean monthly climate data during cropping season in Sheeb area, 1995-98 †.

Month	Air temp.	Relative humidity	Wind speed	Wind run	Solar radiation	ET_O Class-A pan ‡	ET_O PenMon § (Sheeb)	ET_O PenMon¶ (Massawa)
	°C	%	km h^{-1}	km d^{-1}	MJ $m^{-2}d^{-1}$	mm d^{-1}	mm d^{-1}	mm d^{-1}
September	33.4	54.2	7.0	64.8	29.5	6.0	6.9	6.8
October	30.9	62.8	5.6	53.8	29.4	5.4	6.6	5.7
November	29.6	74.6	6.6	56.5	26.4	4.9	5.8	4.6
December	27.1	82.6	6.7	51.9	23.5	3.7	5.3	3.9
January	24.8	88.3	5.5	55.6	22.2	3.9	4.6	3.7
Mean	29.2	72.5	6.3	56.5	26.2	4.8	5.8	4.9
Total	-	-	-	-	-	734.4	887.4	749.7

† Source: adapted from Water Resources Department (1998).

‡ ETo in Sheeb area (1998 & 1999).

§ ETo (1998) using Penman-Monteith.

¶ Penman-Monteith calculated using 27-years mean climatic record of Massawa by Halcrow (1997).

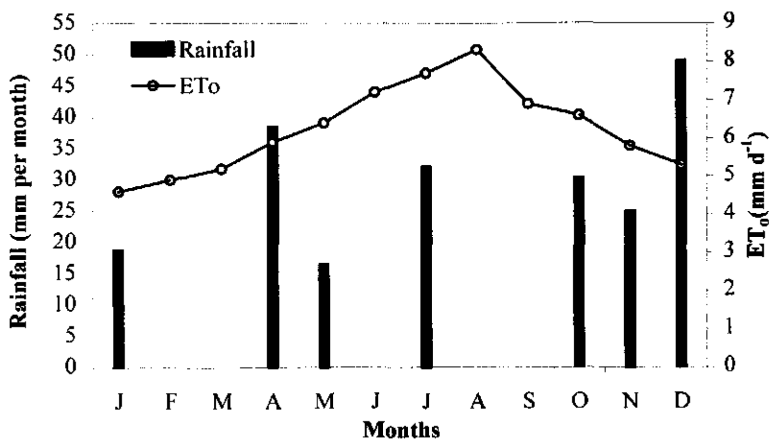


Figure 8.2. Monthly rainfall for 1999 and daily ETo (Penman-Monteith) in Sheeb area.

The monthly rainfall and the daily ETo in Sheeb area are shown in Figure 8.2. The daily ETo ranged from 4.6 mm in January to 8.3 mm in August. The annual ETo was estimated to be 2,280 mm which exceeded the annual rainfall by more than ten times and the monthly ETo exceeds the rainfall through out the year. Moreover, the ratio of rainfall to ETo was 0.09, which is in the range of 0.03-0.2 for arid climate indices according to UNESCO (1977).

Table 8.4. Mean daily measured evaporation from Class-A pan and its estimated ETo in Sheeb area, 1998-99.

Month & decade	No.of records days	1998 Epan	Kpan†	ET_O‡	1999 Epan	Kpan†	ET_O‡
September		mm d^{-1}	-	mm d^{-1}	mm d^{-1}	-	mm d^{-1}
II	2	10.5	0.65	6.8	nd	0.65	nd
III	10	8.0	0.65	5.2	nd	0.65	nd
October							
I	10	8.0	0.65	5.2	10.3	0.65	6.7
II	10	7.1	0.65	4.5	7.9	0.65	5.1
III	11	7.6	0.65	4.9	9.2	0.65	6.0
November							
I	10	7.3	0.75	5.5	7.4	0.75	5.6
II	10	6.9	0.75	5.2	5.9	0.75	4.4
III	10	6.3	0.75	4.7	6.0	0.75	4.5
December							
I	10	5.7	0.75	4.3	5.7	0.75	4.3
II	10	5.1	0.75	3.8	3.9	0.75	2.9
III	11	4.7	0.75	3.5	4.4	0.75	3.3
January							
I	4	5.3	0.75	3.9	nd	0.75	nd
Mean	-	6.9	-	4.8	6.7	-	4.8
Total	108	-	-	-	-	-	-

† Pan coefficients derived from Table 5 of Allen et al. (1998). Kpan 0.65 for mean RH of 40-70% and Kpan 0.75 for RH >70% and light wind speed (<2 m s^{-1}) where Class-A pan is sited at 100 m windward side distance of dry fallow.

‡ ETo calculated by Eq.[4].

nd: not determined because of sowing on 30/9 and harvesting on 30/12.

The daily measured pan evaporation and estimated ETo are given in Table 8.4. In general, the evaporation rate from the pan (Epan) and the ETo values in both years (1998 and 1999) showed a decreasing trend from September to January. The high relative humidity combined with low temperature, light wind speed and low solar radiation (Table 8.3) led to decreased evapotranspiration in the cropping season. The mean daily values of Epan during the cropping seasons were 6.9 and 6.7 mm per day in 1998 and 1999, respectively which are both high. The mean ETo (4.8 mm per day in both years) has a moderate evaporative power of the atmosphere according to Allen et al. (1998). The similar values of Epan and ETo in 1998 and 1999 can be explained by the uniformity of the climate of Sheeb area.

8.4.3 Estimated ETc of sorghum

Figure 8.3 shows a crop coefficients (k_c) curve for 'hijeri' sorghum grown under spate irrigation condition. As shown in the Figure 8.3, the k_c values increased from a value of 0.25 during initial stage to the maximum value 1.1 in the mid-season stage. The value of k_c begins to decrease towards the late season stage and reaches a lower value (0.52) at the end of the late stage.

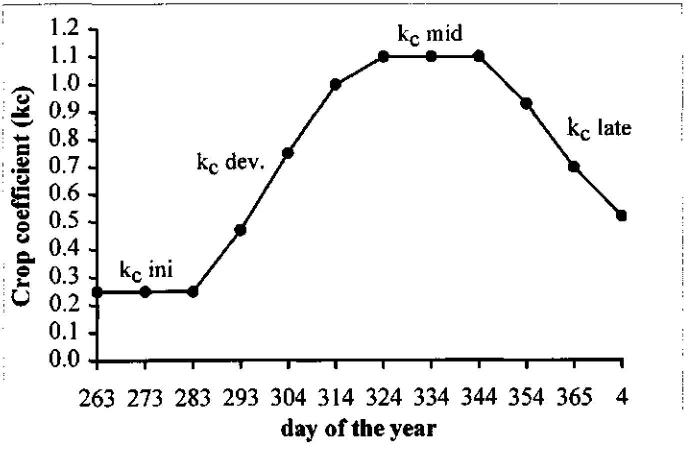


Figure 8.3. Constructed k_c curve (from 19 September to 4 January) per decade for spate irrigated sorghum in Sheeb area.

The crop coefficients and ETc in the various crop-growing stages are presented in Table 8.5. During initial growth stage, the ETc rate was as low as 1.7 and 1.6 mm per day in 1998 and 1999 respectively, mainly because of incomplete ground cover. Thereafter, the ETc progressively increases towards the mid-season stage and then declines during late season. The declining of ETc during the late season is due to decreasing value of k_c as a result of plant senescence. The peak ETc values were 6.4 mm per day in 1998 as well as in 1999, which occurred during mid-season (reproductive stage). The highest ratio of ETc to ETo (in other words the highest k_c = 1.1) was recorded when crop water requirement for flowering and grain formations reached its maximum value.

Table 8.5. Estimated crop ET by growth stages for 'hijeri' sorghum in Sheeb area.

Growth stage	Length of growth		ET_O		Crop coeff.	ETc	
	date	days	mm d^{-1} †	mm ‡	k_c	mm ‡	mm d^{-1}
1998							
Initial	19/9 - 7/10	19	6.9	131.1	0.25	32.8	1.7
Development	8/10 - 8/11	31	6.6	204.6	0.62 §	126.9	4.1
Mid-season	8/11 - 8/12	30	5.8	174.0	1.10	191.4	6.4
Late season	8/12 - 4/01	28	5.3	148.0	0.77 §	113.9	4.1
Mean	-	-	6.2	164.5	-	116.3	4.1
Total	-	108	-	658.1	-	465.1	-
1999							
Initial	30/9 - 12/10	13	6.6	85.8	0.25	21.4	1.6
Development	13/10 - 3/11	21	6.6	138.6	0.62 §	85.9	4.1
Mid-season	4/11 - 29/11	26	5.8	150.8	1.10	165.9	6.4
Late season	30/11 - 30/12	31	5.3	164.3	0.84 §	138.0	4.4
Mean	-	-	6.1	134.9	-	102.8	4.1
Total	-	91	-	539.5	-	411.2	-

† ETo-Penman-Monteith values for Sheeb (Table 8.3).
‡ Per growth stage calculated for ETo and ETc.
§ Average crop coefficients derived from constructed k_c curve (Figure 8.3).

ETc and ETo amounted to 465 and 658 mm in 1998, while 411 and 540 mm in 1999 during the total growing period. The length of growing seasons (108 days in 1998 and 91 days in 1999) contributes to the difference in values. In these two years, the seasonal ETc averaged 438 mm and falls within the range of 300-650 mm, an approximate range of seasonal sorghum ETc reported by Doorenbos and Pruitt (1977).

By definition, the ETc (under standard conditions) is equal to the so-called crop water requirement (Doorenbos & Kassam 1979; Allen et al. 1998). This means that, the total predicted crop water requirement (CWR) of 'hijeri' sorghum varied from 411 to 465 mm (Table 8.5). The CWR (411 mm) in 1999 corresponds good to 395 mm CWR of sorghum estimate made by NRCE (1996) using the Penman-Monteith approach. The highest CWR of 'hijeri' sorghum per growth stage (166-191 mm) was recorded during mid-season stage from the 1st week of November to the 1st week of December. While, the lowest CWR (21-33 mm) was predicted during initial stage of crop growth from mid-September to mid-October.

8.4.4 The occurrence of water stress

The cumulative values of actual and crop ET (ΣETa and ΣETc, respectively) after sowing of sorghum are shown in Figure 8.4. It can be observed from the figure that, the ΣETa was slightly higher than ΣETc in the first 14 DAS of sorghum. Thereafter, the ΣETa was much higher than the ΣETc until 60 DAS. The gap becomes smaller towards the end of the late stage of crop growth. At the time of crop harvest (91 DAS), the ΣETa was almost equal to ΣETc.

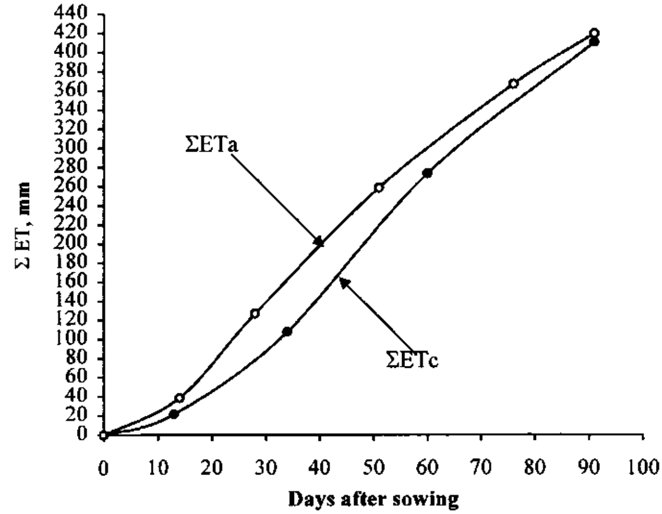


Figure 8.4. Cumulative values of crop ET and actual ET after days of sowing of sorghum in spate irrigated field, 1999.

Whenever the rate of ETa drops below the rate of ETc, water stress is induced in the growing crop. Since ETa/ETc was ≥1 over the entire cropping season in 1999, this implies that crop evapotranspiration was not affected by a lack of water. In other words, the sorghum crop was grown without water stress conditions. According to farmers in Sheeb, 1999 was considered as a 'wet' year in which most of the spate fields have received more than two floods. However, in most of the years, spate irrigated crops experience water stress conditions due to uncertainty of the floods and low efficiency of the spate irrigation structures (Chapter 2).

8.4.5 The water balance

Table 8.6 shows the seasonal soil water balance in the root zone of spate irrigated sorghum field. The total water supply (I + P) was 721 mm, of which 617 mm or 85% was contributed by irrigation (I) via flooding and 104 mm or 15% by rainfall. On the other hand, the consumptive use of water by spate irrigated sorghum fields amounted to 420 mm via evapotranspiration. Evaporation is said to be the major source of moisture loss in the initial stage of crop growth, while from crop development through mid-season and late season stage, transpiration plays the major role. The difference between the input (supply) and output (consumption) gave a positive water balance of about 300 mm of residual moisture in the root zone of sorghum at the time of harvest.

Table 8.6. Seasonal water balance in the root zone (0-1.8 m) of spate irrigated sorghum field, 1999.

Inputs/outputs	Amount, mm
Irrigation (I)	617.4
Rainfall (P)	104.3
Capillary rise (CR)	0.0
Total input	**721.7**
Evapotranspiration (ETa)	419.9
Surface runoff (RO)	0.0
Deep percolation (DP)	0.0
Total output	**419.9**
Balance	**+301.8**

8.4.6 Optimal irrigation depth

Table 8.7 gives an estimate of wetting profile depth and optimal irrigation depth under no stress conditions in spate irrigated sorghum fields. Assuming the moisture content at sowing was close to field capacity (θ_{FC}), we can calculate θ_{FC} from Figure 8.1 and Table 8.2 as θ_{FC} = (617 mm ÷ 1800 mm) = 0.34. Similarly, if we assume that at harvest the moisture is present in readily available (θ_{RA}) form since the crop has grown without water stress, then θ_{RA} = (302 mm ÷ 1800 mm) = 0.16.

Normally, the irrigation (or flooding) period in Sheeb area lasts for about 60 days (i.e. from July to August). During this period there is evaporation of water from the topsoil. Stroosnijder (1987) assumes an average value of 2 mm d^{-1}. However, farmers in Sheeb are well aware of the evaporation losses. Therefore, they apply a special form of tillage (locally called 'mekemet') to create a loose dry surface layer that reduces evaporation losses. It was estimated that this water conservation practise reduces evaporation with 50%. Hence, during the 60 days preceding sowing, evaporation loss was estimated at 1 mm d^{-1}. Therefore, with the average CWR (about 440 mm) and an effective rainfall (Pe) of about 100 mm during the cropping season, the total irrigation water need (TW) would be about 400 mm. With such amount of water supply, the wetting depth could reach up to 2.2 m in the soil profile. In Sheeb area, the spate-irrigated soils are almost dry just prior to the first flooding (1st of July). In other words, the initial moisture contents (θ_I) of the soils after a long dry period is equal to zero. Therefore, the irrigation (or flooding) depth required would be about 750 mm. This application depth assures spate irrigated sorghum crops to grow under no water stress conditions.

Table 8.7. Wetting profile and optimal irrigation depth under no stress conditions in spate irrigated fields of 'hijeri' sorghum.

Parameters	Value	Equation
Crop water requirement (CWR)	440	CWR ≈ ETc †
Evaporation loss (E)	60	$E = (1\ mm\ d^{-1} \times 60\ days)$
Effective rainfall (Pe)	100	-
Total irrigation water needed (TW)	400	TW = (CWR + E) – Pe
Wetting depth (D)	2200	$D = TW \div (\theta_{FC} - \theta_{RA})$ ‡
Irrigation depth (d)	750	$d = (D \times \theta_{FC})$
Soil water depletion fraction (p)	0.60	p = (p §) + 0.04 (5 – ETc ¶)

† Mean ETc (1998 and 1999).

‡ θ_{FC}: Assumed field capacity (0.34 $m^3\ m^{-3}$) and θ_{RA} readily available water (0.16 $m^3\ m^{-3}$).

§ Soil water depletion fraction for no stress taken from Table 22 of Allen et al. (1998).

¶ Mean ETc = 4.1 mm d^{-1} (Table 8.5)

Note that the values in Table 8.7 are expressed in mm except for p, which is a unitless.

The average bunded heights in spate irrigated fields are in the order of 0.5-1.0 m and this would represent the maximum depth of irrigation applied in any one application. The irrigation depth i.e. 0.75 m (Table 8.7) estimated in this study falls within the range of farmers' field application depth (i.e. flooding of fields between 0.5-1.0 m of the bunds height).

Although this study computed only the CWR of the main crop sorghum, the water requirement of the ratoon crop is likely to be less than the main crop because of its shorter length of growing period (70-80 days). In addition, the average grain yield of ratoon crop is often half of the yield of the main crop. At the harvest of the main crop, the soil moisture content is at $\theta_{RA} = 0.16$. The ratoon crop will be able to use the water in the soil profile between θ_{RA} and θ_{WP}. The estimates of θ_{FC} and θ_{RA} can be combined with an estimate of the soil water depletion fraction (Table 8.7) in order to estimate θ_{WP}. According to Allen et al. (1998):

$$\theta_{RA} = \theta_{FC} - p \times (\theta_{FC} - \theta_{WP}) \qquad [6]$$

Using $\theta_{RA} = 0.16$, $\theta_{FC} = 0.34$, and p = 0.60 (Table 8.7) Eq.[6] would give a value of 0.04 for θ_{WP}. We can now estimate the amount of water available for the ratoon crop as follows: $D \times (\theta_{RA} - \theta_{WP}) = 270$ mm, which is about 60% of the CWR of the main crop.

8.4.7 Water management issues

In Sheeb spate irrigation system, irrigation application depth; water distribution in the field and moisture conservation are some of the major on-farm water management concerns.

The primary concern of spate water management in the field might be depth of irrigation application. It was shown in section 8.4.6 that about 750 mm of irrigation depth is needed for the main sorghum crop and the ratooning. One may wonder why farmers have not developed an application system with ≥ 1 m bund height (such as in Yemen) so that the required amount of water can be obtained with one good spate. Aiming at one large water depth instead of the current irrigation practise of at least two smaller applications implies longer supply canals in which water gains height. As it was explained in Chapter 2, percolation losses in the unlined supply canals are very high. So, farmers have found (through experience and knowledge) an optimum irrigation depth of about 0.5 m taking into account the losses in the supply canals.

The second concern would be about water distribution in the spate fields. It is quite common to observe irregular surfaces with high and low spots within a spate irrigated field. These irregular surfaces are usually created due to scouring by inflow of floodwater and no land levelling after the water has receded in the fields. The spate irrigation farmers assume that the floodwater will level the lower spots of the fields by depositing more sediments, but this is not always so. In spate irrigated fields in Pakistan, Steenbergen (1997) reported most of the sediments carried by floods are deposited at the entrance of a field (higher side) where water from a confined channel first spreads out. In due time, this may result in uneven surfaces within the field. In Sheeb area, low spots of the fields are often saturated with water, while high spots receive insufficient water. As a result, crop growth and yield vary within the same field. Improper land levelling results in unequal water distribution, which is one of the major reasons for poor on-farm water use efficiency (FAO 1985). Therefore, the Sheeb farmers should be advised to prepare their land with even surfaces (prior to flooding) to attain a uniform water distribution over their fields.

Soil moisture varies also among the spate irrigated fields in Sheeb area. The soils in the upstream fields often contain more moisture than soils in the midstream and downstream fields. The variation of moisture among the fields is not due to the soil types but due to the water rights system that gives water first to the upstream fields and last to the downstream fields. Such kind of water rights are also applied in other spate irrigation areas of Eritrea and also in other parts of the world, which is attached to Islamic 'shari'ah' water law that allows for the uppermost users to take water first.

The third water management concern would be in-situ moisture conservation techniques in the fields. During the flooding season (July-August), the spate irrigation farmers practise soil tillage ('mekemet') to reduce losses of water by evaporation and to conserve the stored moisture in the deep soil layers. In the interim period of the last flooding and sowing of seeds (about ten days), the flooded fields are tilled shallowly and covered with a thin layer of soil. The soils are then pressed using a heavy cylindrical wooden log (about 20 kg weight) which is pulled by oxen while the operator stands on the log. The purpose is mainly to block the penetration of solar radiation to the soil surface. At sowing time, the tilth layer (which served as blanketing the soil surface) is broken down by shallow tillage followed by drilling the seeds in rows. This kind of conservation tillage indeed reduces the soil evaporation and conserves the moisture stored in the deep soil profiles.

However, such moisture conservation techniques may not be recommended for soils with impeded water movement because the implement ('mekemet') could cause compaction and reduces hydraulic conductivity and infiltration rates (Tesfai and Stroosnijder 2000).

8.5 Conclusions

The water balance approach used in this study has quantified the main processes contributing to addition of water (irrigation and rainfall) and removal of water (evapotranspiration) to and from the crop root zone, respectively at a field scale. The approach indicated also the general state of soil water balance (whether it is positive, negative or in steady state) in the root zone of spate irrigated sorghum. Water losses due to percolation in the canals should be measured in order to be able to use the present field scale data to a higher scale such as the whole spate irrigation schemes in Sheeb.

The Class-A evaporation pan is relatively easy to operate and it is inexpensive equipment compared to other ETo methods that need an agro-meteorological station. In the absence of detailed and long-term climatic data, (for instance in the Sheeb area) the pan method could give reliable ETo that can be used to estimate the crop water requirements of agricultural crops. Using a higher Kpan, the ETo-pan matches with the Sheeb Penman-Monteith data.

Although during the 1999 wet year, the sorghum crop was not affected by a lack of water, in average year spate irrigated crops experience water stress conditions. The causes of water shortage are believed to be the low diversion efficiency; the low conveyance and/or distribution efficiencies (50%) of the irrigation structures (Chapter 2) and also the uneven distribution of water over the fields.

8.6 References

Allen, R. G., Pereira, L.S., Raes, D. and Smith M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements, FAO irrigation and drainage paper 56, Rome, 279pp.

Dastane, N.G., 1979. Effective rainfall in irrigated agriculture, FAO irrigation and drainage paper No. 25, Rome, Italy, 62 pp.

Doggett, H., 1988. Sorghum, tropical agriculture series, IDRC, Canada, pp. 260-282.

Doorenbos, J. and Pruitt, W.O., 1977. Guidelines for prediction of crop water requirements. FAO irrigation and drainage paper No.24, 2nd ed., Rome, Italy, 118 pp.

Doorenbos, J. and Kassam, A. H., 1979. Yield response to water. FAO irrigation and drainage paper No.33, Rome, Italy, 193 pp.

FAO, 1985. Water quality for agriculture, FAO irrigation and drainage paper No. 29 Rev.1, Rome, Italy, 174 pp.

Halcrow, W., 1997. Engineering feasibility study reports, Eastern lowlands wadi development project, MoA, Asmara, Eritrea.

Hillel, D., 1980. Applications of soil physics. Academic press, INC. London, UK. pp. 197-215.

Howell, T. A., Phene, C. J. and Meek, D.W., 1983. Evaporation from screened Class A pan in a semi-arid climate. Journal of agricultural meteorology 29, 111-124.

IFAD, 1995. Appraisal report on eastern lowlands wadi development project, Eritrea, 52 pp.

Lal, R., 1991. Current research on crop water balance and implications for the future: In: proceedings on soil water balance in the Sudano-Sahelian zone, Niamey, Niger, pp. 31-43.

NRCE, 1996. Final report on the reconnaissance of potential agricultural based water development in the eastern slope of Eritrea. Asmara, Eritrea. Vol. IV, pp. 1-30.

Smith, M. 1992. CROPWAT-a computer program for irrigation planning and management. FAO irrigation and drainage paper 46, Rome, Italy, 126p.

Steenbergen, F.van, 1997. Understanding the sociology of spate irrigation: cases from Balochistan. Journal of arid environments 35: 350-365.

Stroosnijder, L., 1987. Soil evaporation: test of a practical approach under semi-arid conditions. Netherlands Journal of Agricultural Science 35: 417-426.

Tesfai, M. and Stroosnijder, L., 2000. The Eritrean spate irrigation system. Agricultural water management (In Press).

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

UNDP/FAO, 1987. Spate irrigation: Proceedings of the sub-regional expert consultation on wadi development for agriculture in the natural Yemen, Aden, 180 pp.

UNESCO, 1977. Map of the world distribution of arid zones. In: Water harvesting for plant production, World Bank technical paper no.91, Washington, D.C., pp 24-37.

Wegehenkel, M. 1998. Using TRIME-TDR for the determination of soil water dynamics on sandy soils. Zeitschrift für pflanzenernahrung und Bodenkunde 161: 577-582.

Chapter 9

A Land Suitability System for Spate Irrigation Schemes

Abstract

A Land suitability classification system was developed for spate irrigation schemes in Eritrea. For instance, the major land utilisation type in the Sheeb area is spate irrigation applied for production of sorghum and maize. The availability of floods, soil moisture, flood hazard, nutrient status, soil drainage and salinity hazards were the main land qualities selected for land suitability classification. The land suitability classification for spate irrigation was determined by matching the land use requirements with the land qualities. Out of the total land area of Sheeb (8,000 ha), about 4,550 ha of land (57%) was suitable for spate irrigation development. Three suitable classes were identified that is S1/S2, S2, S3 and one non-suitable, N1 land class. The S1/S2 land covered about 1,290 ha (16%), the S2 about 1,870 ha (24%) and the S3 about 1,390 ha of land (17%) of the study area. About 3,450 ha of land or 43% of the study area was classified under N1, which is currently Not Suitable land for spate irrigation. Allocating the limited water resources to the better suitable soils will maximise agricultural production of the spate irrigation system in the Sheeb area. Moreover, construction of permanent flood diversion structures at the main wadis (Laba and Mai-ule) would upgrade the land suitability classes and expand the spate irrigable land (in Sheeb area) by about 2,000 ha.

9.1 Introduction

Globally, the need for optimum use of land has never been greater than at present, when rapid population growth and urban expansion compete with agriculture for land, a relatively scarce commodity. The increasing demand for intensification of existing cultivated areas or opening up of new areas of land (extensification) requires that land be classified according to its suitability for different kinds of use (FAO 1983). Land suitability studies form an indispensable part of the basic planning process particularly in irrigation projects and without these very costly mistakes can be and have been made (Landon 1991).

In Eritrea, the need for land suitability studies is unquestionable in view of the ever-increasing demand of land for agriculture in the rural areas to satisfy the food demand of the country's population (3.5 million, which grows at a rate of 2.9%) versus the need of land for construction purposes (housing, infrastructures, etc.) in the urban centres. In the eastern lowlands of Eritrea, agriculture is practised by spate irrigation. Spate irrigation (called locally 'jeriff') is a pre-planting irrigation system which makes use of flash floods in ephemeral streams (wadis) from highland areas of Eritrea which are diverted by structures to irrigate fields in the lowlands of the country.

During the rainy season (July-September) in the highlands, the main wadis Laba and Maiule transport large amounts of runoff with sediments to the lowlands of Sheeb area. The farmers in this area divert the runoff into adjacent irrigable fields using temporary diversion structures called locally 'agims'. The diverted runoff with its sediments is collected in the fields that are surrounded by earthen bunds. Seeds are sown in these fields and crop production is realised using the residual moisture in the soil profiles.

In 1996, Natural Resource Consultancy Engineers (NRCE) undertook a reconnaissance survey in the Sheeb spate irrigation schemes. This survey estimated the total spate irrigable land to be about 9,300 ha, comprising 3,600 ha of Class 1 and 5,700 ha of Class 2 land following the land suitability classification system of US Bureau of Reclamation (1953). These estimates include a large block of non-irrigated lands, excessively stony soils (which are outside the Sheeb area) and rock outcrops as reported by Halcrow (1997). The Class 1 and Class 2 land are equivalent to S1 and S2 land, respectively according to suitability classification system by FAO (1985) described in Table 9.1. On the other hand, Halcrow (1997) during a feasibility study of spate irrigation development project in Sheeb area estimated the irrigable land (S1 and S2) to be only 3,324 ha of land (1/3 of the NRCE estimate).

The disparities in the estimation of irrigable lands above emphasise the need for a detailed field survey of soil resources (Chapter 5) and a land suitability analysis in the Sheeb area. The purpose of this study were (1) to identify suitable lands for crop production under spate irrigation system, (2) to determine the area of land assigned to the different land suitability classes, and (3) to recommend possible land use management practises for sustainable spate irrigation system in the Sheeb area.

9.2 Methods and Approach

9.2.1 A systems approach to land suitability evaluation

The systematic breakdown of the land use system into land qualities, land use requirements and inputs and outputs is the foundation for a systems approach to land suitability evaluation (Beek 1978). A land use system is affected by physical inputs to the land (as land quality improvements) and to the land use (as land use improvements), which interact with the system elements to determine the outputs, or produce, from the system.

In its simplest form, for example, the major land use in Sheeb area is spate irrigation and the dominant land utilisation type is sorghum cultivation by smallholders and the land unit is an area of spate irrigated soils (calcaric Fluvisols). If the inputs include enough water and improved varieties of seed, the output might be 4,000 kg ha^{-1} of sorghum grain from a main crop and 2,000 kg ha^{-1} from a ratoon crop. A change in any one of the input variables causes changes in some or all of the output. If local varieties are used, the same input of water might give an output of only 2,000 kg ha^{-1} of sorghum grain or 1,000 kg ha^{-1} in the case of a ratoon crop. With inputs of less water and improved varieties, the output might also be reduced from 4,000 to 2,000 kg ha^{-1} or less and ratoon crops might not be harvested at all. Any land quality improvements (inputs), for example building permanent flood diversion structures at the wadis, might lead to a rise in the yield of spate irrigated crops because of increasing availability of water for irrigation.

On the other hand, the land utilisation type (outside the Sheeb spate irrigation area) is non-irrigated land covered with thorny scrubs and scattered bushes and the land unit is an area of calcaric Arenosols. In such land unit, unless land improvements (that make water supply available) are undertaken, the output in the form of crop produce would be nil.

9.2.2 Land suitability classification methods

Combining land qualities and land use requirements in a land evaluation gives land suitability. Land suitability has been defined as the fitness of a given type of land for a specified kind of land use (FAO 1976; FAO 1991). Matching the land use requirements with the land qualities and land characteristics assesses the land suitability for a particular area of land. Land suitability in this study is described by a hierarchical system of classification using land suitability order (Suitable land, S and Not Suitable land, N), suitability classes (S1, S2, S3 and N1) and subclasses.

Table 9.1. Definition of land suitability classes for irrigated agriculture (after FAO 1985).

Class	Designation	Definitions
S1	Highly suitable	Land having no significant limitations for sustainable irrigated agricultural development or only minor limitations that will not significantly reduce productivity or benefits and will not raise inputs above an acceptable level.
S2	Moderately Suitable	Land having limitations which in aggregate are moderately severe for sustainable irrigated agricultural development; the limitations will reduce productivity or benefits and increase required inputs to the extent that the overall advantage to be gained from use, although still attractive, will be appreciably inferior to that expected on Class S1 land.
S3	Marginally Suitable	Land having limitations which in aggregate are severe for sustainable irrigated agricultural development and will so reduce productivity or benefits, or increase required inputs, that this expenditure will be only marginally justified.
N1	Currently Not Suitable	Land having limitations which may be surmountable in time but which can not be corrected with existing knowledge at currently acceptable cost; the limitations are so severe as to preclude successful sustainable irrigated agricultural development in the given manner.
N2	Permanently Not Suitable	Land having limitations, which appear so severe as to preclude any possibilities of successful, sustainable irrigated agricultural development in the given manner.

a) Identification of land utilisation types

In assessing the land suitability for spate irrigation system in the Sheeb area, the land utilisation type is a smallholder crop production with irrigated crops notably sorghum and maize at a subsistence level of production and transhumance pastorals practised seasonally (during dry seasons from May to September) to the highlands of Eritrea in search of food, grass and water.

Spate irrigation has a number of peculiar requirements and therefore the classical suitability systems are not applicable. For example, an adequate number of floods and a good water holding capacity of the soils are some of the land use requirements for spate irrigation system. Each land utilisation type must relate to a specific land use requirement. In other words, the requirements of maize for flooding are different from those of a sorghum crop because maize needs more water than sorghum.

b) Selection of land qualities and land characteristics

The suitability of any area for development of irrigated agriculture is dependent on the availability and quality of water for irrigation, and the properties of soils. The critical limits used to assess land qualities for the Sheeb spate irrigation schemes were based on internationally accepted values laid down by FAO (1976) and on the Guidelines for Land Evaluation for Irrigated Agriculture by FAO (1985) with some modifications to accommodate the local conditions of the Sheeb area.

The main land qualities limiting the suitability for spate irrigated field crops are water and soil under the conditions of the Sheeb area. Hence, the selection of land qualities was based on the water availability and soil quality in the schemes. The salinity of surface water in the wadis (Laba and Maiule) was estimated 0.6 $d\ S\ m^{-1}$ equivalent to 400 $mg\ l^{-1}$ of total dissolved salts as reported by IFAD (1995). These amount of salts cause no restriction in the use for surface irrigation (such as spate irrigation) according to FAO (1985). From the soil properties, water holding capacity of spate irrigated soils is one of the most important factors in land suitability classification for spate irrigation (UNDP/FAO 1987).

In general, the availability of floods, soil moisture, flood hazard, nutrient status, soil drainage and salinity hazards were the main land qualities selected for land suitability classification in the study area. The corresponding land characteristics identified were: the number of floods diverted to the fields, available water capacity, damaging floods in years, organic matter content, drainage classes and salinity values. Rooting conditions (as affected by soil depth), soil pH, slope and climate (temperature) have not been included in the selection criteria since these are relatively homogenous throughout the Sheeb area and are not limiting factors for spate irrigated agriculture.

9.2.3 Land suitability mapping method

The basic units of a land suitability map are the land units. In this study, a land unit (LU) is defined as an area with specified characteristics which is homogenous in all aspects of land (soils, location in respect to the wadis, etc.). The term upstream, midstream and downstream is defined on the basis of proximity to the wadis, Laba and Mai-ule. Thus, upstream sites are located nearer to the wadis (in the range of 200 m to 2 km), whereas downstream sites are found at approximately between 5 to 8 km from the wadis. The midstream sites are in between these two.

Two preliminary land units (LU-A: spate irrigable land and LU-B: non-irrigable land) were identified in this study. A base map (on a scale of 1:10,000) showing the land units were produced from the orthophotomaps and topographic maps already used during the soil survey (Chapter 5). Afterwards, field traverses were made (during the cropping season) across the Sheeb spate irrigation schemes to demarcate the boundaries of the land units. On the basis of crop growth and moisture status of the soils, areas where flood reaches or not reach were observed in the field. By matching the land use requirement with the land qualities (Figure 9.1), tentative land suitability mapping units were identified and their boundaries were located at various points on Universal Transverse Mercator (UTM) grid using the Global Positioning System (GPS-Magellan 4000). The UTM co-ordinates were plotted on the base map and were used to demarcate the land suitability mapping units. Final field checking of the areas classified as suitability units or not suitable for spate irrigation were undertaken with the farmers and local extension agents.

After the field survey, the boundaries of each land suitability mapping units were digitised. Geo-reference data (UTM co-ordinates) were transferred into GIS ARC/INFO program. The data were analysed in ARC/View-GIS version 3.1 and finally a digital land suitability map of Sheeb area at 1:10,000 scale was produced (see Map 9.1).

Table 9.2. Description of subclass limitation symbols used in land suitability classification.

Letters symbols	Descriptions
f	flood availability limitation
m	moisture limitations
h	flood hazard
n	nutrient limitations
d	drainage limitations
s	salinity limitations

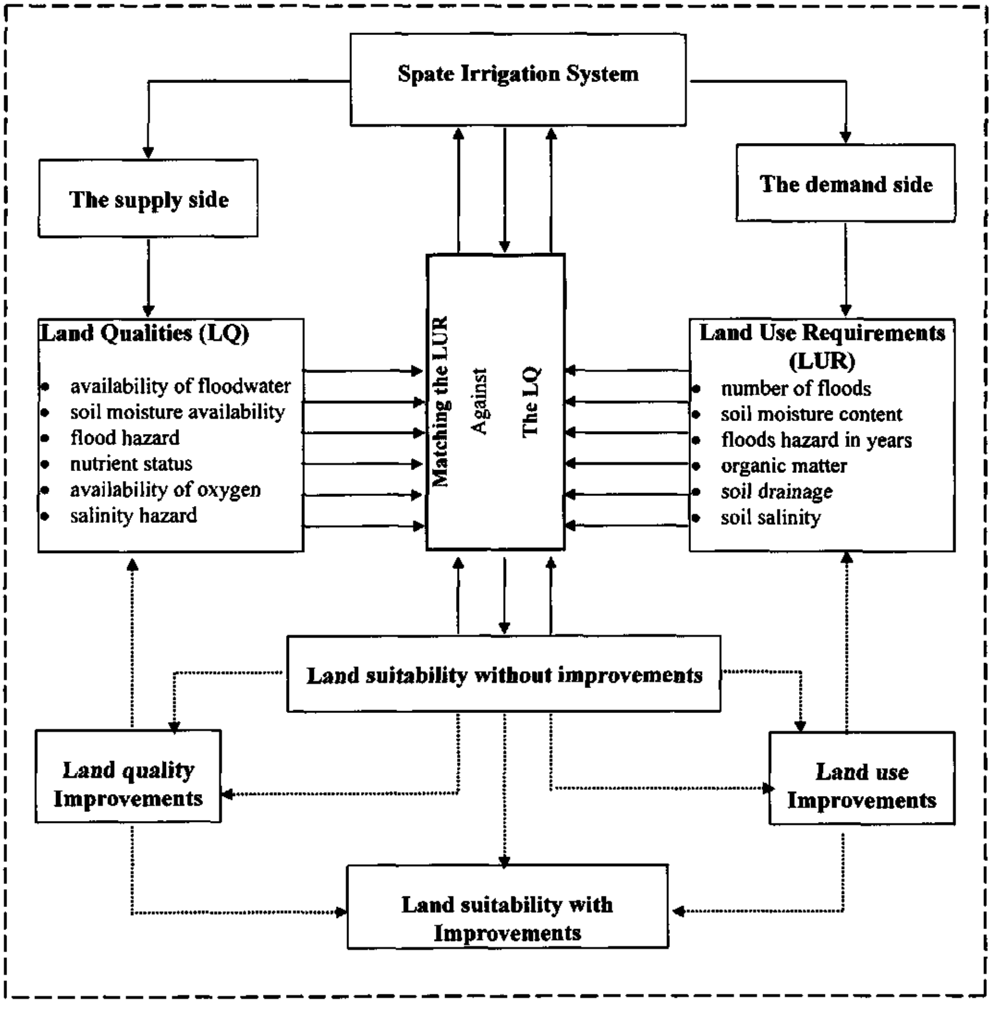


Figure 9.1. Schematic presentation of a land suitability system for Eritrean spate irrigation schemes with and without land improvements.
Existing cycle, ←——→ Improvement cycle, ←·······→ System boundary, – – – – –

The land suitability mapping units (Figure 9.2) are classified and designated according to the FAO land suitability classification system (1985). The kind of suitability is mentioned first whether it is order suitable (S) or not suitable (N), followed by degrees of suitability which is indicated by figure: 1 ('highly'), 2 ('moderately') and 3 ('marginally') suitable and 1 ('currently') and 2 ('permanently') not suitable. The subclasses (designated by lower-case letters) are placed after the class symbols, denoting the kind of limitation that the land possesses.

Generally, only the dominant limitation is indicated (Table 9.2). However, if two limitations are equally important, both are mentioned. e.g. S 3 fm.

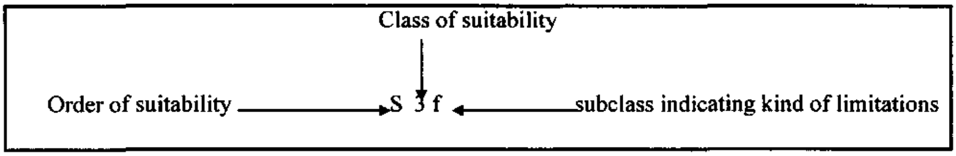


Figure 9.2. Example of land suitability mapping symbol used in this study.

9.3 Results and discussion

9.3.1 Spate irrigation characteristics

The physical and socio-economic settings of the Sheeb spate irrigation system have already been described in detail in the preceding Chapters of this thesis. However, a brief description is given hereunder (see box 9.1)

Box 9.1 A brief description of spate irrigation system in Sheeb

The spate irrigation system in Sheeb area is a labour intensive farming system based on ox-drawn implements with low capital inputs managed by smallholders. The system utilises animal power to build irrigation structures ('agims', 'misghas' and the field bunds); to prepare land for flooding; to sow seeds and to transport the produce. It hardly uses power driven machinery and does not apply either mineral or organic fertilisers into the soils apart from receiving nutrients from the floods by sedimentation.

The people of Sheeb with their livestock migrate to the highlands of Eritrea from May to September and return back to their villages in October. This is practised mainly to search for food, water and grass; to escape from the extreme high temperatures (40-45°C) and the strong dusty winds called locally 'khamsin'. The seasonal movement of people and livestock between the highlands and lowlands can be described as a transhumance pastoral system locally called 'sebek-sagim'. The heads of the household, usually the men, remain behind to divert the floods, to irrigate the fields and to repair the irrigation structures.

The farmers construct diversion structures at the head of the main wadis, Laba and Maiule and using these structures, they divert the flash floods to nearby irrigable fields. The irrigated fields are surrounded by earthen bunds of 0.5 to 1 m high. The individual field sizes of most farmers are 1 ha, often rectangular (50 × 200 m). The fields are aligned along a contour to facilitate gravitational flow of water from field to field. According to the water law, upstream fields receive water first, then midstream and last downstream fields. This implies that users near the head of the wadis generally get more water than the tail-enders.

The major crops grown are sorghum followed by maize and millets. Sesame, groundnuts and some vegetables are also grown in smaller amounts. During good flood seasons, yields are harvested twice (as ratoon crop), sometimes thrice from a seeded sorghum crop. However, production is mainly subsistence-oriented and is very dependent on the soil-water storage capacity for residual moisture after irrigation. The yields vary between 1500 to 2000 kg of grain per hectare for the sorghum main crop and 1000 to 1500 kg of grain per hectare for maize.

9.3.2 The land use requirements

In land suitability ratings for spate irrigation, only the main crops (sorghum and maize) are considered because they have different land use requirements. Millet has more or less similar requirements as sorghum. Therefore, a land unit, which is suitable for sorghum, is also assumed to be suitable for millet.

Sorghum (*Sorghum bicolor,L.*). The sorghum local varieties ('hijeri', 'dura', etc.) grown in the Sheeb area require a warm climate. The optimum temperature for growth is between 24 to 30°C. The water requirement of sorghum ranges from 350 to 650 mm in the growing period. The varieties are tolerant to light sandy soils but grow well on loamy soils, well aerated and well drained. Sorghum is moderately tolerant to salinity and grows at Electrical Conductivity (ECe) values of 6 d S m^{-1} with out any reduction on yield (Landon 1991).

Table 9.3. Rating of land use requirements for spate irrigated lowland sorghum.

Crop requirements		Diagnostic factor ratings			
Land qualities	Land characteristics	Highly suitable	Moderately suitable	Marginally suitable	Not suitable
		S1	S2	S3	N1
Floodwater ava.	No. of floods diverted	> 4	3-4	1-2	nl
Soil moisture ava.	Ava. water (mm m^{-1})	> 200	150-200	100-150	< 100
Big flood hazard	Big flood frequency (yr)	1 in 10	1 in 6-10	1 in 3-5	1 in 1-2
Nutrient status	OM content (%)	> 3.0	1.0-3.0	0.5-1.0	< 0.5
Ava. of oxygen	Soil drainage (class) †	5	4	3, 6, 7	1, 2
Salinity hazard	Soil salinity (d S m^{-1})	0-6	6-9	9-16	> 16

† 1 = Very poorly drained; 2 = poorly drained; 3 = imperfectly drained; 4 = moderately drained; 5 = well drained; 6 = somewhat excessively drained and 7 = excessively drained, FAO (1985). nl: nil and ava.: availability.

Maize (*Zea mays,L.*). The local varieties ('berih', 'wedi-libab', etc.) are planted when there is enough moisture in the soil, usually after sorghum. They require a temperature between 18 to 30°C. Maize grows best on well-drained, well-aerated, deep loams and silt loams and soils with adequate organic matter. The water requirements in the growing period ranges between 500-800 mm. In general, maize is moderately sensitive to salinity and can tolerate ECe values of about 2 d S m^{-1} without any effect on yields (Landon 1991).

Table 9.4. Rating of land use requirements for spate irrigated lowland maize.

Crop requirements		Diagnostic factor ratings			
Land qualities	Land characteristics	Highly suitable	Moderately suitable	Marginally suitable	Not suitable
		S1	S2	S3	N1
Floodwater ava.	No. of floods diverted	> 5	3-5	1-3	nl
Soil moisture ava.	Ava. water (mm m^{-1})	> 250	200-250	150-200	< 150
Big flood hazard	Big flood frequency (yr)	1 in 10	1 in 6-10	1 in 3-5	1 in 1-2
Nutrient status	OM content (%)	> 3.0	1.0-3.0	0.5-1.0	< 0.5
Ava. of oxygen	Soil drainage (class)	5	4	3, 6, 7	1, 2
Salinity hazard	Soil salinity (d S m^{-1})	0-2	2-6	6-9	>10

9.3.3 Land qualities and their ratings

a) Availability of floods

The major sources of water for spate irrigation in the Sheeb area are floods coming from the highlands of Eritrea. If there are no floods, there would be no agricultural production in the area. Thus, the availability of floodwater was rated by considering the frequency of floods occurred and the size of floods diverted to the irrigated fields. The frequency and size of floods (big or small) were recorded during the main flooding season i.e. from July to September.

b) Soil moisture availability

One of the most intrinsic properties of spate irrigated soils is their ability to hold enough water for the crops to grow using residual soil moisture with-out post plant irrigation. This soil quality is mainly dependent on the texture of the soils. Therefore, the availability of moisture in the soils was based on the type of soil texture. The crop water requirements for sorghum and maize were also considered.

c) Big flood hazard

The traditional flood diversion structures ('agims') are not strong enough to withstand the force of big floods. Therefore, the structures are usually breached and the floods create erosion in the irrigated fields. The big flood hazard was rated on the frequency and duration of damaging floods occurring in the Sheeb area. The data on big flood hazards were collected from observation made in the field and farmers' interview.

d) Nutrient status

The rating of the nutrient status of soils was mainly based on the amount of organic matter (OM) in the topsoils (0-0.25 m). The total N, available P and K contents in the topsoil were also considered.

e) Availability of oxygen

The availability of oxygen in the root zone during the crop growing period was rated as a function of the drainage classes of soil profile. The profile drainage is dependent on the texture of the soils, (which correlates with the infiltration rate and hydraulic conductivity of soils) and the depth at which soil mottling commences. The influence of ground water in the Sheeb area is negligible. Because the ground water table is very deep, (often >10 meters deep) and the fluctuations of the depth of ground water are also small through out the year.

f) Salinity hazard

The salinity hazard was rated by the amount of salts present in the top 0.25 m depth and the crop tolerance to salinity. The crop yield reduction attributed by the effect of salinity was also considered. The quality of the floodwater in terms of salinity was not considered because the surface water in the wadis is relatively free of salts (IFAD 1995). The ground water in the Sheeb area is highly saline and therefore it is not suitable for irrigation under ordinary conditions.

9.3.4 The land units and their characteristics

The land unit A (LU-A) covers all irrigable land by spate irrigation. In this study, the LU–A is defined as 'spate irrigation area characterised by subsistence production of mainly sorghum, maize and millet on small scale with individual land holdings sizes.' It is more or less similar to soil mapping unit A (described in Chapter 5) except that it includes other attributes of land listed in Table 9.5. The land unit A in the midstream site is subdivided into LU A-1 and LU A-2. The LU A-1 is currently spate-irrigated land with calcaric Fluvisols (soil mapping unit A-1). Whereas, the LU A-2 comprises all lands currently not irrigated but once were utilised for spate irrigation of crop production and the soils found are salic-calcaric Fluvisols (soil mapping unit A-2).

The land unit B is also similar to soil mapping unit B as described in Chapter 5 except that it includes other attributes of land (such as natural vegetation, infrastructures, etc). The LU-B is defined as 'land never utilised for spate irrigation but some part of it can be used for crop production, if floods are available through major land improvements.' This land covers scattered thorny scrubs and shrubs (which are used for nomadic grazing) and abandoned lands due to a lack of water.

Table 9.5. The average values of land characteristics for land units A and B.

Land characteristics	Land unit A				Land unit B
	Upstream	Midstream		Downstream	
		LU A-1	LU A-2		
Floods diverted to the fields (no.)	4	3	3 †	1-2	nl
Soil texture (class)	SIL	L	L	L	SL
Soil ava. water capacity (mm m^{-1}) ‡	200-250	150-200	150-200	150-200	100-150
Big flood hazard (years)	1 in 3-5	1 in 8	1 in 8	1 in 3-5 §	nr
Organic matter (%)	1.04	1.06	1.42	0.59	0.45
Soil profile drainage (class)	5	4	5	3	6
Soil salinity, ECe (d S m^{-1})	1.98	2.6	9.0	0.97	17.9

† Estimated no. of floods diverted when the land was utilised for spate irrigation.
‡ Estimated range values of available water capacity of soils.
§ Damaging floods from wadis, Harmazo and Gersile.
SIL: silt loam, L: loam and SL: sandy loam and nr: not relevant.

9.3.5 The land suitability classes

Matching the land use requirements with the land qualities

The land use requirements listed in Tables 9.3 and 9.4 have been matched with the land characteristics in Table 9.5 to identify the suitability classes in Tables 9.7 and 9.8 for spate-irrigated sorghum and maize, respectively. In this study, only one class with N1 (currently Not suitable land) has been identified because no physical factors (such as steep slopes) or socio-economic factors (marketing, water rights, etc.) have been found to classify any part of the study area as N2 (permanently not suitable land) for cultivation of sorghum and maize.

Combinations of land suitability ratings

The arithmetic method (Dent and Young 1981; FAO 1991) was used to combine individual land suitability ratings into an overall suitability assessment of the land units for the spate-irrigated sorghum and maize. In the arithmetic procedure, individual land suitability ratings are combined using addition to obtain one land suitability class. In the method of addition, each suitability class was assigned a relative value as follows: S1 = 3.0, S2 = 2.0, S3 = 1.0 and N1 = 0.0. These values were added up for the six land qualities listed in Tables 9.7 and 9.8. The summation was then converted into a land suitability classification by means of a second scale as related to attainable crop yields in Table 9.6. The data on crop yields were extracted from crop survey and farmers' interview.

Table 9.6. Land suitability classes and their value as related to attainable crop yield.

Suitability class	Attainable crop yield †	Score out of 18
S1, Highly suitable land	> 80%	15-18
S2, Moderately suitable land	50-80%	9-15
S3, Marginally suitable land	30-50%	5-9
N1, Currently Not suitable land	< 30%	< 5

† 2000 and 1500 kg ha^{-1} for sorghum and maize, respectively during good season.

Table 9.7. Suitability classes for spate irrigated lowland sorghum.

Land qualities †	Land unit-A								Land unit-B	
	Upstream		Midstream				Downstream		Non-irrigated land	
			LU A-1		LU A-2					
	class	value	c	v	c	v	class	value	class	value
Ava. of flood water (f)	S1	3	S2	2	S2	2	S3	1	nr	-
Ava. of soil moisture (m)	S1	3	S2	2	S2	2	S2	2	S3	1
Flood hazard (h)	S3	1	S2	2	S2	2	S3	1	nr	-
Nutrient status (n)	S2	2	S2	2	S2	2	S3	1	N1	0
Ava. of oxygen (d)	S1	3	S2	2	S1	3	S3	1	S3	1
Salinity hazard (s)	S1	3	S2	2	S3	1	S1	3	N1	0
Overall LSC & value	S1/S2	15	S2	12	S2	12	S3	9	N1	2
Land suitability subclass	S1/S2hn		S2fm		S2s		S3fnh		N1ns	

† Land qualities listed according to order of importance; c: class; v: value; LSC: Land Suitability Class.

The locations of land in the various suitability classes identified in this study are shown in Map 9.1 and their coverage by percent and ha are presented in Figure 9.3 and in Table 9.9, respectively.

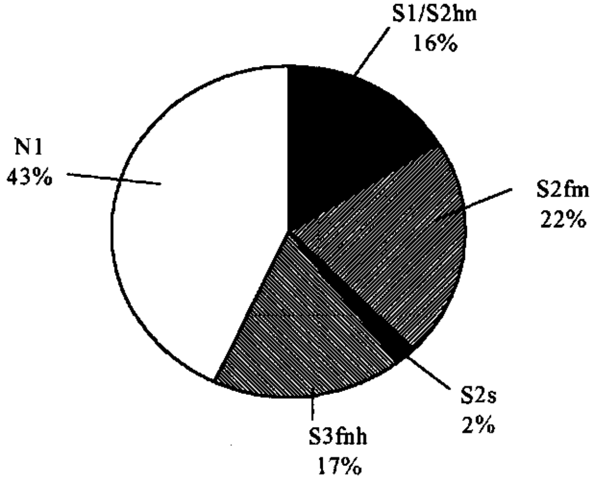


Figure 9.3. Area coverage by % for land suitability classes in the Sheeb area.

Table 9.8. Suitability classes for spate irrigated lowland maize.

Land qualities	Land unit -A								Land Unit-B	
	Upstream		Midstream				Downstream		Non-irrigated land	
			LU A-1		LU A-2					
	class	value	c	v	c	v	class	value	class	value
Ava. of flood water (f)	S2	2	S3	1	S3	1	S3	1	nr	-
Ava. of soil moisture (m)	S2	2	S3	1	S3	1	S3	1	N1	0
Flood hazard (h)	S3	1	S2	2	S2	2	S3	1	nr	-
Nutrient status (n)	S2	2	S2	2	S2	2	S3	1	N1	0
Ava. of oxygen (d)	S1	3	S2	2	S1	3	S3	1	S3	1
Salinity hazard (s)	S1	3	S2	2	S3	1	S1	3	N1	0
Overall LSC & value	S2	13	S2	10	S2	10	S3	8	N1	1
Land suitability subclass	S2hn		S2fm		S2s		S3fhn		N1mns	

Highly to Moderately suitable land (S1/S2)

The upstream site of Sheeb spate irrigated area is classified as 'Highly to Moderately suitable,' for the cultivation of sorghum and maize crops. This land class occupies about 1,290 ha (Table 9.9) or 16% of the Sheeb area (Figure 9.3). The area includes the upper elevations (220-250 m a.s.l) of the spate irrigated fields irrigated by canals locally called Sheebkhetin, Bises, Erem, Tiluk

Kurfotat. At the present condition, this land could not be classified as highly suitable (S1) for crop production because of big flood hazard (h), owing to the proximity of the land to the diversion sites. Big floods usually breach the temporary irrigation structures ('agims' and 'misghas') and overflow into fields, which also breach the bunds and create erosion.

Only one subclass i.e. S1/S2hn has been identified. The soils found in this land class are calcaric Fluvisols. The big flood hazard creates erosion in the fields, which occurs once in every 3 to 5 years. The average organic matter content of the bulk of the topsoils is low and the nutrient status (n), with regard to total nitrogen is also low. The big flood hazard reduces the attainable crop productivity of this land class.

Moderately suitable land (S2)

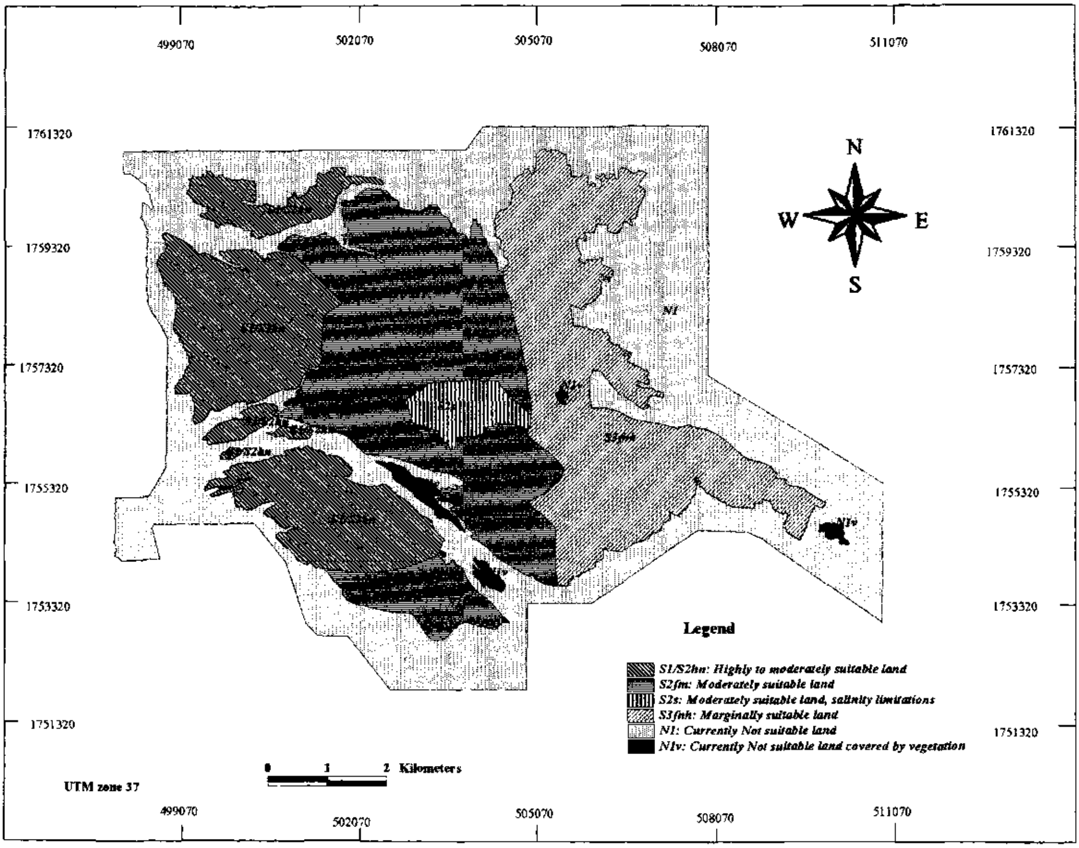
About 41% of the irrigable land or 1,870 ha are 'moderately suitable' for crop cultivation. This land class covers a large portion of the middle part of the Sheeb area (200-220 m a.s.l). It includes the midstream of wadi Laba fields which are irrigated by canals notably Idi-Abai and Debret plus the currently non-irrigated lands and the proposed Ministry of Agriculture (MoA) research site. The soils developed on these irrigated lands are calcaric Fluvisols, whereas salic-calcaric Fluvisols are formed on currently non-irrigated lands. The floodwater and moisture availability posed moderate limitations for crop production in the irrigated lands while severe salinity hazard occur in the currently non-irrigated lands.

About 38% of the irrigable land or 1,720 ha are covered by subclass S2fm. The water rights system (in the Sheeb area) gives priority to the upstream fields. Thus, the number of floods reaching this midstream area is often low particularly when few floods are diverted at the diversion sites. Consequently, the moisture as well as the nutrient contents of the soils remains low.

About 3% of the irrigable land or 150 ha is classified under subclass S2s (currently not irrigated land). Salinity in the topsoil posed severe problem in this land class.

Marginally suitable land (S3)

About 31% of the irrigable land or 1,390 ha are categorised under 'marginally suitable' land. The eastern part of the Sheeb area (downstream of the wadis) is classified as marginally suitable lands for sorghum and maize production. These areas are located at the lower elevations (180-200 m a.s.l) of spate irrigated lands and are irrigated by canals namely Erem, Idi-abai, Emdenai



Map 9.1. Land suitability map of Sheeb area.

and Edi-eket. The availability of water makes severe limitation to crop production in this land class.

The subclass identified under this suitability class is S3fhn. A large part of the area is located quite far (5 to 8 km) from the flood diversion sites of wadis, Laba and Maiule. According to the water rights, this land class receives water after all the upper fields have been sufficiently irrigated. Mostly, few floods reach the site, which petered out before they irrigate all the fields. Sometimes, this land class might not even receive flood at all. It gets enough floods, when there are good rains in the highlands of Eritrea and when most of the floods (in the wadis) are diverted to the fields.

The bulk of the soils in this land class contain low OM and nitrogen. Some part of this land is also threatened by severe gully erosion caused by sporadic damaging big floods discharged from wadis Haramazo and Gersile.

Currently Not Suitable land (N1)

This land class (currently not suitable, N1 for crop cultivation) covers a significant proportions (43% or 3,450 ha) of the Sheeb area. A large part the area is too far from the diversion sites and canals.

Table 9.9. Summary of the land units, land suitability classes and their area coverage in Sheeb.

Land unit	LSMU	Land suitability classes	Area coverage	
			ha	% of irrigable land
LU-A, us	S1/S2hn	Highly to Moderately Suitable land with flood & minor nutrient limitations	1,290	28
LU-A-1, ms	S2fm	Moderately Suitable land with moderate limitations of flood availability & moisture	1,720	38
LU-A-2, ms †	S2s	Moderately Suitable land with salinity limitation	150	3
LU-A, ds	S3fhn	Marginally Suitable land with limitations of flood availability, flood hazard and nutrient	1,390	31
LU-B	N1	Currently Not Suitable land	3,450	-
Total	-	-	8,000	100

† Currently not irrigated spate land.
LU-A, us: upstream; ms: midstream and ds: downstream spate irrigated land. LU-B: non-irrigable land.
LSMU: Land Suitability Mapping Units.

Table 9.10. Summary of land use management practises in Sheeb spate irrigation system.

Land unit	Current land use	Limitations for crop cultivation and livestock grazing	Land use improvements	Recommended land use
LU-A, us (upstream irrigated land)	1. Spate irrigated crop production 2. Transhumance pastoralism	1. Big flood hazard 2. Low OM and N 3. Lack of feed	1. Construction of permanent flood diversion structures at the wadis 2. Application of manure & incorporation of crop residues into the soil 3. Growing forage plants in the wadis	1. Spate irrigation for crop production 2. Sedentary pastoralism (with land use improvements)
LU-A-1, ms (midstream irrigated land)	1. Spate irrigated crop production 2. Transhumance pastoralism	1. Few number of floods 2. Low OM and N 3. Lack of feed	1. Construction of permanent flood diversion structures at the wadis 2. Application of manure & incorporation of crop residues 3. Growing forage plants in the wadis	1. Spate irrigation for crop production 2. Sedentary pastoralism(with land use improvements)
LU-A-2, ms (midstream non-irrigated land)	1. Currently non-irrigated land	1. Soil salinity in the topsoils 2. Absence of distribution canals and field bunds	1. Developing the land for spate irrigation 2. Construction of 'misghas' and field bunds	1. Spate irrigation for crop production 2. MoA research farm
LU-A, ds (downstream irrigated land)	1. Spate irrigated crop production 2. Transhumance pastoralism	1. Very few number of floods 2. Low OM and N 3. Big flood hazard creating gullies in the irrigated fields 4. Lack of feed	1. Construction of permanent flood diversion structures at the wadis 2. Application of manure & crop residues into the soil 3. Construction of earthen embankments across the gully banks 4. Growing forage plants in the wadis	1. Spate irrigation for crop production 2. Sedentary pastoralism (with land use improvements)
LU-B (non-irrigated land)	1. Abandoned non-irrigated land	1. Lack of water 2. Very low in plant nutrients 3. Poor physical fertility 4. Soil salinity in the topsoils	1. Construction of permanent flood diversion structures at the wadis 2, 3 and 4: Developing the land for spate irrigation	1. Spate irrigation for crop production

The N1 land class includes the non-irrigated lands, which are covered by scattered scrubs and shrubs, abandoned lands (due to water shortage) and settlement areas. The soils developed on this land are classified as sali-calcaric Arenosols (Chapter 5). This land class consists of coarse sandy soils, which are dry for almost all the year. The soils are very low in OM and nitrogen contents and poor in soil physical fertility.

9.3.6 Land use improvements

Table 9.10 summarises possible land use management practises that could be implemented in Sheeb spate irrigation system. The S1/S2 land class could be upgraded into S1, when permanent flood diversion structures are constructed at the wadis (Laba and Maiule) and when the OM and N contents of the spate soils are improved by applying organic fertilisers (manure and crop residues).

The S2s land subclass could be revived and be utilised for crop production by constructing canals to the irrigable fields and by repairing the field bunds. Through successive floodings of the fields, the soluble salts present in the topsoils could be leached out. By doing so, this subclass could be upgraded into S1/S2 land class.

The most severe limitation in S3 land class is that very few floods are available in most of the years. The primary improvement required would then be to build permanent flood diversion structures at the upper reaches of the wadis (Laba and Maiule). These structures would divert the floods more effectively so that the floodwater could reach and irrigate the downstream fields in this land class. Secondly, the local government and other development agencies should assist the farmers (by providing earth moving machines) to construct embankments in order to control the expansion of gully erosion in the irrigable lands. With such land use improvements, a large part of the area could be upgraded into S2 land.

When the permanent flood diversion structures are in place at the wadis (Laba and Maiule), more water could be available for spate irrigation. Consequently, some parts of N1, (currently not suitable land) could be developed for spate irrigation crop production. However, before implementing irrigation schemes in this type of land, a comprehensive and detail socio-economic study should be carried out first.

Environmental impacts

One of the environmental impacts of the floods in Sheeb area is sedimentation on the diversion sites and on the irrigated fields. The sedimentation on the diversion sites has a negative impact because the floods deposit large quantities of coarse sediments that often breaches the temporary diversion structures ('agims'). Nonetheless, the sedimentation has a positive impact on the irrigated fields. Because it builds up land with deep soils and deposits plant nutrients and OM on the fields whereby crop production is realised without fertiliser applications.

Health hazards among the local population are another environmental impact in the development of spate irrigation in the Sheeb area. Farmers residing in the upstream sites mentioned that vector-born diseases (such as malaria) create health problems. The wadis, Laba and Maiule create favourable conditions for fast multiplication of pests and diseases in the area. This problem could be alleviated by treating the wadis and water wells and maintaining the drainage channels (Tesfai and de Graaff 2000).

9.4 Conclusions

The major land utilisation type in the Sheeb area is spate irrigation applied for production of sorghum and maize. Two main land units were identified: LU-A, which cover the irrigable lands in the upstream, midstream and downstream of the wadis, and LU-B covering the non-irrigated lands found outside the spate irrigated fields.

Three suitability classes (S1/S2, S2, S3) and one class of currently not suitable land (N1) were identified by matching the sorghum and maize crop requirements with the land qualities and land characteristics. These were: S1/S2 ('highly to moderately') found in the upstream site, S2 ('moderately suitable') in midstream sites, S3 ('marginally suitable') in downstream sites and N1 land located outside the spate irrigated fields of Sheeb. The bulk of the land (41%) in Sheeb spate irrigation schemes is considered to be moderately suitable for sorghum and maize cultivation.

Some parts of the currently not suitable land (N1) could be developed and utilised for crop production when permanent flood diversion structures are constructed at the wadis, Laba and Maiule. This part of the land will then be upgraded into S3 or S2 suitability classes. The total irrigable land of moderately to highly suitable (S1/S2 and S2) in Sheeb spate irrigation schemes was about 3,160 ha, which is more or less comparable with the result of Halcrow (1997) who estimated the average annual suitable land (for spate irrigation) to be 3,324 ha rather than the 9,300 ha of land, estimated by NRCE (1996).

With improvements of the spate irrigation system, about 2,000 ha of additional land could be irrigated in the Sheeb spate irrigation schemes (Table 2.2, Chapter 2). This increases the total spate irrigated land to 5,160 ha commanded by wadis Laba, Maiule, Harmazo and Gersile. The land suitability system presented in this study could be applied in other spate irrigation schemes of Eritrea.

9.5 References

Beek, K.J., 1978. Land evaluation for agricultural development: Some explorations of land-use systems analysis with particular reference to Latin America, Ph.D. Thesis, Wageningen, The Netherlands, 333 pp.

Dent, D. and Young, A., 1981. Soil survey and land evaluation. George Allen & Unwin Inc., London, UK, 278 pp.

FAO, 1976. A framework for land evaluation. FAO soils bulletin 32, Rome, Italy, 72 pp.

FAO, 1979. Land evaluation criteria for irrigation: World soil resources reports no. 50. Report of an expert consultation, Rome, Italy.

FAO, 1983. Guidelines: Land evaluation for rainfed agriculture. FAO soil bulletin no.52, FAO, Rome, Italy 237 pp.

FAO, 1985. Guidelines: Land evaluation for irrigated agriculture, FAO soils bulletin no.55, FAO, Rome, Italy, 231 pp.

FAO, 1991. Guidelines: land evaluation for extensive grazing. FAO soils bulletin no.58, FAO, Rome, Italy, 158 pp.

Halcrow, W., 1997. Inception report, Eastern lowlands wadi development project, Ministry of agriculture, Asmara, Eritrea, 50 pp.

IFAD, 1995. Staff appraisal report on Eastern lowlands wadi development project, Asmara, Eritrea, 52 pp.

Landon, J. R., 1991. Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London, UK. 474 pp.

NRCE, 1996. Final report on the reconnaissance of potential agricultural based water development in the Eastern slope of Eritrea. Asmara, Eritrea Vol. II, pp.1-27 pp.

Tesfai, M. and de Graaff J., 2000. Participatory rural appraisal of spate irrigation system in Eastern Eritrea. Journal of agriculture and human values. (In Press).

UNDP/FAO, 1987. Spate irrigation: Proceedings of the sub-regional expert consultation on wadi development for agriculture in the Natural Yemen, Aden, 180 pp.

USBR, 1953. Bureau of reclamation manual. In: Landon, J. R., 1991. Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman, London, UK. 474 pp.

Chapter 10

General discussion

10.1 Introduction

Spate irrigation has been given insufficient attention world-wide and is not yet well studied and documented. Hence, little has been published in English on this type of irrigation system apart from the proceedings by UNDP/FAO (1987).

The spate irrigation system (SIS) in Eritrea could not be mastered within the short period of research available for a PhD-project, besides the lack of human and technical resources in the country. The major limitations of this study were (1) lack of facilities, absence of field assistant and the remoteness of the study area (i.e. Sheeb) and (2) most of the data on the highland catchment of Sheeb were gathered from farmers' interviews and archive reports and thus should be used with caution.

Main research on socio-economic and biophysical aspects of spate irrigation system have been carried out in the Sheeb area (as a case study) and the results have been presented and discussed in this thesis. However, there are several topics of the system that requires still further study (see Table 10.1).

In the following sections, the major constraints affecting the productivity and sustainability of the Eritrean spate irrigation system in general and the Sheeb spate irrigation system in particular are discussed. Subsequently, the specific opportunities available for improvement of the system and its development potentials are described. At last, further research topics in the field of spate irrigation are recommended.

10.2 Major constraints of the Eritrean spate irrigation system

Water shortage

Water is a precious commodity in (semi-) arid climates of Eritrea, and it is one of the major limited resources in spate irrigated areas of the coastal zones of the country. For instance, the SIS in Sheeb area is totally dependent (for water, nutrients and soils) on the resources of the nearby highlands of Eritrea. The farmers in this area often encounter water shortage because the SIS receives water (in the form of flash floods) mainly from the rainstorms in the mountainous catchment areas of the central highlands of Eritrea and also from the winter rains in the eastern escarpment which are unpredictable, erratic and often scarce in amount (FAO 1994). The mean annual rainfall in the Sheeb area is very little and does not exceed 200 mm y^{-1}, and thus crop production is possible only by spate irrigation.

Breaching of irrigation structures ('agims', 'misghas' and bunds)

The temporary diversion structures ('agims', made from brushwood trees and stones and/or boulders) are not efficient enough to divert a large amount of floods in the main wadis Laba and Maiule, which flow in a short period of time (and often at night). Consequently, the 'agims' are often swept away by destructive big floods. On such occasions, a major section of the 'agim' is washed away, often before its total command area has been irrigated, and water can not therefore be diverted again to the fields until the agim has been rebuilt. The 'agim' should be rebuilt immediately in order to divert the next flood, otherwise quite a number of floods could be lost out of the system and eventually, farmers encounter water shortage during the cropping season.

The conveyance and distribution efficiencies of the 'misghas' (earthen made unlined canals) are low due to substantial losses of water by deep percolation and seepage, particularly for downstream fields which are remote from the diversion sites. The field application efficiency of the SIS is also low (50%) as reported by Halcrow (1997) (Chapter 2).

The sedimentation at the diversion sites of the wadis has negatively affected the SIS by depositing large quantities of bed load materials (about 0.9 million tons y^{-1} in wadi Laba only). These bed materials block the passage of water in the canals and cause the irrigation structures to breach (Chapter 6). Breaching of the 'agims' and 'misghas' by big floods often causes the wadis to change their courses, overflowing into the bunds and erode the agricultural fields thereby forming gullies particularly in downstream areas of Sheeb (Chapter 5).

Water rights issues

According to the traditional water rights system (in Sheeb area), the upper fields are always irrigated first; downstream fields are irrigated only after the upper fields have received a sufficient supply of water via its gravity-fed, field to field system of irrigation. As a result, the upstream fields (in Sheeb) often receive more water than the midstream and downstream fields. In some cases, excess water accumulates in the upper fields, while the next downstream field remains dry. During a bad season the downstream farmers may not even get water at all to irrigate their fields. The water rights system causes soil moisture variations among the spate fields, though the soils are relatively 'homogeneous' over a horizontal distance. Therefore, the floodwater distribution system in spate irrigated fields of Sheeb area is not uniform among the upstream, midstream and downstream users (Chapter 8).

At the present condition (i.e. with the traditional spate irrigation system), expansion of irrigable land seems to be impracticable in the Sheeb area because of a lack of water. Every plot of land that could receive water has already been utilised for spate irrigation. However, with equity water distribution among the fields, some water may be made available to irrigate some additional tracts of land. In general, the SIS in Sheeb area can be categorised as 'inequitable' with respect to distribution of floodwater among the users.

Lack of soil N and organic matter

The main source of soils and nutrients for spate-irrigated soils of Sheeb area is from the eroded soils in the adjacent highland catchments of Eritrea. These catchments are largely covered with degraded lands and sparsely populated natural vegetation, presumably caused by erosion and deforestation. The farmers in Sheeb have never applied either organic or inorganic fertilisers into their soils since the last 100 years of spate irrigation practises. They believe that the spate soils are rich in nutrients because every year the topsoils of the catchment are eroded and deposited on the spate irrigated fields. In the fields, the crop residues are totally removed after harvest and used for livestock feed. Chemical analysis of the spate irrigated soils have shown that most of the soils contain high available phosphorus and available potassium but relatively low organic matter and total N (Table 5.6, Chapter 5).

Although the nutrient balance study (Chapter 7) has revealed that the total elements of N, P and K are not depleted from the soil nutrient stocks, it does not necessarily mean that fertiliser application (especially in the form of N and organic matter) is not required. Improving soil fertility by applying nutrient saving and/or nutrient adding techniques (Table 7.6, Chapter 7) could ultimately increase crop productivity. This has been shown on field experiments conducted in spate irrigated soils in Yemen where application of nitrogen fertilisers and improved farming practises has increased crop production by 30-50% (UNDP/FAO 1987).

10.3 Sustainability of the spate irrigation production system

'Sustainability' is defined here as the ability of a system to maintain its productivity (i.e. amount of output per unit of input) in spite of major disturbances such as stress and catastrophe conditions in the environment (Conway et al. 1987).

When there are good rains in the highlands of Eritrea and when a spate irrigated field receives more than two floods, the crop production of (sorghum, maize, millet) per ha in Sheeb area is the highest among all other rainfed crop production areas of Eritrea. On the other hand, under water stress conditions, the productivity of spate irrigation system falls to a low level of production. During catastrophe conditions such as the droughts in the mid 1960s and mid 1980s, the crop production in the Sheeb area was very low and nil, respectively (see Figures 3.1 and 3.2, Chapter 3).

The productivity of the SIS is entirely dependent on the frequency and size of floods diverted to the fields, which in turn depends on the occurrence of rains in the highlands of Eritrea and also on the efficiency of the 'agims' and 'misghas'. Since the rainfall pattern in the highlands is unpredictable and often is highly variable both spatially and temporally, the number and size of floods occurring in the Sheeb area are also variable in time, which results in good and bad seasons and/or years. The 'agims and 'misghas' are effective to divert and distribute the small to medium sized floods only. But, during a large spate (i.e. when the flow depth in the wadi is > 1.0 m) the agim is either breached deliberately or it is overtopped and breaches as flood rises.

Hence, cropped areas and crop production in SIS vary from year to year and also from field to field mainly due to variations in water supply. The trend diagrams (Figure 3.2, Chapter 3) have shown that the quantities of floods and crop production were highly variable over time in the Sheeb area. Therefore, the productivity of spate irrigation system in the Sheeb area is considered to be 'unstable' in time and space.

Other problems that constantly threats the sustainability of the SIS are the repetitive construction and maintenance of the 'agims' and 'misghas' every year, which require huge human and animal labour, large number of trees and a considerable time. For instance, annually tens of thousands of dry acacia trees are deforested from the nearby catchments and transported by oxen over long distances mainly for the purpose of 'agim' construction. As a consequence, the natural resource base of the Sheeb catchment has been severely degraded. Since replanting of trees have not (yet) been well performed, the Sheeb catchment has reached an alarming stage of vegetation catastrophe. Nowadays, the Sheeb area is left only with few thorny scrubs found on the non irrigated lands and few scattered trees along the wadi courses.

The seasonal migration (i.e. transhumance system) to the highlands of Eritrea is also a major threat to the sustainability of the SIS in Sheeb area, though it has some positive aspects. The migration sometimes hinders agricultural activities (e.g. repairing of irrigation structures, flooding of fields, sowing of seeds are not performed at the right time) and also the development of infrastructures (such as roads, buildings, etc.) in the Sheeb community is impeded by the migration of the people. Moreover, the need to rebuild the temporary houses (locally called 'agnet') year after year is also a drain on labour and capital resources (Chapter 4).

During bad years, the spate irrigation farmers encounter serious cash deficits to carry out their agricultural activities. In such years, most of the farmers could not even save seeds for the next planting season. Lack of off-farm employment opportunities and non-existence of credit giving institutions in Sheeb area exacerbates the lack of capital faced by farmers. These farmers borrow money from friends and local money lenders to buy seeds, drought animals and farm implements.

In general, the problems mentioned above seriously threat the sustainability of the SIS in Sheeb area. Therefore, we can conclude that the 'sustainability' of the traditional spate irrigation system in Sheeb area remains to be a standing question. However, there are several opportunities available to improve the traditional SIS i.e. to make the system more productive, equitable and sustainable as well.

10.4 Major opportunities of the Eritrean spate irrigation system

Since the beginning of the 20th century, the local farmers in Sheeb area have developed indigenous technical knowledge (ITK) on spate irrigation system. Some of the most important indigenous practises are the construction of flood diversion and distribution structures ('agims' and 'misghas', respectively) which are used to divert and distribute the floods to nearby irrigable fields; the 'mehar' to construct the interior and exterior soil bunds ('kifaf' and 'tewali', respectively) which collect the floodwater and allow the water to infiltrate into the deep soil layers and at the same time to harvest the nutrients and sediments; the soil tillage ('mekemet') to reduce soil evaporation and to conserve the stored soil moisture in the deep profiles; the tillage implements ('jihaz' and its accessories) to plough the fields; the planting implements ('jeleb') to sow the seed in rows; the feeding system ('zeriba') to feed the animals by cut-and-carry grass; the seasonal migration ('sebek-sagim') to the highlands of Eritrea in search of food, water and grass, when these resource are scarce in the lowlands. These indigenous practises are important community knowledge, which have been transferred from generation to generation over the last 100 years of spate irrigation practises in the area. They are adaptable to the dynamic nature of the spate irrigation system (with some limitations) and can successfully cope with environmental changes in a way that was neatly described for Burkina Faso by Mazzucato and Niemeijer (2000).

However, ITK should be integrated with scientific know-how in order to increase the productivity and to make the system more sustainable. The old masters in the Sheeb community could be invited to teach the younger generation the skills and attitudes they have developed on the system. Any outside intervention should not overlook the indigenous practises but rather try to make use of these for the development of a database on spate irrigation system.

Construction of permanent flood diversion structures

The government of Eritrea has formulated various strategies and approaches to assure food security in the country. For example in 1996, the government has launched a project called Easter Lowlands Wadi Development Project (ELWDP) at two spate irrigation pilot areas namely Sheeb (the area studied) and Wadi-Labka (about 30 km north of Sheeb). The project has five components i.e. spate irrigation development, domestic water supply, road construction, agricultural research and training. One of the objectives of the project was to improve the traditional spate irrigation system through construction of permanent flood diversion structures at wadis Laba and Mai-ule in Sheeb and at Wadi-Labka in Ghadem-halib. The feasibility study and design of the structures have been completed but the construction of the flood diversion structures is not yet implemented. Once these structures are in place, it is believed that they would increase the irrigation efficiencies and improve the water management system by reducing the losses of water at the diversion sites and thus making more water available for irrigation purposes and enabling a more equitable distribution of water among the users. Moreover, the establishment of the structures would reduce the amount of bed load materials deposited at the diversion structures; minimise the cutting of trees; decrease the human and animal labour involved in repairing the 'agims' and 'misghas' and also reduces the capital spent in constructing these structures. As a result, increase the farmers' productivity and make the traditional SIS stable and more sustainable. (Chapter 2).

It is strongly believed that the local farmers (in Sheeb and Wadi-Labka) could easily manage the operation and maintenance of the proposed flood diversion structures (through on-the-job training) and owing to their collective experience and knowledge of the spate irrigation system. However, farmers' commitments to accept the responsibilities and feel ownership of the work are very vital. Halcrow (1997) recommended a fully constituted farmers' organisation that need to be established in these areas to undertake the management activities and the farmer desire to contribute in cash, kind or labour to the organisation for the success and sustainability of the proposed structures.

Lining the main canals of the spate irrigation schemes (in Sheeb) with cements at an affordable cost could reduce the loss of water by percolation and seepage in the permeable alluvial bed of the 'misghas'. Moreover, water can be channelled faster and more directly to fields further away. This could eventually improve the equity of the water distribution system in Sheeb area. There are also possibilities of improving water management in the spate-irrigated fields, amongst others, appropriate land levelling before flooding of the fields and also after the floodwater has receded.

Use of manure and crop residues

In spate irrigation system, the crop production enterprise contributes crop residues (which are the main source of feed) for the livestock subsystem. These residues such as straw from sorghum, maize and millet increase the yield of livestock products (meat, milk and manure). But on the other hand, the manure is neither dropped in the fields nor applied into the soils, that could have otherwise improved the productivity of spate irrigated soils. In Sheeb area, there are possibilities of improving soil fertility and productivity by applying manure that is produced in considerable quantities but not used at this moment because farmers think that it is not profitable.

The shortage of livestock feed could be alleviated by growing forage plants along the wadi courses or canals; by planting leguminous trees (that are adaptable to the Sheeb area) along the field bunds or planting fast growing forage legumes between rows, if the spate crops are adequately spaced. Therefore, there is a scope for enhancing the integration of cropping and livestock products (in Sheeb area) and this would make the SIS more productive and sustainable.

The development of the infrastructure

One of the greatest achievements in the history of Sheeb community is the construction of all-weather road of Gahtelai-Mensheeb-Wadi-Labka by the ELWDP. The road to Mensheeb (administrative town of Sheeb sub region) links the town also to the main road network of Asmara-Massawa and to other regions of Eritrea. The construction of the road has given (the farmers) access to transport agricultural products to distant markets and to bring external inputs thereby alleviates the marketing problems faced by the farmers. Nowadays, the Sheeb community has got access to education, medication and drinking water supply through the establishments of schools, health centre and water wells by the local government and other development agencies.

In general, the construction of the road, the proposed flood diversion structures (when they are established) and other developments of the infrastructure in the northern Red Sea region of Eritrea would enhance the economic activities, improve the living conditions of the spate irrigation farmers and the Sheeb community as a whole in the near future.

10.5 Development potentials of the spate irrigation system

The Sheeb area

The potential of the spate irrigation system (in Sheeb) for agricultural production and its contribution to food security in the region is considerable. At present, the system appears to be functioning below its potential yield (i.e. 3.0-4.0 tons ha^{-1} for sorghum and 2.0-3.0 tons ha^{-1} for maize) due to the constraints explained earlier. During good flood seasons for example, the average grain yield of sorghum ranges from 1.5 to 2.5 ton per ha under traditional farming practises. In such seasons, it is also possible to harvest twice, sometimes even three times from a single sorghum plant without fertiliser application. Double cropping and inter-cropping are also possible under this system. Moreover, the spate irrigation production system is a 'cost effective' system, provided that the irrigation structures are properly maintained at low cost and the fields receive enough water and nutrients (Chapter 4).

In the system of spate irrigation, where water (not land) is the major limiting resource, there is a possibility of expansion the irrigable land (with land use improvements) in addition to the 2,500 to 3,000 ha of annually irrigated land in the Sheeb area. With the improvements of the traditional SIS (such as construction of permanent flood diversion structures) about 2,000 ha of additional land could be irrigated in the Sheeb spate irrigation schemes. These areas cover largely the southern part of Sheebkhetin village where still field bunds exist but they have never been irrigated due to a lack of water. Others are found further downstream in

Table 10.1. Main research topics in spate irrigation systems in Eritrea and their corresponding justifications.

Scale	Research topics	Justifications
National	• Quantifying the spate irrigation development potentials in the eastern lowlands of Eritrea	• The existing data on spate irrigation development potential are rough estimates, which lack ground truthing.
	• Exploring the development potentials of spate irrigation in the western lowlands of Eritrea (bordering Sudan)	• There are potential rivers (such as Gash and Barka) which can be used for spate irrigation development in the western lowlands.
Catchment	• Characterisation of soils and land use in the highland catchments of Sheeb.	• Characterising the soil and land use in the catchments helps to compare with the soil and land use data of Sheeb area.
	• Rainfall and runoff analysis in the highland catchments of Sheeb	• Lack of measured data on runoff in wadis Laba and Maiule basin and other hydrological characteristics of these wadis.
Village/farm	• Impact assessment of seasonal migration in Sheeb spate irrigation system.	• Evaluation of the positive and negative impacts of migration to the highlands.
	• Annual water balance of the spate irrigation system in Sheeb	• Lack of measured data on surface and groundwater water resource potentials in Sheeb area.
	• Traditional water rights of spate irrigation system.	• The traditional water law requires a revision with in-depth study.
	• Efficiencies of spate irrigation structures	• Lack of measured data on spate irrigation efficiencies.
	• Operation and maintenance of spate irrigation improvements works	• Proper management of user-groups infrastructures (e.g. when the proposed structures are established).
	• The ratoon cropping in Sheeb spate irrigated crop production system	• Lack of data on ratoon cropping subsystem.
	• Improved livestock feed management system in Sheeb area.	• Finding alternative feed sources (other than crop residues).
Field/plot	• Soil fertility research on spate-irrigated fields in Sheeb area.	• Determination of whether the spate soils need fertilisers or not.
	• Water use efficiency in spate irrigated fields of Sheeb area	• Achievement of maximum yield per unit of water.

hamlet Ediket where there are also bunds but not yet irrigated because the flood does not reach the site (Chapter 9).

Coastal zones of Eritrea

There are potential areas (about 11) covering extensive irrigable lands in the coastal plains of Eritrea where spate irrigation is being practised and in areas that were once used for spate irrigation but now abandoned due to the destruction of the infrastructure by the war for liberation. At present, only about 14,000 ha out of the 5 million ha coastal land area (i.e. less than 0.3 %) has been developed under spate irrigation (Tesfai and Stroosnijder 2000). The conservative estimates for the total potential spate irrigable land in the coastal plains of Eritrea is variously reported as 90,945 ha by IFAD (1995) and 60,135 ha by NRCE (1996).

10.6 Further research

Many questions remain unanswered and much more remains undiscovered in the field of spate irrigation system in Eritrea. The main research topics that need to be studied in the near future at different hierarchical levels using a systems approach are listed in Table 10.1.

10.7 References

Conway. G.R., McCracken J.A., and Pretty, J.N., 1987. Training notes for agroecosystem analysis and Rapid Rural Appraisal, IIED, London, UK. pp.12-19.

FAO, 1994. Eritrea agricultural sector review and project identification, Annex 5, Rome, Italy. pp 3-4

Halcrow, W., 1997. Engineering feasibility study report, Eastern lowlands wadi development project, MoA, Asmara, Eritrea.

IFAD, 1995. Staff appraisal report on Eastern lowlands wadi development project, Asmara, Eritrea, 52 pp.

Mazzucato,V. and Niemeijer, D., 2000. Rethinking soil and water conservation in a changing society: a case study in eastern Burkina Faso, PhD thesis, 380 pp.

NRCE, 1996. Final report on the reconnaissance of potential agricultural based water development in the Eastern slope of Eritrea. Asmara, Eritrea Vol. II pp.1-27

Tesfai, M. and Stroosnijder, L., 2000. The Eritrean spate irrigation system. Agricultural water management (In Press).

UNDP/FAO, 1987. Spate irrigation: Proceedings of the sub regional expert consultation on wadi development for agriculture in Yemen, Aden, PDR, 180 pp.

Annex A: Household Questionnaire

A. Identification

1. Name of household: .... Village............................
2. Gender
   - Male 1
   - Female 2

B. Family member

Family size	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sex														
Age														

3. Ethnic
   - Tigre 1 — Saho 3
   - Rashaida 2 — Others 4
4. Marital status
   - Married 1 — Divorced 3
   - Unmarried 2 — Widowed 4
5. Education
   - Illiterate 1 — Grade 6-7 5
   - Can only read 2 — Grade 8-11 6
   - Can read and write 3 — Grade >11 7
   - Grade1-5 4
6. Do you involve in off farm work?
   - Yes 1
   - No 2
7. Do you migrate to other places?
   - Yes 1
   - No 2
8. If yes, to which places and how far? ....

C. Gender issue

9. (a) Do women get engaged in agricultural activity?
   - Yes 1
   - No 2

   (b) If yes, in which activity
   - Ploughing 1 — Threshing grain 4
   - Seeding 2 — Transporting grain 5
   - Harvesting 3 — Other (specify) 6

   (c) If women work in the fields, state the type of women?
   - Young women with one child 1 — Divorced or widowed women 4
   - Women more than 3 children 2 — Other (specify) 5
   - Women without children 3
10. (a) Do your women here get involved in trade activities?
    - Owning a shop/teashop 1 — Sell vegetables 3
    - Selling handicraft 2 — Other (specify) 4

    (b) How do men react to this untraditional women activity?
    - Support it 1 — Have mixed feelings 3
    - Reject it 2 — Other (specify) 4
11. (a) Do women in your village get involved in community affairs? if yes,
    - Member of the 'Baito' 1 — Activation in local politics 3
    - Development programmes 2 — Other (specify) 4

(b) If no, would you kindly give reasons? ....

D. Land & water management

12. Do you own land?
    - Yes 1
    - No 2
13. If no, since when you did not own a land, specify the year ....
14. What is the main reason for not owning a land?
    - Shortage of irrigable land 1
    - High population density 2
    - Lack of capital 3
    - Unknown reason 4
    - Other, specify 5
15. Farm land inventory

Land / Plot	I	II	III	IV
Land holding size ('tsimidi')*				
Soil type				
Soil and water conservation practices				
Irrigation source				
Restriction factors				

16. How many floods do you get during this flood season (1997)
    Big floods .... Small floods ....
17. How many floods occur on average every year? ....
18. Have you observed an increase in soil depth in your farm?
    - Yes 1
    - No 2
    - Not sure 3
19. If yes, what is the average sediment height deposited per year in your field?
    - 3-5 cm 1
    - 5-10 cm 2
    - 10-20 cm 3
    - more than 25 cm 4
20. Do you like this deposition of soil in your field?
    - Yes 1
    - No 2
21. If yes, why?
    - Increases fertility 1
    - Increases cultivable land 2
    - Increases crop yield 3
    - Other specify 4
22. Do you have sediment deposition problem in your field?
    - Yes 1
    - No 2
23. If yes, what measures do you take to control the high sediment loads carried by the spates?
    - Repairing irrigation structures 1
    - Raising the bunds height 2
    - Other, specify 3
24. What is the average bund height you maintain in every flood year?
    - 0.5 meter 1
    - 1.0 meter 2
    - Other, specify 3
25. Have you noticed the effect of wind erosion ('Khamsin') in your field?
    - Yes 1
    - No 2
26. If yes, what measures do you take to reduce the wind erosion problem?
    - Establishing windbreaks 1
    - Mulching with crop residues 2
    - Regeneration of vegetation 3
    - Application of manure 4
    - No measure 5
    - Other, (specify) 6
27. Have you observed any soil crusting problem in your field?
    - Yes 1
    - No 2

* 'Tsimidi' is a local measurement unit equal to 0.25 ha of land.

28. If yes, what measures do you take to alleviate the problem?

Breaking the soil	1	Flooding the soil	3
Growing deep-rooted crops	2	Soil mulching	4
Other, specify	5		

29. Have you observed any salinity problem in your land?

Yes	1
Not at all	2
Rarely	3

30. If yes, at what period of the year

Before flood season	1
After flood season	2
During flood season	3

31. Do you have water shortage to grow crops in your field?

Yes	1
No	2

32. If yes, what do you do to alleviate the problem?

Growing short season crops	1	Reducing the cultivable land	4
Growing deep rooted	2	Other specify	5
Soil mulching	3		

E. Crop husbandry

33. What is your source of seed?

Own stock	1	Purchase	3
Exchange with other farmers	2	Aid	4

34. What is your criteria when choosing next year's seed?

Yield	1	Straw yield	5
Seed size	2	Market price	6
Earliness	3	Emergence	7
Grain colour	4	Short variety crops	8
		All	9

35. What are the main constraints to crop production?

Lack of water	1	Lack of farm inputs	3
Crop pests and diseases	2	Marketing	4
Other (specify)	5		

36. Do you collect straw of the crops?

Yes	1
No	2

37. If yes, for what purpose do you use the straws? ....

38. Who does harvest your crop?

You yourself only	1	Your family &	4
You & your wife	2	You & hired labour	5
Whole family	3		

39. If you sell grains, what % of your product do you sell?

10%	1	30%	4
20%	2	50%	5
25%	3		

40. If you do not sell grains, what is the reason?

Poor harvest	1	Drought	3
Only enough for consumption	2	Other (specify)	4

41. What were the prices of sorghum just before harvest ....and after harvest ....

42. What are the major constraints you face in marketing your agricultural products?

Low prices	1	Lack of credit	5
Lack of transport	2	Shortage of packing materials	6
Absence of markets	3	Lack of liquidity	7
Lack of diversified products	4	Other (specify)	8

F. Livestock husbandry

43. Do you own draught animals?

Yes	1		
No	2		

44. If no, what do you do to alleviate the problem?

Share animals with relatives	1		
Rent animals	2		
Others specify	3		

45. What is the main reason for not owning animals?

Lack of capital	1	Poor veterinary services	4
Lack of grazing areas	2	Destroyed due to war	5
Prevalence of diseases	3	Others (specify)	6

46. If you sell animals, for what purpose:

To get additional income	1	To pay taxes	4
To pay back loans	2	To buy food items	5
To use for weddings/death rituals	3	Others (specify)	6

47. What was the trend of your livestock population before liberation ………… ? after liberation?…………

Increase	1		
Decrease	2		

48. What are the main constraints to livestock production in your area?

Lack of feed	1	Shortage of water	5
Lack of grazing area	2	Drought	6
Diseases	3	Market problem	7
Wild animals, dogs	4	Others	8

49. When do you have critical shortage of feed and drinking water in your area?

Feed shortage: ……………………

Water shortage: ……………………

50. What do you do in months of feed shortage?

Migrate to the highlands	1	Purchase additional feed	4
Planting forage plants	2	Others specify	5
Reduce no. of animals	3		

51. What is the source of water for the animals? ……………………
52. What are the common livestock diseases in your area? ……………………
53. Why you do not vaccinate your livestock? ……………………

G. Credit facilities

54. Do you get credit for your spate irrigation operation?

Yes	1		
No	2		

55. If yes, what is your source of credit?

Ministry of Agriculture	1	Friend	5
Bank	2	Local money lender	6
Co-operative	3	Other specify	7
Neighbour/relative	4		

56. For what purpose do you use the credit?

Buy food items	1	Invest outside agriculture	5
Buy draft animals	2	Farm capital	6
Buy seed	3	Other home Consumption	7
Buy chemicals	4		

57. In what form do you pay the credit?

Grain	1	Labour	4
Cash	2	Others	5
Animal	3		

58. Which month of the year do you have serious cash deficit? ……………………

H. Crop Budget (1997)

59. Crop input-output

input/output data	main crop	ratoon crop (1st)	ratoon crop (2nd)
i) Crop type: .... Yield/ha (kg.) Price in ('nakfa')			
ii) Material cost: type, qty., cost ( ) Seeds Pesticides			
iii) Labor cost ('nakfa') Land preparation Diversion structures: repairing Bund construction Flooding of fields Planting Harvesting 1 (cutting stalk) Harvesting 2 (cutting head) Threshing Transporting Storing			
iv) Animal power cost: Preliminary ploughing Main ploughing Repair & creation of diversion structures Repair & construction of field bunds			
v) Wage labour ('nakfa')			

I. Livestock budget (1997)

60. Livestock input-output

Draught/ Pack animals	Oxen	Cow	Camel	Donkey	Goat	Sheep	Chickens
i) Number owned							
ii) Breed: local, improved							
iii) Production/yr. Milk Egg Butter Hides							
iv) Material cost /yr. Fodder Drugs/ veterinary Others							
v) Labour cost: days /yr. Herding Feeding Watering Milking Other activities							

Note: 'Nakfa' is a local currency of Eritrea. In 1997, the exchange rate was US $1= 7.20 'nakfa'.

J. Farm implements and tools inventory

61.

Kind	Owned (number)	Value ('nakfa')
Plough tip and accessories (set)		
'Mihar'		
'Jeleb'		
Spade		
Winnower		
Axe		
Basket		
Sacks		
Others, specify		
Total		

K. Farm buildings inventory

62.

Description	Multipurpose housing	Storage house
Construction material		
Age (years)		
Remaining life (years)		
Repair and maintenance cost/ yr., ('nakfa')		
Original construction cost ('nakfa')		
Deprecation cost ('nakfa')		
Present value('nakfa')		
Total value('nakfa')		

L. Food security

63. How much does your household consume per month (1997)?

Item	Unit of measure	Quantity	Price/unit	Total ('nakfa')
Cereals				
Meat				
Vegetables				
Pulses				
Milk				
Coffee				
Tea				
Sugar				
Salt				
Edible oil				
Butter				
Tobacco				
Water				
Others (specify)				

64. Would you please give your food production, sales and purchase (1996)?

Type of crop	Production (kg)	Sales		Purchases	
		kg	Price('nakfa')	kg	Price ('nakfa')
Sorghum					
Maize					
Pearl millet					
Sesame					
Watermelons					
Tomato					
Groundnut					
Cow					
Goat					
Donkey					
Camel					
Other, specify					

65. For how months did your harvest (1996) feed your family?

12 months	1	3-5 months	4
9-12 months	2	1-2 months	5
6-8 months	3	Less than one month	6

66. How does your household adjust to food shortages?

By selling animals	1	By renting pack animals	5
By working for wages	2	By taking food/cash for credit	6
By migrating to highlands	3	By petty trading	7
By taking food aid	4	By remittance	8
		By other means (specify)	9

67. Was 1996 a very good/ good/ average/ bad/ very bad year?........................

Thank you!

Annex B: Soil profile descriptions

Profile - P1

Soil classification (FAO):	calcaric Fluvisols, salic phase
(USDA):	calcic Fluvents
Soil name (local):	'merid' or 'shemshem'
Mapping unit:	SMU A-1
Location:	Mensheeb wadi bank, about 500m NW of Mensheeb town
Coordinates (UTM)	503913 E, 1754511 N
Date:	98 04 09
Authors:	Mehreteab & Mehari
Topography:	almost flat
Land element:	wadi bank
Irrigation:	wadi Laba
Slope:	1%
Land use:	irrigated sorghum cultivated
Parent material:	alluvial deposits
Drainage class (FAO)	moderately well
Surface characteristic:	water deposition
Moisture conditions:	dry to 250 cm, moist below.

Depth (cm)	Horizon/Layer[4]	Profile descriptions
0-90	Apc	light yellowish brown (10YR 6/4) dry and brown (10YR 4/3) moist; no mottles; clay loam; stratified structure; slightly hard when dry; slightly sticky when wet; interstitial pore type; very fine to fine pore size; strongly calcareous; abrupt boundary.
90-100	S1	pale red (2.5YR 7/2) dry and reddish brown (2.5YR 5/3) moist; stratified structure; slightly to moderately calcareous; abrupt boundary.
100-123	S2	light yellowish brown (10YR 6/4) dry and brown (10YR 5/3) moist: very weak, very fine subangular and angular blocky; moderately to strongly calcareous; diffuse boundary.
123-178	S3	brownish yellowish (10 YR 6/6) dry and brown (10 YR 4/3) moist: loam; weak to moderate, very fine, angular and subangular blocky; slightly hard when dry; sticky when wet; strongly calcareous; abrupt boundary.
178-258	S4	pale red (2.5 YR 7/2) dry; reddish brown (2.5 YR 5/3) moist; stratified structure; slightly to moderately calcareous; abrupt boundary.
258-328	S5	dark yellowish brown (10 YR 4/4) moist; light clay; weak to moderate, very fine, angular and subangular blocky; slightly hard; when dry sticky to very sticky when wet; strongly calcareous; abrupt boundary.

Profile - P3

Soil classifcation (FAO):	calcaric Fluvisols, eroded phase
(USDA):	calcic Fluvents
Soil name (local):	'tinfeshah'
Mapping unit:	SMU A-1
Location:	Ghineab, about 3 km east of Ghineab hill
Coordinates (UTM)	506783 E, 1760164 N
Date:	98 04 10
Authors:	Mehreteab & Mehari
Topography:	almost flat
Land element:	gully bank
Irrigation sources:	wadi Mai-ule, wadi Sheleka, wadi Harmazo
Slope:	<2%
Land use	millet irrigated cultivated
Parent material:	alluvial deposits

[4] S refers to layer of soils

Drainage class (FAO) somewhat poorly drained
Surface characteristics: sever gully erosion
Moisture conditions: dry throughout

Depth (cm)	Horizon/Layer	Profile descriptions
0-35	Apc	light yellowish brown (10YR 6/4) dry, dark yellowish brown (10YR 4/4) moist, clay loam; moderate platy; slightly hard when dry; slightly sticky when wet; many pores; many roots; strongly calcareous; diffuse boundary.
35-50	S1	light yellowish brown to yellowish brown (10YR 5.5/4) dry, dark yellowish brown (10YR 4/4) moist, moderate, angular and subangular blocky, few voids, few roots, strongly to extremely calcareous; diffuse boundary.
50-85	S2	brownish yellow (10YR 6/4) dry; dark yellowish brown (10YR 4/4) moist, moderate, angular blocky, many pores, few roots, moderately calcareous, diffuse boundary.
85-110	S3	light yellowish brownish to yellowish brown (10YR 5.5/6) dry; dark yellowish brown (10YR 4/4) moist; moderate to strong, angular to angular blocky, few voids, very few roots, strongly calcareous; diffuse boundary.
110-165	S4	reddish yellow to strongly brown (7.5YR 5.5/8) dry, dark yellowish brown (10YR 4/4) moist, sand, massive, stratified structure, soft when dry; slightly sticky when wet , strongly calcareous, clear boundary.
165-255+	S5	brown (10YR 4/3) dry, dark brown (10YR 3/3) moist, sand, massive stratified structure; soft when dry, non sticky when wet; slightly to moderately calcareous.

Profile - P4

Soil classification (FAO) : calcaric Arenosols (Arc)
(USDA): calcic Psamments
Soil name (local): 'hutsa hamed'
Mapping unit : SMU-B
Location : Sheebkhetin, 500m east of Sheebkhetin village
Coordinates (UTM) 503447 E, 1752206 N
Date : 98 04 11
Author: Mehreteab & Mehari
Topography: almost flat
Land element : bund
Irrigation sources: no water, if available from wadi Laba
Slope: 2%
Land use: non-irrigated land since 1964
Parent material: alluvial deposits
Drainage class (FAO) somewhat excessively drained
Surface characteristics bleached sand grains
Moisture conditions dry throughout

Depth (cm)	Horizon	Profile descriptions
0-20	Ac1	brownish yellow (10YR 6/6) dry, dark yellowish brown (10YR 4/4) moist, clay loam; weak very fine, angular blocky; slightly hard when dry ; slightly sticky to sticky when wet; very few roots; moderately calcareous; diffuse boundary.
20-65	Ac2	brownish yellow (10YR 6/6) dry, dark yellowish brown (10YR 4/4) structureless, many buried roots, slightly to moderately calcareous, diffuse boundary.
65-130	ABc	brownish yellow (10 YR 6/4) dry; dark yellowish brown (10 YR 4/4) moist; sand; stuctureless, slightly hard when dry, non sticky when wet slightly to moderately calcareous, clear boundary.
130-157+	Bc	yellowish brown (10 YR 5/6) dry ; dark yellowish brown (10 YR 4/4) moist; weak, very fine, sub-angular, moderately calcareous ; diffuse boundary.

Profile : P5

Soil classification (FAO):	calcaric Fluvisols (FLc)
(USDA):	calcic Fluvents
Soil name (local):	'tin hamed'
Mapping unit:	SMU-A-1
Location:	Sheebkhetin, about 500m north of Sheebkhetin village
Coordinates (UTM)	501394 E, 1754695 N
Date:	98 04 11
Authors:	Mehreteab & Mehari
Topography:	almost flat
Land element:	bund
Slope:	1%
Land use:	irrigated cultivation
Parent material:	alluvial deposits
Drainage class (FAO)	well drained
Surface characteristics	slight water and wind erosion
Moisture conditions	dry throughout
Irrigation sources:	wadi Laba

Depth (cm)	Horizon/Layer	Profile descriptions
0-20	Apc	light yellowish brown (10YR 6/4) dry, yellowish brown (10YR 5/4) moist; few mottles; loam; strong; very fine, angular blocky; hard when dry; sticky to very sticky when wet, few voids, many roots, moderately calcareous; diffuse boundary.
20-42	S1	light yellowish brown (10YR 6/4) dry, dark yellowish brown (10YR 3/4); few mottles; weak, very fine, subangular blocky; few voids; many roots; strongly calcareous; diffuse boundary.
42-85	S2	light reddish brown (2.5YR 7/3) dry, dark yellowish brown (10YR 4/4) moist; very weak, very fine, angular and subangular blocky; many, strongly calcareous; clear boundary.
85-111	S3	light reddish brown (2.5 YR 6/3) dry, dark reddish brown (2.5YR 3/3) moist; common mottles; light clay; strong, very fine, angular blocky; very hard when dry, sticky to very sticky when wet; many voids; many roots; strongly calcareous; diffuse boundary.
111-136	S4	light reddish brown (2.5YR 6/3) dry, dark reddish brown (2.5 YR 3/3) moist; very few mottles; very weak, very fine, subangular blocky; few roots; strongly calcareous; clear boundary.
136-156	S5	light reddish brown (2.5YR 6/3) dry, grayish brown (2.5R 5/2) moist, stratified structures, few roots, slightly to moderately calcareous, clear boundary.
156-191$^+$	S6	light reddish brown (2.5YR 6/3) dry, grayish brown (2.5R 5/2) moist, common, clay loam, weak, very fine, angular blocky parallelepiped, hard when dry, sticky when wet, few roots, slight calcareous, abrupt boundary.

Profile: P6

Soil classification (FAO):	calcaric Fluvisol, eroded phase
(USDA):	calcic Fluvents
Soil name (local):	'Kurfotat'
Mapping unit:	SMU-A
Location:	Bises, about 11km N of Bises village
Coordinates (UTM)	498676 E, 1754695 N
Date:	98 04 12
Authors:	Mehreteab & Mehari
Topography:	almost flat
Land element:	gully
Slope:	2%
Land use:	Irrigated cultivation
Parent material:	alluvial deposits

Drainage Class:	somewhat excessively drained
Moisture condition:	dry through out
Irrigation source:	wadi Maiule

Depth(cm)	Horizon/Layer	Profile descriptions
0-20	Apc	light yellowish brown (10YR 6/4) dry, dark yellowish brown(10YR 4/4) moist; loam; weak, very fine, angular blocky; slightly hard when dry; slightly sticky when wet; few voids; many roots; strongly calcareous; diffuse boundary.
20-210	S1	light reddish brown (2.5YR 6/4) dry, dark reddish brown(2.5YR 3/3) moist; strong, very fine, angular and subangular blocky; few voids; common roots; strongly calcareous; diffuse boundary.
210-240	S2	light reddish brown (2.5YR 6/4) dry, dark reddish brown (2.5YR 3/3) moist, common mottles; weak, very fine, subangular blocky, few voids, few roots, moderately to strongly calcareous, clear boundary.
240-300$^+$	S3	Brown (10YR 4/3) moist; clay loam; moderate, very fine, angular and subangualr blocky; slightly hard when dry; sticky to very sticky when wet; few voids; moderately to strongly calcareous; clear boundary.

Profile: P7

Soil classification (FAO):	calcaric Fluvisol
(USDA):	calcic Fluvents
Soil name (local):	'hutsa hamed'
Mapping unit:	SMU A-1
Location:	Bises, about 400m east of Bises village
Coordinates (UTM)	499076 E, 1756232 N
Date:	98 04 12
Authors:	Mehreteab & Mehari
Topography:	almost flat
Land element:	bund
Slope:	4%
Land use:	irrigated cultivation
Parent material:	alluvial deposits
Drainage class:	excessively drained
Surface characteristics:	few bleached sand grains
Moisture conditions:	dry throughout
Irrigation source:	wadi Laba

Depth(cm)	Horizon/Layer	Profile description
0-27	Apc	light reddish brown (2.5YR 6/3) dry, dark reddish brown (2.5YR 3/3) moist; many mottles; loamy sand; strong, very fine, angular blocky; slightly hard; non sticky when wet; few voids; many roots; strongly calcareous; abrupt boundary.
27-82	S1	pale red (2.5YR 6/2) dry, weak red (2.5YR 5/2) moist, stratified structure; many roots; slightly calcareous; abrupt boundary.
82-182$^+$	S2	dark yellowish brown (10YR ¾) moist; few mottles; clay loam; weak, very fine, angular and subangular blocky; slightly hard to hard when dry; slightly sticky when wet; very few voids; strongly calcareous; abrupt boundary.

Profile: P8

Soil classification (FAO):	calcaric Fluvisol
(USDA):	calcic Fluvents
Soil name (local):	'merig hamed'
Mapping unit:	SMU A-1
Location:	Tiluk, about 3 km east of Tiluk village
Coordinates (UTM)	501299 E, 1758026 N
Date:	98 04 13

Authors:	Mehreteab & Mehari
Topography:	gently undulating
Land element:	bund
Slope:	3%
Land use:	irrigated cultivation
Parent material:	alluvial deposits
Drainage class:	excessively drained
Surface characteristics:	none
Moisture conditions:	dry to 30 cm, moist below
Irrigation source:	wadi Mai-ule

Depth(cm)	Horizon/Layer	Profile description
0-30	Apc	pale red (2.5YR 6/2) dry, weak red (2.5YR 5/2) moist; stratified structure; many roots; strongly calcareous; clear boundary.
30-155	S1	dark yellowish brown (10YR 4/4) moist; common mottles; clay loam; moderate, very few, angular blocky; slightly hard to hard when dry; sticky when wet; few voids; many roots; strongly calcareous; diffuse boundary.
155-180	S2	yellowish brown (10YR 5/4) moist; stratified structures; very few roots; strongly calcareous; diffuse boundary.

Profile P9

Soil classification (FAO):	calcaric Fluvisols (FLc) , salic phase
(USDA):	calcic Fluvents
Local soil name:	'hutsa hamed'
Mapping unit:	SMU A-1
Location:	Tiluk, about 500 m south east of Tiluk village
Coordinates (UTM)	500085 E, 1758817 N
Date:	98 04 13
Authors:	Mehreteab & Mehari
Topography:	almost flat
Land element:	bund
Slope:	2%
Land use:	irrigated cultivation
Parent material:	alluvial deposits
Drainage class:	excessively drained
Surface characteristics:	none
Moisture conditions:	dry throughout
Irrigation source:	wadi Mai-ule

Depth(cm)	Horizon/Layer	Profile description
0-40	Apc	light yellowish brown (2.5YR 6/4) dry; dark grayish brown (2.5YR 4/2) moist; abundant, medium gravel; stratified structures; common roots; moderately to strongly calcareous; abrupt boundary
40-75	S1	light brownish gray (2.5YR 6/2) dry; olive brown (2.5YR 4/3) moist; stratified structures, few voids; slightly to moderately calcareous, diffuse boundary.
75-130	S2	light yellowish brown (2.5YR 6/4) dry; light olive brown (2.5YR 5/4); silt loam; weak, very fine, subangular and angular blocky; slightly hard when dry; slightly sticky when wet; few voids; moderately to strongly calcareous; clear boundary.
130-148	S3	grayish brown to light olive brown (2.5YR 5/2.5) dry; olive brown (2.5YR 4/3)moist; stratified structure; few voids; moderately to strongly calcareous; clear boundary.
148-168^{+}	S4	light yellowish brown (2.5YR 6/4) dry; olive brown(2.5YR 4/3) moist; common, fine mottles; loam; very weak, angular to subangular blocky; hard when dry; sticky when wet; few voids; strongly calcareous; clear boundary.

Profile: P10

Soil classification: (FAO) salic Fluvisols (FLs), salic phase
(USDA): salic Fluvents
Soil name (local): 'hutsa hamed'
Mapping unit: SMU A-1
Location: Dige, about 150m west of Dige remnants building
Coordinates (UTM) 503250 E, 1756410 N
Date: 98 04 14
Authors: Mehreteab & Mehari
Topography: gently undulating
Land Element: settlement area
Slope: 5%
Land use: residential use
Parent material: fluvial deposits
Drainage class: excessively drained
Surface characteristics: bleached sand grains
Moisture conditions: dry up to 50 cm, moist below
Irrigation source: previously from wadi laba

Depth(cm)	Horizon/Layer	Profile description
0-45	Az	brownish yellow(10YR 6/6) dry, dark yellowish brown (10YR 4/4) moist loamy sand; weak, stratified structures; soft to slightly hard when dry, slightly sticky when wet; many voids; debris of roots; slightly calcareous, diffuse boundary.
45-112	S1	light yellowish brown to yellowish brown (10YR 5.5/4) dry; olive brown (2.5YR 4/4) moist; stratified structure; moderately to strongly calcareous; clear boundary.
112-129	S2	light yellowish brown (2.5YR 6/4) dry, olive brown (2.5YR 4/4) moist; silt loam; weak; angular to subangular blocky; slightly hard when dry; slightly sticky when wet; strongly calcareous; clear boundary.
129-184$^+$	S3	light yellowish brown (2.5YR 6/4) dry, light olive brown(2.5YR 5/4) moist; stratified structure; strongly calcareous; clear boundary.

Profile: P11

Soil classification (FAO): calcaric Fluvisol (FLc)
(USDA): calcic Fluvents
Soil name (local): 'Dibret'
Mapping unit: SMU A-1
Location: Dige, about 500m south of Dige village.
Coordinates (UTM) 504159 E, 1755266 N
Date: 98 04 14
Authors: Mehreteab & Mehari
Topography: gently undulating.
Land element: wadi bank
Slope: 4%
Land use: irrigated cultivation
Parent material: alluvial deposits
Drainage class: somewhat excessively drained
Surface characteristics: crust (1 mm thickness)
Moisture condition: dry throughout
Irrigation source: wadi Laba

Depth (cm)	Horizon/Layer	Profile description
0-45	Apc	yellowish brown (10YR 5/4) dry, very dark grayish brown (10YR 3/2) moist; light clay; very weak subangular and angular blocky; hard when dry; sticky when wet; many voids; many roots; moderately to strongly calcareous; clear boundary.
45-70	S1	light gray (2.5Y 7/2) dry, dark olive brown (2.5Y 3/3). moderate, angular blocky; common voids; few roots; moderately to strongly calcareous; abrupt boundary.
70-150	S2	yellowish brown (10YR 5/4) dry, brown (10YR 4/3) moist, many mottles, light clay, moderate, subangular and angular blocky; very hard when dry, sticky to very sticky when wet , many voids, few roots; strongly calcareous, clear boundary.
150-165	S3	light gray to light brownish gray (2.5Y 6.5/2) dry, weak red (2.5YR 4.5/2) moist; stratified structure; few voids; few roots; slightly to moderately calcareous; abrupt boundary.
165-215	S4	light yellowish brown (10YR 6/4) dry, dark yellowish brown (10YR 4/4) moist; strong, angular blocky; common voids; very few roots; strongly calcareous; abrupt boundary.
215-230	S5	light gray to light brownish gray (2.5Y 6.5/2) dry, weak red (2.5YR 4.5/2) moist; stratified structure; few voids; moderately to strongly calcareous; abrupt boundary.
230-280$^+$	S6	yellowish brown (10YR 5/4) dry, dark yellowish brown (10YR 4/4) moist; weak, angular and subangular blocky; few voids; strongly calcareous; clear boundary.

Profile: P12

Soil classification (FAO):	salic Fluvisol, slic phase.
(USDA):	salic Fluvents
Soil name (local):	'chew hamed'
Mapping unit:	SMU B
Location:	Dimnadige, 200 m east of Dimnadige village.
Coordinates (UTM)	506297 E, 1756748 N
Date:	98 04 15
Authors:	Mehreteab & Mehari
Topography:	almost flat
Land Element:	bund
Slope:	2%
Land Use:	irrigated cultivation
Parent material:	alluvial deposits
Drainage class:	somewhat poorly drained
Surface characteristics:	severe wind erosion
Moisture condition:	moist throughout out
Irrigation source:	wadi Laba; Mai-Ule

Depth (cm)	Horizon/Layer	Profile description
0-25	Azc	yellowish brown (10YR 5/4) dry, dark yellowish brown (10YR 4/4) moist; light clay; weak to moderate, angular blocky; slightly hard when dry; sticky when wet; very few voids; strongly calcareous; diffuse boundary.
25-110	S1	light yellowish brown (10YR 6/4) dry, dark yellowish brown (10YR 3/4) moist; light clay; moderate, sub angular and angular blocky; slightly hard to hard when dry; sticky when wet; very few voids; strongly calcareous; diffuse boundary.
110-155	S2	brown (10YR 5/4) moist; common mottles; moderate, angular blocky; strongly calcareous; diffuse boundary.
155-180$^+$	S3	Yellowish brown (10YR 5/4) dry; dark yellowish brown (10YR 3/4) moist; weak, angular and sub angular blocky; few voids; very strongly calcareous; diffuse boundary.

Profile: P13

Soil classification (FAO): calcaric Fluvisol, eroded phase.
(USDA): calcic Fluvents
Soil name (local): 'tin hamed'
Mapping unit: SMU A-1
Location: Dimnadige, about 700m north east of Dimnadige village.
Coordinates (UTM) 505782 E, 1757006 N
Date 98 04 15
Authors: Mehreteab & Mehari
Topography: almost flat
Land Element: gully
Slope: 2%
Land Use: irrigated cultivation
Parent material: alluvial deposits
Drainage class: somewhat poorly drained
Surface characteristics: dry throughout
Irrigation source: wadi Laba

Depth (cm)	Horizon/Layer	Profile description
0-20	Apc	light yellowish brown (2.5Y 6/4) dry; dark yellowish brown (10YR 4/4) moist; clay loam; weak, very fine, subangular blocky; hard when dry; sticky when wet; many voids; many roots; strongly calcareous; diffuse boundary.
20-55	S1	light yellowish brown (2.5Y 6/3) dry, dark yellowish brown (10YR 4/4) moist; loam; very weak, very fine, subangular blocky; slightly hard to hard when dry; sticky when wet; few voids; few roots; strongly calcareous; diffuse boundary
55-117	S2	light yellowish brown (10YR 6/4) dry, brown (10YR 4/3) moist; very weak, very fine, subangular blocky; many voids; strongly calcareous; diffuse boundary.
117-139	S3	light yellowish brown (10YR 6/4) dry, brown (10YR 4/3) moist; very weak, very fine, subangular blocky, few voids, very strongly calcareous, clear boundary.
139-169	S4	light yellowish brown (10YR 6/4) dry, dark yellowish brown (10YR 4/4) moist; very weak, very fine, subangular and angular blocky; few voids; strongly calcareous; diffuse boundary.

Profile: P14

Soil classification (FAO): calcaric Fluvisol (FLc)
(USDA): calcic Fluvents
Soil name (local): 'tin hamed'
Mapping unit: SMU A-1
Location: Ghineab, about 150 m east of Haroda hill
Coordinates (UTM) 504962 E, 1759583 N
Date 98 04 16
Authors: Mehreteab & Mehari
Topography: almost flat
Land Element: bund
Slope: 2%
Land Use: irrigated cultivation
Parent material: alluvial deposits
Drainage class: well drained
Surface characteristics: medium cracks
Surface characteristics: dry to 61cm, moist below
Irrigation source: wadis Shelak and Harmazo

Depth (cm)	Horizon/Layer	Profile description
0-18	Apc	yellowish brown (10YR 5/4) dry, dark yellowish brown (10YR 4/4) moist, clay loam; very weak; sub angular and angular blocky; slightly hard to hard when dry; slightly sticky when wet; common voids; few roots; strongly calcareous; clear boundary.
18-61	S1	brownish yellow to yellowish brown (10YR 5.5/6) dry, light yellowish brown (10YR 6/4) moist, weak to moderate, angular and sub angular blocky, many voids, few roots, strongly calcareous, diffuse boundary.
61-139	S2	yellowish brown (10YR 5/4) moist, light clay; weak, angular blocky, slightly hard when dry, sticky when wet, common voids, very few roots, strongly calcareous; diffuse boundary.
139-169+	S3	dark yellowish brown (10YR 4/4) moist; medium, angular to sub angular blocky; many voids; strongly calcareous; diffuse boundary.

Profile: P15

Soil classification (FAO):	calcaric Fluvisol (FLc)
(USDA):	calcic Fluvents
Soil name (local):	'tin hamed'
Mapping unit:	SMU A-1
Location:	Edieket, about 300 m east of Debir-shum hill
Coordinates (UTM)	509224 E, 1755268 N
Date	98 04 16
Authors:	Mehreteab & Mehari
Topography:	almost flat
Land Element:	bund
Slope:	1%
Land Use:	irrigated cultivation
Parent material:	alluvial deposits
Drainage class:	somewhat poorly drained
Surface characteristics:	severe wind erosion, cracks
Surface characteristics:	dry throughout
Irrigation source:	all wadis (Laba, Maiule, Shelaka and Harmazo)

Depth (cm)	Horizon/Layer	Profile description
0-25	Apc	light yellowish brown (10YR 6/4) dry, brown (10YR 4/3) moist, silt loam; weak angular and sub angular blocky; slightly hard when dry; slightly sticky to sticky when wet; many voids; few roots; moderately to strongly calcareous; clear boundary.
25-68	S1	yellowish brownish to light yellowish brown (10YR 5.5/4) dry, brown (10YR 4/3) moist, moderate, angular blocky, few voids, common roots, strongly calcareous, clear boundary.
68-100	S2	light yellowish brown (2.5Y 6/4) dry, olive brown (2.5Y 4/4) moist, clay loam; weak, angular and sub angular blocky, slightly hard to hard when dry, slightly sticky to sticky when wet, common voids, strongly calcareous; diffuse boundary.
100-123	S3	light yellowish brown (2.5Y 6/4) dry; dark yellowish brown (10YR 4/4) moist, light clay, weak, sub angular to angular blocky; hard when dry, sticky when wet common voids; moderately to strongly calcareous; clear boundary.
123-147+	S4	Light yellowish brown (2.5Y 6/4) dry, olive brown (2.5Y 4/4) moist, few mottles; very weak, angular blocky, common voids, strongly calcareous; clear boundary.

Annex C: Soil physical and chemical data

Sample	Depth	Sand	Silt	Clay	pH H_2O	EC (1:5)	OM	Total, N	P-Olsen	K-available	Ca^{2+}	Mg^{2+}	Na^{+}	CEC
ID	cm	%	%	%	(1:2.5)	d S m^{-1}	%	%	mg kg^{-1}	mg kg^{-1}	meq 100 g^{-1}			
P1/S1	0-90	32.6	41.5	25.9	8.04	2.39	0.70	0.02	26.03	175.36	17.0	0.5	0.98	6.14
P1/S4	123-178	22.2	56.1	21.8	7.93	0.52	0.4	nl	14.77	227.97	29.8	2.75	0.41	7.12
P1/S6	258-328+	13.3	55.2	31.5	7.66	0.46	0.62	0.01	15.88	227.97	19.4	0.88	0.21	12.01
P3/S1	0-35	15.7	59.1	25.3	7.9	0.12	0.76	0.01	12.67	175.36	30.5	0.75	0.35	32.1
P3/S5	110-165	64.5	25.0	10.5	8.10	0.12	0.10	nl	3.29	122.75	11.0	0.25	0.06	5.16
P3/S6	165-255+	69.2	19.4	11.4	8.07	0.69	0.28	nl	3.66	140.29	10.5	1.87	0.21	6.63
P4/S1	0-20	50.0	37.8	12.7	8.23	0.14	0.29	0.03	7.92	350.72	11.4	2.75	15.0	6.14
P4/S3	65-130	69.7	27.3	3.0	8.19	0.19	0.15	nl	4.45	175.36	11.4	0.74	12.7	3.21
P5/S1	0-20	8.8	65.2	26.0	7.90	0.50	1.38	0.01	11.08	140.29	33.8	0.75	0.35	11.03
P5/S4	85-111	12.3	57.8	30.0	7.71	0.16	2.06	nl	28.61	157.82	40.4	1.50	0.70	17.88
P5/S7	156-191+	17.1	57.8	25.1	7.83	0.50	1.31	nl	23.08	140.29	36.4	1.00	0.70	16.90
P6/S1	0-20	27.2	57.4	15.4	7.89	0.45	0.89	nl	24.92	140.29	29.4	0.88	0.21	9.08
P6/S4	240-300+	5.3	58.6	36.1	7.58	2.53	2.24	0.05	48.00	227.97	47.0	0.37	0.80	22.28
P7/S1	0-27	23.0	66.2	10.9	7.94	0.15	1.31	0.01	16.25	139.27	33.0	3.38	0.20	9.57
P7/S3	82-182	30.1	52.6	17.3	8.10	0.18	0.50	0.01	15.69	121.87	24.0	2.25	0.64	5.65
P8/S2	30-155	10.7	55.9	33.4	7.80	0.45	1.29	0.01	30.46	174.09	45.3	3.50	0.64	18.37
P9/S3	75-130	36.4	50.6	13.0	7.15	0.73	0.44	0.02	13.58	104.46	34.4	1.13	0.64	6.63
P9/S5	148-168+	30.4	52.7	16.9	8.00	0.69	0.77	nl	14.05	104.46	39.0	2.12	0.20	7.61
P10/S1	0-45	37.9	47.1	15.0	7.70	7.00	1.38	0.04	70.80	6386.22	15.3	1.75	7.65	8.59
P10/S2	45-184+	47.9	45.1	7.0	8.44	0.71	0.15	0.01	4.02	139.27	22.3	nl	0.20	4.18

Sample	Depth	Sand	Silt	Clay	pH H_2O	EC (1:5)	OM	Total, N	P-Olsen	K-available	Ca^{2+}	Mg^{2+}	Na^{+}	CEC
ID	cm	%	%	%	(1:2.5)	d S m^{-1}	%	%	mg kg^{-1}	mg kg^{-1}	meq 100 g^{-1}			
P11/S1	0-45	24.9	52.7	22.4	7.88	0.40	1.42	0.01	25.29	208.91	36.8	nl	2.56	13.97
P11/S3	70-150	16.9	58.5	24.6	7.76	0.53	0.84	0.01	20.60	139.27	34.3	1.00	1.29	12.99
P12/S1	0-25	20.7	46.6	32.7	7.57	2.80	1.24	0.02	27.16	313.37	47.3	0.25	0.55	15.92
P12/S2	25-110	23.4	49.1	27.5	7.71	1.05	0.62	0.01	5.87	121.87	56.3	1.00	0.31	12.99
P13/S1	0-20	31.9	43.0	25.1	7.95	0.26	0.56	0.01	10.30	156.68	36.5	0.50	0.20	9.08
P13/S2	20-55	27.7	44.8	27.5	7.83	0.26	0.73	0.02	7.49	191.50	37.0	1.00	0.20	10.54
P14/S1	0-18	16.0	63.1	20.9	7.97	0.11	0.59	nl	26.41	139.27	24.5	1.00	0.35	9.08
P14/S3	61-139	23.7	56.7	19.6	7.68	0.57	0.72	nl	13.20	156.68	31.5	14.8	0.20	12.01
P15/S1	0-25	32.3	47.8	19.9	7.91	0.11	0.54	nl	12.17	174.09	30.5	2.00	0.69	8.59
P15/S3	68-100	27.1	41.6	31.3	7.60	1.02	0.77	0.01	7.73	262.44	43.8	0.75	0.31	19.35
P15/S4	100-123	21.9	50.5	27.6	7.74	0.94	0.96	nl	11.13	174.96	62.3	1.50	0.31	16.90
A1/S1	0-25	27.7	54.7	17.6	7.97	0.18	0.59	nl	7.96	192.46	43.0	0.50	0.80	12.50
A1/S2	25-125	36.3	39.7	24.0	7.81	0.94	0.54	0.01	8.90	209.95	27.5	1.50	0.31	11.03
A2/S1	0-25	54.8	25.9	19.3	7.88	0.10	0.48	nl	12.17	192.46	32.3	2.00	1.78	6.14
A2/S2	25-125	16.9	50.7	32.4	7.67	0.10	0.62	nl	9.83	174.96	49.5	nl	0.20	12.01
A3/S1	0-15	21.7	68.6	9.7	7.38	8.44	1.03	0.01	31.65	437.40	27.5	0.50	12.1	20.33

Note: P: the soil profile pit number
S: the soil layer from which sample was collected.
A: the auger pit number.
nl: nil

Summary

This thesis is about spate irrigation in Eritrea with special reference to soil and water management practises. Spate irrigation is a pre-planting method of irrigation where use is made of flash floods produced from highland areas of Eritrea, are diverted to irrigated land in the lowlands. In the lowlands, the floods are diverted to nearby irrigable fields by temporary diversion structures (locally called 'agims') and distributed by canals (locally called 'misghas') to a series of fields that are surrounded by bunds of 0.5-1.0 m high. In the fields, the diverted water infiltrates into the deep soil profiles, while sediment that includes plant nutrients and organic matter are deposited on the soil surface. Seeds are sown on these fields and crop production is sustained under residual moisture in the soil profile and the sporadic precipitation (< 100 m).

Spate irrigation (in Eritrea) has been practised since the beginning of the 20th century and it has many advantages: (1) spate irrigation provides water for one or more crops in arid areas of the Red Sea coastal zones of Eritrea, (2) spate irrigation builds up land by depositing fertile soils on irrigable fields, (3) spate irrigation offers a livelihood to a large number of farmers living in the coastal zones of Eritrea.

The spate irrigation system in Eritrea

The principles and practises of the Eritrean spate irrigation system (SIS) in general and in Sheeb area in particular are described in Chapter 1 and 2 of this thesis. The main sources of water for spate irrigation (in Sheeb area) are floods carried by wadis Laba and Maiule, which spring from the adjacent highlands of Eritrea. The farmers in Sheeb mentioned that one of the major constraints of the spate irrigation system is water shortage and breaching of the 'agims' and 'misghas' by destructive big floods. The causes of water shortage are the irregularity of rains in the highlands of Eritrea and low diversion and distribution efficiencies of the 'agims' and 'misghas', respectively. The low irrigation efficiencies of 'agims' and 'misghas' structures is due to the difficulties of controlling the unpredictable floods (because of their weak structures) and the substantial losses of water by percolation and seepage in the unlined canals.

The farming community and the household

The farmers in Sheeb community (through experience and knowledge) have developed a system of spate irrigation that enables them to produce crops with 1500-2000 kg grain per ha in such arid environment where rainfed agriculture is totally unthinkable. To fully understand how the

SIS operates, a Participatory Rural Appraisal (PRA) approach was undertaken with the farmers and extension agents in the area. The spatial aspects of the spate irrigation system (in Sheeb) revealed a resource variation of land and water availability between the upstream and downstream villages. There is more land for development of spate irrigation in downstream villages. However, this land can only be cropped if the floods are controlled by constructing permanent diversion structures at the head of the wadis and improvements in the water law that will lead to a more equitable distribution of water among the users. The development trends in the spate irrigation system showed that the number of floods, food production, pest prevalence and diseases vary considerably over time in the Sheeb community. The farmers in Sheeb area have developed various livelihood strategies to combat the problems of spate irrigation. For example during the dry season, the people migrate to the highlands of Eritrea in search of food, water and grass when these resources are scarce in the lowlands (Chapter 3).

About 70% of households in Sheeb area mentioned that lack of water, pest damage and lack of capital are the most serious constraints to crop production and that shortage of feed and prevalence of diseases posed problems to livestock production in the area. During the 1997 production year, most of the household farm incomes were greater than their cost of production due to adequate floods occurred in the area. In general, spate irrigation production system is a 'cost effective' system provided that the irrigation structures can be maintained at low cost so that the fields receive enough water and nutrients (Chapter 4).

Soils of the Sheeb area

The main factors that influence the formation of soils in the Sheeb area are the effects of human activities on the land, the floods and the kind of parent material. The dominant soil types found in the area are the Fluvisols (spate irrigated soils) which cover about 4,550 ha and the Arenosols (non-irrigated soils) that cover about 3,450 ha out of the total land area of Sheeb (8,000 ha). The spate-irrigated soils are high in available phosphorus and available potassium but relatively low in total nitrogen and organic matter (OM). The spate soils are non-saline because of the flooding of the fields, which leaches the soluble salts deep into the soil profiles. Whereas, the non-irrigated soils showed salinity in the topsoils and were very low in physical and chemical fertility. The irrigated soils have better physical and chemical properties than the non-irrigated soils due to the annual deposition of nutrients and OM by sedimentation (Chapter 5).

Sedimentation rate

Annual sedimentation in Sheeb spate irrigated fields enabled the farmers to harvest a crop without application of organic or inorganic fertilisers, but on the other hand, the sedimentation increases the surface level of the fields, which often requires raising the bunds. Also the difference in elevation between the water inlet point (at the wadi) and the irrigated fields gradually decreases. In the long run fields may become un-irrigable unless the inlet is moved higher up in the wadis. However, this increases the channel length (and travel time) with a subsequent increase in water loss due to percolation and seepage. The average measured sediment layer was 13 mm per year inside the irrigated fields. The advantages of sedimentation outweigh its disadvantages as far as the SIS in Sheeb area is concerned (Chapter 6).

Nutrient balance

The nutrient inputs to the SIS are mainly by sedimentation, followed by atmospheric deposition in dust. The nutrient outputs are dominated by the removal of nutrients through harvested crop products and crop residues. The total of the two input factors minus the total of the two output factors rendered the values +137 kg total N, +68 kg total P, and +1378 kg total K per ha per year. Hence, the total element contents of N, P, and K showed a positive balance indicating nutrient accumulation in the soil rather than nutrient depletion, as it is a common problem in many other tropical agricultural systems. The positive balances of the nutrients were contributed mainly by high input of sedimentation.

The spate irrigation farmers in Sheeb could obtain higher yields by adopting integrated nutrient management practises such as applying organic fertilisers; growing leguminous crops in a crop rotation to improve the soil organic matter content of their soils. Besides this, the farmers could also grow forage plants along the wadi courses or plant agroforestry trees (that are adaptable to the area) along the field bunds to alleviate the lack of livestock feeds (Chapter 7).

Water balance

Addition of water into the crop root zone is mainly through flooding and in smaller amounts by rainfall. Evaporation from soil surface and transpiration from plants constitute the largest portion of removal of water during the cropping season. In 1999 (a relatively wet year), the actual crop evapotranspiration, ET (about 420 mm) was about the same as the estimated crop water requirement. The latter was calculated using the reference ET according to Penman-Monteith and seasonal crop factors. The spate fields should receive at least two flood irrigations to 0.4 m bunds high in order to meet the water requirement of sorghum main crop. With better levelling, farmers could attain a more uniform water distribution over their spate fields (Chapter 8).

Land suitability for spate irrigation

A land suitability system for spate irrigation in Sheeb has been developed which can also be applied in the rest of Eritrea. The land suitability study revealed that 4,550 ha (57%) of the Sheeb area is suitable for spate irrigation development. The highly to moderately suitable land covers about 1,290 ha, the moderately suitable land about 1,870 ha and the marginally suitable land covers about 1,390 ha. The bulk of the irrigable land (41%) in the Sheeb spate irrigation schemes is considered to be moderately suitable for sorghum and maize cultivation. About 3,450 ha or 43% of the study area is currently classified as not suitable for spate irrigation mainly because of a lack of water and poor soils. At present, about 2,500 to 3,000 ha of land is annually irrigated in the Sheeb area. When the flood diversion structures (at wadis Laba and Maiule) are made more permanent, an additional 2,000 ha of land can be irrigated. In addition, these structures make the SIS more stable, productive and sustainable as well (Chapter 9).

In conclusion, the information presented in this thesis has helped to upgrade the knowledge of spate irrigation system in Eritrea. It also contributes to the knowledge of development options for spate irrigation in Sheeb area in particular and in comparable areas of Eritrea in general.

Samenvatting

Dit proefschrift gaat over aspecten van bodem- en waterbeheer welke bij 'spate-irrigatie' in Eritrea een belangrijke rol spelen. Rivieren met incidentele afvoeren, de zogenaamde wadi's, zorgen voor de watervoorziening van een spate-irrigatie systeem. Piekafvoeren (de 'spates') uit hoger gelegen delen van Eritrea worden, als ze de lager gelegen kustvlakte bereiken, voor irrigatie gebruikt. Elk jaar worden in de wadi's tijdelijke dammen (agims) opgeworpen en het opgestuwde water wordt via aarden kanalen (misghas) naar de landbouwvelden geleid. De velden zijn omringd door 0,5 – 1 meter hoge aarden dijkjes. Het water infiltreert in de diepe bodems en het meegevoerde sediment, met daarin organisch materiaal en voedingsstoffen voor het gewas, wordt afgezet. Nadat er voldoende water op deze wijze is ingelaten beginnen de boeren te zaaien. Tijdens het groeiseizoen vindt geen additionele irrigatie plaats; het watergebruik van het gewas wordt volledig gedekt door het in de diepe bodem opgeslagen water en de sporadische neerslag (< 100 mm).

In Eritrea wordt spate-irrigatie al sinds het begin van de 20ste eeuw toegepast. Deze speciale vorm van watergebruik (water harvesting) heeft een aantal voordelen; (1) spate-irrigatie voorziet de aride kustzone aan de Rode Zee van voldoende water voor één of meer oogsten, (2) de regelmatige afzettingen van vruchtbaar sediment dragen bij aan de vorming van goede diepe bodems en (3) spate-irrigatie levert een groot aantal boeren in de kustzone bestaansmiddelen.

De principes van het bodem- en waterbeheer in spate-irrigatie in Eritrea, en die in het gebied rond Sheeb in het bijzonder, worden beschreven in de Hoofdstukken 1 en 2. Het meeste water in het Sheeb-gebied wordt aangevoerd door de wadi's Laba en Maiule welke hun oorsprong vinden in het Eritrese hoogland. Boeren in het gebied noemen twee belangrijke tekortkomingen van het irrigatie-systeem; (1) een tekort aan water en (2) het regelmatig doorbreken van de opgeworpen dammen en afleidingskanalen bij hoge piekafvoer. Het tekort aan water is enerzijds te wijten aan de onregelmatigheid van regens in het hoogland en anderzijds aan de lage effectiviteit van de afleidingsdammen en –kanalen. Eén van de problemen hierbij is de moeilijkheid om met tijdelijk opgeworpen dammen de onvoorspelbare piekafvoeren te beheersen. Daarnaast vinden er lekverliezen plaats in de afleidingskanalen.

Boeren

Boeren in het Sheeb-gebied hebben in de afgelopen 100 jaar het spate irrigatie systeem ontwikkeld door het opbouwen en overdragen van lokale kennis en ervaring. Hierdoor is een gewasproductie van 1500-2000 kg graan per hectare mogelijk in een aride zone waar dat zonder irrigatie onmogelijk zou zijn. Om het spate-irrigatie systeem ook vanuit sociaal-

economisch oogpunt te leren begrijpen is een PRA (Participatory Rural Appraisal) uitgevoerd onder boeren en voorlichters in het Sheeb-gebied. De ruimtelijke dimensie van het onderzoek heeft geleerd dat er een verschil bestaat in de mate waarin bovenstroomse dorpen en de lager gelegen gemeenschappen kunnen beschikken over de natuurlijke hulpbronnen bodem en water. Er is meer land beschikbaar in de lager gelegen dorpen maar dit land kan alleen voor gewasteelt gebruikt worden als aan twee voorwaarden wordt voldaan; (1) er dient bovenstrooms minder water verloren te gaan, wat bereikt kan worden door een betere (meer permanente) constructie van de afleidingsdammen en –kanalen en (2) door de heersende waterwet aan te passen. Dit laatste zou tot een eerlijkere verdeling van het water over hoog- en laaggelegen dorpen moeten leiden.
Een analyse van tijdsprocessen bracht aan het licht dat het aantal piekafvoeren, de grootte van deze afvoeren en het optreden van ziekten en plagen van jaar tot jaar sterk variëren. De boeren in het Sheeb-gebied hebben verschillende overlevingsstrategieën ontwikkeld om met deze grote variaties om te gaan. In het droge seizoen bijvoorbeeld migreert de bevolking uit de hete droge kustzone naar het koeler en vochtiger hoogland. Hier vinden mens en dier het voedsel dat in de kustvlakte schaars is geworden (Hoofdstuk 3).

Ruim 70 % van de huishoudens noemen watergebrek, schade door plagen en gebrek aan krediet als belangrijkste hindernissen voor ontwikkeling van de graanteelt. Gebrek aan voedsel en het voorkomen van ziektes zijn de belangrijkste hinderpalen voor de ontwikkeling van de veehouderij. In 1997 overstegen de huishoudinkomsten de productiekosten omdat zowel het aantal als de grootte van de piekafvoeren voldoende waren. Het spate-irrigatie systeem kan als zeer kosten efficiënt aangemerkt worden mits de irrigatie-infrastructuur tegen lage kosten onderhouden kan worden waardoor de velden voldoende water en meststoffen ontvangen (Hoofdstuk 4).

Bodems

Belangrijkste bodemvormende factoren zijn het moedermateriaal, de piekafvoeren en de menselijke invloed. Overheersende bodems zijn de fluvisolen op de geïrrigeerde velden welke 4550 ha omvatten en de arenosolen van de niet-geïrrigeerde gebieden welke 3450 ha bedekken. Geïrrigeerde velden zijn rijk aan voor plant beschikbaar fosfaat en kalium maar bevatten relatief weinig stikstof en organische stof. De geïrrigeerde velden zijn niet zout omdat door het regelmatig onderwater zetten van de velden de zouten naar de diepere bodemlagen uitspoelen. De niet-geïrrigeerde gronden daarentegen hebben wel een hoog zoutgehalte in de bovengrond en de fysische en chemische vruchtbaarheid van deze gronden is laag. (Hoofdstuk 5).

Sedimentatie

De jaarlijkse sedimentatie maakt het de boeren mogelijk om jaar-in-jaar uit opbrengsten te verkrijgen zonder toediening van organische- of kunstmest. Aan de andere kant leidt deze sedimentatie tot het almaar ophogen van de velden waardoor de omringende dijkjes regelmatig verhoogd moeten worden. Ook neemt het hoogteverschil tussen inlaat vanuit de wadi en de velden af. Mits de waterinlaat naar een locatie hoger in de wadi wordt verlegd, raken de velden op den duur on-irrigeerbaar. Verlenging van de kanalen door het verleggen van de inlaat resulteert in een toename van de waterverliezen. De gemiddelde ophoging van de geïrrigeerde velden door sedimentatie is 13 mm per jaar. In het Sheeb-gebied wegen de voordelen van de sedimentatie (nutriënten) op tegen de nadelen (ophoging) (Hoofdstuk 6).

Nutriënten

Aanvoer van nutriënten in het landbouwsysteem vindt plaats via sedimentatie en als gevolg van atmosferische depositie. Afvoer uit het systeem treedt op als gevolg van het oogsten van het graan en de gewasresten (voor de veehouderij). Een balansstudie leert dat er per jaar een netto invoer van 137 kg N, 68 kg P en 1378 kg K plaatsvindt. Dit zijn totaal-gehalten die nog niet veel zeggen over de beschikbaarheid van deze elementen voor de plant. Maar de balans is tenminste positief en niet negatief zoals in zoveel andere landbouwproductiesystemen in Afrika.

De boeren in het spate-irrigatie gebied van Sheeb zouden een hogere productie kunnen verkrijgen door toepassing van een geïntegreerd nutriëntenbeheer. Dit omvat het toedienen van organische mest en het telen van leguminosen in een gewasrotatie waardoor het organische stof gehalte van de bodems verhoogd wordt. Om het tekort aan veevoer te verminderen kunnen langs de wadi's voedergewassen worden verbouwd en op de dijkjes rond de velden bomen worden gepland (agroforestry) (Hoofdstuk 7).

Water

De watervoorziening van het gewas gebeurt vooral door de velden onder water te zetten waardoor de bodem zich met water vult en in mindere mate door middel van de regen. Verdamping van water uit de bodem en gewasverdamping zijn de belangrijkste processen waardoor de voorraad water in de bodem afneemt. In 1999 (een relatief nat jaar) bedroeg de evapotranspiratie gedurende een heel groeiseizoen 420 mm water. Dit was ongeveer gelijk aan de geschatte gewasbehoefte op basis van een berekening waarbij gebruik werd gemaakt van de referentieverdamping volgens Penman-Monteith en zogenaamde gewasfactoren. Om aan de gewasbehoefte van sorghum te voldoen moeten spate-irrigatievelden tenminste twee keer met een laag van 0,4 meter water geïrrigeerd worden. Met een betere egalisatie kunnen de boeren een uniformere waterverdeling over de velden krijgen (Hoofdstuk 8).

Landevaluatie

Voor het Sheeb-gebied is een landevaluatie-systeem ontwikkeld dat ook voor andere spate-irrigatie gebieden in Eritrea gebruikt kan worden. Toepassing van het systeem voor het Sheeb-gebied leert dat 4550 ha (57 % van het Sheeb-gebied) geschikt is voor irrigatie. Hiervan zijn 1290 ha zeer tot matig geschikt, matig geschikt zijn 1870 ha en marginaal geschikt zijn 1390 ha. Momenteel worden er jaarlijks 2500-3000 ha geïrrigeerd. Een groot deel (41%) hiervan is matig geschikt voor de verbouw van sorghum en maïs. Ongeveer 43 % van het Sheeb-gebied is ongeschikt voor gewasgroei door onvoldoende water of bodemdiepte. Indien de huidige kwetsbare tijdelijke afleidingsdammen vervangen zijn door permanente stabiele dammen kan 2000 ha extra geïrrigeerd worden. De dammen zullen resulteren in een hogere en stabielere productie in het spate- irrigatie systeem. Dit komt de duurzaamheid van het systeem ten goede. (Hoofdstuk 9).

Samenvattend kan worden gesteld dat de gegevens die voor dit proefschrift werden verzameld de kennis over spate-irrigatie in Eritrea hebben verdiept. Dit draagt bij aan het inzicht in de ontwikkelingsmogelijkheden van zowel het Sheeb-gebied alsook van andere vergelijkbare gebieden in Eritrea.

Curriculum vitae

Mehreteab Tesfai was born on 7 January 1959 in Eritrea in a village called Adi-Bahilai. He studied agriculture at Alemaya Agricultural University in Ethiopia from 1979 to 1982, where he obtained a B.Sc. degree in Plant Sciences. He worked for the Ministry of Agriculture as an Agronomy expert in Eritrea until October 1985. In 1988, he obtained his Master's degree in Soil Sciences in Bulgaria. Afterwards, he was employed by the Department of Land use Planning of the Ministry of Agriculture and worked as a soil survey expert until 1992 in Ethiopia.

In October 1992, he went back to his native country Eritrea and served as a senior expert in the Land Resources Department of the Ministry of Agriculture. In 1994, he joined the University of Asmara, College of Agriculture and Aquatic Sciences as a lecturer at the department of Soil and Water Conservation. He has taught various soil sciences and related subjects to under graduate students of Agriculture. He has also advised students in carrying out research projects for the partial fulfilment of their B.Sc. degree. In addition, he was also involved in consultancy works in various local institutions.

In November 1996, he was admitted as a Ph.D. student to the Soil and Water Conservation Group of Wageningen University, The Netherlands through the linkage programme established between the UoA and WU. Since then, he conducted research on Soil and Water Management in Spate Irrigation Systems in Eritrea, which is the subject of this thesis. At the moment, he is a father of two sons. He can be reached by e-mail at mehretab@caas.uoa.edu.er