DEVELOPMENT AND MANAGEMENT OF IRRIGATED LANDS
IN TIGRAY, ETHIOPIA

Development and Management of Irrigated Lands in Tigray, Ethiopia

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Summary

Ethiopia is a landlocked country in the East of Africa. With the involvement of 90% of the population, agriculture is the major source of employment, revenue and export earnings. The total area of Ethiopia is about 110 million ha of which 67% is arid or semi-arid. With about 90% living in rural areas, the population of Ethiopia has raised from 22 million in 1961 to about 69 million at present with an average annual growth rate of 3%.

Ethiopia is characterised by famine as a result of high population pressure, resource base degradation, and insufficient rainfall for rainfed production. With 22 major drought occurrences in the past 40 years alone, the country generally faces an annual cereal food deficit of 0.03 – 3.3 million tons. On the other hand, it is endowed with a huge annual water resource potential of about 110 billion m^3, a potentially irrigable land of 3.6 million ha and productive manpower of about 48% of the total population. However, only about 3 billion m^3 of the water resource and 190,000 ha of the potentially irrigable land is utilised so far.

Taking into account the potentials of land and water resources, and the problems of food insecurity, population increase, and limited rainfall, agricultural development has been a priority for the new Ethiopian government since 1991. The Agricultural Development-Led Industrialization (ADLI) development strategy adopted in August 1992 has set irrigation as a major pillar to increase food production and to achieve food self-sufficiency for the country.

With a total land area of 8 million ha, Tigray is one of the most degraded and drought prone regions of Ethiopia. The present population stands at 3.7 million, with an average annual growth rate of 3.3%. The annual cereal food deficit is estimated at about 180,000 tons. There are many causes of the structural food shortage of which moisture deficit plays a significant role. The climate of Tigray is mainly semi-arid and most of the region receives limited and erratic rainfall that is insufficient for crop production. On the other hand, about 9 billion m^3 of water leaves the region as runoff annually. For instance, if 50% of this runoff would be used for irrigation, half-a-million hectare of land can be irrigated, which would be sufficient to feed three times the present population of Tigray. The estimated irrigation potential is about 325,000 ha out of which only about 15,000 ha is irrigated through traditional practices.

Realising these problems and potentials, the regional Government has been engaged in earthen dam irrigation development activities for the last few years. The Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (CoSAERT) was established in 1994 to construct 500 dams and to irrigate 50,000 ha within ten years. The principal objectives were to change the agrarian system to widespread small-scale irrigated agriculture and to gradually attain self-sufficiency in food production.

So far 44 earthen dams with related irrigation facilities have been constructed and, on average, about 1,418 ha land is annually irrigated. The earthen dam irrigation schemes consist of a catchment area, a reservoir, an earthen dam, and a command area. The command area of most of these schemes is further divided into a primary and a secondary command area. The primary command area is the one irrigated by the proper canal water released from the reservoir through the outlet, while the seepage water from the reservoir through the dam irrigates the secondary

command area. The average catchment area, reservoir area, reservoir capacity, dam height, crest length, potential irrigable area and actual irrigated area per dam are 950 ha, 25 ha, 1.1 million m^3, 15.5 m, 378 m, 67 ha and 32 ha respectively. There is, however, a considerable variation among individual schemes.

The success of the present and future small-scale irrigation schemes to reduce poverty and gradually ensure food-security in the region depends on their sustainability. The general principle of sustainability is the development, use and management of the land and water resources in such a way that the future generation will not be put at risk. According to Savenije (1997), the major aspects of sustainability are:

- environmental sustainability (no long-term negative or irreversible effects);
- technical sustainability (balanced demand and supply, no mining);
- economic sustainability (sustaining economic development or welfare and production);
- financial sustainability (cost recovery);
- social sustainability (stability of population, stability of demand, willingness to pay);
- institutional sustainability (capacity to plan, manage and operate the system).

The focus of the few studies carried out so far in the earthen dam irrigation schemes in Tigray has been on a single component such as reservoir sedimentation and salinity of the irrigated fields. No attempt has been made to study the whole scheme as one integral entity, taking into account the catchment area, the reservoir and dam, and the command area.

This research has been initiated and carried out in two earthen dam irrigation schemes, Gumsalasa and Korir, with the main objective of developing an integrated approach for sustainable development and management of irrigated lands in Tigray. The Gumsalasa earthen dam was constructed in 1995 with a reservoir capacity of 1.9 million m^3. The Korir earthen dam was constructed a year later with a reservoir capacity of 1.6 million m^3. With more than 85% of the total annual rain falling within a period of four months from June to September, rainfall in both sites is unimodal. The average annual rainfall is 513 mm at Gumsalasa and 543 mm at Korir. The dams were constructed by the CoSAERT, while the Bureau of Agriculture and Natural Resources and the farmers carry out the operation and maintenance activities.

Primary and secondary data were collected and analysed on major sustainability issues covering the catchment area, the reservoir and dam, the command area and the beneficiaries for the formulation and appraisal of the integrated approach. These include climate, institutional and water management, erosion and sedimentation, waterlogging and salinity, reservoir water balance, and socio-economic issues. The possible impact of the earthen dam irrigation schemes on the regime of the Nile river has also been investigated in general terms.

Long-term climatic data at Gumsalasa were used to assess the reliability of rainfed agriculture in the region. Meteorological data of the area, two dominant soil types, clay and loam, and the most commonly grown crop, wheat, were used for the assessment of irrigation scheduling and dry-spells during the growing season. The Penman-Monteith method was used for the calculation of the irrigation interval for wheat under the prevailing conditions at Gumsalasa. The probability of occurrence

of dry-spell duration of equal to or longer than this interval was then determined for the growing period by dry-spell analysis of 26 years of daily rainfall data.

Relevant data on the farming system, social, economic, institutional and water management practices were collected from farmers, development agents and the Wereda Bureau of Agriculture and Natural Resources, using a questionnaire.

The runoff plot and HR Wallingford methods were employed in order to present a general assessment of the catchment sediment yield. These were compared with the results of two other empirical approaches used for the assessment of reservoir sedimentation in Tigray by Poesen, *et al.,* (2001), namely, the Verstraeten, *et al.,* and the Pacific Southwest Inter Agency Commission (PSIAC) methods.

Rainfall, change in the reservoir water level, evapo(transpi)ration, canal discharge, seepage, groundwater recharge and livestock consumption were measured over a specified period to assess the reservoir water balance. Rain gauge, diver data logger and barometer diver, class A pan and float method were used to measure the rainfall, reservoir water level, evapo(transpi)ration and discharge respectively. The livestock consumption was estimated based on the average number of livestock drinking water from the reservoir. The groundwater recharge was estimated indirectly from the water balance equation of the dry period.

Field evaluation of the irrigation water application was made on different furrow lengths to assess the present water management practice and its impact on crop yield and salinity.

For the salinity investigation, the irrigation schemes were divided into rainfed, catchment, reservoir, primary command, and secondary command areas and profile pits were excavated at relevant locations. The rainfed area was included as a control for the impact of irrigation development on salinity. Surface soil, surface water, subsurface soil and groundwater samples at different times and locations were collected and analysed.

Finally, an evaluation of the implications of the major results of the study on sustainability was carried out at two levels, namely, the irrigation scheme level and the downstream area including on the Nile river. Alternative scenarios to the existing practice were also presented and simulated aiming at improving the utilization of the limited water supply, increasing crop production and minimizing the salinity problems. The obtained results are summarized underneath.

The irrigation interval for wheat at Gumsalasa ranges between 13 and 28 days. Dry-spell analysis results show that there is almost a 100% probability of occurrence of a dry-spell of duration longer than the mentioned intervals at least once in the crop season. This indicates that rainfed agriculture is practically impossible in the region without supplementary irrigation.

The major objective of the earthen dam irrigation schemes is to improve the livelihood of the poor farmers of Tigray. The situation in the study sites has proven so. An increase in yield of 170 – 285% has been recorded compared to rainfed agriculture. The average number of households benefiting from irrigation is 425 and 330 at Gumsalasa and Korir respectively. Since the introduction of irrigation, the cropping pattern has changed from small grains to maize and vegetables. The yield, the market prices and subsequently the household income generated from the irrigated fields are nowadays higher than in the rainfed situation.

Proper planning and implementation of the reservoir operation is very important for the success of the earthen dam irrigation schemes. Two scenarios, the present operation (January – June) and an alternative operational plan (September –

January), were evaluated in this regard. Since the irrigated fields of the schemes are also used for rainfed agriculture during June – December, the main irrigation season and reservoir operation at present generally starts in January and extends till June. This period, however, coincides with the highest evaporation rate of the year. As a result, more than 40% of the water available at the beginning of the irrigation season is lost as evaporation from the reservoir. The percentage would be even much higher if the period between September to December, when there is only reservoir evaporation without any discharge, is taken into account. Considering the small size of the irrigated landholding (0.2 – 0.3 ha per household), the unreliability and low level of the rainfed yield and the fact that each beneficiary owes about 1.2 ha of land mainly for rainfed production, terminating the rainfed production at the irrigated fields and starting irrigation immediately after the rainy season (in September) seems a better option. This arrangement can increase the efficiency of the reservoir operation in two ways compared to the present practice, i.e., by reducing the reservoir evaporation loss and the water requirement of the crops. The evaluation reveals that a potential average area of 38 ha at Gumsalasa and 26 ha at Korir can be additionally irrigated by the water that can be saved if the start of the irrigation season is shifted from January to September. Based on the average household irrigated landholding of the schemes, about 190 and 80 more households than the existing could benefit from the irrigation at Gumsalasa and Korir respectively. Besides, the average annual yield from the irrigation per household will be about ten-fold of the production that can be obtained from rainfed agriculture.

The existing water management practice and institutional arrangements seem to jeopardize the sustainability of the irrigation schemes. The original design recommended a delivery time of 2 hrs for each 0.2 ha, at a farm discharge of 2.5 l/s. At present, water is distributed among farmers based on direct observation of soil and plant conditions and the discharge to the farms is not monitored. Water allocation is on a rotational basis, but the individual farmer decides on the delivery time. The 2 hour delivery time does not seem to be applied and the common practice is that a farmer passes the water to the next user only after he/she feels that his/her farm is well irrigated. As a result, wastage of water by runoff and over-watering is common. Field evaluation of the irrigation practice at Gumsalasa indicated three major problems: short furrow lengths, inadequate water application to the crop root zone and poor leaching. Based on the results of the field evaluation, the total depth of water applied during the irrigation season was about 128 mm for onion and 176 mm for maize. However, the net irrigation water requirement of onion and maize calculated using the CROPWAT model for a maximum yield (100% yield level) is about 429 mm and 571 mm respectively. The effect of the water deficit on the yield reduction was estimated to range from about 60% for maize to 70% for onion. Comparison of the present actual average yield of the irrigation scheme with the potential yield also reflected the same trend. Proper implementation of the proposed irrigation scheduling and improving the field irrigation method is recommended in this respect. A user-friendly spreadsheet furrow evaluation and design program based on the equations for open-end furrows developed by the Soil Conservation Service (SCS) of the US Department of Agriculture was assessed based on the field test results and can be used for the situations in the study sites.

Results of the salinity study reveal that the salinity of the irrigation water of the primary command area is about 0.3 dS/m in both irrigation schemes. On the other hand, the seepage water used for irrigating the secondary command is about 0.8

dS/m at Gumsalasa and 1.2 dS/m at Korir. The salinity hazard of the irrigation water can be classified as moderate at primary and high at the secondary command. Leaching is generally recommended in such situations to keep the salinity level of the root zone within a suitable range for crop growth and production. The reality in the study sites is that the leaching requirement is not taken into account in the operational plan and the soil salinity is not monitored. As a result, the soil salinity of the schemes has increased by more than two-fold since the start of full irrigation in 1999. However, the present average root zone salinity is about 0.75 dS/m and does not pose any danger to the yield of the main irrigated crops. But, if the leaching practice continues to be inadequate, as is the case at the moment, the salt concentration may develop to a point where crop production might be greatly reduced or even impossible. Simulation of the effect of poor leaching on the long-term salt accumulation at Gumsalasa indicated that salinity will start to reduce the crop yield as of the second year of the implementation of the plan. The success of the newly proposed operational plan depends on maintaining the salinity level at least at its current level through leaching. The annual leaching requirement from the irrigation scheme was estimated at 100 mm and 200 mm for the primary and secondary command areas respectively. This will be about 20% of the irrigation water requirement at the primary command and 40% at the secondary. The percentage at the secondary command is high but covers a small area.

Community participation in the development and management of earthen dam irrigation schemes is encouraging in Tigray. The development strategy emphasized on the importance of incorporating the wishes, ideas and aspirations of the farming community and the need for enhancing participation of women as a basis for sustainability. Farmers actively participate in the construction of the earthen dam irrigation projects and the rehabilitation of catchments. They are generally involved either individually or through their representatives in all decisions made with respect to the operation and maintenance of the irrigation schemes. Promising developments have also been witnessed with regard to the access of women to irrigated land and other basic resources and services. Female heads at Korir and Gumsalasa own about 41% and 21% of the total irrigated land respectively. The development effort would have to continue to empower the farmers and facilitate the hand-over of the operation and maintenance of the schemes to the beneficiaries.

It, however, seems that very important policy, institutional and socio-economic aspects which can play a major role in the success of the irrigation schemes are not yet given due attention. There is no regionally implemented institutional set-up and irrigation policy so far. As a result, community established Water Users Associations play a major role in the water allocation and distribution, conflict management, and operation and maintenance of the irrigation systems. The existing operation and maintenance rules are based on local by-laws *('Serit laws')* developed by the users in consultation with the Wereda Bureau of Agriculture and Natural Resources. However, the Water Users Associations and the local judiciaries at the study sites are not implementing the traditional operation and maintenance rules and regulations to properly run and monitor the operation, maintenance and legal aspects. Therefore, the formulation and implementation of a comprehensive and participatory regional irrigation policy would have to be given priority. CoSAERT and the regional Government suggested key recommendations with respect to distribution of water among beneficiaries, water charges and marketing. These were: dividing the irrigated fields into two or three blocks and providing all the beneficiaries a plot in each block so as to improve the equitable distribution of water, introduction of water charges for the maintenance and reconstruction activities and formation of marketing cooperatives that can create a strong network of necessary credits and markets. None of these are implemented so far. As a result, the current practice during water shortage victimizes the downstream, lower reach farmers. Local market prices are also low.

The objective of the sedimentation study was to provide a simple empirical tool for rapid assessment of catchments with a high risk of erosion. Considering the situation at Korir, the HR Wallingford method gives a good estimation of the sediment yield and can be used for preliminary assessment.

Ethiopia contributes about 75 billion m^3 of the 84 billion m^3 Nile river discharge that annually reaches the Aswan dam. The plan of the Government is to construct 1,000 earthen dams in two of the major river basins, Abay (Blue Nile) in Amhara region and Tekeze in Tigray. The impact of these developments on the regime of the Nile river may include change in water quality, change in the groundwater recharge, change in soil erosion and sedimentation and change in the amount of annual flow. The potential implication is presented below in general terms based on the design capacities of the existing dams in Tigray. The quality of groundwater and the drainage water from the earthen dam irrigation schemes was found to be highly saline. The impact might be of relevance to the immediate downstream users who depend on the springs resulting from the recharge of the dams. These farmers will have to grow salt tolerant crops along with leaching whenever possible. However, due to its little contribution to the total flow, the effect on the water quality of the Nile river will be marginal. The earthen dams can generally recharge the groundwater and enhance spring sources of the downstream areas. The maximum amount of water that can annually percolate into the groundwater from all the reservoirs was estimated to be about 36 million m^3, which is 3% of the design reservoir capacity and only 0.04% of the total Nile flow. The contribution of the groundwater recharge was, therefore, found to be only significant to the immediate downstream users. An increase in spring discharge of 5 l/s – 25 l/s was recorded in downstream areas after the construction of surface water harvesting structures. About 140 million tons of sediment is annually transported by the Blue Nile river to Sudan and Egypt. The rapid siltation of the dams in Sudan is a direct consequence of this high erosion. If the total planned dams in the highlands of Ethiopia would be constructed, they will be able to store an average of about 13 million tons of sediment annually, which is a maximum of 9% of the total sediment transport of the Nile. Taking into account the process of deposition, not all sediment can be transported and, hence, the actual contribution of the dams would be less than 9%. Since the number of dams constructed so far is very small compared to the original plan, the effect on the overall Nile flow is marginal. If the total proposed dams would be constructed in the years to come, the potential impact will be at maximum about 1.5% of the total discharge to the Nile river originating in Ethiopia.

As a major contributor to the total Nile flow, developments in the highlands of Ethiopia should always consider the impacts on the downstream riparian countries. In this regard, a basin–wide effective cooperation for the benefit and welfare of the riparian societies is a major task ahead. The riparian countries need to work jointly for a more equitable and increased productivity of the Nile water. The ongoing negotiations and agreements among the three major players, Egypt, Sudan and Ethiopia, in particular and the whole riparian countries in general to cooperate in irrigation development, conservation works and hydropower development is a vital step forward and would have to be strengthened.

1 Introduction

1.1 General

According to the United Nations, the present world population stands at about 6.3 billion and with an average annual growth rate of 1.3%, this population is estimated to reach 8 billion in 2025 (United Nations Population Reference Bureau, 2004).

The majority of the worlds' population lives in the emerging and least developed countries. The emerging countries include most of the eastern European countries (including Russia), most of the countries in Central and South America, most of the countries in Asia (including China, India and Indonesia), and several countries in Africa. The least developed countries, on the other hand, comprise most of the countries in Africa, several countries in Asia, one country in Central America and most of the smaller countries in Oceania. The population growth will also take place in these countries, while almost no growth is expected in the developed countries (Schultz, *et al.*, 2005). Even if the standard of living in the emerging countries is rapidly rising, about 1.2 billion people in the least developed and emerging countries are still poor (less than 1 US$ per day), and of them about 70% live in the rural area (World Bank, 2001). The population of some least developed countries including Ethiopia is expected to double in the coming 20 years (Table 1.1). The increase in the numbers of mouths to be fed and the improving diet requirement is increasing the food demands. The main challenge in this regard remains how to double the global food production in general and in Asia and Africa in particular in the next 25 years (Van Hofwegen and Svendsen, 2000). Most of African nations are categorised as least developed countries.

Table 1.1 Present (2004) and projected (2025) population of different regions (United Nations Population Reference Bureau, 2004)

Region	Present population in 10^6	Rate of annual increase in %		Projected population in 10^6	Project population increase (2004 – 2025) in %
		Average	Range		
World	6,396	1.3	0.1 – 1.8	7,934	24
Asia	3,875	1.3	0.6 – 2.0	4,778	23
Africa	885	2.4	1.0 – 2.8	1,323	49
Europe	728	- 0.2	- 0.5 – 0.1	722	- 8
Latin America and Caribbean	549	1.6	1.2 – 2.1	685	25
USA	294	0.6	0.6	349	19
Oceania	33	1.0	0.6 – 3.7	41	24
Canada	32	0.3	0.3	36	13

According to the Food and Agriculture Organization of the United Nations (FAO) (2002), the present global food production is more or less sufficient to meet the needs. However, about 815 million people still remain undernourished due to the unbalanced geographic distribution of food production and wealth (FAO, 2001). The trend of the present world cereal production indicates that the developed countries have an average export surplus of about 12% of their total production. On the other hand, the emerging and least developed countries have an average net import surplus of 5% and 39% of their total cereal production respectively (Schultz, *et al.*, 2005). This deficit coupled with the alarming population increase and the limited financial capacity to import would make the problem of raising the food supply more critical in the least developed countries. The problem could even be more severe in the least developed countries of the arid and semi-arid regions, as the marginal and erratic rainfall in these areas renders rainfed agriculture generally unreliable. Under such circumstances, irrigation development may be taken as a primary means for realizing a sustainable agricultural production. Irrigated agriculture may provide a degree of self-sufficiency in food, or at least contribute to ensuring national food security, raising the rural population's living standard, creating employment opportunities, and reducing urbanization pressure. With arid and semi-arid regions covering about 67% of its total area, Ethiopia is one of the countries included in this category (Elahi, 1992).

Many countries, including Ethiopia, apply irrigation as an important means of achieving food self-sufficiency. Besides, it could also be used as a means of surplus production if there is no limitation of water and land resources (Hillel, 1997 and FAO, 1997). Water resources development has been the focus of Governments to address the twin problem of food insecurity and water scarcity (Rosegrand and Perez, 1997). In dryland areas, irrigation intervention is believed to improve the productive potential from very low to better. Yield increases by 100 to 400% have been recorded in developing countries through irrigation (FAO, 1997). Irrigation also reduces the risk of crop failure and can lead to multiple cropping.

Irrigation development can meet its objectives if it is managed properly. Poor management may result in adverse effects. In many irrigation schemes in arid and semi-arid areas, crop yields are reduced and even land is abandoned due to environmental hazards such as waterlogging, salinity, erosion and sedimentation of reservoirs (Umali, 1993 and Ritzema, *et al.*, 1996).

The other challenge of the world in general and of arid and semi-arid areas in particular in the endeavour of meeting the growing food demand is how to utilize the limited fresh water more equitably and efficiently in the context of transboundary river basins. At the moment, 40% of the world's population lives in more than 200 river basins. In most cases, water management is fragmented among various users, institutions and physical aggregation levels, with little regard for solving conflicts and competition. Table 1.2 presents some of the river basins where disputes among riparian countries have been observed. Integrated water resources management in river basins provides an understanding of inter-sector competition of scarce water supplies, water quality, significance of water recycling, and multiple uses of water (Bastiaanssen, 2000). The Nile river basin, whose major contributor is Ethiopia, is one of the greatest concerns in this regard. The Nile basin and its people are at crossroads facing a future full of risks and complexities of unprecedented dimensions. The population of the countries in the basin is expected to increase from about 300 million at present to 460 million by 2025 and 650 million by mid of the twenty-first century (United Nations Population Reference Bureau, 2004). On the other hand, the average annual flow of the Nile at Aswan has declined from 110 billion m^3 during 1870 – 1899 to 84 billion m^3 at the moment as a result of variations in rainfall (Yahia, 1994).

The aim of this study is to present an analysis of the environmental, hydrological, socio-economic and institutional impacts of irrigation development in the Tigray region, Ethiopia and to develop an integrated approach for sustainable land and water development and management in Tigray in particular. It will also attempt to generalize the result of the envisaged development in this region to the Nile river basin in general terms.

Table 1.2 International water disputes (After Gupta, 1995)

River	Countries in dispute	Issues
Nile	Egypt, Ethiopia, Sudan	Water flows, siltation, flooding, diversion
Euphrates, Tigris	Iraq, Syria, Lebanon	Reduced water flow, salinization
Jordan, Yamruk, Litani, West Bank aquifer	Israel, Jordan, Syria, Lebanon	Water flow, diversion
Indus, Sutleji	India, Pakistan	Irrigation
Ganges, Brahmaputra	Bangladesh, India	Siltation, flooding, diversion
Salween	Myanmar, China	Siltation, flooding
Mekong	Cambodia, Laos, Vietnam, China, Thailand	Water flow, flooding
Parana	Argentina, Brazil	Dam, land inundation
Lauca	Bolivia, Chile	Dam, salinization
Rio Grande, Colorado	Mexico, United States of America	Salinization, water flow, agrochemical pollution
Rhine	France, Netherlands, Switzerland, Germany	Industrial pollution
Meuse, Scheldt	Belgium, Netherlands	Salinization, industrial pollution
Elbe	Czech Republic, Slovak Republic, Germany	Industrial pollution
Szamos	Hungary, Romania	Industrial pollution

1.2 Problem description

As a new experience in Tigray, the earthen dam irrigation development has various researchable issues. The success of the present and future small-scale irrigation schemes to reduce poverty and gradually ensure food-security in the region depends on their sustainability. The general principle of sustainability is the development, use and management of the land and water resources in such a way that the future generation will not be put at risk. The focus of the few studies carried out so far in the earthen dam irrigation schemes in Tigray has been on a single component such as reservoir sedimentation and salinity of the irrigated fields. No attempt has been made to study the whole scheme as one integral entity, taking into account the catchment area, the reservoir and dam, and the command area. This research aims to fill this gap.

In Ethiopia, large-scale irrigation schemes such as Amibara, Melkasedi, Omo Ratti and Children's Amba have many hectares of abandoned land due to the build-up of soluble salts in the root zone. This resulted in saline-sodic and sodic soils thereby reducing the value of the land for agricultural production. Main causes are lack of appropriate irrigation water management based on crop water and leaching requirements, and lack of appropriate drainage facilities.

Tigray, located in the semi-arid part of Ethiopia, faces the same problems. Irrigation scheduling is based on field observations of the soil moisture status and the plant conditions. The same delivery time is allocated for fields with equal area irrespective of the soil and crop type. In worst scenarios, decisions on the delivery time are left to individual farmers in which case over-watering of and runoff from irrigated fields is witnessed. No attention is given to analyse the discharge, soil type, crop type, efficiency, and subsequently to amend the scheduling of irrigation. Leaching requirement is not accounted for and drainage facilities are poor. These all can aggravate the problem of salinity build up. The farmers also irrigate their fields with seepage water that comes from a reservoir through the earthen dam. Though this water looks clean due to filtration, it picks up some salt as it passes through the dam. A study at Gumsalasa earthen dam has indicated that the electrical conductivity of the seepage water was about fourfold (1.1 dS/m) of that in the reservoir (0.27 dS/m) (Mitiku, *et al.,* 2002). Irrigation using this seepage water could therefore aggravate the salinity problem of Tigray.

Preliminary studies on a few earthen dam irrigation schemes in Tigray have generally indicated a progressive accumulation of soluble salts in the irrigated fields (Mitiku, *et al.,* 2002). As a result of this and other related factors, the yield of irrigated lands in Tigray is low (Table 1.3). The problem of crop yield reduction due to waterlogging and salinity and subsequent abandonment of the land would have to be prevented, as Tigray has to feed its increasing population with its limited irrigated land, and the unreliable rainfed agriculture.

Table 1.3 Average yield of irrigated crops in Tigray (Mitiku, *et al.*, 2001)

Crop type	Average yield in kg/ha
Maize	1,550
Wheat	1,760
Barley	2,290
Onion	2,940
Potato	6,400

Salinity has long been noticed as a major impediment in achieving increased yield. Accordingly, the United Nations Conference on Desertification held in Nairobi in 1977 adopted the following recommendation:

"It is recommended that urgent measures be taken to combat desertification in the irrigated lands by preventing and controlling waterlogging, salinization and sodification by modifying farming techniques to increase productivity in a regular and sustained way, by developing new irrigation and drainage schemes, where appropriate always using an integrated approach and through improvement of the social and economic conditions of people dependent on irrigated agriculture" (United Nations, 1977).

However, water management, leaching and drainage practices are poor in Tigray and are continuing in the same manner. This may cause adverse environmental impacts such as waterlogging and subsequent salinity, which would hamper the increase of productivity in a sustainable manner. No attempt has been made so far to study the extent, main sources, and the long-term effects of salinity. If the main processes and causes of salinity problems of an irrigation scheme are not known, the mitigation will not be easy. It will be even more dangerous if additional earthen dams are implemented without detailed investigation of this problem. The study of the present irrigation practice and its impact on the salinity and yield of the irrigated fields is, therefore, crucial.

Studies in African irrigation schemes have shown the lack of social and institutional considerations in irrigation development. In most cases engineers based their designs on physical data. Based on the available water, irrigable area, and other physical limitations, the designs involved the selection of off-take points, layout of canals, plots, and application methods that gave a congruent physical system. This conventional design approach has often an outcome of technical considerations, which were mixed with assumptions of the future use of the system. The assumptions made by the engineers about the cropping pattern, size and layout of the tertiary units, management and operation, available labour force, etc. were mostly different from farmer's expectations (Mitiku, *et al.,* 2001). Except for some positive initiatives such as community participation in site selection, construction and catchment treatment, the social and economical impacts of the schemes in Tigray are not well known. Therefore, the role of social processes in the development, operation and maintenance of irrigation schemes has to be well studied. Issues such as beneficiary selection, users' involvement, interest of beneficiaries, role of women and minority groups, displacement, compensation/resettlement, water rights, water charges, legal aspects, etc. will have to be focused in this regard.

The other issue of earthen dam projects are the changes caused to the hydrology of the command area in particular and the river basin in general. This includes reservoir evaporation, groundwater recharge, streamflow, erosion, sedimentation, and related waterlogging and water quality problems. This issue becomes even more crucial as Tigray is located in the Nile basin. Most of the Nile riparian countries, particularly Ethiopia, Sudan and Egypt are dependent on irrigated agriculture to ensure their crop production. In this case, it is vital to understand how water resources are presently being used and how changes may affect future use of water.

In this regard, the policies of the Ethiopian Government with respect to transboundary waters are (Ministry of Water Resources, 1998):

- study on sustainable basis Ethiopia's stake and national development interests in the allocation and utilization of transboundary waters;
- promote the establishment of an integrated framework for joint utilization and equitable cooperation and agreements on transboundary waters;
- ascertain and promote Ethiopia's entitlement and use of transboundary waters based on those accepted international norms and conventions endorsed by Ethiopia;
- foster meaningful and mutually fair regional cooperation and agreements on the joint and efficient use of transboundary waters with riparian countries based on "equitable and reasonable" use principles;
- comply with those international covenants adopted by Ethiopia and manage transboundary waters accordingly.

The study of the hydrological impacts of the earthen dams at the irrigation schemes and river basin scale will be an important instrument for making sound decisions and reasonable utilization of transboundary water resources in line with the set policies.

The hydrological impacts at the irrigation schemes may include the sedimentation of reservoirs, availability of more water for irrigation and increase in groundwater level. No detailed catchment sediment yield studies were carried out for the design of the earthen dam irrigation schemes in Tigray. The procedure mostly involves a rough estimation of the sediment yield from available regional secondary data. Such approach could result in either an over-estimated or under-estimated sediment yield, the latter being more critical. As a result, reservoirs are being silted up before serving for their designed life. If the development of the earthen dam projects continues without an analysis and amendment of the present sedimentation, it will be dangerous. The provision of a simple empirical tool for rapid assessment of catchments with high risk of erosion is vital.

The availability of water in reservoirs for irrigation is very important for semi-arid areas like Tigray. But, equally significant is the efficient utilization of the stored water. The present irrigation and reservoir operation in the earthen dam schemes generally starts in January. This exposes the dams for loss of water as reservoir evaporation during September – December. A study on the effectiveness of the existing plan can contribute to the improvement of the operational plans.

Ethiopia contributes about 75 billion m^3 of the 84 billion m^3 Nile river discharge that annually reaches the Aswan dam. The plan of the Government is to construct 1,000 earthen dams in two of the major river basins, Abay (Blue Nile) in Amhara region and Tekeze in Tigray. The impact of these developments on the regime of the Nile river may include change in water quality, change in the groundwater recharge, change in the soil erosion and sedimentation and change in the amount of annual flow. A general investigation into these aspects can assist in the design and construction of sound interventions, and efficient and equitable utilization of the water resources of the region. Otherwise social, political and technical constraints may prevail in the future.

1.3 Objectives and methodology

The overall objective of this study is to create a scientific insight into sustainable land and water development and management options as a means to increase agricultural production and water use efficiency. The specific objectives are:

- to develop an integrated approach for sustainable land and water development and management in Tigray based on the earthen dam projects for irrigation development. This approach would also have to be more generally applicable to similar irrigation projects in semi-arid regions;
- to investigate the reservoir hydrology of the earthen dams under the conditions in Tigray;
- to assess the social, economic and institutional impacts of the earthen dam irrigation schemes;
- to investigate in general terms the hydrological impacts of the implemented and proposed earthen dam schemes on the regime of the Nile river;
- to present recommendations for sustainable development of the land and water resources in Tigray, taking into account the potential and need for irrigated agriculture development, reservoir operation, waterlogging, salinization, sedimentation, social and institutional aspects and requirements by the Nile river;
- to give an account of the future outlook about land and water development and management in Ethiopia in general and in Tigray in particular.

In order to realize the objectives, the following activities have been carried out:

- review of available secondary data;
- collection and analysis of primary data on farming systems, socio-economy, institutional and management aspects from the farmers and other relevant stakeholders;
- field data collection and analysis on the rainfall, evapo(transpi)ration, groundwater recharge, erosion and sedimentation, and water and soil quality;
- review and selection of appropriate approaches and simulation of relevant processes;
- establishment and simulation of relevant alternative scenarios to the existing practice aiming at improving the utilization of the limited water supply, increasing crop production and minimizing the salinity problems;
- development of an integrated approach for sustainable land and water development in Tigray based on the results of the institutional, water management, environmental, socio-economic and hydrological aspects;
- generalization of the integrated approach to enable application to the Nile river basin and other semi-arid areas.

1.4 Set-up of the thesis

The next chapter provides a general overview of Ethiopia with special emphasis to the major land and water resource potential, constraints and development aspects, as well as the relationship with the Nile river basin. It also gives the description and detailed characterization of the study sites. Chapter 3 presents the major land and water development and management aspects in Tigray. It discusses issues such as the status of regional rainfed agriculture, the drought risks, the land and water potentials and the need of irrigated agriculture. In addition, the chapter describes the irrigation development strategies, the earthen dam irrigation schemes, and the related management and maintenance aspects. The major institutional, water management, environmental, socio-economic and hydrological issues that have to be considered for the development of sustainable earthen dam irrigation projects are discussed in chapter 4. The methodology employed in the study for the collection of data related to the issues is also included. Chapter 5 focuses on the data analysis, interpretation, discussion and conclusions of the reservoir sedimentation and water balance of the earthen dams, while the institutional, operation and maintenance, socio-economic, and waterlogging and salinity aspects of the irrigation schemes are presented in chapter 6. In chapter 7, the research results indicated in the preceding two chapters are evaluated with respect to their impact on the success and sustainability of the irrigation schemes and relevant recommendations forwarded. The implications of the results and experiences in Tigray on the Nile river basin are also included. The last chapter summarizes the writer’s outlook on the possible future land and water development in Tigray based on the research results and other relevant aspects such as regional policies and strategies.

2 Background

2.1 General overview of Ethiopia

2.1.1 Introduction

Ethiopia is located in East Africa between the latitudes 5° N and 15° N, and longitudes 35° E and 45° E. Its neighbouring countries are Eritrea in the North, Djibouti and Somalia in the East, Kenya and Somalia in the South, and Sudan in the West (Figure 2.1) (United States Central Intelligence Authority, 2000 and International Commission on Irrigation and Drainage, 2001).

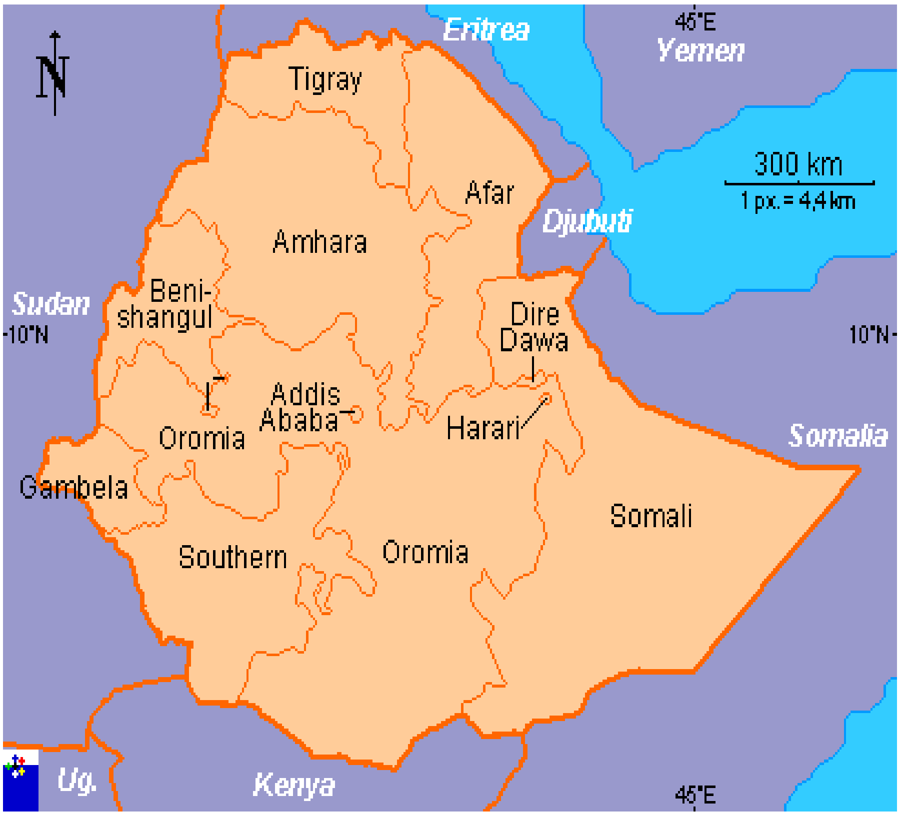


Figure 2.1 Map of the administrative regions of Ethiopia (Martins, 2005)

With a total area of 110 million ha, Ethiopia stands as the fourth largest country in sub-Saharan Africa. The country consists of nine ethnically-based administrative regions and two chartered cities. They are Afar, Amhara, Benishangul Gumuz, Gambela, Harar, Oromiya, Southern Nations, Nationalities and Peoples Region, Tigray, Addis Ababa, and Dire Dawa respectively (United States Central Intelligence Authority, 2000). With about 90% living in rural areas, the population of Ethiopia has raised from 22 million in 1961 to about 69 million at the moment with an average annual growth rate of 3% (Figure 2.2) (Central Statistics Authority, 2003). The average population density is 49 persons per 100 ha, but varies from less than 10 in Oromiya to almost 250 in Kembata in the Southern Nations, Nationalities and Peoples Regional State. The total labour force of the country constitutes about 48% of the population (Pausewang, *et al.*, 1990, Webb and Braun, 1994, FAO, 1995, Ethiopian Telecommunication Corporation, 2000 and United Nations Population Reference Bureau, 2004).

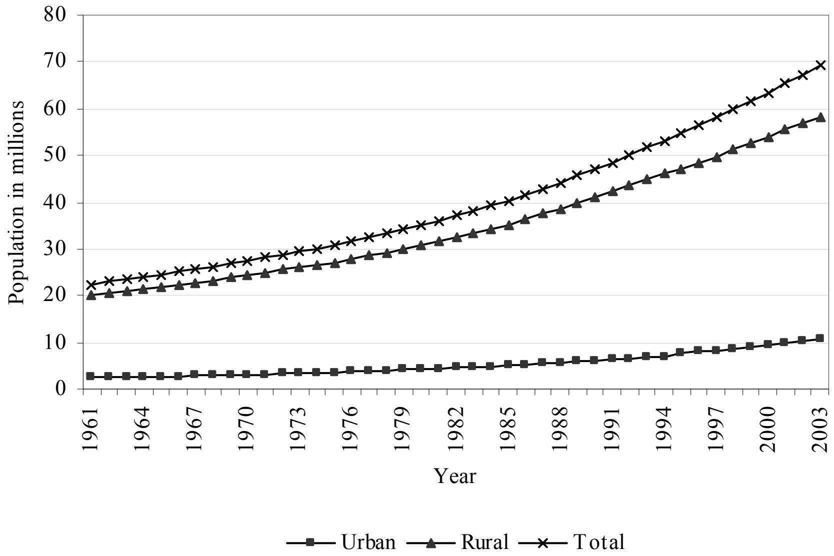


Figure 2.2 Population growth in Ethiopia (Central Statistics Authority, 2003)

Ethiopia extends over the three physiographic sub-divisions of the African continent: the Rift Valley System, the Eastern Highlands and the Nile Basin, and covers the two major landform regions of Africa, namely, Low Africa and High Africa (International Commission on Irrigation and Drainage, 2001).

The country is dominated by a highland complex of mountains and plateaux above 1,500 m+MSL (Mean Sea Level) and is split from Northeast to Southwest by the East African Rift Valley, some 40 - 60 km wide and occupied by a string of lakes. The extreme elevations are 125 m-MSL at the Danakil depression and 4,620 m+MSL at the Ras Dashen Mountain (FAO, 1995 and United States Central Intelligence Authority, 2000). Ethiopia experiences a mild climate and temperature changes are not extreme. In the highlands, temperatures are around 16 ^{o}C in the wet season and 21 ^{o}C in the dry season. Decrease in altitudes takes them to 27 ^{o}C in the wet and 35 ^{o}C in the dry season. The arid Danakil lowlands experience temperatures in the vicinity of 49 ^{o}C (International Commission on Irrigation and Drainage, 2001).

According to Webb and Braun (1994) Ethiopia's history is punctuated with famine as a result of three closely related factors, namely:

- population pressure, especially on the highlands with an altitude of higher than 1,500 m+MSL where about 80% of the total population is concentrated;
- natural resource base degradation;
- drought.

As recorded in a variety of contemporary and historical sources, Ethiopia faces major drought crises with a chance of occurrence of once in two years. Table 2.1 shows the occurrence of droughts in 22 of the past 40 years. Famine in Ethiopia can generally be summarized as a continuous and cyclic phenomenon. As a result, there is neither food self-sufficiency nor food-security in the country.

Table 2.1 Chronology of Ethiopian droughts and food shortages (EM-DAT Emergency Disaster Database, 2004)

Year	Total number of people affected in 10^6	Total number of deaths
1965	1.5	2,000
1973	3.0	100,000
1974	3.0	200,000
1977	0.3	-
1978	1.4	-
1983	7.0	-
1984	7.8	300,000
1987	7.3	-
1989	5.7	-
1990	6.5	-
1991	6.2	-
1992	0.5	-
1993	6.7	-
1994	3.9	-
1997	1.0	-
1998	0.8	-
1999	8.4	-
2000	10.5	-
2001	1.0	-
2002	16.3	-
2003	13.2	-
2004	7.2	

2.1.2 Land and water resources

Land resource potentials and constraints

According to an estimation of 1993, the land use of Ethiopia consists of 12% arable land, 1% permanent crops, 40% permanent pastures, 25% forests and woodland, and 22% others (United States Central Intelligence Authority, 2000). The country has about 66 million ha of agricultural potential area (Barghouti and Le Moigne, 1990 and Ethiopian Telecommunication Corporation, 2000) out of which about 3.6 million ha is potentially irrigable land.

There are two predominant soil types in the highlands. The first, found in areas with relatively good drainage, consists of red-to-reddish-brown clayey loams that hold moisture and are well endowed with needed minerals, with the exception of phosphorus. These types of soils are found in much of Ilubabor, Kefa, and Gamo Gofa provinces. The second type consists of brownish-to-grey and black soils with a high clay content. These soils are found in both the Northern and the Southern highlands in areas with poor drainage. They are sticky when wet, hard when dry, and difficult to work. But with proper drainage and conditioning, these soils have excellent agricultural potential. Sandy desert soils cover much of the arid lowlands in the Northeast and in the Ogaden area of Southeastern Ethiopia. Because of low rainfall, these soils have limited agricultural potential, except in some areas where rainfall is sufficient for the growth of natural forage at certain times of the year. Pastoralists who move back and forth following the availability of pasture for their animals use these areas. The plains and low foothills west of the highlands have sandy and grey-to-black clay soils. Where the topography permits, they are suitable for farming (1Up Info, 2003).

According to Bot, *et al.,* (2000), Ethiopia is affected by five major inherent soil constraints that create problems to soil management for agricultural production. They are:

- *high phosphorus fixation*. This problem is primarily caused by a high content of free ferric oxides (Fe_2O_3) in the clay fraction, which fixes phosphate ions in unavailable forms. It is also closely associated with the presence of aluminium toxicity. As added phosphorus fertilizers are fixed rapidly, phosphorus deficiency caused by this constraint is difficult to overcome. Slow-release forms of phosphorus are preferable. According to Bot, *et al.* (2000), a recent research on the addition of rock phosphate has also shown a significant attempt to tackle this problem;
- *vertic properties*. This is common in Vertisols (‘black cotton soils’). These soils swell on wetting and shrink, causing wide cracks, in drying. The cause is a high clay content coupled with > 50% 2:1 lattice (mont-morillonitic) clay minerals. Vertisols are chemically fertile, but their management for cultivation is difficult due to their physical properties. They are stiff and sticky when wet, and hard when dry;
- *salinity and sodicity*. These occur naturally on low-lying areas in semi-arid and arid regions. They are caused by accumulation of free salts in the soil (salinity), or dominance of the soil exchange complex by sodium ions (sodicity). The reclamation of naturally saline soils is uneconomical or impractical, due to the very high cost or unavailability of non-saline water. Reclamation of salinized soils of irrigation schemes is also very costly. Controlling sodicity is still difficult but methods involving drainage, leaching and vegetation can be used;
- *shallowness*. These are soils with rock or a hard, cemented horizon near the surface, have a depth of less than 0.50 m and are often stony or gravely. This mostly occurs on steep lands and in arid regions. Ethiopia stands 21st in the world. In the tropics including Ethiopia, population pressure has resulted in the cultivation of shallow soils on steep slopes. Such cultivation will, however, be short-lived unless measures are taken to control erosion. If possible, such lands

should be kept under natural vegetation and used for controlled grazing and fuel wood purposes;

- *erosion hazard*. According to the method employed in Bot, *et al.,* (2000), areas having a severe erosion hazard are those with predominantly very steep slopes (> 30%), together with areas of steep slopes (8 – 30%) in conjunction with an abrupt textural contrast in the soil profile on the Soil Map of the World. With 40.6 million ha of steep slopes (8 – 30%) and 32.6 million ha of very steep slopes (> 30%), 66% of Ethiopia's landmass is categorized as steep land.

Table 2.2 shows the degree of the above constraints in Ethiopia. As it is common for soils to be affected by more than one constraint, the areas given can be partly overlapping.

Table 2.2 Areal coverage of inherent soil constraints in Ethiopia (Bot, *et al.,* 2000)[1]

Soil constraint	Areal coverage	
	in 1,000 ha	in % [2]
High phosphorus fixation	8,800	8
Vertic properties	10,100	9
Salinity and sodicity	7,600	7
Shallowness	33,100	30
Erosion	34,200	31

Note:
1 = the area considered is the total land area, not the agricultural land only.
2 = total area considered is 110 million ha.

In total 37 million ha of Ethiopia's land is not affected by any of the above eight major inherent soil constraints (Bot, *et al.,* 2000). However, human induced land degradation is still a major problem in Ethiopia, primarily as a result of overgrazing. Over-cultivation and deforestation also play an important role. The rugged topography of the highlands, the short but extremely heavy rainfalls that characterize many areas, and centuries-old farming practices without conservation measures have also accelerated soil erosion in much of Ethiopia's highland areas. In the dry lowlands, persistent winds contribute to soil erosion (1Up Info, 2003).

The situation is said to have worsened considerably during the 1970s and 1980s, especially in Tigray and parts of Gondar and Wollo. During the Imperial era, the Government failed to implement widespread conservation measures, largely because the country's complex land tenure system hindered attempts to halt soil erosion and improve the land. After 1975, the revolutionary Government used peasant associations to accelerate conservation work throughout rural areas. The 1983/1984 famine also provided a motivation to promote conservation. The Government mobilized farmers and organized "food-for-work" projects to build terraces and plant trees. During 1983 and 1984, the Ministry of Agriculture raised 65 million tree seedlings, planted 18,000 ha of land, and terraced 9,500 ha through the "food-for-work" projects. Peasant associations also used 361 nurseries to plant 11,000 ha of community forest. Between 1976 and 1985, the Government constructed 600,000 km of bunds on cultivated land and 470,000 km of hillside terraces, and closed 80,000 ha of steep slopes for regeneration. However, the removal of arable land for conservation projects has threatened the welfare of the increasing number of rural poor. For this reason, some environmental experts maintain that large-scale conservation work in Ethiopia has been ineffective (1Up Info, 2003).

According to the Global Assessment of Soil Degradation (GLASOD), 10%, 57%, 8%, 20% of the total area of Ethiopia are affected by light, moderate, strong (severe) and extreme (very severe) land degradation respectively (Bot, *et al.,* 2000). The main cause of erosion is related to water. The description of the land degradation severity classes is presented below:

- *light*: somewhat reduced agricultural productivity;
- *moderate*: greatly reduced agricultural productivity;
- *strong*: biotic functions largely destroyed; non-reclaimable at farm level;
- *extreme*: biotic functions fully destroyed; non-reclaimable.

However, this Global Assessment of Degradation was made based on estimates of national experts on the type, severity, extent of degradation, together with the major causes. More recording and monitoring of land degradation, including quantitative and replicable methods are required to achieve more reliable data (Bot, *et al.,* 2000).

Water resource potentials and constraints

In Ethiopia, the annual rainfall varies from less than 100 mm along the border with Somalia and Djibouti to 2,400 mm in the Southwest highlands, with a national average of 744 mm/year. In the Southern and Eastern highlands, there is a pronounced bi-modal rainfall distribution, with generally smaller rains during the months of January and February (Belg), and the main rains during June to mid-September (Kiremit). Rainfall variability is important, particularly in the lower areas of the Northeast highlands (FAO, 1995 and Girmay, *et al*., 2000).

Taking into account the annual rainfall pattern and relief and its aspects, the moisture regime of Ethiopia can be divided into four zones, namely, humid, sub-humid, semi-arid and arid. The sub-humid and semi-arid zones can be further divided into wet and dry sub-zones (Table 2.3). The classification is based on the moisture index calculated with the modified Thornthwaite's approach (Engida, 2001).

Table 2.3 Area coverage of moisture regimes of Ethiopia (Engida, 2001)

Area	Moisture regime						Lakes	Total
	Arid	Semi-arid		Sub-humid		Humid		
		DSA	WSA	DSH	WSH			
In %	38.8	10.5	18.3	15.4	9.9	6.4	0.7	100
In 10^6 ha	42.9	11.6	20.2	17.1	10.9	7.1	0.7	110

Note:

DSA = dry semi-arid, WSA = wet semi-arid, DSH = dry sub-humid, WSH = wet sub-humid.

The main drainage basins and their major characteristics are indicated in Table 2.4 and Figure 2.3 (FAO, 1995, Ministry of Water Resources, 1998 and BCEOM, *et al.*, 1999). The drainage basins include:

- Blue Nile (Abay) and the Baro-Akobo towards Sudan;
- Tekeze and Mereb towards Eritrea and Sudan;
- Wabi-Shebelle and the Genale-Dawa towards Somalia;
- Omo-Gibe towards Lake Turkana;

- Danakil, Awash, Rift Valley lakes, Ogaden and Aysha basins that are landlocked.

Table 2.4 Major characteristics of river basins of Ethiopia (FAO, 1997 and BCEOM, *et al.*, 1999)

Drainage basin	Area in 10^6 ha	Runoff in 10^9 m^3/yr	Irrigation		Hydropower	
			Potential in 10^3 ha	Utilised in %	Potential in 10^6 KWH/yr	Utilised in %
Nile						
Abay (Blue Nile)	20.0	56.0	1,000	2.1	55,000	1.2
Tekeze	9.0	7.6	313	0.6	8,969	-
Baro-Akobo	7.4	11.9	905	0.0	19,826	-
Indian ocean						
Genale	17.1	5.9	435	-	12,508	-
Wabi-Shebelle	20.3	3.2	204	9.9	6,143	8.8
International closed basins						
Mereb	0.7	0.3	38	21.3	n.a	-
Omo-Gibe	7.8	16.1	450	6.1	n.a	-
Internal closed basins						
Danakil	0.2	-	3	-	n.a	-
Awash	11.3	4.6	204	34.2	5,589	7.8
Rift Valley	5.3	5.6	122	10.0	12,240	-
Ogaden	7.7	-	-	-	n.a	-
Aysha	0.2	-	-	-	-	-
Total	107.0	111.0	3,674	4.4	120,275	1.4

Note:
KWH = KiloWatt Hour; n.a = not available

Ethiopia is quite rich in water resources and its drainage pattern is of great importance for its neighbouring countries. The total annual water resources are estimated at 111 billion m^3 of which 75.5 billion m^3 in the Nile basin. The main river basins contributing to the Nile are the Abay, Baro-Akobo, and Tekeze. Most of the rivers in Ethiopia are seasonal, and about 70% of the total runoff takes place during the months of June, July and August. Dry season flows originate from springs, which provide base-flows for small-scale irrigation (FAO, 1995).

One of the main water resource problems in Ethiopia is the uneven spatial distribution of the river basins. Between 80 – 90% of Ethiopias' water resources are found in four river basins, namely, Abay (Blue Nile), Tekeze, Baro-Akobo, and Omo-Gibe in the North, West and Southwestern part of Ethiopia where the population is not more than 30 – 40% of the total population. The water resources in the eastern and central river basins are only 10 – 20%, whereas the population in the river basins is over 60% of the total population (Ministry of Water Resources, 1998).

The temporal distribution of rainfall also poses the same trouble. On annual basis, Ethiopia gets plenty of rainfall, but it is quite erratic in nature and mostly falls either too early or comes too late or even recesses in mid season of the cropping period. In short, the required amount is not available at the right time. Accordingly, recurrence of drought is a common phenomenon in Ethiopia (Ministry of Water Resources, 1998).

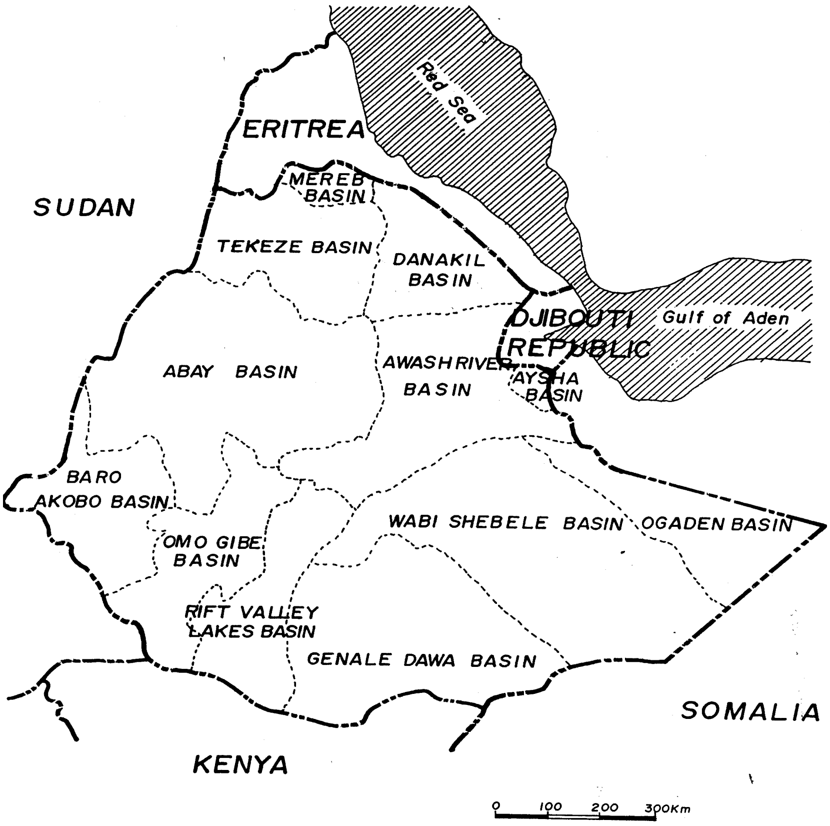


Figure 2.3 Map of the drainage basins of Ethiopia

2.1.3 Land and water development

Agriculture is the major source of employment (90% of the population), and of the revenue and export earnings for Ethiopia, contributing about 50% of the total Gross Domestic Product (GDP) (Pausewang, *et al.*, 1990 and Ethiopian Telecommunication Corporation, 2000). Main agricultural products are cereals (teff, maize, sorghum, barley, wheat and millet), oil seeds, pulses, coffee and sugarcane (Central Statistics Authority, 2003). The country is richly endowed with sufficient manpower (about 48% of the total population), huge annual surface water potentials and large potential agricultural land. However, much of its land and water potential is not yet exploited. Out of the 66 million ha of land suitable for rainfed and irrigated agriculture, only about 16% is currently developed (Table 2.5) (Barghouti and Le Moigne, 1990, Ethiopian Telecommunication Corporation, 2000 and Central Statistics Authority, 2003). With respect to irrigation, only about 190,000 ha (nearly 5.2%) of the 3.6 million ha potentially irrigable land is utilised (Hillel, 1997). According to FAO (2003(a)), out of its annual water resources of 111 billion m^3, Ethiopia withdraws only 3 billion m^3 with 6% use in the domestic sector, 1% in industry and 93% allocated to agriculture.

Table 2.5 Cultivated area in Ethiopia (Central Statistics Authority, 2003)

Crop type	Area cultivated in 10^3 ha		
	1998/1999	1999/2000	2000/2001
Cereals	7,456	7,176	8,092
Oil seeds	379	410	563
Pulses	983	1,115	1,409
Fenugreek	21	16	14
Sugarcane	21	22	23
Coffee	295	295	295
Total	9,155	9,034	10,396

Inaccessibility, water shortages, and infestations of disease-causing insects, mainly mosquitoes, prevented the use of large parcels of potentially productive land. In Ethiopia's lowlands, for example, the presence of malaria in many areas kept farmers from settling.

Most agricultural producers are subsistence farmers with small holdings, often broken into several plots. Most of these farmers live on the highlands, mainly at elevations of 1,500 to 3,000 m+MSL. The population in the lowland peripheries (below l,500 m+MSL) are nomadic, engaged mainly in livestock rearing (1Up Info, 2003).

Ethiopia’s agriculture is dominated by rainfed farming of low productivity. The annual grain production, which is on average 7 million tons, is too low to support the national food demand (Figure 2.4). The annual food demand was determined based on the annual population and per capita grain demand of 173 kg/annum (FAO, 2003(b)). Figure 2.4 indicates that the country was able to produce sufficient grain in only 4 years during 1980 – 2001. The rest shows generally an annual grain deficit which can be up to 3.3 million tons. As a result and due to lack of resources to finance food imports, the country is dependent on international food aid. According to FAO (2003(c)), Ethiopia’s food aid request ranges from 0.3 to 1.2 million tons of grains per year, which is about 4 – 17% of its own production.

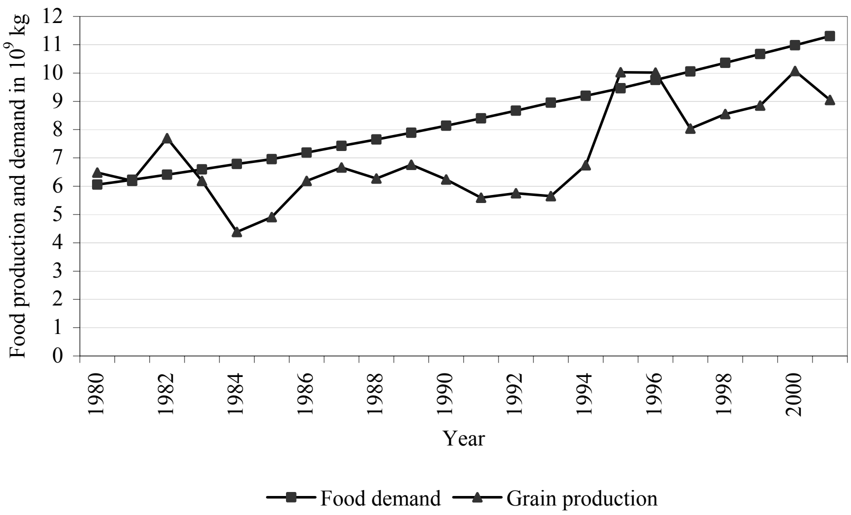


Figure 2.4 Annual food production and demand in Ethiopia

Irrigated agriculture is not well developed in the country and its impact to support the food demand is very small. The Awash River basin supports most of the large-scale irrigated commercial farms and several smallholder-irrigated lands (1Up info, 2003). According to FAO (1995), there are three categories of irrigation schemes in Ethiopia, namely:

- *small-scale (63,581 ha):* smallholder schemes for a single peasant association and up to 200 ha in size, for which assistance in development or improvement is carried out on a self-help basis, eventually with support from the Ministry of Agriculture. About 360,000 farmers are involved in traditional small-scale irrigation;
- *medium-scale (44,837 ha)*: schemes between 200 and 3,000 ha, extending beyond one peasant association, and requiring a greater degree of government assistance in development, provided through the Water Resources Development Authority (WRDA). At first intended as self-help, low-cost developments, they were later modified to include commercial production (coffee, sugar, or cotton);
- *large-scale (81,138 ha):* centrally managed state farms for commercial production, and covering 3,000 ha or more, to be planned and designed by WRDA and constructed under its supervision.

The problems related to land and water development in Ethiopia go back to the Feudo-Bourgeois regime before 1975. Though traditional irrigation practices are centuries old, their area coverage and contribution towards food self-sufficiency was very minimal. There was no initiative by the farmers to invest in irrigation due to the land policy of the regime. By this policy, a great proportion of the land was owned by only a few landlords and the farmers were tenants. The poor land policy along with the lack of technical know-how has hampered irrigation development during this period (Tadesse, 1988).

After the fall of the Feudo–Bourgeois, land was made under public ownership by the Proclamation of 1975 by the Dergue regime. This is taken as a benchmark for the start of both small-scale and large-scale irrigation schemes in Ethiopia (Tadesse, 1988). In addition to the effort of individual and groups of farmers to develop irrigated land, the Government has also invested in large-scale irrigation state farms like the Ami-bara, Borkena, Children's Amba, Melkasedi, Omo Ratti, etc. (FAO, 1995 and Mitiku, *et al*., 2000). However, similar to the other sub-Saharan countries as indicated in Barghouti and Le Moigne (1990), most of the schemes failed to meet their objectives due to poor design and construction, and poor irrigation management. The latter due to lack of feeling of ownership by the irrigation scheme managers (Mitiku, *et al*., 2000).

In 1988, the costs of developing large-scale irrigation schemes were between US $ 18,000 and 25,000 per ha, without accounting for water storage. Development costs of medium-and small-scale schemes were between US $10,000 and 15,000 per ha and between US $ 2,300 and 3,400 per ha, respectively. These high costs are one of the reasons for low economic returns from irrigation in Ethiopia, especially for large-scale schemes, and can explain why the irrigated area is less than 5% of the potentially irrigable area (FAO, 1995 and Hillel, 1997). This high development cost could have been to a certain extent caused by corruption and poor management of funds.

Moreover, in addition to the long-standing structural problems, the previous Government was transforming the economy along a socialist line, which abolished private ownership and instead established a centrally planned economic system. This restricted private investors from involvement in irrigation development. As a result of this and other factors, the performance of the economy between 1974 and 1991 showed a dismal picture. Other factors included economic mismanagement, severe fluctuations in weather conditions, land degradation and excessive military outlays (about 50% of the recurrent budget). Accordingly, the real Gross Domestic Product (GDP) growth, after averaging 4% per annum for 10 years before 1974 fell to about 1.5% during 1974 – 1991. In contrast, population growth picked up from 2.6% to about 3%, rendering a continuous fall in per capita income and worsening living conditions. The growing deficit in the Government budgets and balance of payments as well as the increase in external debts servicing ratio further created constraints in the national capacity to improve the situation (Ethiopian Telecommunication Corporation, 2000).

The lack of a comprehensive water resources management policy in Ethiopia has also caused adverse impacts. The most significant ones are (Ministry of Water Resources, 1998):

- lack of efficient utilization of water resources;
- prevalence of unrealistic and unattainable plans and programs;
- non-objective oriented programs and projects;
- uncertainties and ambiguities in planning;
- presence of intensive centralism that does not focus on rural development;
- lack of proper operation and maintenance of irrigation schemes.

In response to challenges posed by the decline in economic and social performance, the present Government, established in 1991, has adopted a new economic policy in 1992 with the following major principles (Ethiopian Telecommunication Corporation, 2000):

- reducing the role of the State in the economy;
- promoting domestic and foreign private investments;
- enhancing community participation in development;
- mobilizing external resources;
- involving regional administrations in economic management.

Taking into account the potentials of land and water resources, and the problems of food insecurity, population increase, and insufficient rainfall, agricultural development is a priority. Accordingly, the development strategy adopted in August 1992 set the country's strategy to be an Agricultural Development-Led Industrialization (ADLI). The strategy focuses on improvement of productivity of smallholder agriculture by combining resources of the farmers and introducing new technologies (Ethiopian Telecommunication Corporation, 2000). The resources include land, labour and capital. The technologies are irrigation, improved seeds, better farm implements, fertilizers and pesticides, widespread use of better cultivation practices, minimization of post-harvest losses, greater and more efficient use of extension work and management techniques. The high dependency on rainfed farming in the drylands of Ethiopia and the erratic nature of the rainfall require alternative ways of improving the availability of food. In the agricultural development strategy of the nation, water resources development has been given an important role. Accordingly, irrigation development is taken as an essential component of the food security strategy for improving food production and agricultural productivity, particularly in the food insecure areas. This is believed to bring food self-sufficiency for the rapidly increasing population (Girmay, *et al.,* 2000). Moreover, the country has also adopted a Water Resources Management Policy with an overall goal of enhancing and promoting all national efforts towards the efficient, equitable and optimum utilization of the available water resources (Ministry of Water Resources, 1998).

The general objectives of the Water Resources Management Policy are (Ministry of Water Resources, 1998):

- development of the water resources for economic and social benefits of the people, on an equitable and sustainable basis;
- allocation of water based on comprehensive and integrated plans and optimum allocation principles that incorporate efficiency of use, equity of access, and sustainability of the resources;
- managing and combating drought as well as other associated disasters through efficient allocation, redistribution, transfer, storage and efficient use of water resources;
- combating and regulating floods through sustainable mitigation, prevention, rehabilitation and other practical measures;
- conserving, protecting and enhancing water resources and the overall environment on a sustainable basis.

In line with this, the Government policy in irrigation consists of channelling direct investment and support to farmers, while promoting commercial investments in agriculture (FAO, 1995). To this effect, the Federal and Regional Governments have established organizations like the Ethiopian Social Rehabilitation and Development Fund (ESRDF), the Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (CoSAERT) and the Commission for Sustainable Agricultural and Environmental Rehabilitation in Amhara Region (CoSAERAR), to be in charge of the design and construction of small-scale irrigation schemes. As a result many small-scale river diversions, pressurized (pumped) and earthen dam irrigation schemes have been developed. Many non-governmental and community organizations, like World Vision, Norwegian Church Aid (NCA), and Relief Society of Tigray (REST) also assist the farming communities in irrigation development. In this way, traditional irrigation practices of the communities are also encouraged and enhanced (Girmay, *et al.,* 2000).

The present strategy also promotes private commercial-scale agriculture by leasing land not occupied by small-scale cultivators and which does not jeopardize the livelihood of pastoralists. Within this framework, there are already good starts in mechanized irrigated agriculture in the country (Ethiopian Telecommunication Corporation, 2000).

Since the adoption of the new policy, the Gross Domestic Product (GDP) growth of Ethiopia was encouraging except for some years (Table 2.6). The low performance in 1993/1994, 2001/2002 and 2002/2003 was due to failure of agricultural production, while in 1997/1998 it was the result of war.

Table 2.6 Gross Domestic Product (GDP) of Ethiopia (Central Statistics Authority, 2003)

Year	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03
GDP (%)[1]	+ 12	+ 1.7	+ 5.4	+ 10.6	+ 4.7	-1.4	+ 6	+ 5.4	+ 7.7	+ 1.2	-3.8

Note: 1 = this is increase (+) or decrease (-) in GDP

Owing to the existing economic policy in general and the agricultural policy in particular, the future direction of Ethiopia with respect to land and water development can be summarized as small-scale to large-scale land and water development by the Government, communities, non-governmental organizations and investors.

2.2 Description of the study area

2.2.1 Tigray

Location and topography

Tigray is the most Northern region of Ethiopia with a total land area of approximately 8 million ha (Figure 2.5). It is located between latitudes 12º 15’ N and 14º 50’ N, and longitudes 36º 27’ E and 39º 59’ E and stretches from the Sudan border in the West to Eritrea in the North. The Ethiopian regions of Amhara and Afar border it in the South and East.

The topography is mainly characterised by a mountain plateau with undulating terrain interspersed with low situated valleys, hills and flatlands in the central highlands and plain lowlands in the Eastern and Western escarpments. The highlands are composed of massifs and plateaux dissected by small gorges and form impressive features in raggedness. Though there are some peaks such as Asimba and Alage, which rise to 3,248 and 3,293 m+MSL, respectively, the highlands have a general altitude range of 2,000 to 3,000 m+MSL. The Tekeze and Mereb rivers and their tributaries have cut broad valleys and broken the plateau, resulting in considerable erosion. The Western plateaux comprise most lowland areas of the Western zone extending up to the Tekeze valley, while the Eastern lowlands are located along the border with the Afar region (Kindeya, 1995).

Administration and land tenure

Ethiopia is a Federal Democratic Republic composed of different Regional States. These regional states are autonomous to administer their regions. They can also formulate and implement various strategies and policies that are coherent to the country’s constitution and policies. The administration hierarchy of Tigray follows the following sequence:

- Regional Government, with the regional state parliament as the highest organ;
- Zonal administrations;
- Wereda (district) administrations;
- Kushet administrations;
- Tabia administrations, which are the lowest units at village level.

One of the major issues in land and water development is the land tenure. Land tenure describes the conditions, obligations and rights of land ownership and use. An ill-defined land ownership and use can lead to improper utilization of the land and lack of commitment to irrigation development (Carter, 1989). The Government of the Regional State of Tigray has formulated the rural land tenure policy in 1997 in Proclamation number 23/89 (National Regional State of Tigray, 1997).

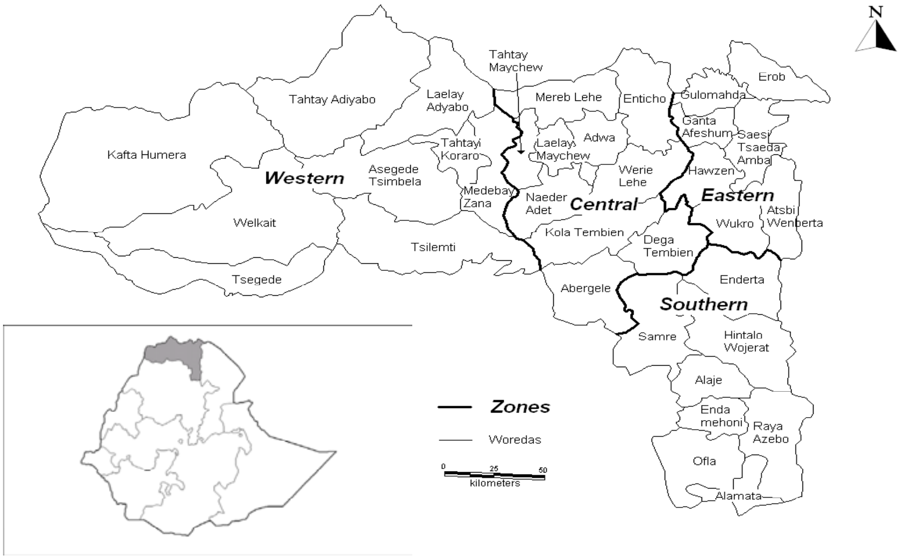


Figure 2.5 Administrative Weredas of Tigray (FAO, 2003(c))

According to the proclamation, the Government and the people communally own the land. It allows all other use rights except selling and mortgaging. Except in earthen dam irrigation schemes, the proclamation prohibits further redistribution of agricultural land. A summary of the main concepts of the proclamation is presented below:

- individually owned farms can be leased out for up to two years under traditional cultivation practices and ten years if improved technology is used. Government owned lands can be leased out for up to 50 years;
- farmers have the right to use, lease out, or transfer their land. Guidelines on the terms of transfer of land are clearly indicated in the proclamation. Farmers are also obliged to use soil and water conservation practices in their farmland. The right of use of farmland will automatically expire if the holder is absent from the area for two years. This does not work for two situations, namely, if at least one of the two household heads are in the area and for those who are living in urban areas but were given land in 1997;
- non-agricultural lands are administered by the Government. These include forests, deserts, sites reserved for various construction (houses, schools, roads, etc.) and social purposes (churches, mosques, etc.);
- private investment on agricultural lands that are not owned by farmers is allowed;
- the proclamation has also put contingency plans for future demands of agricultural lands. These include demands by grown up children (22 years for male and 16 year for female) and returnees from previous resettlement (villagization) programs. In this case, an area of 0.04 ha (400 m^2) is provided

per person from agricultural lands reserved for the purpose. Non-agricultural lands can be distributed in absence of a reserved agricultural land. Some guiding rules are set by the proclamation for this purpose;

- communal grazing lands are managed and utilized based on existing local by-laws. A new management policy can be formulated at tabia (village) level, if necessary;
- in earthen dam irrigation schemes, priority of allocation is given to farmers who already own land in the command area and to those displaced from the reservoir. The proclamation has set the following mandatory activities in earthen dam irrigation schemes:
    - in order to maintain the sustainability of the schemes, beneficiaries have to carry out watershed rehabilitation works and maintenance of embankments and irrigation canals;
    - watersheds of earthen dams have to be used as per the recommended land use plan. The plan may include use for agriculture, grazing, homestead, forest and closed areas;
    - beneficiaries have to pay water charges;
    - the beneficiaries, local administration and the health services have to work together in the prevention and treatment of water-borne diseases.

Geology and soils

The highland area of Tigray contains a small portion of Tertiary lava, which is located in the Southeast. The remaining part of Tigray is underlain by shales, limestones and sandstones of the Tertiary and Mesozoic eras, and beneath these are Palaeozoic and Precambrian limestones, slates, granites, schists and gneisses of the basement complex (Kindeya, 1995).

Table 2.7 Overview of major soil types and properties in Tigray (Mitiku, 1997)

Soil Unit (FAO, 1977)	Series	Depth in cm	Texture	OC in %	CEC in cmol(+)/kg	Olsen P in ppm
Lithosol	Dindera	30	SCL	-	-	-
Vertisol	Humera	200	C	1.2	72	19.0
Vertisol	Gormedo	115	C	2.6	29	5.0
Fluvisol	Lahama	160	SL	2.4	20	1.4
Gleysol	Kesafi	120	L	-	27	-
Arenosol	Menchebu	180	SL	1.0	13	1.8
Rendezina	Mosebo	45	C	3.3	41	2.3
Xerosol	Kalla	100	SL	2.0	22	4.0
Luvisol	Tabeldi	200	SCL	0.4	20	7.0
Luvisol	Romanat	130	CL	1.4	25	27.0
Cambisol	Yemad	144	SCL	1.1	12	8.6
Cambisol	Senda	125	SCL	1.0	16	2.0

Note:

OC = Organic carbon, CEC = Cation exchange capacity, P = Phosphorous, BS = Bulk density, S = Silt, C = Clay, L = Loam

No systematic soil survey has been carried out in Tigray. The only extensive reconnaissance survey of a 2 million ha area in central Tigray was conducted by Hunting Technical Services (Hunting and MacDonald, 1976). Generally, the relief has a strong influence on the soil development in the region. The following distinct slope elements can be distinguished in this regard (Mintesinot, 2002):

- deeply weathered residual soils on the level upper plateaux;
- rock or very shallow soils on the vertical scarps;
- unconsolidated coarse stony soils on the undulating topography;
- moderately deep alluvial soils on the level terraces and lower parts of alluvial deposits.

A summary of the most commonly occurring soil types in Tigray is given in Table 2.7. Cambisols are the most extensive arable soils in Tigray. These soils are derived from limestones and shales (of all ages). They are generally moderately deep, sandy clay loams/clay loams, often stony, and of moderate fertility with low organic matter, medium potash and low phosphorus. As they are of very restricted occurrence in other parts of the Ethiopian highlands, little is known of their chemistry and agronomic requirements (Kindeya, 1995).

Climate

The climate of Tigray is mainly semi-arid and for the larger part of the region the main rainfall season (locally called Kiremti/Meher) is for three to four months during June to mid-September. During this season the region receives 80% of the total annual rainfall (Natural Resource Development and Environmental Protection Bureau, 1994). However, some areas in the Southeastern highlands and Northeastern lowlands get some rainfall during January and February (Belgi/Belg). In Tigray rainfall is erratic, but heavy rains alternate with dry periods resulting in alternating floods and dry periods. The region receives the least rainfall compared to other parts of Ethiopia. The average annual rainfall for the period (1961 – 1987) was 571 mm, which was 38% less than the national average for the same period, which was 921 mm (Webb and Braun, 1994). The mean annual rainfall ranges from 980 mm on the Central plateaux to 450 mm on the Northeastern escarpments of the region (Solomon, 1999). The annual rainfall shows a high degree of variation ranging from 20% in the Western to 49% in the Eastern parts of Tigray (CoSAERT, 1994). The rainfall shows highly intense showers up to 68 mm/hour (Girmay, 1995). The mean monthly and annual rainfall data for some stations in Tigray are given in Table 2.8 and Figure 2.6.

Tigray enjoys different temperature ranges depending on the altitude. The average annual temperature is around 22 ^{o}C and above 26 ^{o}C in the highlands and lowlands respectively. The average maximum temperature is recorded in June (28 ^{o}C), while the lowest average minimum temperature occurred in December (9 ^{o}C) (Mintesinot, 2002). In general, the average temperature drops about 0.6 ^{0}C per 100 m altitude (CoSAERT, 1994).

The predominant wind direction from October to January is East with an average speed of about 8 m/s. From February till May, it changes to Southeast or Northwest with an average speed of 6 m/s. In July and August, the prevailing wind is from West with a average speed of about 5 m/s (Netherlands Engineering Consultants, 1997).

Table 2.8 Average monthly and annual rainfall in mm of different locations in Tigray (CoSAERT, 2002)

Station	Zone	January	February	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.	Annual
Adigrat	Eastern	6.7	11.1	40.5	76.2	47.0	27.5	197.3	181.2	19.8	15.2	9.0	12.4	644
Wukro	Eastern	2.1	2.9	25.3	25.5	15.2	35.2	174.2	209.0	41.5	6.0	2.6	3.5	543
Senkata	Eastern	9.0	16.6	56.2	74.4	48.0	96.4	237.5	200.1	39.2	29.1	36.6	20.0	863
Illala	Southern	0.4	6.2	14.0	37.7	39.7	23.7	153.0	193.2	25.1	5.2	2.7	0.6	501
Hagersalem	Central	4.5	5.4	41.2	46.6	47.1	84.8	243.1	223.6	73.4	22.1	10.5	6.8	809
Edgahamus	Eastern	7.2	10.6	52.4	93.5	82.1	65.1	153.9	213.9	39.3	27.6	21.7	6.7	774
Hawzen	Eastern	3.8	3.6	27.8	32.6	32.1	39.6	172.7	161.2	28.3	19.3	14.3	3.2	538
Mekelle	Southern	2.4	8.6	28.8	35.9	30.2	36.2	199.6	199.3	33.6	3.6	5.7	1.0	585
Abi Adi	Central	1.1	0.4	22.2	6.9	41.2	95.3	244.0	227.5	68.5	12.7	2.0	5.5	727
Adi Gudom	Southern	0.4	2.1	8.2	20.8	20.5	39.1	170.4	203.3	42.5	4.1	1.4	0.2	513
Adi Shuhu	Southern	11.5	7.0	29.7	41.8	15.1	30.3	177.4	223.8	40.8	12.1	18.4	5.1	613
Adwa	Central	1.8	2.1	24.1	24.5	56.0	77.5	208.5	234.2	117.7	37.6	10.8	0.3	795
Axum	Central	4.5	2.4	16.1	30.9	40.9	61.8	207.7	194.3	42.4	23.3	18.4	1.1	644
Betmera	Southern	1.8	20.5	50.9	37.0	17.7	10.7	185.0	190.3	30.5	14.0	4.5	1.2	564
Chercher	Southern	21.4	24.3	60.1	47.6	48.6	19.1	125.4	171.3	68.9	54.8	11.2	7.0	659
Dengolat	Eastern	1.8	6.6	38.1	39.6	23.9	49.4	199.5	185.7	42.5	15.3	9.1	3.7	615
Endaselassie	Western	1.5	0.4	5.0	26.7	49.3	116.2	298.4	257.9	127.7	35.3	8.4	0.2	927
Maichew	Southern	10.9	25.1	58.3	75.4	74.0	28.2	150.1	192.7	68.6	42.3	16.2	15.2	757
May Kinetal	Central	6.5	2.4	23.0	23.8	43.9	138.3	206.5	180.4	55.8	24.6	20.6	10.9	736
Quiha	Southern	2.7	4.5	22.8	38.6	25.3	33.7	205.5	219.7	39.3	1.7	4.2	1.2	599
Samre	Southern	3.8	2.3	23.8	24.6	19.1	48.0	176.8	207.2	55.8	7.4	17.0	5.5	591
Selekleka	Western	0.7	1.2	12.9	27.4	55.0	126.4	281.2	241.3	74.4	24.0	7.8	1.1	853

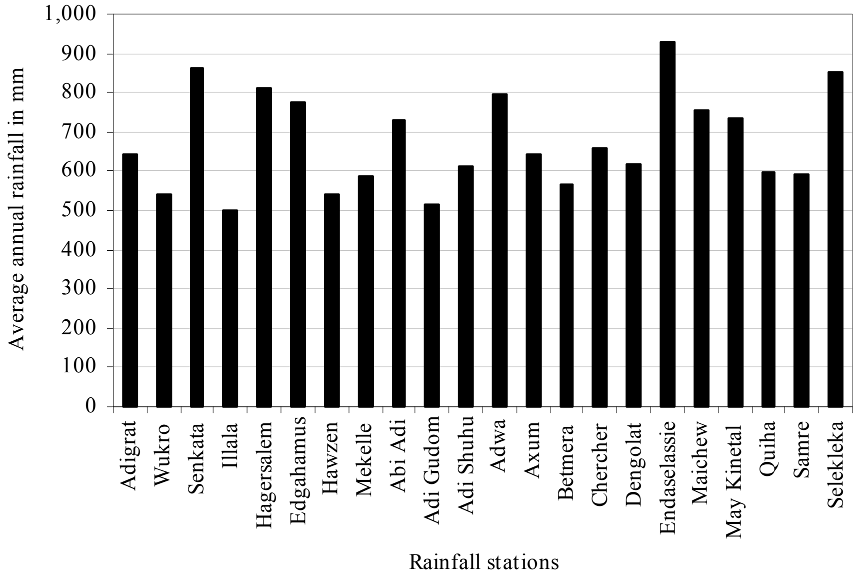


Figure 2.6 Average annual rainfall at different locations in Tigray

According to the Netherlands Engineering Consultants (NEDECO), the average annual potential evapotranspiration of the region is about 1,540 mm. Evaporation rates remain high even during the colder period due to the high rates of radiation and the persistence of strong dry Easterly winds coming from the Danakil depression. The rainfall amount exceeds the potential evapotranspiration in two months of the year, i.e. July and August. The evapotranspiration is largely determined by the solar radiation, which is fairly constant between years. As a result evapotranspiration varies little from year to year, especially in the dry season.

The minimum average monthly relative humidity is around 40% and occurs in the dry season, while the maximum average monthly humidity occurs during the rainy season with values of above 70%. The average monthly hours of sunshine in Tigray range between 6.5 and 8.5 hr/day with highest values of up to 10 hr/day in the dry season and lowest values of less than 4 hr/day during the rainy season (Netherlands Engineering Consultants, 1997).

Demography and agriculture

Tigray has a population of 3.3 million and an annual population growth rate of 3.3%. With an average of about 41 persons, the population density ranges from 28 persons in the Western zone to about 106 persons per 100 ha in the densely populated highlands. Population density and, hence, settlement is found to be strongly related to the agro-ecology and certain topographic conditions of the region. The Central highlands, with more favourable climatic conditions, are highly populated while the Western lowlands with hotter climatic conditions, poor infrastructure and high malaria infestation are sparsely populated (National Regional

State of Tigray, 1999). The average family size varies and ranges from 4 persons per family for lowlands to 5 persons for midlands and highlands (Mitiku, *et al*., 2001). Except in case of a widow or divorce, the households in Tigray are lead by men. In most cases, the women are restricted to household activities while the men are active in farm works. However, the assistance of women in farm activities, especially in livestock rearing, ploughing, weeding and harvesting is vital.

The farming system of Tigray is entirely dominated by traditional methods of crop production and livestock rearing. About 90% of the population depends on this ancient form of plough-based cultivation. Subsistence farming has been practised on the plateaux and the mountain slopes of the highlands for centuries without showing improvements. Limited mechanised farming has also been practised by the state or private companies in the Western lowlands (Leul, 1994 and Girmay, 1995). Cropping practices are usually dominated by cereal production, which occupies 88% of the total arable land. Teff (*Eragrotis teff)*, wheat, and barley are the dominant cereal crops in the region, followed by finger millet, sorghum, maize and beans. Pulses and oil crops occupy 5% and 7% respectively (Natural Resource Development and Environmental Protection Bureau, 1994). On the other hand cattle, sheep, goat and poultry are the dominant livestock.

Nearly 56% of the total area is cultivated. Other land uses include 40% pasture and shrubs and the rest constitutes other minor land use types (Solomon, 1999). Agriculture counts for 64.5% of the regional Gross Domestic Product (GDP) (National Regional State of Tigray, 1997). However, the annual production growth is only 1.2%, which is below the national average (Solomon, 1999). Except for some surplus producing areas in the Western and Southern zones during good rainfall years, the rest either produces just enough for subsistence during good rainfall years or faces a chronic food deficit. For example, the estimated food deficit for the entire Tigray region during 1992/1993 was about 100,000 tons (CoSAERT, 1994). The causes of the structural food deficit include inadequate and erratic rainfall, severe environmental degradation, vulnerability to pests, lack of appropriate technology, small size and fragmentation of land holdings, lack of diversification in economic activities, and little use of modern inputs (Berhanu, *et al*., 2000).

Water resources

The water resources of Tigray are not well studied. Available documents reveal that there are about 600 perennial and about 1,600 seasonal streams. However, only about five of the streams are said to have a flow above 10 l/s (Leul, 1994).

The Tekeze, Mereb and Danakil are the major river basins in the region. The annual loss of water through the three major drainage basins during the rainy season is immense. About 9 billion m^3 of runoff flows through the basins from Tigray every year (GebreMedhin and Kiflom, 1997 and Leul, 1994). Tekeze and Mereb rivers, and their tributaries (Werii, Giba, Arkawas and Terer for Tekeze, and Berber for Mereb) are the main rivers of the region (Table 2.4).

During the drilling program in central Tigray, Hunting and MacDonald (1976) suggested the following hydraulic parameters of the groundwater: hydraulic conductivity of 1 m/day, transmissivity of 50 m^2/day, specific yield of 7%, an average annual variation in groundwater level measured at 34 sites (1974 – 1975) of 5.2 m and a recharge of 300 million m^3/year (5.5 m^3/s), which is equivalent to 4 mm/year. Well yields in the basin have a mean value of 2.6 l/s varying between 3.6 and 1.6 l/s. Besides, productive springs of 10 l/s in the Hintalo limestone in Mekelle area and 8 l/s in the Tekeze sandstone have been recorded (Hunting and MacDonald, 1976). According to the Tekeze River Basin Integrated Development Master Plan Project, the groundwater potential of Tigray largely depends on the geological formation as a result of which trap volcanics and Antalo limestone have a high groundwater potential where secondary porosity is well developed. The annual groundwater potential of the region is estimated to be 250 million m^3 (Hunting and MacDonald, 1976).

Irrigation development

According to some documents, traditional irrigation systems based on surface water are centuries-old practices in Tigray (GebreMedhin and Kiflom, 1997). Some historical evidences dating back to 500 BC indicate that irrigation has been practiced in the ancient village of Yeha in Adwa. Irrigation has been practiced for a long period in places such as the Church of Debre Menkole in Wukro Maray Woreda, Adiha in Kolla Tembein, Aenzat and Seraa in Adwa, Chelekot in Enderta, Senefti in Hawzen, Berki in Tsrae, Hiwane in Adi Gudom, Tekea in Alaje and Adi Buye in Medebay Zana (Ibid, 1999).

The rainfall amount and distribution in Tigray is very erratic. Even in periods of relatively good rainfall, soil moisture is insufficient during the crop growing period, due to the extreme fluctuation of rainfall distribution, low moisture holding capacity of the soils and high runoff rate from sloping lands after each intensive rainfall. As a result, the total regional food production is low (Leul, 1994 and Berhanu, *et al.,* 2000). As shown in Table 2.9, the actual yield is very low as compared to the potential yield. The low level of the actual yield is not fully attributed to water deficit alone but also to the lack of improved agricultural inputs. Nevertheless, climatological data of the region reveal that the decrease in moisture had a significant share in crop yield reduction. An analysis carried out by the CoSAERT revealed that under average conditions and presuming that moisture deficit is uniformly distributed over the growing season, the relative yield decrease of maize ranges from 29% in the Central zone to 72% in the Eastern zone. The relative yield decrease was found to be worst for a decrease in moisture during the critical growing period of the crop (CoSAERT, 1994).

Table 2.9 Average rainfed yield obtained in Tigray and potential yield (CoSAERT, 1994 and Central Statistics Authority, 2003)

Crop	Average yield in kg/ha	Potential yield in kg/ha
Barley	846	3,000
Wheat	887	5,000
Pulses	310	1,500
Maize	1,300	7,000

In Tigray the estimated irrigation potential is about 325,000 ha out of which about 15,000 ha is actually irrigated, mainly through traditional practices (Solomon, 1999). CoSAERT (1994) indicated that if 50% of the 9 billion m^3 of the runoff is used for irrigation, from a water availability point of view, half-a-million hectare of land, which would be sufficient to feed three times the present population of Tigray, can be irrigated. Besides, the topography lends itself conveniently to small-scale irrigation through earthen dams.

Realising these problems and potentials, the regional Government of Tigray has embarked on a conservation based agricultural development program within the framework of the national Agricultural Development-Led Industrialization (ADLI) policy. The regional Government emphasizes as its main goal to promote agricultural productivity in order to achieve self-sufficiency in food on the medium term (National Regional State of Tigray, 1997). Thus, irrigation development is taken as a means to increase and stabilize food production. Since the establishment of the CoSAERT, several earthen dams and river diversions have been built and rehabilitated. Non-governmental organizations and communities have also undertaken water resources development activities with the same objective. The principal objectives of the CoSAERT are to change the agrarian system to widespread irrigated agriculture. This is to minimize dependency on rainfed systems, and to gradually attain self-sufficiency in food production. The plan of the CoSAERT was to construct 500 dams and to irrigate 50,000 ha within ten years (CoSAERT, 1994).

To satisfy the food demand of the region, modern irrigation has been recently developed through the construction of earthen dam irrigation schemes. Out of the planned 500 dams, 44 earthen dams with related irrigation facilities have been constructed so far, while 47 have been designed. With a potential reservoir capacity of 50.7 million m^3, the 44 dams have a potential irrigable area of about 2,965 ha of which about 1,420 ha is currently being irrigated. The reduced irrigated area is caused by lack of adequate design data, inadequate water management practices and fluctuations from year to year in the amount of rainfall. 18 river diversions constructed by the same commission are irrigating 299 ha (Table 2.10).

Table 2.10 Status of irrigation development in Tigray (Compiled from various CoSAERT reports and Girmay, *et al*., 2000)

Zone	Quantity of constructed schemes		Area irrigated in ha		
	Dams	Diversions	Dams		River diversions
			Potential	Actual	Actual
Southern	33	16	2,163	925	249
Eastern	8	2	508	298	50
Central	2	-	194	128	-
Western	1	-	100	67	-
Total	44	18	2,965	1,418	299

2.2.2 Characterization of the study sites

Introduction

The study was carried out in two earthen dam irrigation schemes in Tigray, namely, Gumsalasa and Korir (Table 2.11). The average annual rainfall of Gumsalasa and Korir is 513 mm and 543 mm respectively. Rainfall at the two study sites tends to be unimodal, with more than 85% of the rain falling within the period of four months from June to September (Figure 2.7 and Figure 2.8).

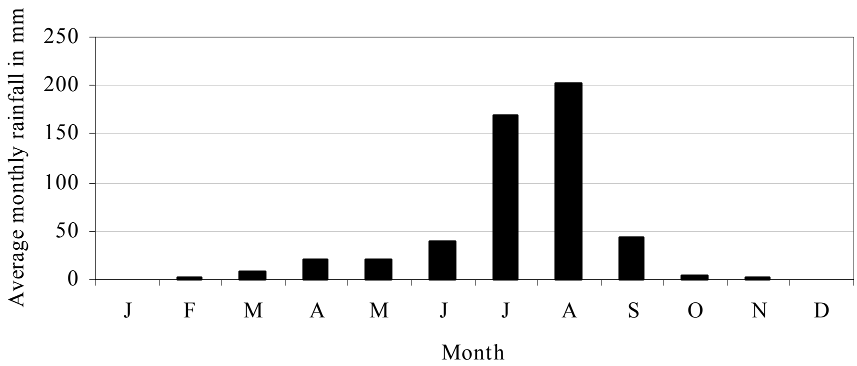


Figure 2.7 Average monthly rainfall of 27 years at the Gumsalasa irrigation scheme

Table 2.11 Basic characteristics of the study sites

Criteria	Gumsalasa	Korir
Location		
Administrative zone	Southern	Eastern
Altitude in m+MSL		
Reservoir point	1,960	1,960
Highest point in the catchment	2,060	2,100
Latitude (N)	$13^0$15’45’’ - $13^0$13’10’’	$13^0$45’00’’
Longitude (E)	$39^0$32’30’’ - $39^0$35’00’’	$39^0$31’08’’
Population	7,834	4,761
Average family size	6	6
Basic scheme data		
Construction year	1995	1996
Start of irrigation	1997	1997
Catchment area in ha	1,855	1,550
Reservoir		
Area in ha	48	32
Fetch length in m	1,200	860
Capacity in million m^3	1.9	1.6
Embankment		
Effective dam height in m	11	15
Free board in m	2.5	1.2
Crest length in m	428	505
Crest width in m	6	5
Designed irrigable area in ha	110	100
Soil types and their area coverage in %[1]		
Vertisol (Walka)	30	23
Luvisol (Mekayih)	10	13
Cambisol (Baekel)	45	45
Regosol (Hutsa)	5	19
Mixture of vertisol and regosol (hutsa-walka)	10	-

Note. 1 = the names between brackets represent the local names of the soils

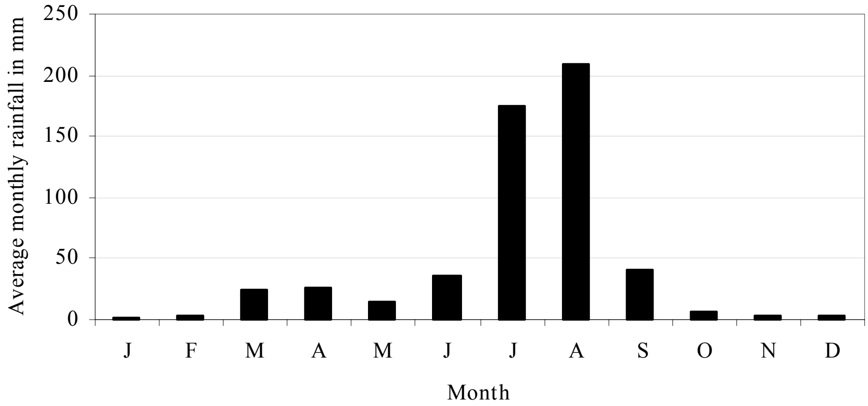


Figure 2.8 Average monthly rainfall of 9 years at the Korir irrigation scheme

There is a high annual rainfall variation in the two irrigation sites (Figure 2.9 and Figure 2.10). At Gumsalasa, the rainfall record of 27 years showed a standard deviation of 247 mm, with a maximum value of 1,152 mm recorded in 1986 and a minimum value of 53 mm in 1987, the latter of which coincides with one of the drought occurrences of Ethiopia. On the other hand, 9 years rainfall data at Korir showed a standard deviation of 187 mm, with a minimum value of 238 mm recorded in 1992 and a maximum value of 927 mm in 1996.

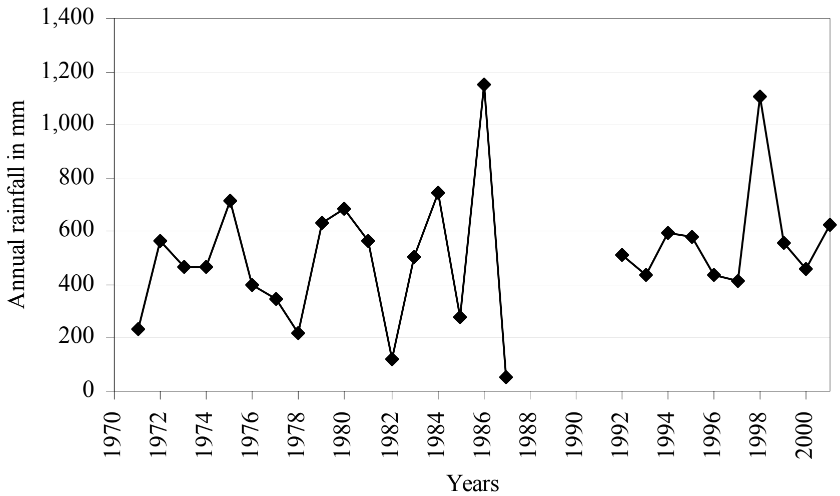


Figure 2.9 Annual variation of rainfall at the Gumsalasa irrigation scheme

Figure 2.10 Annual variation of rainfall at the Korir irrigation scheme

Rainfed agriculture

In Tigray cultivation is carried out using a traditional plough, known locally as 'maresha', drawn by a pair of oxen. This chisel type plough penetrates the soil to a depth of 5 – 10 cm and breaks it open without actually turning it, forming small incomplete ridges at the soil surface. Repeated ploughing, the frequency of which depends on the crop type, is done to destroy weeds (Table 2.12). The actual ploughing frequency, however, depends on the availability of a draught animal. Farmers without oxen are forced to lease out their land, plough at lower frequencies than the optimal, or plant crops that demand less tillage frequency.

In most parts of Tigray, harvesting of rainfed production is completed before the end of November and the first tillage for the forthcoming rainy season commences in December. According to farmers, ploughing in December is easy due to the possible presence of residual moisture in the soil from the previous season.

Table 2.12 Frequency of ploughing for different crops (Mintesinot, 2002)

Crop type	Frequency
Barley	3
Maize	3
Wheat	3
Chickpea	1 – 2
Vetch	1 – 2
Teff	5 – 7

Similar to other parts of Tigray, rainfed agriculture of the study sites is dominated by cereal crops. Wheat, barley and teff are the major cereals. A summary of the rainfed cropping pattern of the study sites is given in Table 2.13.

Table 2.13 Rainfed cropping patterns of the study sites

Crop	Surface cover in %	Sowing date	Growing period in days
Gumsalasa			
Wheat	37	15 June – 15 July	150
Teff	31	20 July – 10 August	120
Barley	29	15 June – 15 July	150
Vetch	3	20 – 31 August	90
Korir			
Wheat	21.5	15 June – 15 July	150
Teff	14.0	20 July – 10 August	120
Barley	16.6	15 June – 15 July	150
Hanfets[1]	22.6	15 June – 15 July	150
Azmera-zeraeti[2]	17.0	1 – 15 June	150
Bean, pea, chickpea	6.0	20 – 31 August	90
Oil crops	2.3	15 June – 15 July	150

Note: 1 = mixture of wheat and barely, 2 = Maize, sorghum, and millet

Due to the increased population, rural farmland was redistributed in Tigray in 1997. As a result, the rainfed landholding per household has decreased. Accordingly, the average rainfed landholding at Gumsalasa has reduced from 2.2 ha per household before 1997 to 1.2 ha per household afterwards. The rainfed landholding at Korir has decreased from 1.5 ha per household to 1.2 ha per household. Similar to the other parts of the region, the yield of the rainfed agriculture in the study sites is lower than the production potential (Table 2.14).

Table 2.14 Average yields of major rainfed cereal crops in the study areas

Crop	Average yield in kg/ha	
	Gumsalasa	Korir
Barley	770	625
Wheat	840	725
Teff	470	533

Irrigated agriculture

Irrigated agriculture was introduced to the study sites during 1997. However, due to the delay in the completion of the irrigation infrastructure, the two schemes were brought to operate at their present capacity in 1999. The preliminary development plan was to irrigate a total area of 110 ha at Gumsalasa and 100 ha at Korir per irrigation season. But results show that, on average, the Gumsalasa earthen dam irrigates about 67 ha using proper canal water and 18 ha using seepage water, while Korir irrigates 55 ha using proper canal water and 2.5 ha using seepage water (Table 2.15). The proper canal water is the water that is released through the reservoir outlet, while the seepage water is the one that leaks through the dam. This reduced irrigated area is caused by lack of adequate design data, inadequate water management practices and fluctuations from year to year in the amount of rainfall. Both the proper canal water and the seepage water irrigate the command area. The Gumsalasa earthen dam irrigates more area and supports a higher number of farmers (425 households) compared to Korir (330 households). The irrigated land holding at Gumsalasa is 0.2 ha per household irrespective of the family size (Teshome, 2003).

The irrigated land holding at Korir takes into account the family size. With an average landholding of 0.32 ha per household, it varies between 0.125 ha to 0.75 ha per household based on the family size.

Table 2.15 Total irrigated area and beneficiary households at the two study sites

Year	Proper canal water[1]				Seepage water[2]			
	Irrigated area in ha		No. of beneficiary household		Irrigated area in ha		No. of beneficiary household	
	Gumsalasa	Korir	Gumsalasa	Korir	Gumsalasa	Korir	Gumsalasa	Korir
1997	18	35	91	141	7	2.5	35	8
1998	8	26	40	156	7	2.5	35	8
1999	60	59	300	372	12	2.5	60	8
2000	69	46	345	314	16	2.5	80	8
2001	70	56	350	302	20	2.5	100	8
2002	70	58	350	302	25	2.5	125	8
Average[3]	67	55	335	322	18	2.5	90	8

Note:
1 = the water that comes directly from the reservoir through canals
2 = the seepage from the reservoir through the dam is diverted and used by the downstream farmers
3 = the last four years are considered when the schemes have been fully operational

Since the introduction of irrigation, the cropping pattern of the areas has changed from small grains to maize and vegetables (Table 2.16).

Table 2.16 Irrigated cropping patterns of the study sites

Crops	Sowing date	Growing period in days
Gumsalasa		
Maize	15 – 30 December	110 – 140
Potato	20 December – 5 January	120 – 150
Onion	10 – 30 December	100 – 135
Tomato	20 December – 5 January	90 – 120
Pepper	1 – 15 January	120 – 150
Vegetables	10 – 20 January	120 – 140
Pulses	1 – 10 January	70 – 100
Korir		
Maize	30 Dec. – 1 January	110 – 140
Onion	1 – 15 October	90 – 120
Tomato	1 15 September	90 – 120
Pepper	1 – 15 February	120 – 150
Vegetables	10 – 20 January	120 – 140

The yield and subsequently the potential household income generated from the irrigated fields are higher compared to the rainfed situation (Table 2.17).

Table 2.17 Average yield of irrigated crops in the study sites

Crop	Average yield in kg/ha	
	Gumsalasa	Korir
Maize	5,085	5,028
Tomato	15,780	23,330
Onion	9,397	8,637

Soil fertility management

In many parts of Tigray, including the two study sites, topsoils are depleted due to erosion. As a result, one of the principal constraints for crop productivity in the study areas is nutrient deficiency. Accordingly, soil fertility management practices such as application of manure, incorporation of crop residues, crop rotation, fallowing and chemical fertilizers are used by farmers.

The local name of manure is “Dukie” and could be cattle, sheep, goat and equine dung. Manure is first broadcasted on the farmland and mixed into the soil during tillage. Farmers put manure from goats, sheep, cattle, and equines in order of preference. The application of manure to the field by farmers is, however, limited due to various reasons:

- limited availability of dung due to the relatively small number of livestock per household;
- animal dung is often used as source of fuel;
- transportation of dung is laborious and expensive, especially in the case of fields that are far from the homestead.

Similar to manuring, the use of crop residue for soil fertility management by farmers is very limited, because it is mainly used as animal feed, construction material and source of fuel. If grasses or weeds are grown on the farmlands, only a few farmers plough the weeds into the soil as green manure. Most farmers use these weeds as fodder for livestock.

Fallowing, which is locally known as “Tsigie”, is considered as the most effective traditional soil fertility management practice. Two types of fallowing are practiced in Tigray, namely “Mekan Tsigie” and “Chickpea or vetch sown tsigie”. In the first case, the field is ploughed and left in complete fallow for a year without planting a crop in order for grass to grow on it. In the second type, chickpea or vetch is sown to restore the fertility.

Nowadays, farmers feel that it is becoming more difficult to fallow farmland compared to the previous decades, owing to the fact that their landholdings have become smaller (Mintesinot, 2002).

With the introduction of “Sasakawa Global 2000” program, farmers are using urea and di-ammonium phosphate (DAP) chemical fertilizers. The current recommended application rate is 100 kg DAP and 100 kg urea per hectare. However, there is a tendency to reduce the application rate for the following reasons:

- farmers lack purchasing power for chemical fertilizers;
- farmers believe that the crop residues of teff and pulses act as “tsigie” and can be used as substitute for chemical fertilizers;
- farmers claim that urea has a burning effect on crops when rainfall is low.

2.3 Ethiopia and the Nile

2.3.1 General

The Nile river basin is situated in the arid and semi-arid part of Africa where food security is a major challenge due to drought, land degradation and population pressure. Since Ethiopia is the major contributor of the total Nile flow, a review of the historical and development background of the Nile basin is provided below.

The Nile, which is composed of the White and Blue Nile, is the world's longest river (6,700 km) and covers an area of about 311 million ha (Petry, *et al*., 2001 and FAO, 1997). The White Nile originates in the Great or Equatorial Lakes region, and is also fed by the Bahr-el-Jebel water system to the North and East of the Nile–Congo Rivers divide. Its catchment area includes Tanzania, Rwanda, Burundi, Uganda, Congo, Kenya, Sudan and Egypt. The Blue Nile on the other hand originates from the highlands of Ethiopia and Eritrea and crosses Sudan on its way to Egypt, which is the most downstream riparian country (Table 2.18 and Figure 2.11) (Yahia, 1994 and Mahmoud, 1999).

Table 2.18 The Nile river basin: areas and rainfall by country (FAO, 1997)

Country	Total area of the country in 10^6 ha	Area of the country within the basin in 10^6 ha	Total area of the basin in %	Total area of the country in %	Average annual rainfall in the basin area in mm		
					Min.	Max.	Average
Burundi	2.78	1.33	0.4	47.6	895	1,570	1,110
Rwanda	2.63	1.99	0.6	75.5	840	1,935	1,105
Tanzania	94.51	8.42	2.7	8.9	625	1,630	1,015
Kenya	58.04	4.62	1.5	8.0	505	1,790	1,260
Congo	234.49	2.21	0.7	0.9	875	1,915	1,245
Uganda	23.59	23.14	7.4	98.1	395	2,060	1,140
Ethiopia	110.00	36.51	11.7	33.2	205	2,010	1,125
Eritrea	12.20	2.49	0.8	20.4	240	665	520
Sudan	250.58	197.85	63.6	79.0	0	1,610	500
Egypt	100.14	32.68	10.5	32.6	0	120	15
Total	888.96	311.24	100.0		0	2,060	615

White Nile

The most upstream tributary of the Nile is the River Kagera, which drains the mountains of Burundi and Rwanda, with average annual rainfall up to 1,800 mm (Figure 2.11). It flows into Lake Victoria after meandering through a series of lakes and swamps adjoining the river channel. This tributary has a drainage basin of 6.3 million ha. The Kagera basin is a complex of streams of varying order, which are intercepted and interconnected by lakes and swamps (Shahin, 1985 and Sutcliffe and Parks, 1999).

Lake Victoria is a depression with a total area of about 6.9 million ha, 4% of which is occupied by islands in the Northeast and Southeast. The elevation is 1,134 m+MSL (Shahin, 1985 and Sutcliffe and Parks, 1999). In addition to River Kagera, the direct precipitation on the lake surface and the runoff from the catchment contributes to the net supply of the lake.

Surplus water in Lake Victoria flows north towards Lake Kyoga (1,031 m+MSL) in a single channel, passing over several shallow falls and rapids. The river is about 130 km long and the difference in elevation between its head and tail is about 103 m. This difference is mainly brought by the Owen and Ripon falls. Lake Kyoga is a grass-filled valley and in spite of the 1,300 mm annual rainfall, the excessive evapo(transpi)ration from the swamps and the vegetation and the insignificant supply brought by many of the rivers make the lake a source of loss.

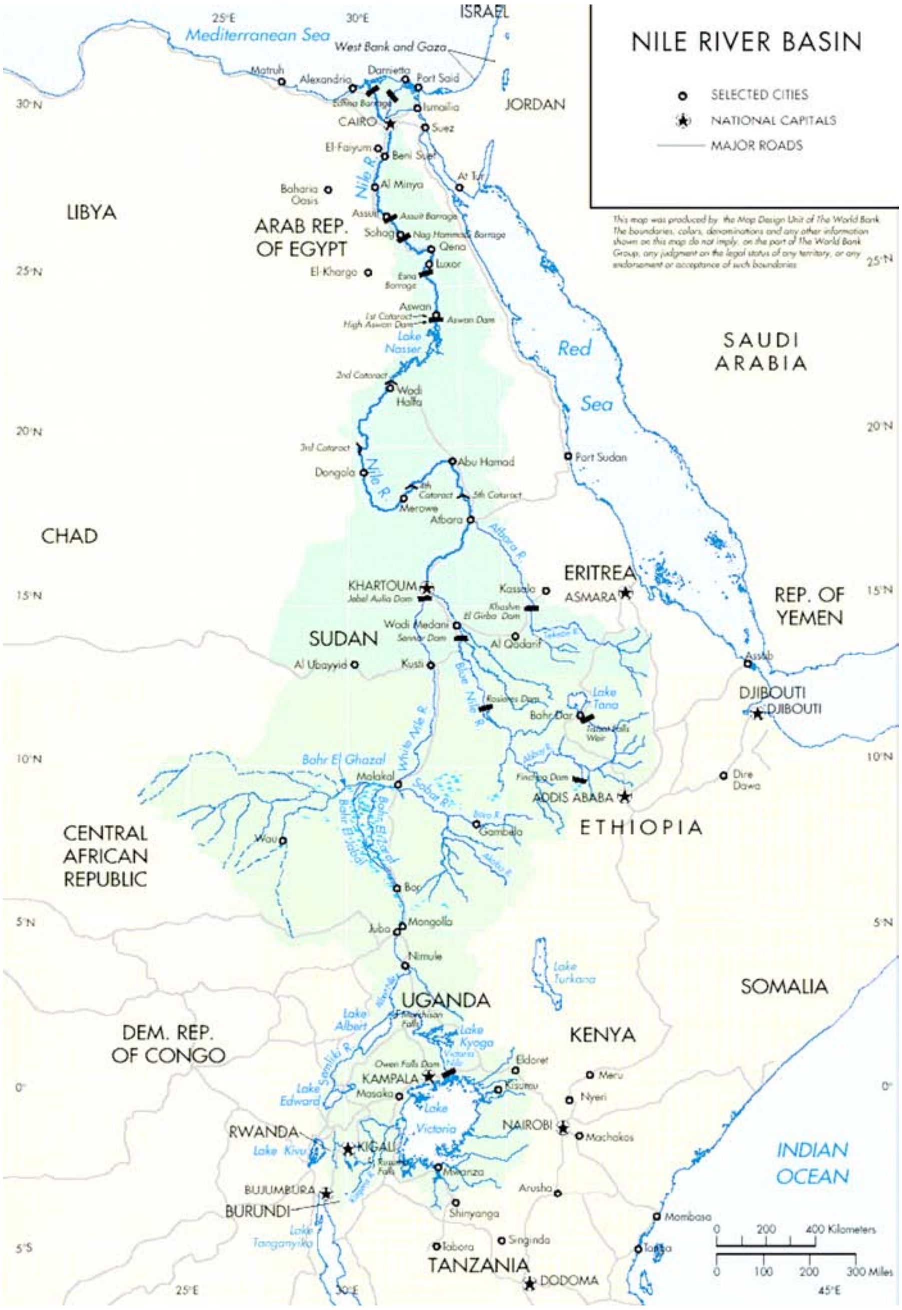


Figure 2.11 Map of the Nile River basin (Ismail, 2004)

The Kyoga Nile flows West from the lake towards the western arm of the Rift Valley. The river enters Lake Albert (Mobutu Sese Seko) (620 m+MSL) through a swamp near the northern end of the lake. The lake also receives the inflow of the

River Semliki, which drains Lake Edward (912 m+MSL) and the Ruwenzori and other mountains. The drainage basin of the Semliki is about 3 million ha including the surfaces covered by Lakes George and Edward. As the lake is found within the Rift Valley, evapo(transpi)ration is relatively high compared to the rainfall over the lake. As a result, the runoff from its drainage basin (1.7 million ha) and the direct precipitation on the lake surface are all lost by evaporation.

The Albert Nile or Bahr el Jebel leaves Lake Albert at its Northern end and flows Northeast towards Nimule, 225 km downstream, in a flat reach fringed with swamp vegetation. The Bahr el Jebel from the outlet of Lake Albert to Nimule has an average slope of only about 2.2 cm/km. It is a shallow river with a width varying from 100 to 300 m. At Nimule, the river crosses the Sudan border, turns abruptly to the Northwest and flows in a steeper channel, with several rapids, towards Juba and Mongalla. The river drops at an average slope of 1 m/km till it reaches a place called Rejaf, which is located 156 km from Nimule. Between Rejaf and Mongalla, 56 km long, the river descends 0.3 m/km on average. In the reach from Lake Albert to Mongalla, the river receives seasonal runoff from a number of small but torrential streams such as the Assua, the Kaia and Kit that provide high flows to the river following heavy rains. The river flow at Mongalla is therefore made up of the contribution from the East African lakes and seasonal and sediment-laden flows of the torrents.

On the reach from Rejaf to Malakal, the river is not confined to a single channel except at Mongalla. North of Bor, the valley widens and becomes more swampy, while the sides are less defined. Extensive swamps spread out on either side of the river and continue down to Lake No. This region is known as the Sudd or Bahr el Jebel.

At Lake No the Bahr el Jebel turns East and becomes the White Nile, and the Bahr el Ghazal enters into the lake from the West. The Bahr el Ghazal is relatively large and has the highest rainfall of any basin within the Sudan. Though the length of the stream is about 160 km, the size of its basin is approximately 52.6 million ha which makes it the largest of any of the sub-basins of the tributaries of the Nile River. The annual rainfall on the basin amounts 500 billion m^3, of which only 0.6 billion m^3 reaches the basin outlet at Lake No. All along the Bahr el Ghazal and to the South and East of it are large swamp areas. The flows of the various tributaries of the Bahr el Ghazal are spilled into these seasonal and permanent swamps.

The White Nile is joined by Sobat from the East. The main tributaries of Sobat are Baro and Akobo that drain the Southwestern part of the Ethiopian highlands. The Pibor river is also a tributary and receives occasional high runoff from Southeast Sudan. However, the Baro and Akobo, which are the principal feeders of Sobat, spill in high flow periods into adjoining wetlands. Besides, at some 40 km upstream of the junction with Pibor, some water leaves the Baro through the Khor Machar to feed a large swampy area north and east of El-Nasir causing a permanent loss from Baro. Thus the hydrological regime of the Sobat is complicated by the influence of the wetlands and their remoteness.

The regime of the White Nile from Malakal to its junction with the Blue Nile at Khartoum is relatively simple. The river flows in a single channel. This channel is almost free of swamps but, as the average slope is about 1.4 cm/km, it is sluggish. In the stretch from Lake No to the mouth of Sobat, the river flows in an undefined vegetated course in a plain with a width of 1 km at Malakal.

Blue Nile

The Blue Nile provides the major flow of the main Nile at Khartoum, with its smaller tributaries the Dinder and Rahad (Figure 2.11). The Blue Nile and its tributaries drain a major part of the Western Ethiopia highlands at an elevation of 2,000 – 3,000 m+MSL, with a small part of its basin subject to storage in Lake Tana (Shahin, 1985 and Sutcliffe and Parks, 1999). According to Hurst (1950), the source of the Blue Nile is a small spring at an altitude of 2,900 m+MSL at about 100 km South of Tana. From this spring, the Little Abay (Gilgel Abay) flows down to Lake Tana (1,829 m+MSL). Lake Tana has 60 affluents, of which Little Abay is the most important.

The White and the Blue Nile converge in Khartoum and they flow for 1,885 km to Aswan.

Atbara

The River Atbara is the last tributary of the Main Nile and enters at about 320 km downstream of Khartoum. It is 880 km long and the greater part of its catchment is situated in Ethiopia. The flow in Atbara relies on many small tributaries, of which Tekeze is the principal one.

The Blue Nile, Tekeze and Baro-Akobo river basins of Ethiopia constitute about 36.4 million ha of the total Nile river basin area (Table 2.4 and Table 2.18).

2.3.2 Hydrology of the Nile

A water balance often leads to the understanding of hydrological systems. This water balance states that the water inflow to an area must equal the outflow, plus any change of water storage within the area. This can be equated as:

$$I = O + \Delta S \qquad 2.1$$

Where:
I = inflow
O = outflow
ΔS = change in storage

The major hydrological components that play a role in the water balance are precipitation, river flow, evapo(transpi)ration, water storage and groundwater flow. In the Nile River basin, the inflow is largely made up of rainfall and river discharge, while outflow is the water that leaves the area as river discharge or diversion, and evapo(transpi)ration from open water and vegetation. The groundwater flow is a component of both inflow and outflow, but is generally small compared to the river flow in the basin (Sutcliffe and Parks, 1999). The water storage is made up of soil moisture and groundwater storage along with channel and lake or wetland storage.

In light of the water balance, the White and the Blue Nile have totally different contributions to the Main Nile.

The White Niles' flow is affected by the natural perennial storage of the Great Lakes particularly Lake Victoria and the Sudd region in the Sudan. The annual storage of Lake Victoria is 2,910 billion m^3. In general, with the rainy season extending from 8 – 10 months per annum, the water input in the equatorial region amounts to 400 billion m^3. However, the annual flow at the Sudanese border varies between 20 – 22 billion m^3. In the Southern Sudan, the White Nile meanders throughout the year through the Sudd swamp lands losing half of its flow to evapo(transpi)ration.

On the other hand, the high rainfall over the Ethiopian highlands in a single season and the steep topography give rise to a relatively high and concentrated runoff. The direct rainfall (3 – 5 months per annum) in the Ethiopian highlands amounts to 250 billion m^3 and contributes about 50 billion m^3 annual discharge to the Blue Nile system.

The annual discharge that reaches the Aswan dam (Southern Egypt) in normal years is 84 billion m^3. Out of this, the Blue Nile, Tekeze and Sobat, originating from the Ethiopian highlands contribute 86%, with only 14% coming from the Great Lakes through the White Nile (Table 2.19).

Table 2.19 The annual discharge of the Nile river at Aswan (Yahia, 1994)

River	Percent contributed	
	Normal years	Flood time
Blue Nile	59	68
Tekeze	14	22
Sobat	13	5
Bahr-el-Jebel	14	5

Although Ethiopia is the major contributor to the Main Nile flow, there is limited information about the hydrology of the Upper Blue Nile in Ethiopia. As a result, the assessment of the water balance of the Blue Nile is more dependent on the downstream measurements (Sutcliffe and Parks, 1999). The mean monthly flows of the Nile at different key sites within the basin are given in Table 2.20.

According to Yahia (1994), the average annual flow of the Nile at Aswan has declined from 110 billion m^3 during 1870 – 1899 to 84 billion m^3 during 1954 – 1988 as a result of variations in rainfall. This is also supported by Ghaas (1998), which mentioned the decline of the annual flow from 110 billion m^3 during 1860 – 1880 to 58 billion m^3 during the third quarter of the twenties century (Figure 2.12).

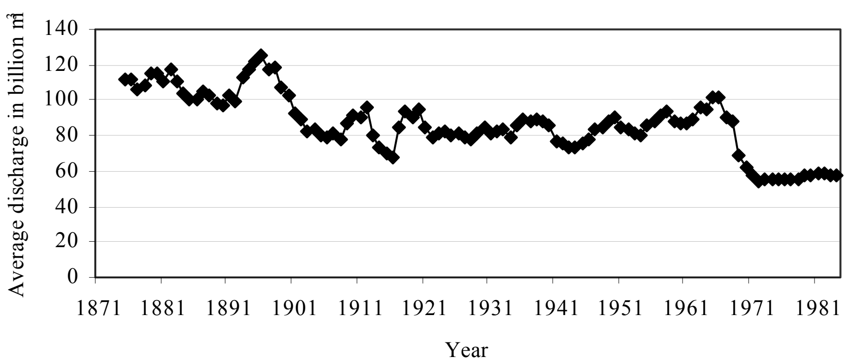


Figure 2.12 The 5 years moving average discharge of the Nile at Aswan for the period 1869 – 1984 (Ghaas, 1998)

Table 2.20 Mean monthly flows of the Nile at key sites in million m^3 (Sutcliffe and Parks, 1999)

Measurement site	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.	Annual
Kagera at Kyaka Ferry (1940-1978)	452	420	491	518	617	627	647	603	531	499	460	467	6,332
Other Lake Vctoria tributaries (1956-1978)	819	578	972	2,103	2,474	1,342	1,201	1,387	1,332	999	1,151	1,207	15,565
Victoria Nile at Jinja (1896-1997)	2,162	1,973	2,204	2,212	2,412	2,369	2,372	2,277	2,143	2,160	2,057	2,160	26,501
Kyoga Nile at Kamdini (1940-1980)	2,511	2,200	2,372	2,301	2,526	2,550	2,679	2,695	2,660	2,733	2,609	2,657	30,439
Semliki at Bweramule (1940-1978)	359	292	327	363	415	371	392	417	409	423	435	419	4,622
Bahr el Jebel at Mongalla (1905-1983)	2,534	2,180	2,327	2,360	2,767	2,663	2,920	3,317	3,295	3,244	2,975	2,751	33,332
Jur at Wan (1904-1986)	45	17	10	19	98	212	450	818	1,115	1,149	623	176	4,730
Sudd outflow (1905-1983)	1,515	1,318	1,392	1,280	1,262	1,188	1,227	1,284	1,328	1,444	1,379	1,473	16,091
Baro at Gambella (1905-1959)	257	169	163	202	454	1,154	1,946	2,590	2,971	2,022	816	440	13,184
Sobat at Doleib Hill (1905-1983)	967	431	273	232	413	851	1,301	1,608	1,780	1,992	1,964	1,718	13,530
White Nile at Malakal (1905--1997)	2,479	1,756	1,675	1,528	1,696	2,042	2,556	2,914	3,117	3,434	3,340	3,178	29,714
White Nile at Mogren (1911-1995)	2,469	1,905	2,014	2,225	2,026	1,792	1,368	1,435	2,236	3,024	2,786	2,747	26,026
Blue Nile at Roseires/el Deim (1912—1997)	762	446	364	324	612	1,659	6,763	15,228	12,111	6,484	2,559	1,348	48,658
Dinder at Mouth (1907-1997)	0	0	0	0	0	16	318	1,005	1,009	392	51	6	2,797
Rahad at Mouth (1908-1997)	0	0	0	0	0	2	119	346	378	228	27	2	1,102
Blue Nile at Khartoum (1900-1995)	724	448	406	427	503	1,084	4,989	15,237	13,625	7,130	2,451	1,257	48,279
Main Nile at Tamaniat (1911-1995)	3,099	2,302	2,378	2,555	2,490	2,860	6,398	16,151	15,584	9,996	5,067	3,810	72,691
Main Nile at Hassanab (1909-1995)	3,146	2,320	2,286	2,428	2,359	2,690	5,937	15,607	15,859	10,460	5,351	3,894	72,337
Atbara at Mouth (1903-1994)	17	6	1	3	8	88	1,536	5,126	3306	770	145	46	11,052
Main Nile at Dongola (1890-1995)	3,577	2,547	2,268	2,239	2,175	2,169	5,268	18,701	20,554	13,337	6,767	4,538	84,138
Main Nile at Aswan (Water arriving) (1869-1992)	3,738	2,651	2,257	2,011	1,980	1,943	4,754	18,207	21,189	14,318	7,478	4,849	85,376

So far Egypt and Sudan are the main users of the Nile water. Accordingly, an account of the water balance of the two countries in particular and the overall river basin in general is summarized in Table 2.21 to Table 2.23.

Table 2.21 Estimated water balance of Sudan in 1995 (FAO, 1997)

Component of water balance	Amount in 10^9 m^3
Water inputs	
Sudan share of Nile water[1]	20.6
Other regional surface runoff	1.4
Internal runoff	0.7
Jonglei Canal and swamp reclamation	0.0
Groundwater	0.7
Total water input	***23.4***
Water demands	
Irrigation	16.8
Domestic	0.8
Industrial	0.2
Other (including reservoir evaporation)	0.2
Total water demand	***18.0***
Net surplus	***5.4***

Note

1 = Under the Nile Water Agreement between Sudan and Egypt, the quantity of water allocated to Sudan is 18.5 billion m^3/year at Aswan, which corresponds to 20.55 billion m^3 further upstream

Table 2.22 Estimated water balance of Egypt in 1993 (FAO, 1997)

Component of water balance	Amount in 10^9 m^3
Water inputs	
Surface water resources	56.0
Groundwater in Nile Valley and Delta	2.3
Agricultural drainage water	4.0
Treated sewage water	0.2
Improved water management	0.0
Total water input	*62.5*
Water demands	
Irrigation	47.4
Municipal	3.1
Industrial	4.6
Navigation, etc.	1.8
Total water demand	***56.9***
Net surplus	***5.6***

For the sake of simplicity Table 2.23 was based on the assumption that if a certain quantity of water is abstracted upstream, this same quantity is subtracted from the resource downstream, except in cases where more information was available (FAO, 1997). As it can be seen, the sum of the irrigation potential of the countries leads to a water deficit of over 26 billion m^3. This, however, doesn't consider possibilities of re-using water as indicated by the Egypt and Sudan water balances, but after deducting the water "losses" in the Sudd region.

Table 2.23 Nile basin: irrigation potential, water requirements, water availability and areas under irrigation (FAO, 1997)

Country	Irrigation potential	Gross irrigation water requirement		Actual flows		Flows after deduction for irrigation and losses		Area already under irrigation
	in 10^3 ha	in m^3/ha/yr	Total in 10^9 m^3/yr	Inflow in 10^9 m^3/yr	Outflow in 10^9 m^3/yr	Inflow in 10^9 m^3/yr	Outflow in 10^9 m^3/yr	in 10^3 ha
Burundi	80	13,000	1.04	0.00	1.50	0.00	0.46	0.00
Rwanda	150	12,500	1.88	1.50	7.00	0.46	4.08	2.00
Tanzania	30	11,000	0.33	7.00	10.70	4.08	7.45	10.00
Kenya	180	8,500	1.53	0.00	8.40	0.00	6.87	6.00
Con go	10	10,000	0.10	0.00	1.50	0.00	1.40	0.00
Uganda	202	8,000	1.62	29.10	37.00	24.22	30.50	9.12
Ethiopia	2,220	9,000	19.98	0.00	80.10	0.00	60.12	23.16
Eritrea	150	11,000	1.65	0.00	2.20	0.00	0.55	15.12
Sudan	2,750	14,000	38.50	117.10	55.50	90.62	31.12	1,935.20
Egypt	4,420	13,000	57.46	55.50	Rest to sea	31.12	- 26.34	3,078. 00

2.3.3 Developments in the Nile basin

Past developments

The first storage work in the Nile Valley, the old Aswan Dam, was built in 1902 in Upper Egypt with a capacity of 1 billion m^3. Later the dam was raised in height twice, in 1907 – 1912 and in 1929 – 1934, which ultimately increased its capacity to 5 billion m^3. In 1952, the Egyptian president Gamal Abdal Nasser decided to build the Aswan High Dam, about 6 km upstream of the old Aswan dam. The construction started in 1960 and was finalized in 1970. With reservoir capacity of 162 billion m^3, the dam is 111 m high and 1,000 m long (Shahin, 1985 and Kjeilen, 2003).

As a result of agreements between Egypt and Britain in 1929 and between Egypt and Sudan in 1959, Sudan has also constructed four dams in the Nile (Shahin, 1985 and Sutcliffe and Parks, 1999). The Senar (Makwar), Roseires and Khashm el Gibra were constructed primarily for irrigation but are also used for hydropower.

The Senar dam was built with an original capacity of 0.8 billion m^3 in 1925 in the Blue Nile some 530 km Southeast of Khartoum to supply water to the Gezira irrigation scheme (Shahin, 1985). The current capacity of this dam is, however, about 0.5 billion m^3 (Sutcliffe and Parks, 1999). The Roseires dam was completed in 1966, upstream of the Senar dam, with a capacity of 3.3 billion m^3 for storing water and passes it downstream when required by Gezira, Managil extension and the river bank pump schemes. Since the beginning in 1973, it also provides 275 MW hydropower. The capacity of this dam had reduced by 0.9 billion m^3 in 1995. This reduction in capacity was caused by the high sediment load of the Blue Nile, especially during rising floods. El Moushid, *et al,*. (1997) have estimated a suspended sediment load at el Deim (Roseires) of 140 million tons per year during the flood season. As a result the operation policy of the dams is to draw down the reservoirs during the rising flood season, which has a major impact on the hydropower operation. The Khashm el Gibra dam was constructed on the Atbara in 1964 with an initial capacity of 1.3 billion m^3 to supply the water to the Atbara irrigation scheme. This dam also faces the same sedimentation problem as the above two. Its capacity was reduced by 0.95 billion m^3 in 1971, with a predicted further reduction rate of 40 million m^3 annually (Shahin, 1985 and Sutcliffe and Parks, 1999). Consequently, alternative sites are being investigated for Khashm el Gibra while the Roseires dam is being raised to increase its capacity (Sutcliffe and Parks, 1999).

The fourth dam, Jebel Aulia, was constructed in the White Nile in 1937 with a capacity of 3.5 billion m^3. Unlike the other three, this dam was constructed to store the flows of the White Nile for release to Egypt when the flow in the Blue Nile is low.

The 1929 the Nile Waters Agreement between Egypt and Britain provided 48 billion m^3 per year to Egypt, 4 billion m^3 to Sudan and left the remaining 32 billion m^3 per year unallocated. It also prohibited the upper riparian states from undertaking any development activities on the tributaries or the equatorial lakes without permission, which would alter the flow of the Nile to Egypt. After World War II, the Nile water became an important issue in the inter-basin state relationships. In addition, due to the strategic position of the riparian countries, the basin also became an important scene of great power rivalries during the Cold War. Accordingly, despite many initiatives, development of meaningful basin cooperation became futile especially between upstream and downstream states. As a result, the only riparian countries substantially utilizing the Nile water for irrigated agriculture are the two most downstream states, Sudan and Egypt. Similar to the Egypt–British agreement, the 1959 Sudan–Egypt agreement prohibited the other East African countries to construct any works or modify the flow without consultation and agreement with the two downstream countries. By the terms of this agreement, significantly called the "Treaty for the Full Utilization of the Nile", Egypt and Sudan divided the annual flow between them with 66% (55.5 billion m^3) going to Egypt, 22% (18.5 billion m^3) to Sudan and the remaining 12% (10 billion m^3) allocated to evaporation and seepage losses. Besides, the agreement had set equal split of any additional water resulting from conservation or discovery. In addition, under this initiative a Permanent Joint Technical Commission was formed mandated to control the river and cooperate to increase its yield to meet future demands of the two countries. The fact that developments are concentrated in the two most downstream riparian countries is the result of these agreements.

No other riparian country was party to the 1959 accord, nor was any share in the annual flow left for them (Mahmoud, 1999 and Waterbury and Whittington, undated). This agreement has provoked much opposition. For example, Ethiopia rejected this agreement, stressed its rights to the waters originating from its territory and began to work with the United States Bureau of Reclamation to study its water resources and asses the irrigation and hydropower potential. Irrespective of war threats from Egypt and repeated concerns from Sudan and Egypt, Ethiopia’s position was that it has all legal rights to exploit its natural resources (Mahmoud, 1999). However, the Cold War rivalry, internal political instability, civil war and their feeble economies did not allow the other upper riparian countries to press ahead any realistic claims to the Nile water originating or traversing their territories (Waterbury and Whittington, undated).

Present and future developments

The Nile basin and its people are at crossroads facing a future full of risks and complexities of unprecedented dimensions. The population of the countries in the basin is expected to increase from 300 million at the moment to 650 million by mid of the twenty first century (Table 2.24) (United Nations Population Reference Bureau, 2004). This fact along with the presence of some political stability has initiated some upper riparian countries to ask the revision of the 1959 Agreement. The present and possible future interventions are presented below.

Rwanda, Burundi and Congo

Rwanda and Burundi comprise much of the Kagera and its tributaries. The runoff of the Kagera is high, and at Rusumo Falls the annual total discharge averages 7 billion m^3 from a catchment area of 3 million ha. This is equivalent to a rainfall depth of 230 mm over the whole catchment. There are plans for developing irrigated rice schemes in the valleys of various tributaries, largely in swamps, which are inundated seasonally or permanently. If implemented, the irrigation demand of these shemes is unlikely to result in a greatly reduced runoff compared to the annual evaporation from the swamps. The other potential project identified in this region is the hydropower scheme at Rusumo Falls on the border between Rwanda and Tanzania. Again, the effect on evaporation from this storage reservoir would not be different from the lakes and wetlands that cover the area at present. In general, developments in Rwanda and Burundi do not seem to have much effect on the volume of the flow of the Nile river (Sutcliffe and Parks, 1999).

The interest of Congo, on the other hand, is the development of irrigation around Lake Edward and the upper Semliki. This might have a certain effect on the volume of the flow of the Nile.

Table 2.24 Projected population of the Nile riparian countries over the coming decades (United Nations Population Reference Bureau, 2004)

Country	Annual growth rate in %	Population in millions		
		2004	2025	2050
Burundi	2.2	6.2	10.1	15.4
Rwanda	1.9	8.4	11.7	17.2
Tanzania	2.3	36.1	52.1	74.0
Kenya	2.2	32.4	39.9	49.9
Congo	2.9	3.8	6.8	10.6
Uganda	3	26.1	47.5	82.6
Ethiopia	2.4	72.4	117.6	173.3
Eritrea	2.6	4.4	7.0	10.5
Sudan	2.8	39.1	61.3	84.2
Egypt	2.0	73.4	103.2	127.4
Total		302.3	457.2	645.1

Uganda, Kenya and Tanzania

Uganda, Kenya and Tanzania need to supplement rainfall to grow some perennial crops like sugarcane. According to FAO (1997) the irrigation need of these countries is estimated to be 3.5 billion m^3. An estimate made by the World Metreological Organization (1982) for the year 2000 has set 5.8 billion m^3 annual water requirement for the five countries, including Rwanda and Burundi. However, the estimate was based on population statistics and information supplied by Governments on irrigated schemes and industrial demand, rather than on a detailed survey. This underlines the need of more detailed studies. What so ever, any irrigation abstraction, except those offset by swamp reclamation, would reduce the inflow to Lake Victoria and the outflow to the Nile by a similar amount (Sutcliffe and Parks, 1999).

Ethiopia, Eritrea, Sudan and Egypt

The contribution of Eritrea to the Nile is limited to a portion of the Setit tributary of the Atbara and the impact of any development would have an insignificant effect on the Nile water flow.

Ethiopia is the major contributor of the total Nile flow. But, except for the recently completed Fincha stage I project that irrigates 6,205 ha and the 111.5 MW hydropower reservoir at Blue Nile, it has not used a portion of it. The rapid increase in population and the need to maintain food security after the famines of the 1980's have prompted Ethiopia to press ahead with plans to divert Nile waters for irrigation. However, its first practical move to develop irrigation schemes through a loan from the African Development Bank in 1990 was not successful due to the disapproval of Egypt. Following this, the Ethiopian government signed an agreement with Sudan to cooperate over the use of the Nile water in 1991. As a result, the political dominance of Egypt was weakened and the 1993 bilateral agreement between Ethiopia and Egypt followed marking the first peaceful initiative in history between the two countries (Mahmoud, 1999).

In line with the peaceful efforts, the Ethiopian Government also confirmed that it will undertake the construction of required projects and pursue with a master plan study of the Blue Nile and its tributaries. Accordingly, it is undertaking the construction of earthen dam irrigation schemes in the Tigray region (Tekeze river basin) and the Amhara region (Blue Nile/Abay basin) (CoSAERT, 1994 and Gwang-Man, *et al.,* 1997). Though it still needs further investigation, this intervention is estimated to lower the flow to Sudan and Egypt by as much as 2 – 3 billion m^3 annually (Mahmoud, 1999). Besides, Ethiopia has started the construction of the first major hydropower dam on the Tekeze River, which will have a final water storage capacity of 8 billion m^3 and 200 MW power. Ethiopia is financing this project itself and, more importantly, has not formally notified Egypt and Sudan of this plan (Waterbury and Whittington, undated).

Furthermore in 1997 Ethiopia presented its demand for a greater share of the Nile water during a four–day annual conference on the use of the Nile River. During the same year, the Foreign Minster of Ethiopia stated in an address to the United Nations that Ethiopia would not achieve food security unless it utilizes its water resources for irrigation. He also called on the Nile basin riparian countries to commit themselves to real, fair, equitable and just utilization of the water. Ethiopia avails of a potential irrigable area of about 2.2 million ha in the Nile basin, of which about 23,000 ha is currently under irrigation (Table 2.4 and Table 2.23).

Moreover, the relations between Sudan and Egypt also deteriorated in 1989 as the Sudanese government unilaterally abolished the 1959 agreement, started the construction of small dams and developed plans for further irrigation (Mahmoud, 1999).

On the other hand, the plan of Egypt is to increase its productivity through expansion of the irrigated area, economic liberalization, shifting to higher valued crops and increasing the yield of existing land (Molden, *et al.,* 1998). The expansion involves land reclamation and settlement, called the New Valley project, in the Western desert. Egypt plans to pump 5 - 10 billion m^3 of water per year from the Aswan High Dam reservoir to irrigate this new area. At the end of this project, the area under irrigation is expected to be 300,000 - 500,000 ha (Waterbury and Whittington, undated). This is equivalent to a total annual water supply of about 16,600 – 20,000 m^3/ha. The current average annual irrigation water supply is about 17,000 m^3/ha (Ismail, 2004). Ismail (2004) also indicated that the expansion of agriculture is one of the most important solutions to overcome the food balance crisis resulting from increase in population. Accordingly, the cultivated land needs to increase to 4.68 million ha by 2025.

A closer look at the above presented development plan of individual states clearly indicates a conflict of interest between riparian countries. This conflict of interest is more crucial among the three countries in general and Egypt and Ethiopia in particular. The most interesting question here is where would the water come for this increased demand in the most downstream riparian counties?

Egypt contends that it will find the water supplies needed for the New Valley project by using existing irrigation water supplies more efficiently, fostering water conservation efforts, abstracting groundwater, using reclaimed wastewater, and shifting out of sugar cane and rice to less water demanding crops. Egypt thus argues that it will not withdraw more than its share specified in the 1959 Nile Waters Agreement. One of the measures includes decreasing the annual irrigation water supply to about 12,000 m^3/ha by 2025 (Ismail, 2004). These measures, particularly conservation efforts and shifts in cropping pattern, could have a significant effect on Egypt's water use.

Provided that this is possible, the question of how to satisfy the increasing water demand of Ethiopia and the other upstream riparian countries remains another unsolved issue. At the time the 1959 Agreement was signed, both Egypt and Sudan recognized that this assumption of zero water use by the upstream riparian countries was not realistic in the long-run, and they made a provision for how the 1959 Agreement would be revised as upstream riparian states started to claim rights to use the Nile water. Specifically, Egypt and Sudan agreed to reduce their water allocations equally to accommodate increased use by upstream riparians (Waterbury and Whittington, 1999).

2.3.4 Cooperation in the Nile basin

With respect to cooperation the Nile basin, the 1967 initiative of the Hydromet survey of the Equatorial Lakes is to be mentioned as the first successful cooperation among the riparian countries. In this initiative, which was assisted by the United Nations Development Program (UNDP) and the World Metreological Organization (WMO), all the riparian countries have participated with only Ethiopia taking part as an observer. Accordingly, a Technical Committee was established from all participating countries except Ethiopia to collect hydrometreological data and analyse the flows downstream. However, due to the refusal of Ethiopia to participate, the survey area has been restricted over the catchment of the equatorial region that contributes only 14% of the flow of the Nile.

After the completion of the Hydromet survey in 1992, a meeting among the Water Resource Ministers from Egypt, Sudan, Tanzania, Uganda, Zaire and Rwanda created a three-year project on Nile cooperation. The technical Committee for the Promotion of the Development and Environmental Protection of the Nile Basin (Tecconile) came into operation from 1993 – 2002 with the objective of promoting cooperation through yearly conferences. In these conferences, participants from Egypt, Rwanda, Sudan, Tanzania, Uganda, and Congo and observers from Burundi, Eritrea, Ethiopia and Kenya had meetings to exchange views and foster cooperation. However, papers presented in the 1996 conference by Ethiopia and Egypt were contradicting and both exchanged fairly non-cooperative policy papers each stating its right to use the Nile water as it sees it fit (Mahmoud, 1999).

The present and future potential conflicts in the basin stem from the rapidly increasing population, unreliable and erratic rainfall and the cyclic drought in the riparian countries. For example, many parts of the basin, including Ethiopia and Sudan, are characterized by cyclic drought. These climatic conditions coupled with the population growth increased the problems and grievances among the riparian countries. In addition to internal and inter-state political unrest, the famine and mass immigration of rural people to already strained urban centers and across borders have contributed to serious environmental degradation and spread of desertification in the basin. This is particularly severe in Ethiopia where about 1.5 billion tons of topsoil is eroded annually, part of which is transported by the Blue Nile towards Sudan and Egypt (Ethiopian Herald, 1998). The reservoir sedimentation problems of the lower reach countries are attributed to this high rate of erosion from the Ethiopian highlands.

Taking into account all these problems and conflicts, a basin–wide effective cooperation for the benefit and welfare of the riparian societies remains a major task with respect to equitable water sharing, reducing non-process depletion of water, reducing drainage outflow, increasing water use efficiency, and monitoring erosion and water quality.

The expansion of irrigated agriculture in the years to come will require more friendly basin–wide cooperation in the management and utilization of the available water resources. A joint study to support this initiative becomes equally important at this moment.

3 Development and management of irrigated lands in Tigray

3.1 The status of rainfed agriculture

Over 90% of Tigray's cultivated land is under cereal production, with almost all produced crops consumed at the farm household level. Table 3.1 presents the major cereal crops, their area coverage and average yield at zonal and regional level. The use of improved seeds is very limited and farmers grow land race seeds. This traditional form of farming has been practiced on the plateaux and the mountain slopes of the highlands for centuries without showing improvements. The result has been a decline in the degree of subsistence during the past three decades, except for some periods of sufficient rainfall (Mintesinot, 2002). Table 3.2 and Figure 3.1 confirm this fact. Let alone the regional demand, the rainfed production in Tigray cannot even meet the need of the rural people producing it. As it can be seen in Table 3.2, the region faces an average annual food deficit of about 180,000 tons.

Table 3.1 Average yield of cereals in Tigray (Central Statistics Authority, 2003)

Zone	Crop type					Total
	Teff	Wheat	Barley	Maize	Sorghum	
Central						
Average cropped area in 1,000 ha/yr	49.1	21.9	14.3	18.9	37.2	141
Average yield in 10^6 kg/yr	34.2	14.5	13.7	24.6	41.4	128
Average yield in kg/ha	697.5	662.5	952.8	1,297.3	1,113.2	907
Eastern						
Average cropped area in 1,000 ha/yr	7.2	13.0	23.3	5.3	3.5	52
Average yield in 10^6 kg/yr	4.3	12.4	23.7	4.3	4.3	49
Average yield in kg/ha	602.8	948.0	1,017.8	813.8	1,212.3	936
Western						
Average cropped area in 1,000 ha/yr	27.4	0.4	0.6	20.4	48.9	98
Average yield in 10^6 kg/yr	29.3	0.4	0.4	32.1	79.2	141
Average yield in kg/ha	1,069.4	1,124.6	596.5	1,572.9	1,619.0	1,447
Southern						
Average cropped area in 1,000 ha/yr	30.6	21.8	34.6	13.0	17.7	118
Average yield in 10^6 kg/yr	17.6	23.3	23.9	14.1	15.8	95
Average yield in kg/ha	577.3	1,071.4	691.1	1,080.4	890.7	805
Regional						
Average cropped area in 1,000 ha/yr	114.2	57.1	72.8	57.7	107.4	409
Average yield in 10^6 kg/yr	85.5	50.6	61.6	75.1	140.7	413
Average yield in kg/ha	748.5	886.7	846.4	1,301.7	1,310.1	1,010

The degree of food deficit among zones varies with respect to the level of cereal production and population. The Western zone is generally a potentially productive area. However, the farmers still face food shortages. The surplus yield in the zone (Table 3.2) is contributed by the presence of private investment especially in sorghum production (Table 3.1).

Table 3.2 Average annual food production and demand in Tigray (Central Statistics Authority, 2003)

Production and demand	Zone				Total
	Central	Eastern	Western	Southern	
Average annual food production					
Cropped area in 10^3 ha	141.5	52.3	97.7	117.7	409.2
Cereal production in 10^6 kg	128.4	49	141.4	94.7	413.5
Population size					
Urban in 10^6	0.11	0.10	0.10	0.24	0.55
Rural in 10^6	0.92	0.54	0.70	0.72	2.88
Total in 10^6	1.03	0.64	0.80	0.96	3.43
Average annual cereal requirement in kg/person	173	173	173	173	173
Annual food demand					
Urban in 10^6 kg	19	17.3	17.3	41.5	95.2
Rural in 10^6 kg	159.2	93.4	121.1	124.6	498.2
Total in 10^6 kg	178.2	110.7	138.4	166.1	593.4
Total annual food deficit					
in 10^6 kg	-49.8	-61.7	+3	-71.4	-179.9
as % of own production	-39	-126	+2	-75	-43.5

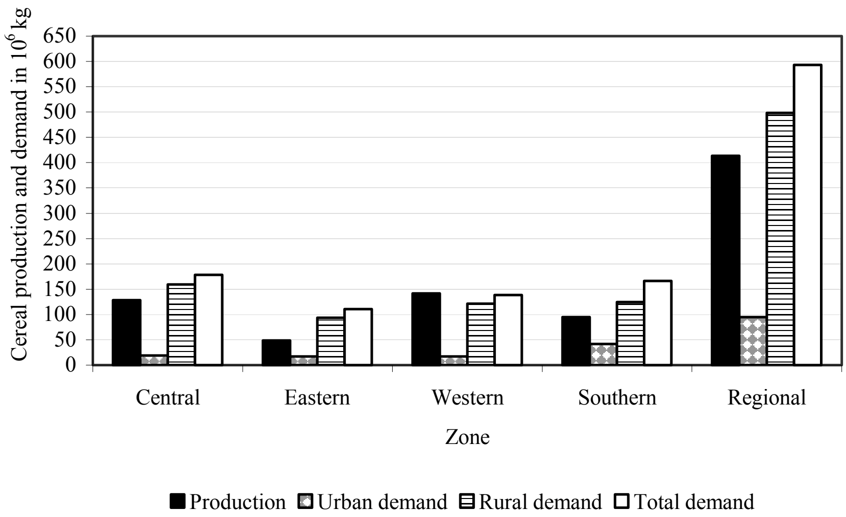


Figure 3.1 Average annual food production and demand in Tigray

The problem of rainfed agriculture in Tigray is not only limited to low productivity. It is rather aggravated by a high degree of uncertainty due to the erratic nature of the regional rainfall in terms of the spatial and/or temporal distribution during the crop-growing season. The effect of changing rainfall patterns is especially notable in the shortening of the growing season, up to the point that the risk of crop failure dramatically increases if no supplementary irrigation is available. According to Leul (1994), total crop failures have been witnessed in Tigray even during periods of high rainfall due to a prolonged interval between consecutive rains. As a result, farmers are not sure to get the same low level of yield every year and chronic food deficits are common. Studies in other parts of Ethiopia have shown the same result (Abebe, 2000).

When rainfall is erratic during the growing period, it can cause moisture deficit and corresponding damage to the yield. The extent of the damage depends on the frequency of occurrence of a dry-spells of different duration, which depends on the soil moisture holding capacity and the type of crop. The situation of the Gumsalasa area is considered here to show the erratic nature of the regional rainfall. Meteorological data of the area, two dominant soil types, clay and loam, and the most commonly growing crop, wheat, are used for the assessment of irrigation scheduling and dry-spells during the crop-growing season.

The most important element in rainfed agriculture is to determine the probability of occurrence of dry-spell duration longer than the one that causes damage to the crop yield. This would require the estimation of the interval that a crop must be supplied with water for its growth. This interval, which is taken as the irrigation interval, is usually calculated with equation 3.1 (Abebe, 2000):

$$T = \frac{(p * AM) * D}{ET_{crop}} \qquad 3.1$$

Where:

T = irrigation interval (frequency of irrigation) in days

p = fraction of the total available soil water which can be used by the crop without affecting its growth

AM = total available soil moisture in mm/m

D = depth of the root zone of the crop in m

ETcrop = consumptive crop water requirement in mm/day

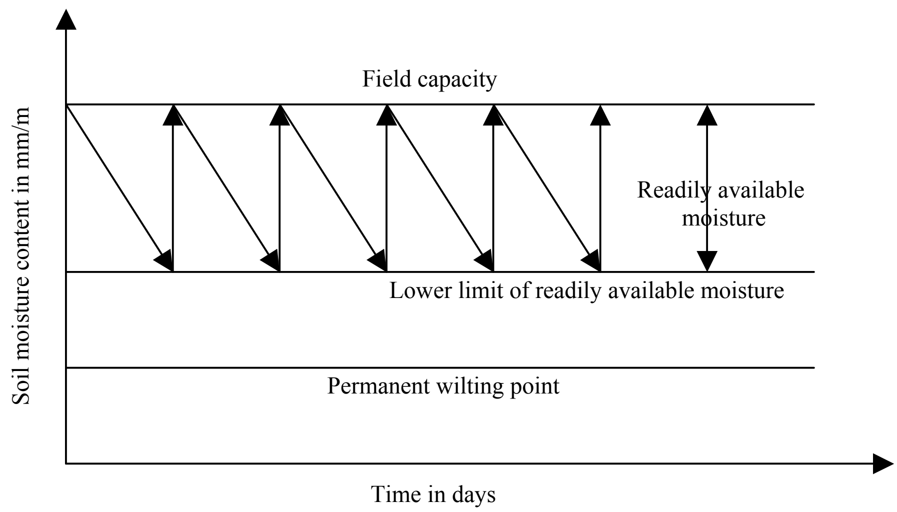


Figure 3.2 Theoretical frequency of irrigation (Abebe, 2000)

In this section, the CropWat model (Clarke, *et al.,* 1998) was used to calculate the irrigation interval for the situation at the study site. The probability of occurrence of dry-spell duration of equal to or greater than this interval was then determined by a dry-spell analysis of daily rainfall events.

The CropWat computer program, based on the Penman-Monteith method, was used for the calculation of the potential evapotranspiration (ETo) (Table 3.3) and crop and irrigation water requirements (Table 3.4) (Clarke, *et al.,* 1998). In Tigray in general wheat is grown during 15 June – 15 July. The planting date in this case is taken as 1st July and the total growing period is determined as 130 days using the CROPWAT program.

Table 3.3 Potential evapotranspiration (ETo) of Gumsalasa according to Penman-Monteith (Clarke, *et al.,* 1998)

Month	Maximum temp. in ^{0}C	Minimum temp. in ^{0}C	Humidity in %	Wind speed in km/d	Sunshine in hours	ETo in mm/d
January	23.4	9.1	61	130	10.6	3.7
February	24.6	10.1	58	138	10.6	4.3
March	25.7	11.7	57	147	10.5	4.9
April	26.1	13.1	54	156	10.4	5.2
May	27.0	13.7	48	173	11.1	5.6
June	27.5	13.4	51	164	10.1	5.3
July	23.4	12.4	78	156	7.6	4.0
August	22.7	12.1	82	156	7.0	3.7
September	25.1	11.3	65	147	10.1	4.7
October	23.9	11.3	55	181	10.5	4.7
November	22.5	9.7	58	121	10.2	3.8
December	22.4	8.3	62	112	10.7	3.5

Table 3.4 Crop and irrigation water requirement for wheat at Gumsalasa (Clarke, *et al.,* 1998)

Month	Decade	Stage	kc	ETcrop in mm/decade	P_{eff} in mm/decade	Irr. req. in mm/decade
July	1	initial	0.30	13.1	7.7	5.4
July	2	initial	0.30	11.7	11.9	0
July	3	initial	0.31	13.2	16.5	0
August	1	develop.	0.47	17.5	10.9	6.7
August	2	develop.	0.75	27.1	10.5	16.7
August	3	develop.	1.02	44.6	2.1	42.5
September	1	mid	1.15	51.0	0	51.0
September	2	mid	1.15	55.2	0	55.2
September	3	mid	1.15	54.8	0	54.8
October	1	mid	1.12	52.7	0	52.7
October	2	late	0.95	44.7	0	44.7
October	3	late	0.65	31.7	0	31.7
November	1	late	0.40	11.5	0	11.5
Total				428.9	59.6	372.7

Note:

kc = crop coefficient, ETcrop = crop water requirement, P_{eff} = effective rainfall

Rainfall that reaches the ground has different fates. Taking into account a cropped field, part of the rainfall evaporates back to the atmosphere, part flows as surface runoff and the rest infiltrates into the ground. The amount that infiltrates is further divided as the water stored in the root zone and water that percolates beyond the root zone. The water stored in the root zone is usually termed as effective rainfall while the one that goes beyond is the percolation.

The effective rainfall indicated in Table 3.4 is determined using the empirical formula developed by FAO (1984) (Equation 3.2 and 3.3).

$$P_{eff} = 0.6 * P_{dep} - 3.3, \text{if } P_{monthly} \leq 70\,\text{mm} \qquad 3.2$$

$$P_{eff} = 0.8 * P_{dep} - 8, \text{if } P_{monthly} \rangle 70\,\text{mm} \qquad 3.3$$

Where:
P_{eff} = effective rainfall in mm
P_{dep} = dependable rainfall of a decade in mm/decade

The most important issue here is the determination of the dependable rainfall. 26 years of daily rainfall data of Gumsalasa within the period of 1972 – 2001 were used for the analysis. The rainfall data within the growing period of the crop were categorized by decade, ranked in decreasing order and the probability of exceedance was calculated by using Weibull's formula (Equation 3.4).

$$P = \frac{m}{n+1} \qquad 3.4$$

Where:
P = probability of exceedance of the rainfall event
m = rank of the rainfall event in decreasing order
n = total number of observations

Table 3.5 Calculation of the dependable rainfall for Gumsalasa

Month	Decade	Stage	Regression equation	Coefficient of determination R^2	P_{dep} in mm
July	1	Initial	Y = -65.7X + 144	0.90	19.6
July	2	Initial	Y = -103X + 220	0.95	24.9
July	3	Initial	Y = -124X + 266	0.97	30.6
August	1	develop.	Y = -138X + 285	0.98	23.7
August	2	develop.	Y = -165X + 338	0.98	23.0
August	3	develop.	Y = -150X + 295	0.99	9.0
September	1	mid	Y = -122X + 234	0.94	1.0
September	2	mid	-		0.0
September	3	mid	-		0.0
October	1	mid	-		0.0
October	2	Late	-		0.0
October	3	Late	-		0.0
November	1	Late	-		0.0

Note:
Y = rainfall in mm/decade
X = normal log of the probability of exceedance
P_{dep} = dependable rainfall with a probability of exceedance of 80% (log probability of exceedance of 1.9) in mm/decade

The graph of the decade rainfall was drawn against the normal and the log normal probability of exceedance. In general, the graph of the rainfall versus the log normal probability of exceedance showed a better correlation and was used for the determination of the dependable rainfall (Table 3.5). The dependable rainfall is the rainfall with a probability of exceedance of 80%. The procedure for the analysis of the dependable rainfall of the first decade of July is given in Table 3.6 and Figure 3.3 as an example.

The soil and crop data indicated in Table 3.7 were used for the calculation of the mean interval of irrigation. The irrigation intervals of wheat in the study site were calculated assuming an application efficiency of 70% and refilling to 100% of the field capacity (Table 3.8). Since the effective rainfall of the last decade of June was determined as zero, the same value was used for the initial soil moisture in the calculation of the irrigation intervals. The result shows that the irrigation interval for wheat at Gumsalasa ranges between 17 – 28 days in clay soils and between 13 – 27 days in loam soil. This irrigation interval takes into account the effective rainfall. The interval would be longer if there was no rainfall.

Table 3.6 Analysis of probability of exceedance for the first decade of July at Gumsalasa

Actual year of occurrence	Rainfall in mm/decade	Rank (m)	Probability of exceedance (P) (P=m/n+1)	P in %	log P
26	89.3	1	0.04	3.7	0.57
15	77.5	2	0.07	7.4	0.87
24	77.3	3	0.11	11.1	1.05
8	76.4	4	0.15	14.8	1.17
1	68.0	5	0.19	18.5	1.27
2	60.5	6	0.22	22.2	1.35
10	60.4	7	0.26	25.9	1.41
6	58.3	8	0.30	29.6	1.47
19	52.8	9	0.33	33.3	1.52
5	46.1	10	0.37	37.0	1.57
21	43.3	11	0.41	40.7	1.61
13	37.8	12	0.44	44.4	1.65
18	33.4	13	0.48	48.1	1.68
9	33.3	14	0.52	51.8	1.71
22	33.3	15	0.56	55.6	1.74
3	31.6	16	0.59	59.3	1.77
4	28.6	17	0.63	63.0	1.80
25	28.4	18	0.67	66.7	1.82
23	27.6	19	0.70	70.4	1.85
7	22.6	20	0.74	74.1	1.87
20	21.0	21	0.78	77.8	1.89
17	15.7	22	0.81	81.5	1.91
14	12.5	23	0.85	85.2	1.93
12	4.2	24	0.89	88.9	1.95
11	0.0	25	0.93	92.6	1.97
16	0.0	26	0.96	96.3	1.98

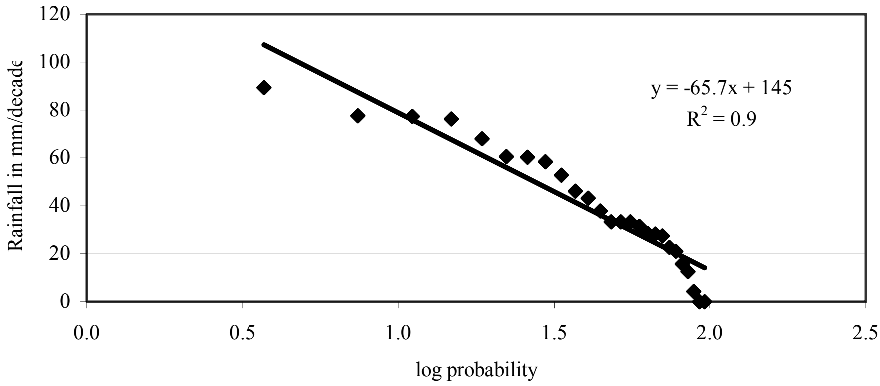


Figure 3.3 Semi-log plot of the probability of exceedance of rainfall for the first decade of July at Gumsalasa

Table 3.7 Relevant crop and soil data for calculation of irrigation interval for wheat at Gumsalasa

Crop and soil characteristics	Clay soil	Loam soil
Total growing period in days	130	130
Allowable depletion factor (p)	0.5	0.5
Maximum crop root zone in m	1.2	1.2
Total available soil moisture (AM) in mm/m	180	140

Table 3.8 Irrigation interval for wheat for the two dominant soil types at Gumsalasa

No. of irrigation	Interval in days	Date	Stage	Depletion in %	Net gift in mm	Gr. gift in mm	Flow in l/s/ha
Clay soil							
1	19	20 July	initial	86	90.5	129	0.79
2	28	17 Aug.	develop.	51	92.5	132	0.55
3	17	3 Sept.	mid	42	91.3	130	0.89
4	17	20 Sept.	mid	42	90.5	129	0.88
5	17	7 Oct.	mid	43	92.0	131	0.89
6	23	30 Oct.	late	42	91.7	131	0.66
End	10	8 Nov.	late	8	-	-	-
Loam soil							
1	20	21 July	initial	84	70.3	100	0.58
2	27	17 Aug.	develop.	52	72.6	104	0.44
3	15	1 Sept.	mid	44	73.2	105	0.81
4	14	15 Sept.	mid	43	73.1	104	0.86
5	13	28 Sept.	mid	43	71.5	102	0.91
6	14	12 Oct.	late	44	73.6	105	0.87
7	20	1 Nov.	late	43	71.9	103	0.59
End	8	8 Nov.	late	7	-	-	-

The 26 years daily rainfall data were used for the analysis of the occurrence of dry-spells of different duration. In this case, the total number of times (I) that a dry-spell of duration longer than or equal to t days occurs in the 26 years of records were counted. The methods used for the calculation of the remaining variables are summarized in Table 3.9 and the corresponding results of the dry-spell analysis in Table 3.10 and Figure 3.4.

Table 3.9 Summary of formulae used in the frequency analysis of different duration dry-spells

Variable	Formula used
The number of times i that a dry-spell of duration t occurs is calculated	$i = I_t - I_{t+1}$
The number of days n within a crop season[1] (m) on which a dry-spell of duration t could start	$n = m + 1 - t$
The total possible number of starting days (N) over Y years of record	$N = n * Y$
The probability p that a dry-spell starts on a certain day within the crop season	$p = \frac{I}{N}$
The probability q that a dry-spell of duration longer than t does not occur on a certain day during the crop season	$q = 1 - p$
The probability Q that a dry-spell of duration longer than t does not occur during the entire crop season	$Q = \left[1 - \frac{I}{N}\right]^n$
The probability P that a dry-spell of duration longer than t does occur at least once in a crop season	$P = 1 - Q$

Note:
1 = actual crop season is 130 days (1st July – 8th November). However, for the dry-spell analysis, a total of 138 days were used (16th June – 31st October) in order to include the right times where moisture is required by the crop.

Table 3.10 Frequency analysis of different duration of dry spells for Gumsalasa

Spell duration t in days	Cumulative no. of spells I	No. of spells of duration t i	Days per season n = 138+1-t	Total no. of days N=n*26	p=I/N	q=1-p	P=1-(q)^n
5	1,528	99	134	3,484	0.44	0.56	1
6	1,429	35	133	3,458	0.41	0.59	1
7	1,394	115	132	3,432	0.41	0.59	1
8	1,279	61	131	3,406	0.38	0.62	1
9	1,218	54	130	3,380	0.36	0.64	1
10	1,164	49	129	3,354	0.35	0.65	1
11	1,115	47	128	3,328	0.34	0.66	1
12	1,068	46	127	3,302	0.32	0.68	1
13	1,022	44	126	3,276	0.31	0.69	1
14	978	39	125	3,250	0.30	0.7	1
15	939	39	124	3,224	0.29	0.71	1
16	900	36	123	3,198	0.28	0.72	1
17	864	32	122	3,172	0.27	0.73	1
18	832	32	121	3,146	0.26	0.74	1
19	800	31	120	3,120	0.26	0.74	1
20	769	29	119	3,094	0.25	0.75	1
21	740	29	118	3,068	0.24	0.76	1
22	711	27	117	3,042	0.23	0.77	1
23	684	27	116	3,016	0.23	0.77	1

Table 3.10 Cont'd Frequency analysis of different duration of dry spells for Gumsalasa

Spell duration t in days	Cumulative no. of spells I	No. of spells of duration t i	Days per season n = 138+1-t	Total no. of days N=n*26	p=I/N	q=1-p	P=1-(q)^n
24	657	27	115	2,990	0.22	0.78	1
25	630	27	114	2,964	0.21	0.79	1
26	603	27	113	2,938	0.21	0.79	1
27	576	26	112	2,912	0.20	0.8	1
28	550	26	111	2,886	0.19	0.81	1
29	524	25	110	2,860	0.18	0.82	1
30	499	24	109	2,834	0.18	0.82	1
31	475	24	108	2,808	0.17	0.83	1
32	451	24	107	2,782	0.16	0.84	1
33	427	24	106	2,756	0.15	0.85	1
34	403	24	105	2,730	0.15	0.85	1
35	379	24	104	2,704	0.14	0.86	1
36	355	24	103	2,678	0.13	0.87	1
37	331	22	102	2,652	0.12	0.88	1
38	309	22	101	2,626	0.12	0.88	1
39	287	22	100	2,600	0.11	0.89	1
40	265	22	99	2,574	0.10	0.9	1
41	243	22	98	2,548	0.10	0.9	1
42	221	21	97	2,522	0.09	0.91	1
43	200	21	96	2,496	0.08	0.92	1
44	179	20	95	2,470	0.07	0.93	0.999
45	159	18	94	2,444	0.07	0.93	0.998
46	141	17	93	2,418	0.06	0.94	0.996
47	124	16	92	2,392	0.05	0.95	0.993
48	108	16	91	2,366	0.05	0.95	0.986
49	92	14	90	2,340	0.04	0.96	0.973
50	78	13	89	2,314	0.03	0.97	0.953
51	65	2	88	2,288	0.03	0.97	0.921
52	63	19	87	2,262	0.03	0.97	0.914
53	44	8	86	2,236	0.02	0.98	0.819
54	36	7	85	2,210	0.02	0.98	0.752
55	29	6	84	2,184	0.01	0.99	0.675
56	23	5	83	2,158	0.01	0.99	0.589
57	18	5	82	2,132	0.01	0.99	0.501
58	13	4	81	2,106	0.01	0.99	0.394
59	9	3	80	2,080	0	1	0
60	6	3	79	2,054	0	1	0
61	3	2	78	2,028	0	1	0
62	1	1	77	2,002	0	1	0
63	0	0	76	1,976	0	1	0

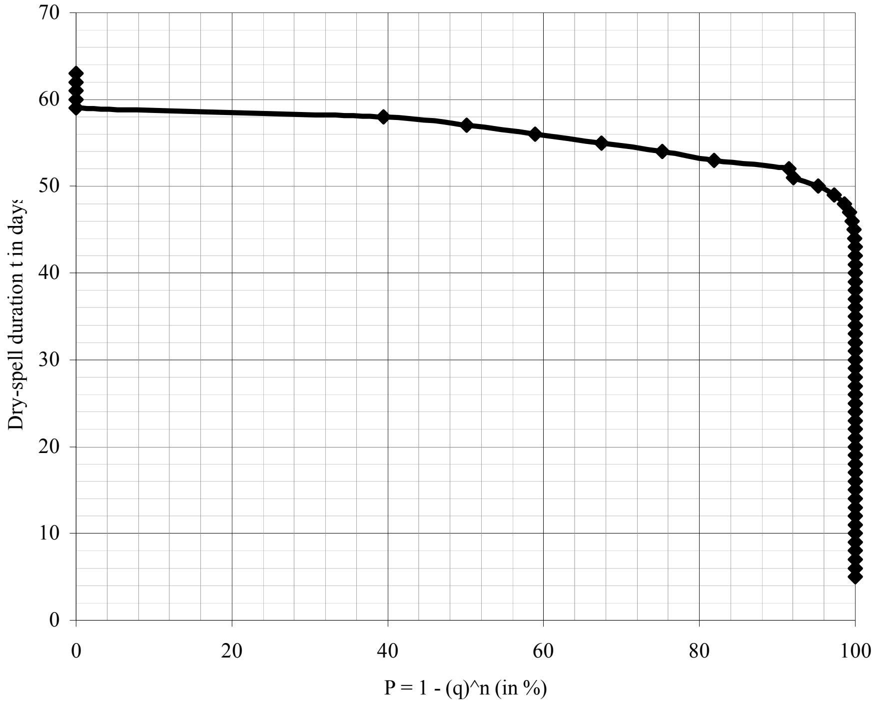


Figure 3.4 Dry-spell probability curve for Gumsalasa

In general the irrigation interval at Gumsalasa ranges between 13 and 28 days. As can be seen from the results, there is almost a 100% probability of occurrence of a dry-spell of a duration longer than the mentioned intervals at least once in the crop season. The graph actually shows that there is almost 100% probability for a dry-spell duration of up to 46 days to occur at Gumsalasa. This shows the unreliability of rainfed agriculture in the area. However, the dry-spell analysis does not consider the effective rainfall but the presence and total absence of rainfall over time and gives the general picture of the rainfall reliability status. Therefore, supporting the dry-spell analysis by an analysis of effective rainfall is very important for getting a clearer picture of the situation. The assessment of the effective rainfall against the crop water requirements for Gumsalasa (Table 3.4) clearly shows that the rainfall in the area is not sufficient to supply the water demand of the crop for most of the growing period. Two basic conclusions can be drawn from these results:

- rainfed agriculture is practically impossible without supplementary irrigation (water supplied by a combination of rainfall and irrigation, when there is some but insufficient rainfall);
- irrigation is compulsory if a crop is to be grown during the dry period.

3.2 The need and potential for irrigated agriculture

Rainfed agriculture is neither sufficient nor reliable to meet the present and the increasing future food demand of Tigray. This demands the planning and proper implementation of alternative solutions in order to improve the present food insecurity and poverty. As a result, water harvesting for the purpose of irrigation is taken as one of the main pillars of the food security strategy by the Government. The water harvesting systems in Tigray generally include spring development, river diversion, flood spreading, earthen dams and ponds. The harvested water is mostly transported and distributed to the irrigated fields by a network of unlined canals.

Irrigated agriculture may provide a degree of self-sufficiency in food, or at least help in ensuring national food security, raising the rural population's living standard, creating employment opportunities, and reducing urbanization pressure. With the involvement of 90% of the population, agriculture is the major source of employment, revenues and export earnings in Ethiopia (Pausewang, *et al.*, 1990 and Ethiopian Telecommunication Corporation, 2000). Hence, land and water development is given a central role in the agricultural development sector of the existing Agricultural Development-Led Industrialization (ADLI) strategy of the country (Ethiopian Telecommunication Corporation, 2000).

Irrigation development in drought prone areas like Tigray can play a very important role in ensuring food security. It makes supplementary and complementary irrigation possible securing two or more harvests a year. Farmers may also shift to high value crops and use improved inputs due to reduced risk of crop failure. The availability of water and the use of improved inputs may increase the yield per hectare. Given the availability of reliable marketing opportunities and other supporting services such as credit, these may lead to higher income for the farm households. The overall increase in income and household welfare may lead to investment in land, thereby positively contributing in reversing the spiral of poverty-induced environmental degradation.

Results of farmers' interviews in seven traditional and introduced irrigation schemes in Tigray have revealed a high increase in yield compared to rainfed agriculture (Table 3.11). Estimates of average irrigated yield at Gumsalasa based on a 1 m * 1 m grid sampling on farmers' fields have also shown the possibility of a better harvest (Table 3.12). The yield in 1998 looks a bit exaggerated. Nevertheless, discussion with farmers has confirmed that 1998 was the best production year so far. There was larger amount of water in the reservoir compared to other years and water management was good.

Table 3.11 Average yield of irrigated crops in Tigray (Mitiku, *et al.*, 2001)

Crop type	Average yield in kg/ha	Increase over rainfed production in %
Maize	1,548	19
Wheat	1,756	98
Barley	2,286	170
Onion	2,942	-
Potato	6,400	-

However, Tigray has utilized only a very small portion of its land and water resources. As indicated earlier, only about 15,000 ha of the total 325,000 ha, most of which is found in the Tekeze river basin, of potentially irrigable land has been developed so far. Similarly, more than 85% of the rain falls during June – September causing a huge surface runoff to leave the region through the major drainage basins.

Table 3.12 Estimates of average yield of irrigated crops at Gumsalasa (Mitiku, *et al.*, 2001)

Crop type	Average yield per season in kg/ha			
	1997	1998	1999	2000
Maize	4,800	10,000	3,500	3,800
Tomato	27,100	10,000	-	24,900
Onion	16,690	14,900	8,300	8,800
Potato	-	19,000	-	8,200

Taking into account the existing constraints and potentials, it can be concluded that irrigated agriculture is one of the major options to alleviate the problem of drought and food insecurity in Tigray. The present land and water development strategy of the region that focuses on storing part of the runoff in earthen dams for use as supplementary and complementary irrigation should be strengthened in this regard. Therefore, studies for the sustainable development and management of irrigated lands with respect to the efficient utilization of the water, land, human and financial resources are very important.

3.3 Earthen dam irrigation schemes in Tigray

3.3.1 General strategy of irrigation development

Planning

Efficient planning of irrigation development should take into account climatic, soil, water, human and physical resources, as well as economic, geographic and demographic factors (Zimmerman, 1966). Ambition should never override rational thinking during planning. A good planning should involve a careful and detailed investigation of the available land and water resources. The required financial, material and human resources and the means of acquisition including contingency plans would also have to be clearly defined at this stage. Moreover, the projection of the area that can be irrigated by a scheme should be carried out on the basis of reliable data on the soil type, hydraulic aspects, irrigation system, intended irrigation management, etc. According to the International Commission on Irrigation and Drainage (ICID) (2001), however, the main factors obstructing adequate development of irrigation in Ethiopia are inadequate hydraulic data, lack of economic power, lack of technical personnel and inadequate research.

Tigray is not exceptional in this regard. The CoSAERT planned to construct 500 dams and to irrigate 50,000 ha within ten years beginning 1995. The interventions consist of watershed management, irrigation infrastructure including earthen dams, irrigation agronomy, and afforestation. Assuming a potential grain production increase of 4 tons/ha, the output expected at the end of the tenth year was 200,000 tons potential increase in production which is enough to feed an extra 930,000 people, who without the project, would almost depend on food aid (CoSAERT, 1994). Five assumptions were set as corner stones for the success of this plan:

- sufficient skilled man-power would be acquired through recruitment and training;
- assistance from donor agencies for the procurement of equipment, advisory services, training, infrastructural facilities and food for work program would be achieved. The envisaged aid was a total of US$ 22 million, 12,000 tons of grain and 407,560 litres of oil;
- sufficient design and construction equipment would be purchased;
- labour for the construction of the schemes would be available at the required number and time;
- suitable locations for the construction of 500 dams would be found in the region.

The strategy seems to have given more emphasis to the total land and water resources of the region and its potential contribution to alleviate the problem of food insecurity. Because, a report by the CoSAERT has revealed that with only 44 dams constructed so far it was not able to meet its target. According to a report by the CoSAERT in 2002, the factors that contributed to the low level of achievement are the following:

- the original plan was to recruit and/or train ten technical teams of multi-disciplinary profession, each capable of carrying out the study, design and construction of an earthen dam irrigation scheme. With five dams constructed by a team, a total of 50 dams were planned to be completed every year. However, with 70% annual turnover of the technical staff, the capacity and the number of the skilled man-power was very low;
- as part of the poverty alleviation program, there were pledges of financial assistance from donor agencies during the planning stage. However, very little was achieved during the implementation. As a result, the regional government was forced to allocate a limited fund from its own annual budget for the program;
- the availability and quality of surveying and geological investigation equipment was very limited. Availability of compaction equipment was also very limited. This is related to the lack of sufficient funds;
- the assumption that farmer’s labour will be available at all times and in required numbers proved to be incorrect;
- locations for the construction of 500 earthen dams were not available. Suitable abutments with no area to be irrigated were found in some places, while suitable irrigated lands with no abutment for the construction of dams were found in others.

Design, construction and transfer

The Ministry of Water Resources is responsible for the management of water resources. In line with the rules and regulations set by the Federal Ministry, the Tigray Bureau of Agriculture and Natural Resources (BoANR) is mandated to manage the regional water resources with regard to the agricultural development.

Public water supply is the responsibility of the regional Water, Energy and Mines Bureau. The CoSAERT is delegated by the regional Government and the Bureau of Agriculture and Natural Resources to handle specifically the construction of the earthen dams with finance from the regional Government and other Governmental and non-Governmental organizations (Table 3.13).

The proper design and construction of irrigation and drainage facilities play a very important role in the sustainable and efficient management of the schemes. Especially at the early stages of the intervention, inadequate design and construction of the earthen dam schemes were among the major problems in Tigray. This can be expressed in over or under-designed reservoirs, reduced irrigated areas, inadequate drainage facilities, seepage through the dam body and the foundation, and inadequate discharge control structures in irrigation canals.

The main factors that contributed to the inadequate design and construction were inadequacies in the design data, and lack of skilled manpower, funds, construction equipment and research input.

The meteorological data available in the region are very limited in spatial coverage and quantity. As a result, design and construction of some dams was carried out with meteorological data of the nearest station. Vagen, *et al.,* (2001) have reported one case where a dam named '*Dibdibo*' was designed using meteorological data from a station 35 km away. In addition the runoff coefficient was determined without accounting for the successive catchment treatments. The result, according to Vagen, *et al,.* (2001), was reduced water availability in the reservoir.

Table 3.13 Role of organisations in irrigation development (Girmay, *et. al.,* 2000)

Organization	Role
Bureau of Agriculture and Natural Resources (BoANR)	Financing, material and technical assistance to develop schemes Organise maintenance of canals and infrastructure Provide technical assistance and training on irrigation agronomy and water management Encourage participation of farmers from within or outside communities in catchment treatment Overall follow-up and evaluation of the performance of irrigation systems provide extension and technology support Encourage farmers to form Water Users Associations Monitor environmental impact of irrigation
CoSAERT	Construct irrigation schemes on selected sites (including site study, design, financing, etc.) Provide maintenance services Training of users Monitoring the status of irrigation systems and environmental effects
Ethiopian Social Rehabilitation Fund (ESRDF)	Financing (co-financing) irrigation schemes
Relief society of Tigray (REST)	Financing/constructing schemes Rehabilitation and upgrading of traditional sources
FARM Africa	Financing schemes
Red Cross	Financing schemes

The construction plan was to use a fifty – fifty mix of machinery and labour. However, construction machinery was introduced late due to lack of funds. The compaction of foundations and dams was done manually. Dams were being constructed of dry soil considerably below the optimum moisture content with inadequate compaction. This was partly caused by inadequate field inspections and site and laboratory testing of soils such as density, water content, Atterburg limits, grain size, etc. The lack of adequate equipment for adding and mixing the moisture, spreading and compaction was also a factor (Engel, 2002). As a result, seepage is one of the problems of the earthen dam irrigation schemes.

Irrigation development performs best with continuous inputs from research undertakings such as crop selection, water management practices, irrigation efficiencies, etc. Equally important is the dissemination of research outputs to the right institutes and users. But both the research undertakings and the dissemination aspects are not satisfactory in Tigray.

The planning and construction of the earthen dams in Tigray is a participatory one. Unlike the previous rigid, bureaucratised and imposed working mechanisms, the development strategy of the CoSAERT acknowledges the support and voluntary participation of the people in every aspect and phase of the project. Through their leaders, farmers take part in the site selection of the schemes with the leading role played by the CoSAERT as a technical institute. Moreover, the farmers are also involved in the construction of the schemes and treatment of the catchment areas through provision of 22 days of free labour annually and on a food-for-work basis during the rest of the time (CoSAERT, 1994).

Once the construction is completed, the CoSAERT transfers the schemes to the community (users) and the Bureau of Agriculture and Natural Resources. Then a water committee will be set up to administer the operation and maintenance of the scheme with technical advice from the Bureau of Agriculture and Natural Resources and other concerned institutes (Girmay, *et al.,* 2000).

3.3.2 Description of the irrigation schemes

The earthen dam irrigation schemes in Tigray consist of a catchment area, a reservoir, an earthen dam, and a command area with irrigation and, in some cases, drainage infrastructure. A view of the schemes is presented in Figure 3.5 – Figure 3.7. As a result of precipitation, water flows from the catchment area (1) to the reservoir (2); the reservoir supplies irrigation water (3) to the command area (4) (Figure 3.5). Usually the flow has to be larger than the quantity required by the crops to be irrigated, because water is also used by non-irrigated vegetation or is lost as evaporation and/or seepage from conveyance and distribution canals, by deep percolation from irrigated fields and as runoff at the tail ends (Bos and Wolters, 1994). In addition to the release of water from the reservoirs through outlet works, water also seeps through the body of these dams. Downstream farmers usually divert this water for irrigation. Consequently, the command area of most of the dams can be divided into two areas, namely an area irrigated by proper canal water and an area irrigated by seepage water (Figure 3.6).

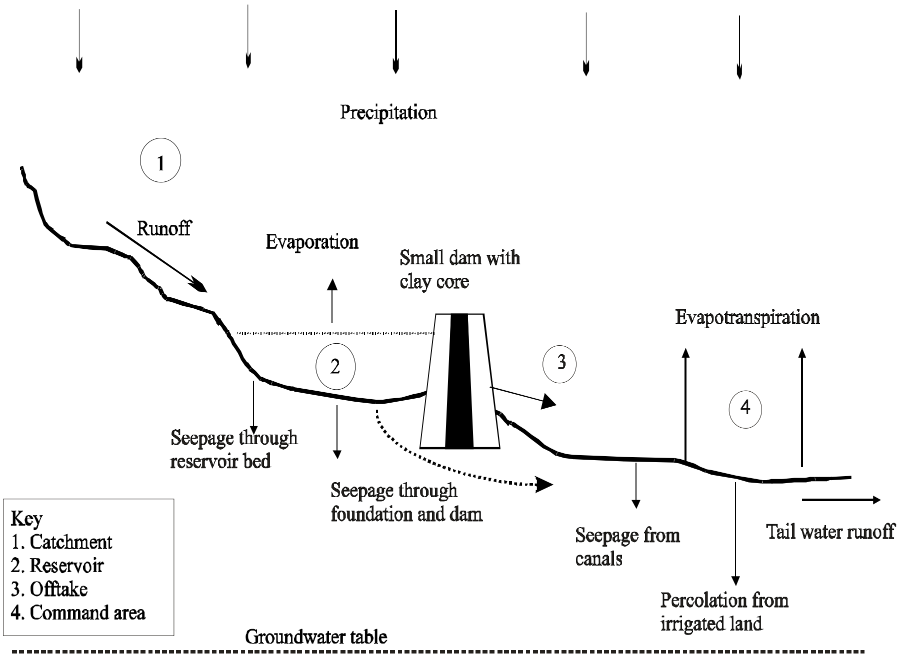


Figure 3.5 Sectional view and major hydrological processes of the earthen dam irrigation schemes in Tigray

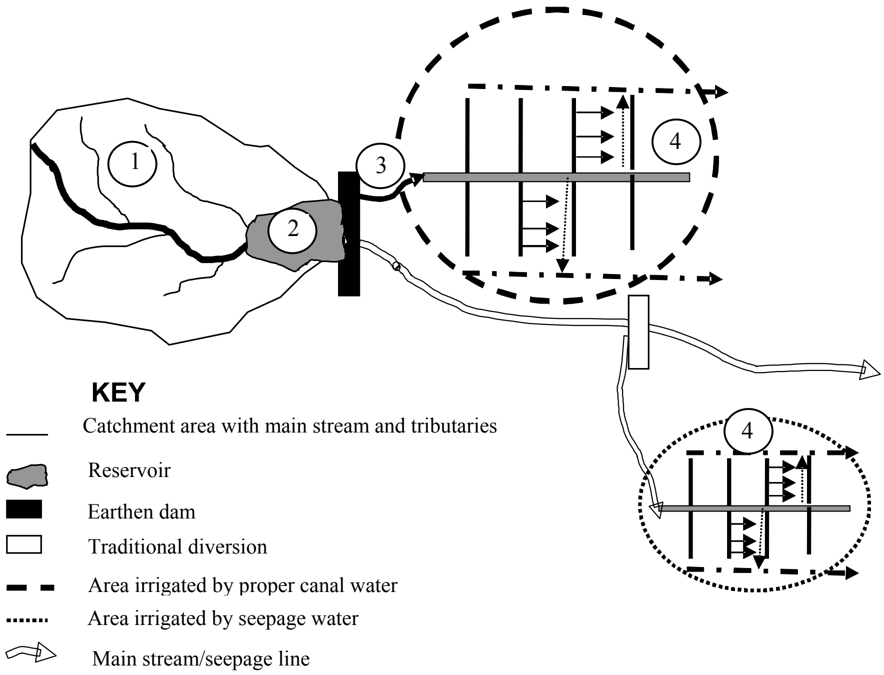


Figure 3.6 Schematic representation of the earthen dam irrigation schemes in Tigray

Figure 3.7 Partial view of the catchment area and the earthen dam at Korir irrigation scheme

As said, so far about 44 earthen dams with related irrigation facilities have been constructed (Table 3.14). The total catchment area covered by these dams is about 41,826 ha. The average catchment area of an individual earthen dam is about 950 ha, with a minimum catchment area of 36 ha at Shilanat 3 and a maximum of 3,001 ha at Hizaeti Wedicheber. As most of these catchments have steep slopes, which are prone to soil erosion because of runoff (Figure 3.8), the strategy has set compulsory and intensive soil conservation and forestation activities in the catchment prior to the construction of an irrigation scheme. The target is to rehabilitate the degraded lands in the project area by physical conservation measures and planting millions of tree seedlings for soil protection and forest products. In this way, soil erosion and siltation of earthen dams will decrease (CoSAERT, 1994).

However, in practice there have been no cases of catchment rehabilitation prior to the construction of the dams. Priority was given to the construction and all the available labour was allocated to it. As a result, the rehabilitation process of most of the dams was started after the completion of the construction. The inadequate coordination among partner institutes particularly between the Bureau of Agriculture and Natural Resources and the CoSAERT has negatively contributed to this effort. The mandate of the CoSAERT was to design the agronomic and water management practices and the watershed management plans. The Bureau of Agriculture and Natural Resources on the other hand was responsible for the planned soil and water conservation activities in the watershed and to deliver the necessary extension services to the farmers. But, lack of communication and action from both sides has minimized the activities thereby contributing to the low performance of the schemes. There is a widespread fear in the region that reservoirs could be silted up before serving their design period.

Figure 3.8 View of the catchment area, the stone-faced trenches and natural regeneration in one of the earthen dam irrigation schemes

Table 3.14 Basic information of the earthen dam irrigation schemes in Tigray

Dam code	Name of the dam	Zone[1]	Catchment Area	Reservoir		Dam height	Dam crest length	Irrigable area	
			in ha	Area in ha	Capacity in Mm^3	in m	in m	Potential in ha	Actual in ha
1	Shilanat 1	S	342	-	1.61	23.0	478	108	43
2	Shilanat 3	S	36	-	0.15	9.0	298	7	3
3	Shilanat 4	S	330	31.5	2.86	24.0	354	181	70
4	Adi Gela	S	878	18.5	1.25	22.0	405	100	6
5	Mai Delle	S	1,010	35.0	1.57	15.0	486	90	52
6	Mai Haidi	S	196	5.7	0.15	9.2	312	9	3.5
7	Mejae	S	315	6.0	0.17	13.5	266	14	20.6
8	Gra Shito	S	288	6.7	0.17	10.0	477	12	4.5
9	Gumsalasa	S	1,855	48.0	1.90	11.5	428	110	78
10	Filiglig	S	320	6.6	0.28	14.0	347	12	3.4
11	Adi Kenafiz	S	880	-	0.67	15.5	-	60	7.5
12	Mai Agam	S	211	6.0	0.17	13.0	266	10	7
13	Dur Anbessa	S	1,007	14.0	0.90	18.0	650	61	24.4
14	Gereb Segen	S	479	11.7	0.34	14.9	208	24	9.6

Table 3.14 Cont'd Basic information of the earthen dam irrigation schemes in Tigray

Dam code	Name of the dam	Zone[1]	Catchment Area in ha	Reservoir Area in ha	Reservoir Capacity in Mm^3	Dam height in m	Dam crest length in m	Irrigable area Potential in ha	Irrigable area Actual in ha
15	Mai Gasa	S	905	42.1	1.30	12.7	867	80	37
16	Gereb Mihiz	S	1,727	30.0	1.30	17.5	365	80	38
17	Betqua	S	613	11.7	0.61	16.0	297	70	25
18	Meala	S	1,437	31.0	1.40	19.0	400	100	80
19	Haiba	S	2,470	95.0	3.10	16.0	189	250	155
20	Meskebet	W	926	52.8	2.70	17.5	579	100	67
21	Mai Negus	C	1,305	38.0	2.38	24.0	338	150	104
22	Mai Gundi	C	450	-	0.80	12.5	-	44	24
23	Gindae	E	1,200	-	0.73	19.5	483	53	6
24	Laelay Wukro	E	916	-	0.93	11.0	660	50	42
25	Korir	E	1,550	32.0	1.60	15.0	505	100	60
26	Ruba Feleg	E	2,810	-	2.70	17.5	380	25	10
27	Teghane	E	880	-	1.08	11.0	-	60	32
28	Adishihu	E	940	36.0	1.00	10.8	301	40	13
29	Felaga	E	816	21.5	0.90	11.9	146	80	40
30	Arato	S	2,077	40.0	2.59	20.0	447	120	27
31	Mai Serakit	S	448	-	0.49	11.0	333	31	9
32	Hashenge	S	2,570	38.0	2.23	19.0	387	120	11
33	Endazeoy	S	165	4.1	0.18	12.3	-	13	5.2
34	Era Quhila	S	1,150	-	1.18	-	-	70	25
35	Adi Akor	S	275	-	0.51	18.0	210	30	20
36	Sewhimeda	S	470	7.8	0.36	14.5	185	23	9.2
37	Gereb Beati	S	540	17.0	1.50	17.8	551	90	36
38	Adi Hilo	S	71	2.5	0.10	11.4	177	9	9
39	Gereb Awso	S	97	2.1	0.11	10.5	197	9	5
40	Emabgedo	S	1,240	36.0	1.78	20.0	328	80	32
41	Adi Amharay	S	600	31.5	0.96	14.7	104	60	5
42	Hizaeti WediCheber	S	3,001	-	1.10	15.5	602	80	50
43	Era	E	1,120	-	1.96	16.7	-	100	95
44	Gereb Shegalu	S	910	17.1	0.91	20.0	378	50	14
Total			41,826	776.0	50.70	666.0	14,384	2,965	1,418
Minimum			36	2.1	0.10	9.0	104	7	3
Maximum			3,001	95.0	3.10	24.0	867	250	155
Average			950	25.0	1.15	15.5	378	67	32
STD			748	20.0	0.85	4.0	162	50	32

Note:

1 = S, C, E, and W stand for Southern, Central, Eastern and Western administrative zones of Tigray

The reservoirs are constructed on a gentle slope and most of them are situated on farmlands causing displacement of a number of farmers. The reservoirs of the 44 earthen dams have in total taken about 776 ha land. The land submerged by a reservoir ranges from 2.1 ha at Gereb Awso to 95 ha at Haiba. The average area submerged by a reservoir amounts to about 25 ha. The existing reservoirs have a total capacity of storing about 50.7 milliom m^3 of water. The earthen dam with the minimum capacity is Adi Hilo (0.1 million m^3) while the maximum belongs to Haiba (3.1 million m^3).

The impermeable core type earthen dams are constructed with an average effective dam height and crest length of 15.5 m and 378 m respectively. The effective dam height ranges from 9 m at Shilanat 3 to 24 m at Mai Nigus, while the crest length ranges from 104 m at Adi Amharay to 867 m at Mai Gasa. The upstream slope of the dams is protected by stone riprap against erosion by wave action, and the crest and the downstream slopes are protected by grass against erosion by wind and rain. Livestock movement around the dam is prohibited.

The original plan of the CoSAERT was to supplement about 300 ha of rainfed agriculture and/or 100 ha of dry season irrigation per dam. Taking into account the dry season irrigation, the present earthen dams should have irrigated about 4,400 ha of land. However, analysis of the present situation shows that the total potential irrigable area available in all the dams is only 2,965 ha, which would mean an average potential irrigable area of only 67 ha per dam. Of this, the actual irrigated area is only about 1,418 ha, with an average irrigated land of about 32 ha per dam. The smallest earthen dam irrigation scheme in Tigray is Shilanat 3, while the largest is Haiba. Out of the potential irrigable area of 7 ha in Shilanat 3, 3 ha is being irrigated at the moment. Similarly, with a potential irrigable area of 250 ha, the Haiba earthen dam irrigates about 155 ha of land.

The correlation between the potential and actual irrigated area (Figure 3.9) and between the reservoir capacity and the actual irrigated area is not good (Figure 3.10). This is because of the fact that some reservoirs are over designed and not filled up to the required capacity to supply water to the whole potential irrigable area.

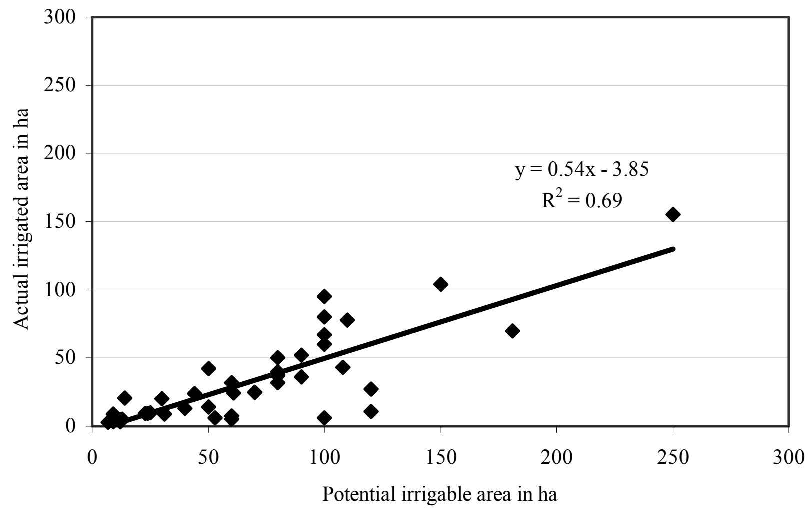


Figure 3.9 Correlation between potential and actual irrigated area in Tigray

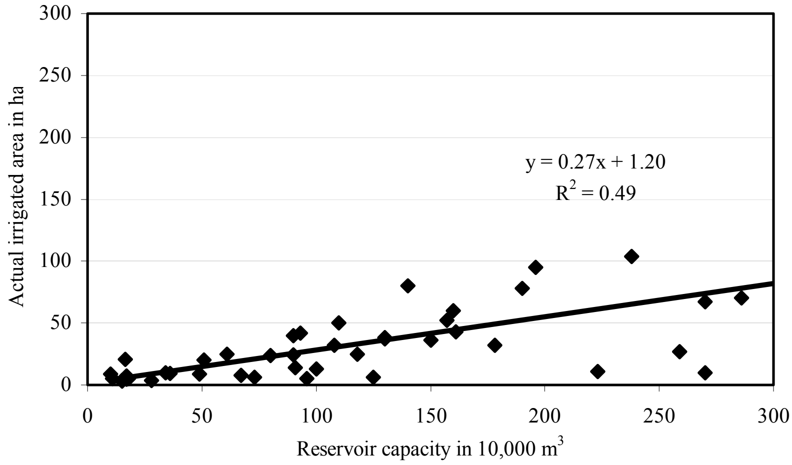


Figure 3.10 Correlation between the reservoir capacity and actual irrigated area in Tigray

The irrigation and drainage infrastructure in most of these dams are open canals made of earth (Figure 3.11). In most cases, the primary, secondary and tertiary irrigation canals are raised in order to maintain the command level for gravity irrigation. On the other hand the drains, where available, and field canals are often excavated.

Figure 3.11 Partial view of irrigation canal being used in Tigray

3.3.3 Institutional set-up

Community organisations can play an important role in irrigation development. Most institutions essential for effective running of smallholder irrigation systems centre around the community. In schemes where communal activities have created dams, canals, and other components of irrigation infrastructure, there is a need for a clear definition of the ownership and control of these assets (Tiffen, 1985). This is important for an agreement amongst those concerned about the division of water and for clarity over the tenure of the irrigated land. Irrigation development creates the need for a strategy in which local people assume greater responsibility for irrigation management.

The strategy of the CoSAERT is to create an empowered Water Users Association in a democratic and participatory context. According to the CoSAERT (1994), these associations should have regulatory and decision making powers and not be simple ones concerned with cleaning the ditches. The water users are legally allowed to form multifunctional Water Users Co-operatives provided that the number of members is not less than 10 (Agricultural co-operatives proclamation number 85/1994). In all the developed schemes, the Bureau of Agriculture and Natural Resources takes the lead in the formation of the Water Users Associations. The existing operation and maintenance rules are based on local by-laws ('*serit laws*') developed by the users in consultation with the Wereda Bureau of Agriculture and Natural Resources. In most irrigation systems, an elected irrigation leader locally known as "*Abo Mai*" administers the schemes (Table 3.15).

Table 3.15 Roles of communities and their organizations in irrigation (Girmay, *et al.,* 2000)

Organization/Committee	Role
Water Users Association/ Co-operatives	Set rules and regulations governing members' rights and obligations and enforce these - on water allocation and use, maintenance, catchment rehabilitation Monitor the condition of the irrigation infrastructure and request technical assistance Select members for training Organize, inform and encourage participation of members Fund raising for water guards and collection of penalty
Abo Mai	Implement irrigation rotation Organize members for maintenance of canal systems Enforce penalties
Farmers', Women's and Youth Associations	Mobilize members to participate in construction and maintenance of the conservation structures
Local Administration Councils (*Baito*)	Identify sites in association with implementing bodies Organize and inform potential participants Encourage and require participation of members during implementation Administer land allocation and compensation of losers Provide other administrative support as requested by the Water User's Association

In Tigray there is a strong tradition of mass mobilisation and participation in resource management and irrigation development. Gender, age, and occupation-based associations are very instrumental in facilitating community participation in resource management and development works. Table 3.15 presents the roles of communities and their organisations in irrigation development (Girmay, *et al.,* 2000).

3.3.4 Operation and maintenance of the irrigation schemes

The potential benefits of completed projects can only be realized if the operation and maintenance are satisfactory (CoSAERT, 1994). If the growing population should be supplied with sufficient food, the efficient utilization of fresh water becomes very important. Therefore, for the schemes to be successful and sustainable, irrigation should be scheduled based on the crop water requirement, the effective rainfall, and the soil type. Besides, the salinity level of the soil and the water should be monitored, and the salt must be leached in time. Also inspection and maintenance of the dams, the conservation works in the catchment, and irrigation and drainage infrastructure should be carried out regularly. Otherwise, poor water management and maintenance can result in loss of water due to excessive application of irrigation, and in waterlogging, salinity, erosion, breach, reduced irrigated area, etc.

However, these activities are not very easy to organize and implement since they require a minimum level of skill and experience at all levels. As a result many projects including irrigation systems deteriorate very quickly (CoSAERT, 1994).

At the initial phase of the adoption of the irrigation practices in Tigray, the engineers, agronomists, extension workers and farmers were facing different problems. The major problems were (Mintesinot, 2002):

- severe salinity, especially in the lower parts of the command area;
- rapid deterioration of the physical infrastructure of the schemes;
- low irrigation efficiency;
- irrigation canals clogged by weeds and silt;
- drainage systems poorly developed.

In both traditional and government constructed irrigation schemes, water distribution is set by the ‘Abo Mai’ in consultation with the users and the Agricultural Development Agents (DAs). The distribution is usually done from head to tail and the interval is determined by hand feel assessment of the soil moisture of plots and the external physical condition of the plant (Solomon, 1999).

In Tigray in general, irrigation scheduling and amount is not based on the crop water requirement and the soil type, but on direct observations of the soil and plant conditions. Based on these assessments the water application time is 2 hours for each 0.2 ha regardless of the soil type. There is no proper control mechanism using discharge-measuring equipment (Solomon, 1999). Drainage systems are poorly developed and drainage water flows from one farm to the other. The inadequate water management coupled with the inadequate drainage facility, seepage from the reservoirs, and lack of leaching is supposed to be the primary reason for waterlogging and the gradual accumulation of soluble salts in the irrigation schemes.

With regard to maintenance, at the beginning of each cropping season, all the beneficiaries collectively repair and clean the irrigation canals. Every farmer provides labour in equal amoount regardless of the size of his or her land holdings. By contributing labour and other resources during the maintenance, farmers gain the right to irrigation water. Farm households who fail to provide labour or other contribution for maintenance are sanctioned and penalised according to the by-laws formulated by the beneficiaries (Girmay, *et al.,* 2000). There are also some problems in the maintenance scheduling. The problems are further aggravated due to lack of skilled manpower, research input, and simple methodologies of scheduling.

As indicated in Table 3.15, the Bureau of Agriculture and Natural Resources is responsible for providing technical support during the maintenance of canals. It is also responsible for training farmers on irrigation agronomy and water management, extension support services and to encourage farmers to establish Water Users Associations. Other roles of the Bureau include planning of the land allocation between cash crops and food crops.

3.4 Recent developments: f*rom small dams to small ponds*

The regional Government of Tigray has been engaged in massive irrigation development activities. The extensive small earthen dam irrigation development program launched by CoSAERT in 1995 can be taken as a major initiative. Taking into account the fact that modern irrigation development in general and earthen dam irrigation development in particular are new interventions in Tigray, it may be concluded that the CoSAERT and the regional Government have made a considerable achievement. Primarily, even if not to the expectation, the Commission has designed, constructed and implemented earthen dam irrigation schemes that are currently irrigating a substantial area. In addition, the regional Government has reviewed the major challenges of the earthen dam irrigation projects and devised new strategies.

The problems of the overall CoSAERT approach have to be summarized so that it can be considered in the future land and water development activities. The general policy issues regarding the overall plan, objective and assumptions of the intervention were the primary factors that undermine the achievements of the CoSAERT. The lack of research input in the process was also one of the fundamental drawbacks for its success. The construction of more new schemes without solving the issue of cooperation with the Bureau of Agriculture and Natural Resources was questionable. Because the success was dependent on the level of cooperation in the catchment rehabilitation, operation and extension services. Last but not least, the management of the Commission would have had to devise a mechanism to retain its experienced technical resource persons.

The absence of clear regional irrigation policy has also added its own share in aggravating the problem. Most schemes are operated and maintained based on local by-laws. There are also unsettled issues of compensation of farmers displaced from the reservoir areas. The challenges met by the CoSAERT in its experience over the last few years include:

- low accomplishment compared to the original plan;
- seepage from dams;
- less water storage in the reservoirs compared to the design capacity;
- relatively high cost of construction;
- sedimentation of reservoirs;
- deterioration of physical infrastructure;
- waterlogging and salinity;
- irrigation canals clogged by weeds and silt;
- wastage of irrigation water and reduced irrigated area.

Based on the lessons learned and with the objective of concentrating the development efforts, the regional Government has restructured the CoSAERT both in organizational set-up and mandate. In this new vision, three organizations – the CoSAERT, the Raya Valley and the Water sector of the previous Water, Energy and Mines Bureau – which were separately engaged in land and water development activities are pooled together to form the Regional Water Resource Development Bureau. Besides, the mandate has changed from high-cost, abutment-centered earthen dams to low-cost, household-centered land and water development activities. These include interventions that could be implemented using household labour as the major input and include in-situ moisture conservation, flood diversion (spate irrigation), small pond construction (*Horoye)*, and river diversions. The construction of feasible small earthen dams, the management of the operational dams and rehabilitation of the failed dams is also considered.

According to the new strategy, water harvesting using ponds at the village or household level is proposed as a practical and effective alternative to improve the lives of rural people at little cost and with minimal outside inputs. In theory, household water harvesting can be done mainly through the effort of the individual farmer. Use of stored rainwater could supplement natural rainfall and make farming families less vulnerable to drought and therefore less dependent on outside help in harder times (Rämi, 2003). The idea is that the household ponds and shallow wells can be used for irrigation in the production of fruits, cash crops and vegetables, which would have to help the individual farmer to obtain additional income and increase household consumption. The farmers would have to start growing vegetables during the rainy season and use the ponds for supplementary irrigation. Accordingly, an extensive construction of ponds and hand-dug wells is in progress since last year to provide water for irrigation, and perhaps for drinking water, at a household level. About 30,000 ponds have been built so far near human settlement areas (Figure 3.12). About 200,000 ponds are planned to be constructed over the next two years in the more drought prone areas of Tigray. The standard design produced suggests for plastic-lined ponds with a dimension of 12 * 12 * 3 m and a capacity of 180 m^3. According to the Relief Society of Tigray, one plastic pond will be sufficient for supplementary irrigation of 0.3 ha of staple crops (about 60 mm of gross irrigation water) (Rämi, 2003 and Tigray Bureau of Water Resources Development and Relief Society of Tigray, 2003). However, crop type, length of dry spell, content of tank, evaporation rate in the tank and evapo(transpi)ration rate are variables that can easily change the computation (Rämi, 2003). As indicated earlier, the high probability of occurrence of dry-spell of longer durations may affect the success of the ponds.

3.5 Conclusions

Farmers in Tigray have been producing different crops under traditional irrigation for a long time. The diversion of perennial streams using temporary structures during the dry season is the major means of irrigation. Spate irrigation of lowland valleys using runoff from upper catchments and spring development are also practiced. These interventions are, however, very limited and their contribution to the regional food security is insignificant. The present effort of the Government to harness and develop the water potential of the region by promoting construction of small earth dams, diversions, ponds and wells is regarded as a major pillar of the regional food security strategy.

In line with this, the measure taken by the regional Government to merge the various institutes involved in land and water development under one umbrella is a wise decision. Equally important is the decision made to construct earthen dams after a detailed feasibility study, as this was one of the major challenges to CoSAERT.

Figure 3.12 Farmer fetching water from his plastic lined pond in Alamata, Tigray (Rämi, 2003)

The shift made to small ponds would have had to be based on the experiences learned from the previous interventions, so as not to repeat the same mistakes. According to Rämi (2003), some problems related to the pond construction have already started to surface, such as lack of skilled technicians, leakage and siltation.

It is clear that the prolonged availability of abundant surface water near human settlements in arid and semi-arid areas has the potential to increase the incidence of water related infectious diseases such as malaria, schistosomiasis and diarrhoea. Malaria is already a major public health problem in Tigray. About 75% of the region is malarious and 56% of the population is at risk (Gebreyesus, *et al*., 1996). In addition the rise in temperature is expanding the areas that are potentially affected by malaria. The extensive construction of ponds and water wells could increase the number of available mosquito habitats around human settlements substantially and for a prolonged period. This may increase the abundance of vector mosquitoes increasing the intensity and duration of malaria transmission.

These interventions will also have positive and negative environmental effects. Yield might increase due to water availability. However, especially taking into account their small capacity, there are outstanding issues that need answer, such as:

- the amount of sediment yield during the rainy season and its effect on the net water storage capacity of the ponds;
- the ratio of the water lost as evaporation and seepage compared to the amount stored;
- the ground water recharge and depletion scenario;
- ultimate impact of the schemes on household food security.

A detailed assessment of the above aspects should therefore be given a priority at small-scale pilot project level before continuation of the mass construction of the ponds.

In summary, if the present efforts of irrigation development in Tigray are to be successful and sustainable, they have to be supported by research. Major problems of the development have to be investigated and better mechanisms and solutions devised. Researches, among others, with respect to the assessment of runoff, sediment rate, water management practices, irrigation efficiencies, waterlogging and salinity problems, key socio-economic aspects are very important. By developing an integrated land and water development approach for the situation in Tigray, this study is believed to contribute towards the sustainable development and management of irrigated lands in Tigray in particular and in Ethiopia in general.

4 Major issues in earthen dam irrigation projects

4.1 Framework for sustainable land and water development

Irrigation development is being used as an important means for achieving food self-sufficiency in many arid and semi-arid countries such as Ethiopia. With 67% of its total area covered by arid and semi-arid zones, Ethiopia is characterised by famine as a result of high population pressure, resource base degradation and insufficient rainfall for rainfed production. As a result, the Agricultural Development-Led Industrialization (ADLI) development strategy adopted in August 1992 has set irrigation as a major pillar to increase food production and to achieve food self-sufficiency for the country. The regional Government of Tigray, one of the most degraded and drought prone regions of Ethiopia, has been engaged in small-scale earthen dam irrigation development activities for the last few years. The principal objectives are to change the agrarian system to widespread small-scale irrigated agriculture and to gradually attain self-sufficiency in food production. These objectives can, however, be realized if efficient and sustainable irrigation schemes are implemented.

This research aims to formulate an integrated approach for the development and management of sustainable irrigated lands in Tigray. The general framework for sustainable land and water development is discussed here, while the integrated approach for the situation in Tigray will be presented in Chapter 8. The conceptual framework for the development of sustainable earthen dam irrigation schemes in Tigray will have to consider the catchment area, the reservoir and dam, the command area, the beneficiaries and downstream areas including the downstream Nile river basin riparian countries. The major elements of the conceptual framework for the situation in Tigray may include (after Savenije, 1997):

- land and water resources (available resources and constraints such as salinity, sedimentation);
- all sectoral interests (agriculture and livestock consumption);
- spatial and temporal variation of resources and demands (scheme level and downstream areas);
- public interest and policy frameworks (national objectives and constraints, equity, poverty alleviation, gender);
- all institutional levels.

The development of an integrated approach within the above mentioned framework can be used as a key tool for the implementation of successful earthen dam irrigation schemes. The success of the present and future small-scale irrigation developments to reduce poverty and gradually ensure food-security in the region depends on the sustainability of the schemes. The general principle of sustainability is the development, use and management of the present scarce land and water resources in such a way that the future generation will not be put at risk. According to Savenije (1997), the major aspects of sustainability are:

- environmental sustainability (no long-term negative or irreversible effects);

- technical sustainability (balanced demand and supply, no mining);
- economic sustainability (sustaining economic development or welfare and production);
- financial sustainability (cost recovery);
- social sustainability (stability of population, stability of demand, willingness to pay);
- institutional sustainability (capacity to plan, manage and operate the shemes).

The focus of a few studies carried out for the earthen dam irrigation schemes in Tigray has been on a single component of the irrigation schemes, particularly on the reservoir sedimentation and salinity of the irrigated fields. No attempt has been made to study the whole scheme as one integral entity, taking into account the catchment area, the reservoir and dam, and the command area.

This research has been initiated and carried out at two earthen dam irrigation schemes, Gumsalasa and Korir, with the main objective of developing an integrated approach for sustainable development and management of irrigated lands in Tigray. Primary and secondary data were collected and analysed on major sustainability issues covering the catchment area, the reservoir, the command area and the beneficiaries for the formulation and appraisal of the integrated approach. These include climate, institutional aspects and water management, erosion and sedimentation, waterlogging and salinity, reservoir water balance, and socio-economic issues. The possible impact of the earthen dam irrigation schemes on the hydrological regime of the Nile river basin is investigated in general terms.

4.2 Impacts of earthen dam irrigation projects

4.2.1 Institutional and water management changes

A transfer from traditional rainfed agriculture to irrigation will demand changes in the institutional set-up and water management aspects. Unlike rainfed production that depends on rainfall and local runoff, irrigated agriculture introduces a system where water from a source is delivered to the command area on a regular basis during the crop growing period. In most cases, the irrigation water is conveyed and distributed from the source to the farms by a network of canals. Division boxes, off-takes and gates are provided in order to distribute the irrigation water among the users. Drainage infrastructure may also have to be constructed for the removal of excess water from the irrigation scheme.

The potential benefit of completed projects largely depends on the level of operation and maintenance, which in turn is affected by the institutional capacity. The participation of the beneficiaries and other relevant stakeholders should be encouraged at all levels of planning, design, construction and implementation of operation and maintenance activities. Irrigation would have to be scheduled based on the crop water requirement, effective rainfall and the soil type. Water will have to be distributed according to the recommended irrigation interval and delivery time, and canals be opened and closed at the right time. Misconducts of and conflict among beneficiaries will have to be resolved on legal basis.

The shift from rainfed to irrigated agriculture will also require the training of farmers in basic water management and crop agronomy practices. Extension services on issues such as water management, cropping pattern, cropping calendar, agronomy, cultivation practices, soil fertility management and marketing are also very important.

Headworks and irrigation and drainage infrastructure have to be inspected and maintained regularly so that they can deliver their intended purpose effectively. It is important that the salinity level of the water and soil be monitored, and salt be leached out in time.

For all the above mentioned issues to be implemented, there needs to be an agreed policy (law) that governs the water allocation and distribution, conflict management and maintenance of the irrigation schemes. The law needs to be equipped with enforcing mechanisms and legal frameworks responsible to implement it. This requires an institutional set-up with sufficient human, material, financial and management capacities and commitment to run the schemes properly. Inadequate institutional capacity is likely to contribute to low economic, social and environmental performance of the irrigation schemes.

The research has made an attempt to investigate the present institutional and water management issues as compared to the original plan, and presents recommendations for the future direction.

4.2.2 Socio-economic aspects

The success of irrigation development is dependent on a variety of socio-economic factors, institutional arrangements and technical considerations. Different studies indicate that the absence of social and economical processes negatively influence irrigation development (Carter, 1992, Minae and Ubels, 1993, Bentum, 1996 and Diemer and Huibers, 1996). Socio-economics is very important in understanding the processes and procedures by which decisions are made with regard to the development and future use of irrigation schemes.

The major social and economic issues are shown in the next paragraphs (Carter, 1992, Minae and Ubels, 1993, CoSAERT, 1994, Bentum, 1996, Diemer and Huibers, 1996 and Sabbah, *et al.,* 2003).

Land tenure and farm size

Land tenure describes the conditions, obligations and rights of land ownership and use. The rural land tenure policy of Tigray has been discussed in Chapter 2.

The ideal size of a farm within a scheme depends on a number of local circumstances and on the scheme's objectives. Experiences in Africa indicate that farm sizes need to be small in order to distribute the benefits of irrigation to as many people as possible. However, if plots are too small, farmers may not gain an adequate income. For example, the Rongo Nyagowa, Kokise, and Aram irrigation schemes in Kenya with plot sizes as small as 0.014 ha (35 * 40 m) are good examples in this regard. In this case, farmers may lack interest in the scheme (Carter, 1989). This indicates that irrigation, in order to be chosen by farmers, will have to compete with other components of the farming system (such as rainfed agriculture, livestock, off-farm employment, etc.) and offer better incentives

(Kortenhorst, *et al*., 1988). On the other hand, if plots are too large, then labour problems can lead to under-utilisation of land and reduction of both cropping intensities and yields. According to Bolch, *et al.,* (1986) and Carter (1989), the ideal size of a farm depends on:

- family size and composition;
- farming systems and technology;
- relation between irrigated and rainfed farming;
- household food security;
- price of inputs and crops produced;
- notion of equity and authority (the idea of local community on allocation criteria);
- non-agricultural income of farmers.

The evidence from many African countries indicates that if irrigated agriculture is to be the principal source of livelihood, the minimum farm size that would generate an adequate income is about 1 ha. However, if off-farm employment is considered, the lower limit of farm size can be substantially less than 1 ha (Bolch, *et al*., 1986). In Africa, it is in most cases witnessed that there is a negative correlation between yield and farm size. For example, in Zimbabwe and Kenya, the farmers with the smallest average farm size (as low as 0.1 ha) obtain the highest yields per unit of area (Bolch, *et al*., 1986). This could be due to the lack of sufficient labour and inputs for the larger sized farms.

Beneficiary selection, displacement and compensation

The question of who has access to land is as important for sustainability of a scheme as the question of how much land each farmer receives. Beneficiary selection criteria on projects involving resettlement will logically differ from those used on projects primarily targeted at existing populations. In the former case, the people to be resettled may be those displaced by a dam, by drought in over-populated dryland farming areas, or by political concerns. The most common case in Tigray is the displacement of farmers due to the reservoir area of the dam. In this case, donors and government will have to insist upon a fair compensation regime for those who loose their land and access to resources as a result of the project. Compensation needs to be reasonable and flexible, and timely so as to facilitate resettlement. It is not always the case that all those affected by a project will be accommodated on the irrigated farms. In such circumstances there is a need for planning on a broad scale to provide viable alternatives (Bolch, *et al*., 1986). According to Bolch, *et al,*. (1986), the typical order of priority for allocation is:

- farmers who have land in the command area and those displaced by the intervention;
- other farmers from the local community.

Water rights and charges

Natural resource tenure systems define the ways in which resources are mobilised for economic development, the equity of access, distribution of benefits and sustainability of resources utilisation (Torori, *et al*., 1995). In irrigated areas clear water rights are necessary for the sustainability of the irrigation practice (Tiffen, 1985, and Dani and Siddiqui, 1987). In some countries water rights are simultaneously treated with right to land (Tiffen, 1985). In areas where water is the most limiting factor, land rights are considered as secondary compared to water rights as the value of land depends on rights to irrigation. Where water is the limiting factor, it is considered as the main object of ownership. Thus, the issue of equitable distribution of water will be the major policy focus. Distribution of water in the most economical way among beneficiaries within the command area may lead to conflicts over equity issues between users on the top-end and bottom-end of the command area.

The issue of water charge and determining the rate is another element of the water policy that requires attention in irrigated areas. In order to improve the irrigation system and overall system efficiency, cost recovery is equally important so that the amount can be reinvested for improving the irrigation schemes. In the absence of cost recovery, the performance and sustainability of the irrigation schemes may be adversely affected due to financial constraints to undertake maintenance and improvement work.

Users participation and role of women

Lack of a social process in the development of irrigation schemes has proven to cause failure of irrigation schemes in many countries (Bentum, 1996, Carter, 1992, and Minae and Ubels, 1993). Studies in African irrigation schemes have shown the lack of social considerations in irrigation development. In most cases engineers based their designs on physical data, taking into account the available water, irrigable area, and other physical limitations. The designs involved the selection of off-take points, layout of canals, plots, and application methods that gave a congruent physical system. This conventional design approach had often an outcome of technical considerations, which were mixed with assumptions on the future use of the system. The assumptions made by the engineers about the cropping pattern, size and layout of the tertiary units, management and operation, available labour force etc. were mostly different from farmer's expectations. As a result, smaller harvests than planned and sometimes other crops than those planned have been witnessed (Dia and Molinga, 1993).

In addition to their responsibilities of maintaining the family and the household, women in rural areas participate in many on-farm activities. Women are active in crop and livestock production, afforestation programs, and construction and management of irrigation schemes. However, they have not traditionally had access to the basic resources and support services.

Marketing of products

Availability of sufficient market facilities is a basic requirement for expansion of irrigated agriculture and increased income of farmers. The success of investment on small-scale irrigated production requires wider market outlets. In the absence of efficient market outlets for high value crops, farmers will use the scarce irrigation water for production of cereal crops with less market value. Better market access encourages farmers to commercialize and shift to high market value crops. In areas far from access roads, improving marketing requires construction of new access roads and improvement of the existing poor road infrastructure. The lack of an efficient transportation system is also a major problem that limits the extent of marketing and lowers the benefit of producers. Particularly the production of perishable horticultural crops requires efficient marketing systems.

An important component to the expansion of potential markets for horticultural production is increasing the local demand or consumption of these crops. The feeding habit of producers and other villagers may need to change in order to increase the level of consumption of vegetables and fruits. This will also improve the diet of the consumers, which is mainly cereal-based.

The research has tried to characterize the above mentioned socio-economic issues based on data collected on the farming systems, social, economic, institutional and water management practices from farmers, development agents and the Bureau of Agriculture and Natural Resources using a questionnaire (Appendix A).

4.2.3 Waterlogging and salinity

Waterlogging

In semi-arid areas, the most important environmental hazards related to irrigation development are the waterlogging and salinity problems.

A waterlogged soil means a soil saturated with water in the root zone. It can be temporary, seasonal or permanent. The causes of excess water can be seepage from uplands, reservoirs and irrigation canals, capillary rise from shallow groundwater, exceedance of rainfall over evapotranspiration, and irrigation. Excess water may occur on the soil surface as ponding, often combined with waterlogging of the topsoil. Moreover, part of the water that infiltrates into the soil may percolate into the saturated zone thereby causing the groundwater to rise. Therefore, excess water may also occur inside the soil profile causing waterlogging of the root zone due to a shallow groundwater table or blocked percolation (Smedema and Rycroft, 1983 and Ritzema, *et al.,* 1996).

Especially with respect to earthen dam projects, the command area lies on a lower relief compared to the reservoir. It is therefore possible that water seeps through the reservoir bed and foundation and causes excess water in the irrigated area.

Introduction of irrigation involves an intensive network of canals. Surface irrigation methods, which are the most widely used ones, have a low efficiency. Besides, diversion of irrigation water to the fields involves in most cases a network of unlined canals. These canals may have a high seepage rate and may contribute significantly to percolation of water to the groundwater. If there is not sufficient drainage in the scheme, the percolating water gradually raises the groundwater table towards the land surface. Once the groundwater is close to the soil surface, appreciable upward movement of the groundwater (capillary rise) due to evaporation from the soil surface takes place resulting in the accumulation of salt in the root zone (Ghassemi, *et al*., 1995). The presence of an impermeable layer such as a clay pan in the sub-soil may also aggravate the problem of waterlogging by blocking or minimizing the movement of the seepage water to the groundwater (Elgabaly, 1971).

Effective water use is very important in this regard because it affects the water balance of irrigation schemes and, hence, has an impact on waterlogging and salinity. A basic knowledge of irrigation water losses is very important for proper planning, design, implementation and management of irrigation schemes. These losses are most commonly expressed in terms of efficiency. According to Bos and Nugteren (1990) and Bos and Wolters (1994), the common indicators of irrigation efficiencies are the following:

- *conveyance efficiency (e_c):* is the efficiency of a canal network from the source to the tertiary off-take;
- *distribution efficiency (e_d):* is the efficiency of the distribution canals supplying water from the tertiary off-take to the individual field inlets;
- *field application efficiency (e_a):* is the relation between the quantity of water delivered at the field inlet and the quantity of water needed, and made available for evapotranspiration by the crops to avoid undesirable water stress in the plants throughout the growing cycle;
- *overall or project efficiency (e_p):* is the relation between the water diverted from the source to the water consumed by the crops.

The irrigation efficiencies are generally expressed by the following equations:

$$e_c = \frac{V_d + V_2}{V_c + V_1} \qquad 4.1$$

$$e_d = \frac{V_f + V_3}{V_d} \qquad 4.2$$

$$e_a = \frac{V_m}{V_f} \qquad 4.3$$

$$e_p = \frac{V_m + V_2 + V_3}{V_c + V_1} \qquad 4.4$$

Where:

V_c = volume diverted or pumped from the source in m^3

V_d = volume delivered to the distribution system in m^3

V_f = volume of water furnished to the fields in m^3

V_m = volume of water needed, and made available, for evapotranspiration by the crops to avoid undesirable water stress in the plants throughout the growing cycle in m^3

V_1 = inflow from other sources in m^3

V_2 = non-irrigation deliveries from the conveyance system in m^3

V_3 = non-irrigation deliveries from the distribution system in m^3

The diagram of the flow of irrigation water in an irrigated area is given in Figure 4.1.

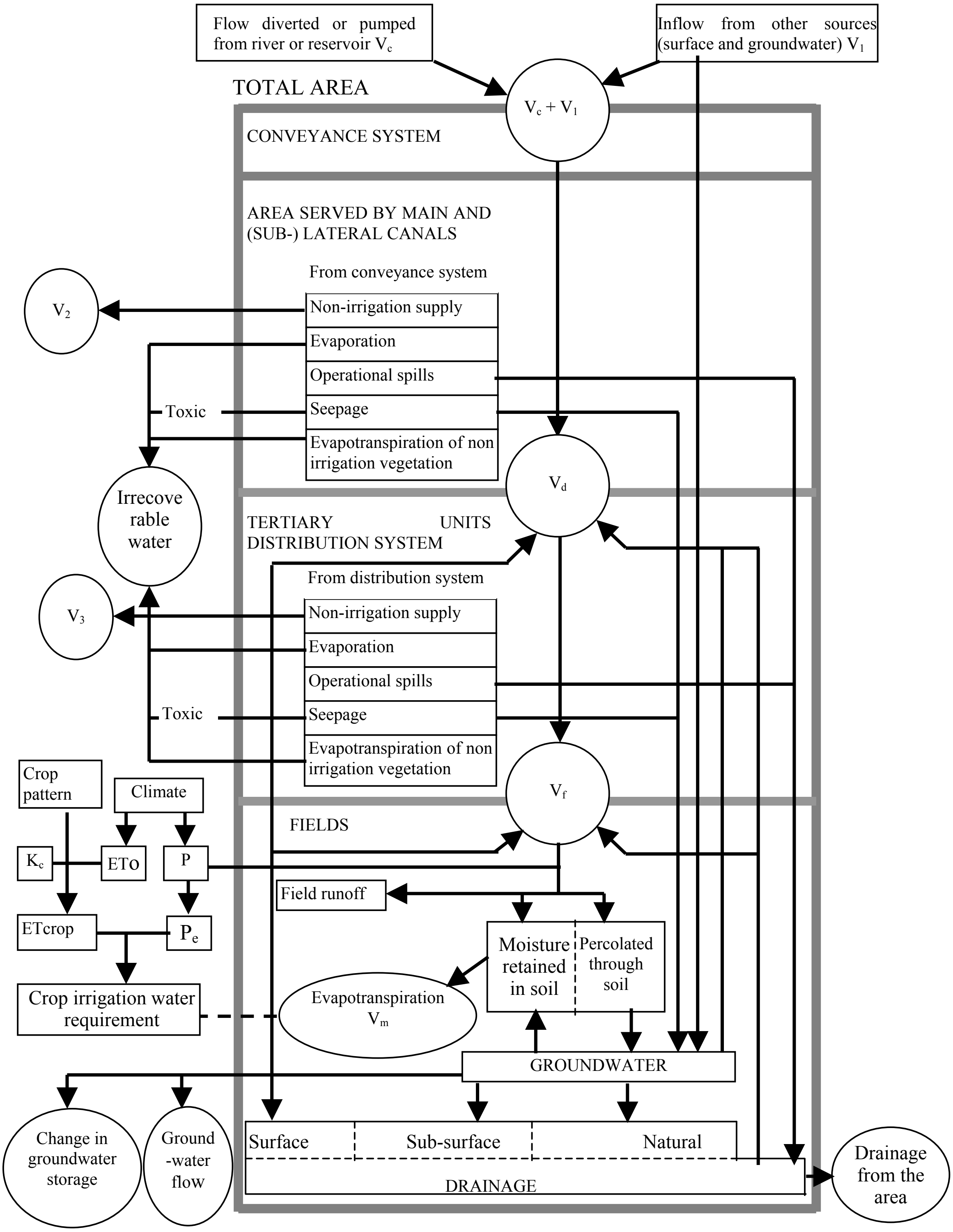


Figure 4.1 Diagram of the flow of water in an irrigation system (Bos and Wolters, 1994)

The water delivered to the scheme can be divided into a ‘recoverable’ volume of water (e.g. seepage from the conveyance and distribution systems, operational spills, surface runoff from fields, percolation) and an ‘irrecoverable’ volume of water (e.g. evaporation from fallow land, evaporation from conveyance and distribution systems, evapotranspiration by non-irrigated crops, groundwater that is not readily or economically utilizable). Water with very high salinity or with toxic elements will also be considered irrecoverable even if it is available in a recoverable form (Bos and Wolters, 1994 and Molden, *et al.,* 1998).

The limited water availability in semi-arid areas like Tigray requires a careful and efficient utilization of the resources. In this regard, Wolters (1992 and 1994) has outlined the following positive effects of increased efficiency:

- a larger area can be irrigated with the same volume of water, and the effect of a water shortage will be less severe;
- the competition between water users can be reduced;
- water can be kept in storage for use during the current or next cropping season;
- groundwater levels will be lower, which can lead to lower investment costs for the control of waterlogging and salinity;
- there will be less flooding;
- health hazards can be reduced;
- energy can be saved;
- there will be fewer irrecoverable losses.

Wolters has also noted the following possible negative effects of increasing the efficiency of irrigation water use:

- soil salinity may increase because of reduced leaching;
- groundwater levels will fall and aquifers will receive less recharge;
- there will be a need for a more expensive infrastructure, and for a more accurate operation and monitoring.

These aspects indicate the need of taking into account different factors in general and the issue of waterlogging and salinity in particular when considering increasing irrigation efficiencies.

Salinity

Salinization is defined as a process whereby the concentration of total dissolved solids in water and soil is increased. The causes of salinity could be natural (primary) or human-induced (secondary). The natural process involves accumulation of salts as a result of long-term processes such as weathering and one-time submergence of soils under seawater (Ghassemi, *et al.*, 1995). On the other hand the two most common causes of secondary salinity, which is most severe in arid and semi-arid areas, are (Smedema and Rycroft, 1983, Umali, 1993, Ghassemi, *et al*., 1995, Ritzema, *et al*., 1996 and Vagen, *et al*., 2000):

- excessive application of irrigation water;
- shallow groundwater table.

In arid and semi-arid areas, the sources of irrigation water are mostly rivers, harvested runoff, and groundwater which in one way or another picks salt from the soil. When surface and groundwater containing mineral salts are used for irrigating crops, the salts are carried into the root zone. As these dissolved salts are often not readily taken by the plants, they are left in the soil after the water is evapo(transpi)rated to the atmosphere. For example, a good quality of irrigation water with a salt content of 500 mg/l contains 0.5 ton of salt per 1,000 m^3 of water. Since irrigation water supply in semi-arid areas may be 10,000 m^3/ha each year, one hectare of land may receive about 5 ton of salt.

The amount of salt which accumulates is further influenced by the groundwater table depth, the capillary characteristics of the soil and the management of the scheme with regard to provision of drainage facilities and leaching (Jensen, 1980). Leaching is the process of dissolving and transporting soluble salts by the downward movement of water through the soil (Arar, 1971). The process depends on the relation between the amount of water applied (irrigation and rainfall) and the amount of percolation and subsurface drainage. These amounts themselves are governed by the irrigation and drainage management, climate and soil permeability (Van Hoorn, 1971).

In many irrigation schemes, crop yields are reduced and even land is abandoned due to waterlogging and salinity (Umali, 1993 and Ritzema, *et al*., 1996). According to the US National Research Council (1989), irrigated agriculture will always be a short-lived enterprise unless salt accumulation in the root zone is prevented by leaching. It is reported that irrigation induced salinity, as a result of wastage of water through seepage, over-watering and inadequate drainage, is the primary cause of farmland loss.

Table 4.1 Global estimates of secondary salinization in the world's irrigated lands (Ghassemi, *et al*., 1995)

Country	Cropped area in 10^6 ha	Irrigated area in 10^6 ha	Percent of irrigated to cropped area	Salt-affected land in irrigated area in 10^6 ha	Percent of salt-affected to irrigated land
China	97	44.8	46.2	6.7	15.0
India	169	42.1	24.9	7.0	16.6
Commonwealth of independent states	233	20.5	8.8	3.7	18.1
United States	190	18.1	9.5	4.2	23.0
Pakistan	21	16.1	77.5	4.2	26.2
Iran	115	5.7	38.7	1.7	30.0
Thailand	20	4.0	19.9	0.4	10.0
Egypt	3	2.7	100.0	0.9	33.0
Australia	47	1.8	3.9	0.2	8.7
Argentina	36	1.7	4.8	0.6	33.7
South Africa	13	1.1	8.6	0.1	8.9
Subtotal	843	158.6	18.8	29.7	18.7
World[1]	1474	227.1	15.4	42.5	19.0

Note:

1 = calculated using the average value of the share of salt-affected land in the 11 surveyed countries, which cover nearly 70% of the world's irrigated land

The global estimation of secondary salinization is very difficult due to the dynamic nature of the problem, lack of data and inconsistencies between the data provided by various sources (Ghassemi, *et al*., 1995). Nevertheless, in a report from

FAO of 1990, it was estimated that about 20 to 30 million hectare of irrigated areas in the world are severely affected by salinity and an additional 60 to 80 million hectares are affected to some extent. This is also supported by Ritzema, *et al.,* (1996) who reported about 10 – 15% of the estimated 235 million hectares of irrigated land in the world to be affected by waterlogging and salinity. On the other hand, a report by Ghassemi, *et al*., (1995) has put an estimation of about 19% of the total irrigated land to be salt-affected (Table 4.1). This all shows the seriousness of the problem worldwide. The problem of salinity is more severe in arid and semi-arid areas due to the high amount of irrigation water applied and the small quantity of rainfall available to leach the salts (Young and Horner, 1986, US National Research Council, 1989 and Vagen, *et al.,* 2000). Because of its occurrence and the special problem it causes in soil and water management, this salinity problem is considered as a very important problem in arid and semi-arid regions like Tigray (Abrol, *et al*., 1988, Landon, 1991 and Umali, 1993).

Impacts of waterlogging and salinity on agriculture

Waterlogging and salinity affect the agricultural productivity through three main adverse effects, namely, impaired crop growth, poor soil workability and salinity and sodicity.

Waterlogging may cause poor aerobic conditions and encourage accumulation of CO_2 and other toxic metabolites, reduced water conveyance within the plant, and nutrient deficiencies. This poor aerobic condition can result in reduced seed germination, root function, growth and development, shoot growth and development, and crop yield and quality.

Excess water on or in the soil also adversely affects the soil workability. A poorly drained soil will cause delayed farm operations such as seedbed preparation, planting and cultivation. On the other hand, if operations are carried out under wet conditions, compaction and smearing of the soil will cause a poor soil structure thereby restricting root penetration, seed germination and infiltration of water.

The effect of salinity and sodicity on crop growth can be classified into three, namely, dispersion, osmotic and toxicity problems. Dispersion problems are caused by a relatively high percentage of sodium in the soil. This results in a poor soil structure due to easy dispersion of the colloids. A state of easy dispersion can result in poor physical soil conditions such as a low hydraulic conductivity, unfavourable soil consistency, waterlogging and a low resistance to slaking (Smedema and Rycroft, 1983). Generally, the decrease in infiltration of water due to the gradual deterioration of the soil structure and consequent partial sealing of the profile by the formation of a surface seal can have a negative impact on crop growth. Besides, the formation of a surface seal can also encourage overland flow and may aggravate soil erosion in irrigation schemes.

Osmotic problems are caused by a high salinity concentration in a solution. This increases the osmotic pressure of the soil solution thereby reducing the availability of water to crops. In this case the crop must apply a greater suction force or face lower water uptake rates. Nonetheless, a large portion of the soil moisture will be held by strong forces and be less readily available or even unavailable to crops. Crops under such situation will show early signs of moisture stress.

Toxicity problems are caused by the presence of a high concentration of a particular cation or anion, or an unfavourable salt composition in the soil solution resulting in an excess or imbalanced uptake by the plant. As toxicity is often linked to high salt concentrations in the soil solution, it occurs concurrently with osmotic effects. Most toxicity problems are related to excess uptake of sodium, chloride and boron. The excess uptake results in accumulation especially, on the leaves and causes leaf burn, scorch and dead outer leaf edges.

Table 4.2 Salinity hazard of irrigation water (Richards, 1954)

Electrical conductivity of irrigation water in dS/m	Salinity class	Salinity hazard	Suitability for irrigation
< 0.25	C1	Low	Suitable for irrigation of most crops on most soils with little danger of salinity development.
0.25 – 0.75	C2	Medium	Can be used with moderate amount of leaching. Plants with moderate salt tolerance can be grown.
0.75 – 2.25	C3	High	Cannot be used on soils with restricted drainage. Can be used on well drained soils growing salt tolerant crops.
>2.25	C4	Very high	Not suitable for irrigation under ordinary conditions. Possible only under high permeable well drained soils growing very salt tolerant crops and applying excess irrigation water for leaching.

The impact of salinity on crop yields varies primarily with the level of the salinity of the irrigation water and soil, and the ability of the crop to tolerate salinity (Table 4.2 – Table 4.4). Soil and water management practices play an important role in controlling the salinity hazard.

Table 4.3 Soil salinity classification (Richards, 1994)

Electrical conductivity of the soil in dS/m	Classification	Crop yield
0 - 2	Non-saline	Not affected
2 - 4	Slightly saline	Sensitive crops affected
4 - 8	Saline	Many crops affected
8 - 16	Strongly saline	Only tolerant crops possible
>16	Extremely saline	A few very tolerant crops possible

Sample collection and analysis

There is a strong relationship between the electrical conductivity of the soil saturated extract (EC_e) and the soil's salt concentration. Measured at a reference temperature of 25 ^{0}C, the EC_e is nowadays expressed in deciSiemens per meter (dS/m) and is an indicator of the osmotic problems in the soil. The most reliable result is found by measuring the salt concentration in soil water at field capacity because it yields the real salt concentration in soil water under field conditions and is directly related to plant growth. It is, however, difficult to obtain a sufficient amount of soil water samples at field capacity in a laboratory. Accordingly, for most soils except sand

and loamy sand, the saturated paste contains about two times the amount of water at field capacity (Van Hoorn and Van Alphen, 1994).

Table 4.4 Yield potentials as function of average root zone salinity (Maas and Grattan, 1999 and Smedema and Rycroft, 1983)

Crop	Average root zone salinity (dS/m) at specific yield potentials (%)		
	50%	80%	100%
A Grain/Forage/ Fiber			
Trobreff wheat (grain) (T *aestivum*)	25	15	9
Wheat (forage) (Triticum *aestivum*)	24	12	4
Durum wheat (forage) (T *turgidum*)	22	10	2
Karnal grass (Diplachne *fusca*)	20	8	3
Durum wheat (grain) (T *turgidum*)	19	11	6
Barley (grain) (Hordeum *vulgare*)	18	12	8
Cotton (Gossypium *hirsutum*)	17	12	8
Rye (grain) (Secale *cercale*)	16	13	11
Sugarbeet (Beta *vulgaris*)	16	10	7
Bermuda grass (Cynodon *dacotylon*)	15	10	7
Sudan grass (Sorghum *Sudanese)*	14	8	3
Wheat (grain) (T *aestivum*)	13	9	6
Barley (forage) ((H *vulgare*)	13	9	6
Berseem clover (T *alexandrinum*)	10	5	2
Sorghum (Sorghum *bicolor*)	10	8	7
Alfalfa (Mdicago *sativa*)	9	5	2
Rice (paddy) (Oryza sativa*)*	7	5	3
Corn (forage) (Zea *mays*)	9	5	2
Corn grain (Z. *mays*)	6	3	2
B Vegetables			
Asparagus (Asparagus *officinalis*)	29	14	4
Zucehini squash (C. *pepo melopepo*)	10	7	5
Celery (Apium *graveolens*)	10	5	2
Red beet (Beta *vulgaris*)	10	6	4
Spinach ((Spinacia *oleracea*)	9	5	2
Egg plant (solanum melongena *esculantum*)	8	4	1
Broccoli (Brassica olera cea *botrytis*)	8	5	3
Tomato (Lycopersicon *Lycopersicom*)	8	4	2
Onion (Allium *Capa*)	4.5	3	1

Salinity varies with time and space. As a result soil and water quality assessments of the study sites were carried out at different times during the irrigation season, and at different locations and depths in the irrigation schemes. In addition to the release of water from the reservoirs through outlet works, water also seeps through the body of these dams. Downstream farmers usually divert this water for irrigation. Consequently, most of the dams in Tigray have primary and secondary command areas. The primary command areas are irrigated by proper canal water while the secondary command areas are irrigated by seepage water. Accordingly, the study sites were divided into rainfed, catchment, reservoir, primary command, and secondary command areas and profile pits were excavated at relevant locations. The rainfed area is included to serve as a control in the investigation of the impact of irrigation development on salinity. Surface soil, surface water, subsurface soil and groundwater samples at different times and locations were collected and analysed (Figure 4.2).

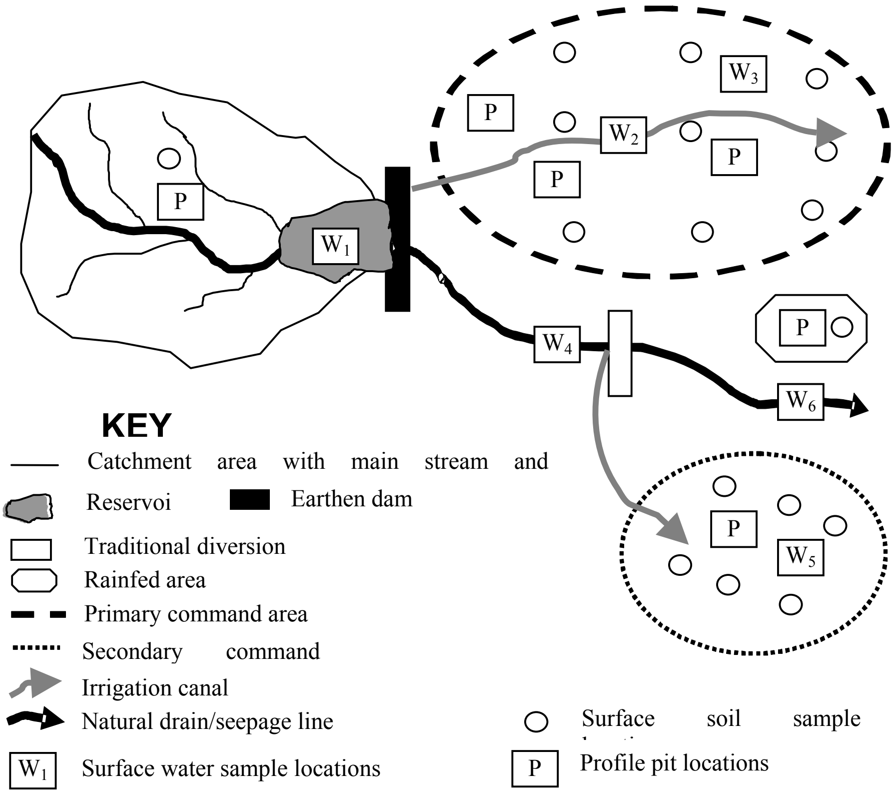


Figure 4.2 Schematic representation of the soil and water sampling locations in the study sites

Surface water samples were taken in the reservoir (W_1), the primary command area [canal (W_2) and irrigated field (W_3)], source (W_4) and irrigated field (W_5) of the secondary command area, and at the natural drain downstream of the command areas (W_6). The surface soil samples were collected from the rainfed, catchment and both command areas. The command areas were divided into top, middle and bottom and 2 – 3 soil samples were collected from each location. The salinity measurements were then averaged to get a representative value per location. Areas with signs of exceptional problems of salinity were sampled and analysed independently.

The groundwater and subsurface soil quality assessments were made in the profile pits excavated across the schemes (P_1 to P_6).

Soil and water samples were collected and analysed at the beginning, middle and end of the irrigation season in order to investigate the temporal variation. In addition, the soil salinity immediately after the rainy season was measured to assess the leaching effect of the rainfall. The irrigation and drainage practices were also assessed to supplement the results of the soil and water analysis. These include water distribution practices, use of seepage water, condition of drainage facilities and leaching practices.

4.2.4 Hydrological aspects

According to Mandel (1973) arid and semi-arid areas are characterised by the following conditions:

- annual potential evaporation is higher than the annual rainfall;
- precipitation occurs only during well-defined seasons and tends to vary from year to year;
- plant cover is limited, primarily by the availability of moisture;
- surface runoff occurs in the form of relatively large floods and at irregular intervals;
- groundwater replenishment is most favourable as a result of the outcrop sands, gravel and fissured rocks.

The construction of reservoirs using earthen dams is one of the possible interventions to store this runoff for various purposes such as irrigation, drinking water supply and recharging the groundwater aquifer. The possible hydrological processes of the earthen dam irrigation schemes in Tigray can be summarized from Figure 3.5. The major hydrological characteristics are related to surface water, groundwater and evapo(transpi)ration. The magnitude of the precipitation, seepage, surface flow and evapo(transpi)ration plays an important role in the surface and groundwater hydrology of the area and the river basin. Seepage occurs from the reservoir through the bed and dam body, from the conveyance and distribution canals and from the irrigated fields in the form of percolation. Depending on the soil type and drainage characteristics, presence of impervious layers in the upper soil profile, and the level of the groundwater table, part of this seepage will return to the river (return flow) in the form of either shallow sub-surface or groundwater outflow. The surface runoff at the tail end of the irrigated fields is also unavoidable from furrow and border applications. The amount depends on the soil conditions and operational farm practices. This water can be consumed by non-irrigated vegetation, re-used by downstream farmers, or reach the stream channels as return flow.

The return flows to the rivers resulting from tail water runoff, shallow sub-surface flows and/or groundwater outflows may be sources of water supply to the downstream users (including downstream riparian countries). Besides, the “recoverable” groundwater, which could be abstracted by the downstream users in the form of hand dug wells or pumps is also another source of water supply.

Water balance analysis can be used as a tool for understanding the hydrological processes. As indicated in Equation 2.1, the water inflow to an area is equal to the sum of the outflow and any change of water storage within the area.

Investigation of the reservoir water balance for the situation in Tigray can be used as a tool to assess the efficiency of the water utilization. It can also be used as input to a proper planning of the reservoir operation. The reservoir water balance over a duration, t, such as a hydrological year includes (Figure 4.3):

- *Inflow* – precipitation is the source of inflow and arrives at the reservoir as:
    - runoff from the catchment area;
    - direct rainfall at the reservoir;
- *Outflow* – this is the part that is withdrawn from the reservoir in the form of:
    - evapo(transpi)ration;
    - canal discharge (discharge to the command area through a proper outlet work);

  - seepage (seepage flow in the drainage stream below the reservoir as a result of leakage);
  - groundwater recharge;
  - water consumed by livestock;
- *Storage* – this is the water that remains stored in the reservoir at the end of the hydrological year.

Different methods were employed for the measurements of the various components in the study sites (Table 4.5).

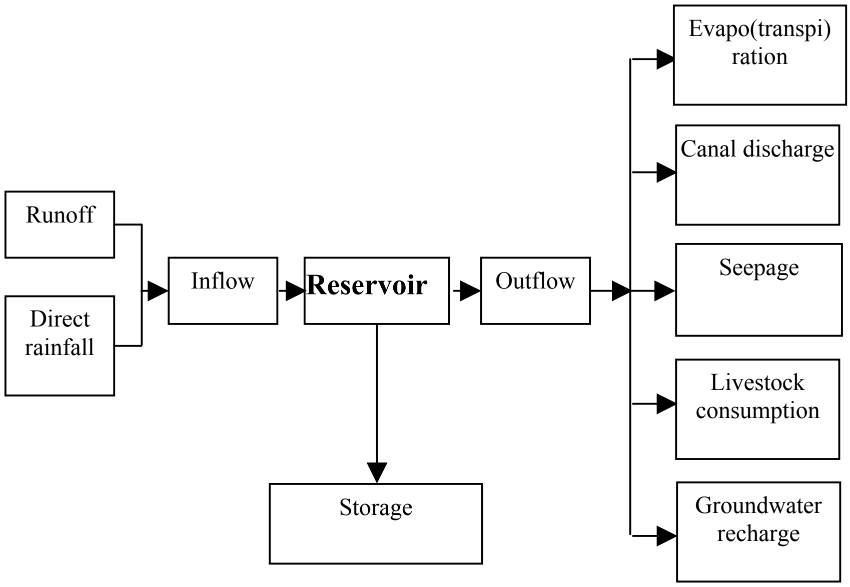


Figure 4.3 Diagrammatic representation of the reservoir water balance

Table 4.5 Measurements of the components for the reservoir water balance

Data type	Symbol	Unit	Frequency	Measuring instrument
Total pressure	P_T	cm	every 6 hr	Diver data logger
Atmospheric pressure	P_A	cm	every 6 hr	Barometer diver
Rainfall	P	mm	every 24 hr	Manual raingauge
Evaporation	E_R	mm	every 24 hr	Class A pan
Canal discharge				
- canal discharge	Q_C	m^3/s		Float method
- opening and closing time		s	daily	Watch
Seepage discharge	Q_S	m^3/s		Float method
Livestock consumption	V_L	m^3	per day	Counting

Volumes and levels will change during the operation of a reservoir. The change in water levels was measured using a diver data logger in the reservoir in a perforated PVC pipe. Figure 4.4 shows the installation of the diver in the reservoir.

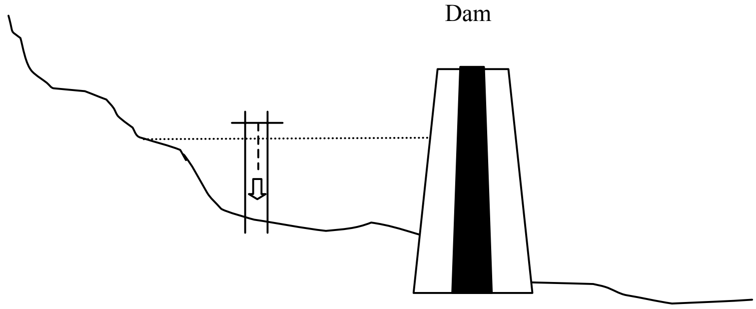


Figure 4.4 Installation of the diver data logger in the reservoir

The diver data logger measured the total pressure, which is the piezometric head with reference to the tip of the diver. A barometric diver is usually kept outside the reservoir to measure the atmospheric pressure.

The daily evaporation was measured by using the US Weather Bureau Class A pan. The pan is circular with diameter and depth of 1.21 m and 255 mm, respectively. It was placed about 150 mm above the ground using a level wooden platform. The water level was maintained between 50 – 100 mm below the rim. With a raingauge the daily rainfall was measured. The pan evaporation was recorded from the water level changes, corrected by rainfall. This pan evaporation is, however, larger than the evaporation from the reservoir. Equation 4.5 represents the relationship between reservoir and pan evaporation (De Laat and Savenije, 1993).

$$E_R = E_{Pan} * K_{Pan} \qquad 4.5$$

Where:
E_R = reservoir evaporation in mm/d
E_{Pan} = pan evaporation in mm/d
K_{Pan} = pan coefficient

The average pan coefficient is about 0.7 but varies over the different climatic regions between 0.67 and 0.81 (De Laat and Savenije, 1993). The higher pan evaporation rates are due to the extra energy that is received from the sides of the pan which are exposed to the sun. In addition, the vapour pressure deficit and the temperature of the air over the pan are generally higher than above the reservoir.

The canal and seepage discharges were estimated using the float method (Equation 4.6 and Figure 4.5).

$$Q = V_{av} * A_{av} \qquad 4.6$$

Where:
Q = canal/seepage discharge in m^3/s
V_{av} = average velocity in m/s
A_{av} = average cross-sectional area of the canal in m^2

The velocity of flow was determined by timing the movement of a float over a known distance (Equation 4.7). The travel time of a float can vary depending on the route it follows. To avoid this problem, a number of runs were carried out and the average time was taken.

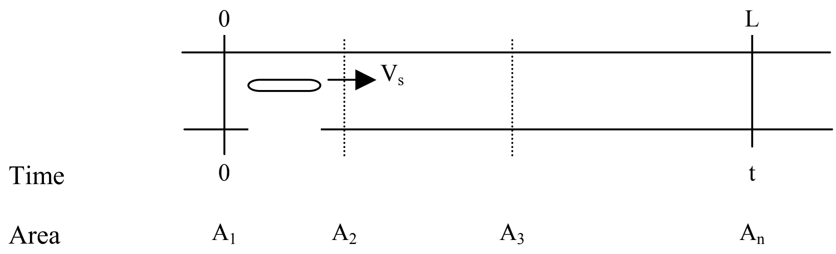


Figure 4.5 Discharge measurement using floats

$$V_S = \frac{L}{t_{av}} \quad 4.7$$

Where:
V_S = surface velocity in m/s
L = distance traveled by the float in m
t_{av} = average time elapsed in s

Surface floats give only the surface velocity and a correction factor must be applied to get the average velocity over a depth (Equation 4.8). According to Shaw (1988), the factor ranges from 0.7 for a stream depth of 1 m to 0.8 for a depth of 6 m or above.

$$V_{av} = V_S * K_V \quad 4.8$$

Where:
V_{av} = average velocity in m/s
V_S = surface velocity in m/s
K_V = velocity correction factor

The canals in the study sites comprise trapezoidal and rectangular cross-sections. The average area was determined by the cross-sectional area of the canal at a number of locations over the distance, L (Equation 4.9).

$$A_{av} = \sum_{i=1}^{n} \frac{A_i}{n} \quad 4.9$$

Where:
A_{av} = average cross-sectional area of the canal in m^2
A_i = cross-sectional area at location i in m^2

At any location, the canal cross-section was divided into segments. The area of the individual segment was calculated by the trapezoidal method and added to get the total area at the particular location.

Field observations revealed the relative consistency in depth and shape of both the main and seepage canals at Korir. At Gumsalasa, the shape of the main canal varies from trapezoidal to rectangular, while the seepage canal varies in width. Discharges were estimated for the varying conditions and the average taken for the water balance analysis. The seepage canals in both areas and the main canal at Korir are unlined canals with shallow depth and high roughness due to the presence of gravels, grass and other vegetation on the bed and banks. The main canal at Gumsalasa is relatively deep and lined with concrete. Taking into account these conditions, the velocity correction factor (Kv) for the main canal at Gumsalasa was taken as 0.6, while 0.5 was considered for the remaining canals.

The amount of water consumed by livestock was estimated by counting the average number and type of animals per day. The average per capita daily water consumption varies depending on many factors of which animal type and climatic conditions play an important role. However, the impact of livestock water consumption on the water balance of the reservoir is not significant and an average of 25 l/head/day was considered.

The water balance equation of the reservoir was derived from Figure 4.3. The water level at any particular time (W_t) with respect to a datum can be calculated by using equation 4.10. The datum in this particular case is the tip of the diver data logger. The atmospheric pressure at sea level varies between 950 and 1050 millibars. The atmospheric pressure at higher altitudes generally exhibits about 10 cm water height decrease for every 100 m increase in altitude. As a result, the zero level for measurements is usually set at 950 cm when the diver is installed at sea level. Adjustment based on the above relationship is applied while installing the diver at higher altitudes. During the study, however, both the piezometric and barometric pressure measurements were carried out taking zero as a reference. A barometric compensation is, therefore, applied to determine the depth of reservoir water above the diver tip. The average daily atmospheric pressure measured by the diver at the study sites was about 127 cm.

$$W_t = P_T - P_A \qquad 4.10$$

Where:
P_T = piezometric head at time t in mm
P_A = atmospheric pressure at time t in mm

The daily water level variation in the reservoir (ΔW_D) can be calculated by equation 4.11.

$$\Delta W_D = W_{t2} - W_{t1} \qquad 4.11$$

Where:
W_{t1} = water level at time 0.0 hours in relation to a datum in mm
W_{t2} = water level at time 24.0 hours in relation to a datum in mm

Taking into account the principles of the water balance and the situation in Tigray, the daily water level variation in the reservoir should generally be equivalent to the difference between the daily inflow and outflow. Equation 4.12 gives the daily water balance of the reservoir based on this principle.

$$\Delta W_D * A_R = I - (E_R * A_R + Q_C * T_{opd} + V_S + R_{GW} * A_R + V_L) \qquad 4.12$$

Where:
ΔW_D = water level variation in the reservoir during 24 hr in m
I = inflow into the reservoir during 24 hr in m
E_R = evaporation from the reservoir during 24 hr in m
Q_C = canal discharge during 24 hr in m^3/s
V_S = seepage during 24 hr in m^3
R_{GW} = groundwater recharge during 24 hr in m
V_L = water consumed by livestock during 24 hr in m^3
T_{opd} = operation time during 24 hr in s
A_R = reservoir area in m^2

Equation 4.12 fits best for a wet season condition where rainfall causes inflow. In dry periods, however, there is no inflow for the conditions in the study sites and the water level is a function of mainly the outflow. As a result, the water level decreases with time. The daily water level variation in such condition can be described by equation 4.13.

$$\Delta W_D * A_R = -(E_R * A_R + Q_C * T_{opd} + V_S + R_{GW} * A_R + V_L) \qquad 4.13$$

Equation 4.12 can be modified to Equation 4.14 for the calculation of the reservoir water balance over a number of days, N.

$$\Delta W_D * A_{Rav} = I - (E_R * A_{Rav} + Q_C * T_{op} + V_S * N + R_{GW} * A_{Rav} * N + V_L * N) \qquad 4.14$$

and

$$\Delta V_R = V_{Rf} - V_{Ri} = \Delta W_D * A_{Rav}$$

$$I = R_O + (P_R * A_{Rav})$$

$$A_{Rav} = \frac{A_{Ri} + A_{Rf}}{2}$$

Where:
ΔW_D = water level variation in the reservoir in m
ΔV_R = change in reservoir water volume during the observation period in m^3
I = inflow into the reservoir during the observation period in m
E_R = evaporation from the reservoir during the observation period in m
Qc = canal discharge during operation days in m^3/s
T_{op} = canal operation time during the observation period in s
A_{Rav} = average reservoir area during the observation period in m^2
V_S = seepage in m^3/d
V_L = water consumed by livestock in m^3/d
R_{GW} = groundwater recharge in m/d
P_R = direct reservoir rainfall during the observation period in m
R_O = runoff from the catchment during the observation period in m^3
V_{Ri} = reservoir volume at the beginning of the observation period in m^3
V_{Rf} = reservoir volume at the end of the observation period in m^3
A_{Ri} = reservoir area at the beginning of the observation period in m^2
A_{Rf} = reservoir area at the end of the observation period in m^2
N = number of days in the observation period

The annual water balance is the difference between the reservoir water volume at the end and beginning of the hydrological year and can be equated as:

$$\Delta V_A = A_F * W_{DF} - A_I * W_{DI} \qquad 4.15$$

Where:

ΔV_A = change in reservoir water volume over the hydrological year in m^3
W_{DF} = average water depth at the end of the hydrological year in m
W_{DI} = average water depth at the beginning of the hydrological year in m
A_F = reservoir area at the end of the hydrological year in m^2
A_I = reservoir area at the beginning of the hydrological year in m^2

4.2.5 Sedimentation of reservoirs

Sedimentation of reservoirs is a natural phenomenon following dam construction and operation. The amount of runoff and sediment transport to the reservoirs depends on the hydrology, topography, soil, vegetation and human activities in the catchment area.

Sedimentation due to erosion and the consequent loss of storage in the long-term is a serious concern globally. The effects will be particularly felt in basins with high geological or human-induced erosion rates, dams in the lower reaches of rivers and dams with small storage volumes (World Commission on Dams, 2000). It has been reported that between 0.5% - 1% of the storage volume of the worldwide reservoirs is lost annually due to sedimentation (Yoon, 1992, Mahmood, 1987 and White, 2001).

Surveys in existing reservoirs in Ethiopia have revealed an annual loss of 0.1% - 0.9% storage capacity (Table 4.6). However, the surveyed reservoirs are very large (10 million m^3 – 9.3 billion m^3) compared to the small earthen dams (0.1 million m^3 – 3.1 million m^3) being constructed in Tigray. Different studies indicate that annual siltation rates usually increase as dams become smaller (Figure 4.6) (Department for International Development (DFID), 2004). This is attributed to “sediment delivery” effects, which usually result in increasing catchment sediment yields per km^2 as catchment areas become smaller. Small dams are constructed on small rivers draining small catchments, and thus tend to silt up more rapidly than major dams located on the main stem of large rivers. Small dams also have smaller ratios of storage capacity to annual inflow than larger dams, and this also has an impact on siltation rates.

According to the Department for International Development (2004), non-governmental organizations and Government agencies have constructed many thousands of small dams in semi-arid regions of East and Southern Africa, but the useful life of many of these dams is reduced by excessive siltation with some silted up after only a few years. This issue is poorly covered in most small dam design manuals, which mostly focus on civil engineering design and construction aspects.

Survey results from seventeen small dams in Zimbabwe and Tanzania revealed an annual sedimentation rate of 0.5% - 50% (Department for International Development, 2004). The situation in Tigray is the same. As a result of inadequate design data and the delay in catchment rehabilitation, more than 50% of the small earthen dams suffer from siltation problems (Poesen, *et al.*, 2001). The problem of erosion in Tigray could even be more severe taking into account the existing vegetation cover. The present vegetation cover of the region is only 0.3%. This decline is caused by land clearance for agriculture, cutting of trees for fuel wood and construction, and outbreaks of fire. This deforestation coupled with the steep nature of the relief has resulted in shortage of wood for various purposes, massive runoff and soil erosion, loss in soil fertility and reduced crop yields. The estimated regional annual soil loss is 17 t/ha.yr (CoSAERT, 1994).

Table 4.6 Sedimentation of reservoirs in Ethiopia (Michael, 2001)

Reservoir	Basin	Construction year	Catchment area in 10^3 ha	Storage capacity in 10^6 m^3	Annual inflow in 10^6 m^3	Total sediment load in t/ha.yr[2]	Annual storage capacity loss in %
Alwero	Baro-Akobo	1988	110	159	1,130	16.2	0.9
Dire	Awash	1999	8	13	50	8.6	0.4
Elbayeh	Wabi-Shebele	1996	47	12	55	2.7	0.8
Fincha	Blue Nile	1973	139	706	432	8.8	0.1
Geferesa	Awash	1955	6	7.5	25	5.2	0.3
Koka	Awash	1960	1,075	1,667	1,602	13.3	0.7
Legedadi	Awash	1970	21	45.9	136	7.6	0.3
Melkawakena	Wabi-Shebele	1989	439	763	801	0.2	0.01
Midimar	Tekeze	1998	8	10	10	11.7	0.7
Gojeb[1]	Omo-Gibe	-	539	997	2,720	2.4	0.1
Tekeze[1]	Tekeze	-	3,039	9,293	3,750	14.3	0.4
Gilgel Gibe[1]	Omo-Gibe	-	423	842	1,589	12.7	0.5

Note:
1 = construction not complete
2 = including 20% bed load (assumed dry bulk density = 1,325 kg/m^3)

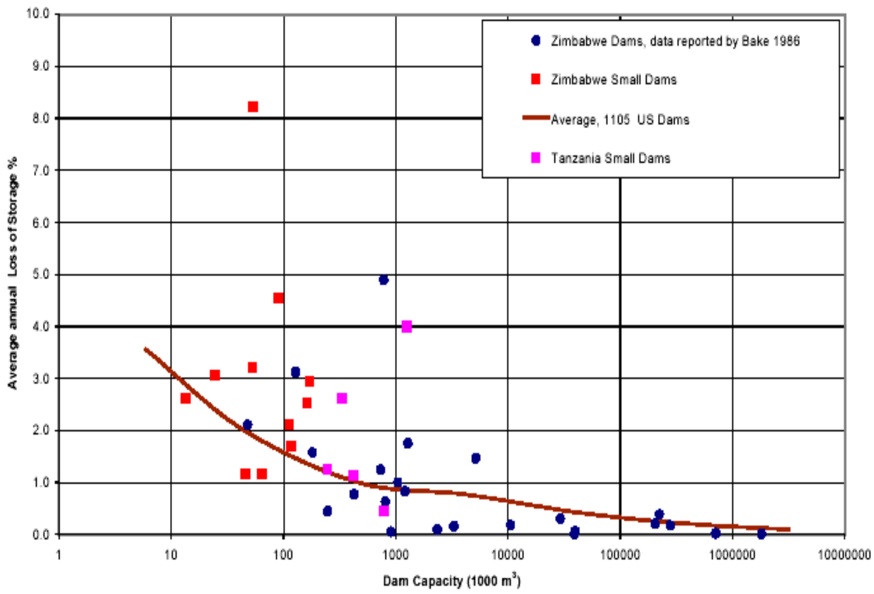


Figure 4.6 Dam size and capacity loss due to sedimentation (Department for International Development, 2004)

A capability to estimate future siltation rates in small dams is essential to ensure that:

- dams are not constructed in catchments with excessively high sediment yields;
- dams are sized correctly;
- catchments with high risk of erosion are identified early enough and rapid rehabilitation carried out if a reasonable dam life is to be obtained.

Assessment of erosion from a catchment area can be made either by field measurement or empirically. The field measurement of erosion is not an easy task especially where there is limitation of measurement facilities. According to Hudson (1993), a valid estimate of runoff and soil loss from a watershed can only be obtained from measurements at the outlet of the watershed. Such approach will need an automatic runoff gauging and sampling station.

When it is difficult to measure the sediment yield, an alternative approach would be to predict the sediment yield by empirical methods. Sediment yield from a catchment is determined by rates of soil erosion, and the sediment transport and deposition processes that control the delivery of eroded sediment to the catchment outlet. The characteristics of the catchment, including soil types, land use, rainfall distribution and intensity, and conservation activities affect sediment yields, which in semi-arid regions vary widely from year to year. Precise predictions of future sediment yields will not be possible due to the high inter-annual variability of rainfall and the resulting large variations in sediment yields between years, the low accuracy of available methods for predicting soil erosion and sediment delivery, and the impact of future changes in the catchment condition. Inaccuracies in predicted sediment yields can be acceptable, provided the prediction allows dams that will have a very short lifetime to be identified rapidly at the preparation stage of projects. The use of simple methods that can distinguish the dams with high risk of siltation with limited available data may be very vital for the future land and water development efforts of Tigray.

Two such empirical methods were employed to predict the sediment yield in the study sites, namely the runoff plot and the HR Wallingford (2003) method.

Runoff plot method

A runoff plot is a physically isolated piece of land of known size, slope, length, and soil type from which both runoff and soil loss are monitored (Figure 4.7). The standard plot is 22 m long and 1.8 m wide, although other plot sizes are sometimes used. The plot edges are made up of sheet metal, wood or any material, which is stable, does not leak and is not liable to rust. The edges should extend 150 mm – 200 mm above the soil surface and be embedded in the soil to sufficient depth so as not to be shifted by alternating wetting and drying of the soil. At the down slope end is a collecting trough, covered with a lid to prevent direct entry of rainfall. A tube connecting the trough with the runoff plot channels the sediment and runoff (Morgan, 1995).

There are alternative ways of collecting the soil and water from the runoff plot in tanks, where the problem is how to take a representative sample of a mixture of water and soil particles of different sizes. According to Hudson (1993), the simplest method is to stir the mixture very well and take a sample, which is filtered, dried and weighed. This method is almost certain to underestimate the soil loss because large particles of soil settle quickly and are hard to keep in suspension while the sample is being taken. In the case of small plots, all the runoff is led into a single collecting tank where it is stored until it can be measured, sampled and recorded. For larger plots, or when large amounts of runoff are expected, it is impractical to store the whole runoff, and some device is used to divide it accurately so that a known fraction can be separated off and stored. In such cases the use of a reserve tank and divisors is recommended (Figure 4.8).

Figure 4.7 Example of a runoff plot for erosion measurement (Hudson, 1993)

Figure 4.8 A runoff plot with primary and secondary barrels and divisors (Hudson, 1993)

The problem with runoff plots is that erosion is measured only from a small plot, and does not take into account the real-life situation of the watershed where deposition takes place farther down the slope. This usually leads to an over-estimation or under-estimation of soil loss from plots. It may, therefore, be misleading to convert the soil loss measured from the small plots into ton per hectare as if there was uniform loss from the whole watershed.

Runoff plots are mostly recommended for demonstration, comparative studies and validation purposes. This involves demonstration of known facts such as showing farmers that serious erosion is taking place, or that erosion is much less from a plot which has a good vegetative cover than from a bare plot. Another valid use is in comparative studies, such as the runoff from a field with or without surface mulch, or the amount of runoff at the top and bottom of a slope. A third possible use is to obtain data, which can be used to validate a model or equation to predict runoff or soil loss. But the difficulties in collecting data of sufficient accuracy and reliability are so great and so numerous that only large experimental programmes conducted at great expense over a long period of time can really meet this objective. The classic example is the validation of the Universal Soil Loss Equation, which in fact is not at all universal, being only applicable to the eastern half of the United States of America (Hudson, 1993).

In the study sites, runoff plots similar to Figure 4.8 were constructed with the edges embedded 25 cm into and extended 25 cm above the soil. The sizes were determined to suit the local conditions, particularly the limitation of available land. Two collecting barrels, primary and secondary, with height of 60 cm and diameter of 50 cm were used to collect the runoff from the plots. The barrels were connected to each other and with the down slope of the plot by metal tubes. The slope, length and width of the runoff plots were 4%, 11.06 m, 2.1 m and 27%, 11.13 m, 2.26 m at Gumsalasa and Korir respectively.

The primary barrel that received runoff from the plot had six holes. One of the holes, with a diameter of 6 cm located at 3.3 cm below the top of the barrel, was connected to the runoff plot by a tube. The other five holes with an equal diameter of 2.9 cm were positioned 6.6 cm below the top of the barrel at equal horizontal interval among each other. These holes were designed as divisors to accommodate the overflow from the primary barrel in case of excess rainfall events. The secondary barrel, which was connected to the middle of the five overflow holes, was assumed to collect 20% of the overflow from the primary barrel. The amount of runoff collected in the barrel(s) was calculated by using equation 4.16. Finally a stirred sample was taken and oven-dried in a laboratory to determine the sediment concentration.

$$V = \pi r^2 H \qquad 4.16$$

Where:

V = volume of runoff in the barrel(s) in m^3

r = radius of the barrel in m

H = total depth of runoff in m (H= depth in the primary barrel + 5*depth in the secondary barrel)

HR Wallingford method

The HR Wallingford (2003) method was developed based on data collected from catchments in Zimbabwe and Northern Tanzania. It is based on an empirical sediment yield predictor that combines quantitative information on the catchment area, annual rainfall and slope, with qualitative factors describing soils, vegetative cover, and evidence of accelerated erosion. The qualitative factors are scored in a rapid catchment characterization exercise (Table 4.7).

The sediment yield can then be predicted using an empirical function developed from small dam catchments and sedimentation data. This function is given in equation 4.17 and combines the slope of the main stream, the catchment area, the mean annual rainfall, and factorial scores of the soil type and drainage, erosion status and vegetation cover.

$$S_y = 0.0194 * A^{-0.2} * P^{0.7} * S^{0.3} * E^{1.2} * SD^{0.7} * V^{0.5} \qquad 4.17$$

Where:

S_y = sediment yield in t/km^2.yr

A = catchment area in km^2

P = mean annual precipitation in mm

S = river slope from the catchment boundary to the dam

E = signs of active erosion (score from Table 4.7)

SD = soil type and drainage (score from Table 4.7)

V = vegetation cover (score from Table 4.7)

The results of the two methods employed in this study were compared to each other and to results of two other scoring approaches previously used by Poesen, *et a1.,* (2001) to assess sediment yield in the earthen dams in Tigray. The methods used by Poesen, *et al.,* (2001) were based on Verstraeten, *et al.,* (2003) and on the Pacific Southwest Inter Agency Commission (PSIAC) (1968).

Table 4.7 Catchment characterization and score form for the HR Wallingford method (Department for International Development, 2004)

Factor	Extreme	Score	High	Score	Normal	Score	Low	Score
Soil type and drainage	No effective soil cover; either rock thin shallow soils	40	Poorly drained compacted soils, much ponding on soil surface after heavy rains	30	Moderately well drained medium textured soils; some ponding after heavy rain	20	Well drained coarse textured soils; little ponding on surface after heavy rain	10
Vegetation condition	Little plant cover, ground bare or very sparse cover over 80% of catchment	40	Fair cover: > 50% of catchment is cultivated with annual crops < 30% of catchment is under good grass cover or protected forest cover	15 15	Good cover: 20 - 50% of catchment is cultivated with annual crops 30 - 60% of catchment is under good grass cover or protected forest cover	10 10	Excellent cover: < 20% of catchment is cultivated with annual crops > 60% of catchment is under well maintained grass cover or protected forest cover	5 5
Signs of active erosion	Many actively eroding gullies draining directly into dam and/or water course; active undercutting of river banks along the main watercourse	40	Some actively eroding gullies draining directly into reservoir and/or water course; moderate undercutting of river banks along the main watercourse	20	Few actively eroding gullies draining directly into reservoir and/or water course; little undercutting of river banks along the main watercourse	10	No actively eroding gullies draining directly into reservoir and/or water course; no undercutting of river banks along the main water course	5

The method of Verstraeten, *et al.,* was developed in Spain using 22 reservoirs, while the PSIAC method was formulated for the western United States. The factorial scoring of both methods is closely related to the HR Wallingford method. The scoring in Verstraeten, *et al.,* is based on topography, gullies, vegetation cover, lithology and catchment slope. The factors for the PSIAC method include surface geology, soils, climate, runoff, topography, ground cover, land use, upland erosion and channel erosion and sediment transport. The Verstraeten, *et al,.* (2003) method employs equation 4.18 for the estimation of the sediment yield.

$$SSY = 4136 * A^{-0.43} + 7 * I - 326 \qquad 4.18$$

Where:

I = T * G * V * L * S

SSY = specific sediment yield in $t/km^2.yr$

A = catchment area in km^2

I = catchment index

T = topography (score from Table 4.8)

G = gullies (score from Table 4.8)

V = vegetation cover (score from Table 4.8)

L = lithology (score from Table 4.8)

S = catchment shape (score from Table 4.8)

Table 4.8 Catchment characterization and score form for the Verstraeten, *et al.,* method (Verstraeten, *et al.,* 2003)

Factor	Score	Description
Topography	1	Very gentle slopes near reservoir and main rivers, elevation difference < 200 m within 5 km
	2	Moderate slopes near reservoir and main rivers, elevation difference between 200 and 500 m within 5 km
	3	Very steep slopes near reservoir and main rivers, elevation difference > 500 m within 5 km
Gullies	1	Bank and ephemeral gullies are very rare
	2	Few bank and/or ephemeral gullies can be observed
	3	Many bank and/or ephemeral gullies can be observed
Vegetation cover	1	Contact cover of the soil is very good (> 75% of the soil is protected)
	2	Moderate contact cover of the soil (25 - 75% of the soil is protected)
	3	Little contact cover of the soil (< 25% of the soil is protected)
Lithology	1	Limestone, sandstone (low weathering degree)
	2	Neogene sedimentary deposits (gravel)
	3	Strongly weathered (loose) material
Catchment shape	1	Elongated shape with one main river channel draining to the reservoir
	2	Catchment shape between elongated shape and (semi-) circular shape
	3	(semi-) circular shape with many rivers draining into the reservoir and/or with much direct runoff from hillsides to the reservoir

Table 4.9 gives the scores for the 9 factors used in estimation of sediment by the PSIAC method. The sum of the scores should be converted to the corresponding sediment yield using Table 4.10.

Table 4.9 Catchment characterization and score form for the PSIAC method (Pacific Southwest Inter Agency Commission, 1968)

Factor	High	Score	Moderate	Score	Low	Score
Surface geology	Marine shales and related mudstones and silt stones	10	Rocks of medium hardness Moderately weathered Moderately fractured	5	Massive hard formations	0
Soils	Fine textured, easily dispersed; saline-alkaline; high shrinkage and swell Single grain silts and fine sands	10	Medium textured soil Occasional rock fragments Caliche layers	5	High percentage of rock fragments Aggregated clays High in organic matter	0
Climate	Storm of several days' duration with short periods of intense rainfall Frequent intense convective storms	10	Storm of moderate duration and intensity Infrequent convective storms	5	Humid climate with low intensity rainfall Precipitation in form of snow Arid climate, low intensity storms	0
Runoff	High peak flows per unit area Large volume of flow per unit area	10	Moderate peak flows per unit area Moderate volume of flow per unit area	5	Low peak flows per unit area Low volume of runoff per unit area	0
Topography	Steep upland slopes (> 30%) High relief, little or no floodplain development	10	Moderate upland slopes (< 20%) Moderate fan or floodplain development	10	Gentle upland slopes (< 5%) Extensive alluvial plains	0
Ground cover	Ground cover does not exceed 20%: sparse vegetation, little or on litter no rock in surface soil	10	Ground cover does not exceed 40%: noticeable litter trees present, under canopy not well developed	10	Area completely protected by vegetation, rock fragments, litter	- 10
Land use	More than 50% cultivated Almost all area intensively grazed Entire area recently burned	10	Less than 25% cultivated 50% or less recently logged Less than 50% intensively grazed Ordinary road and other construction	10	No cultivation No recent road construction Low intensity grazing	- 10
Upland erosion	More than 50% of the area characterized by rill and gully or landslide erosion	25	About 25% of the area characterized by rill and gully or landslide erosion Wind erosion with deposition in stream channels	10	No apparent sign of erosion	0
Channel erosion and sediment transport	Banks eroding continuously or at frequent intervals with large depths and long flow duration	25	Moderate flow depths, medium flow duration with occasionally eroding banks or beds	10	Wide shallow channels with flat gradients, short flow duration Channels in massive rock, large boulders or well vegetated	0

Table 4.10 Estimate of annual specific sediment yield according to the PSIAC method (Pacific Southwest Inter Agency Commission, 1968)

Numerical score	Specific sediment yield			
	in mm/yr	in acre.ft/mi^2.yr[1]	in m^3/km^2.yr	in t/km^2.yr[2]
> 100	> 1.5	> 3	> 1,429	> 2,143
75 - 100	0.5 – 1.5	1 - 3	476 - 1429	714 – 2,143
50 - 75	0.25 – 0.5	0.5 - 1	238 - 476	357 - 714
25 - 50	0.1 – 0.25	0.2 – 0.5	95 - 238	143 - 357
< 25	< 0.1	< 0.2	> 95	< 143

Note:

1 = this means soil loss in acre-feet per square mile per year. 1 acre.ft/mi^2 is equivalent to 0.476 mm depth of soil loss

2 = a bulk density of 1.5 is used to convert m^3/km^2.yr to t/km^2.yr

5 Reservoir hydrology and sedimentation at Gumsalasa and Korir

5.1 Reservoir hydrology

The major hydrological components that play a crucial role in reservoir operation are the inflow and outflow of water. The difference between the two over a certain period gives the change in storage. The major elements that play a role in this study can be summarized as rainfall and catchment characteristics, evaporation, discharge, livestock consumption and groundwater recharge.

5.1.1 Rainfall and evaporation

The rainfall and evaporation are two of the factors that determine the water balance of a reservoir. Some of the important issues with respect to the rainfall and evaporation over a period such as the hydrological year include the total amount, the average daily value over the whole period or per month, the spatial and temporal variability, the correlation of events within and between sites and years, the total number of rainy days and N-day rainfall events, where N is the number of consecutive rainy days.

A time series of hydrological data may exhibit trends referred to as inconsistency and non-homogeneity. Inconsistency is a change in the amount of systematic error associated with the recording of the data. It can arise from the use of different instruments and methods of observation. Non-homogeneity is a change in the statistical properties of a time series. It can be caused by either natural or man-made phenomena such as change in land use, relocation of the observation station and diversion of flows (Dahmen and Hall, 1990).

The presence of inconsistency and non-homogeneity can be detected by split-record tests for stability of variance and mean of the time series. These tests are the F-test for stability of variance and t-test for stability of mean. Spearman's rank correlation test for absence of trends is usually recommended to support the aforementioned tests.

Rough screening of the pan evaporation data of the study sites in 2002 shows inconsistency. The possible sources of the inconsistency can be associated to wrong recordings.

The computer program DATSCR developed by the International Institute for Land Reclamation and Improvement (ILRI) (1991) was used to screen the daily pan evaporation data during April – September, 2002. Each month was tested for trend and stability of variance and mean. The monthly data were split into two non-overlapping sub-sets for the stability of variance and mean tests. Table 5.1 indicates the critical regions of the three tests for (two-tailed) 5% level of significance.

Table 5.1 Critical regions for the various consistency tests

Test	Critical region	Interpretation
Spearman's rank correlation	$t\{v,2.5\%\} < t_t < t\{v,97.5\%\}$	No trend
F-test for stability of variance	$F\{v_1, v_2,2.5\%\} < F_t < F\{v_1, v_2,97.5\%\}$	Stable
t-test for stability of mean	$t\{v,2.5\%\} < t_t < t\{v,97.5\%\}$	Stable

Note:
$v = n – 2$ degrees of freedom, where n is the number of observations
$v_1 = n_1 – 1$ degrees of freedom, where n_1 is the number of observations in the sub-set
$v_2 = n_2 – 1$ degrees of freedom, where n_2 is the number of observations in the sub-set

The summary of the results of DATSCR analysis is given in Table 5.2. The result shows that April, May and July at Gumsalasa and May and September at Korir do not have a trend. Observation of the monthly data revealed two main reasons for the absence of trend. It can occur either when the daily evaporation rates are more or less constant throughout the month or when there is a number of increasing and decreasing patterns within the month.

Table 5.2 Summary of the DATSCR analysis of the pan evaporation during 2002

Site	Month	Spearman's correlation	F-test	t-test
Gumsalasa	April	No trend	Stable	Stable
	May	No trend	Stable	Stable
	June	Negative	Stable	Stable
	July	No trend	Stable	Stable
	August	Positive	Stable	Not stable
	September	Positive	Stable	Stable
Korir	April	Positive	Stable	Not stable
	May	No trend	Stable	Stable
	June	Negative	Stable	Stable
	July	Negative	Stable	Not stable
	August	Positive	Stable	Not stable
	September	No trend	Stable	Stable

The ratio of the variances of the two sub-sets of each month was stable in both sites. On the other hand, April, July and August at Korir and August at Gumsalasa do not show stability of the mean. Inspection of the F and t-test graphs revealed that inconsistency was observed in the months that contain extreme evaporation rates with respect to the surrounding days. As a result, correction to such extreme values was made based on the average daily evaporation of the days immediately before and after. The amendment, however, did not affect the total pan evaporation during the six months. Because the extreme events were generally few and include both very high and low values. The original data resulted in a total pan evaporation of 1,334 mm and 1,279 mm at Gumsalasa and Korir respectively, while the corresponding adjusted totals were 1,334 mm and 1,266 mm.

Rainfall and pan evaporation measurements were carried out during two irrigation and rainy seasons, namely, April – September 2002 and March – August 2004. More care was taken to minimize recording errors in 2004, and rough screening of the pan evaporation showed better consistency. Figure 5.1- Figure 5.4 present the daily reservoir evaporation and the number of rainy days and their corresponding amount during the data collection periods. The reservoir evaporation was calculated from the adjusted pan evaporation by using equation 4.5.

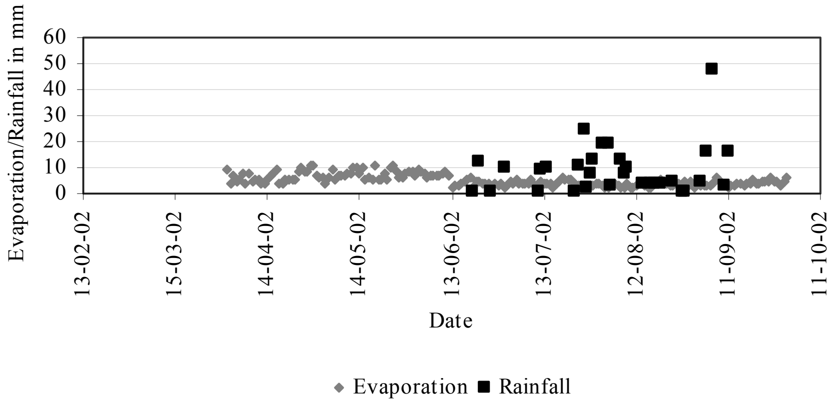


Figure 5.1 Daily evaporation and rainfall at Gumsalasa during the 2002 observation period

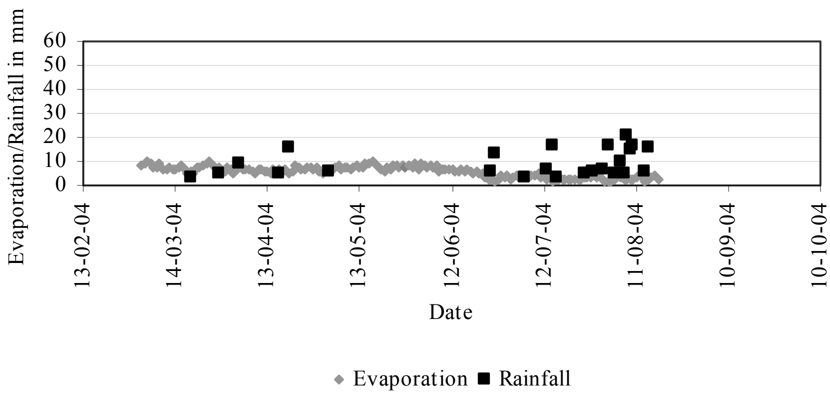


Figure 5.2 Daily evaporation and rainfall at Gumsalasa during the 2004 observation period

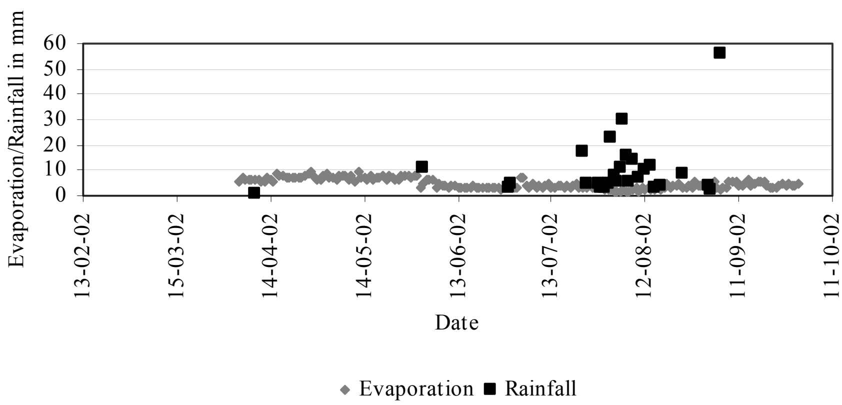


Figure 5.3 Daily evaporation and rainfall at Korir during the 2002 observation period

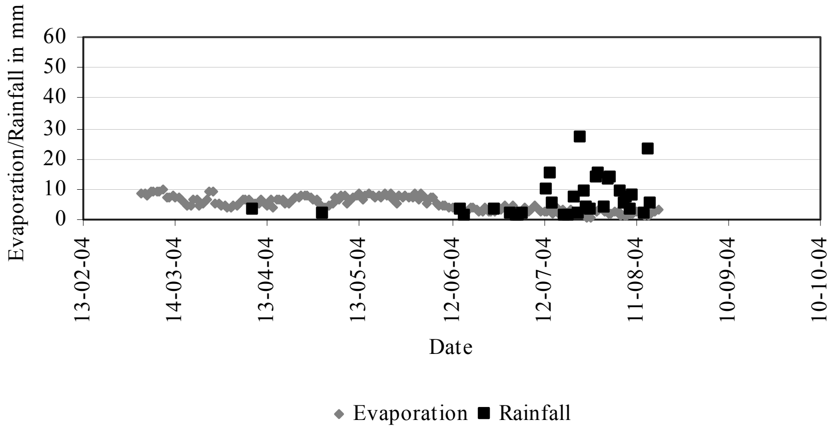


Figure 5.4 Daily evaporation and rainfall at Korir during the 2004 observation period

The main rainfall and evaporation data in 2002 and 2004 are summarized in Table 5.3, Table 5.4, Figure 5.5 and Figure 5.6.

Table 5.3 Summary of rainfall data at the study sites during the data collection periods in 2002 and 2004

Rainfall	Gumsalasa		Korir	
	2002	2004	2002	2004
Data collection period	01/04 - 30/09	03/03 – 18/08	01/04 - 30/09	03/03 – 18/08
Total number of days	183	169	183	169
Total rainfall in mm	284	223	278	224
Rainfall days	31	24	27	33
Average in mm/d	1.5	1.3	1.5	1.3
Minimum in mm/d	0	0	0	0
Maximum in mm/d	48	21	56	27
Standard deviation in mm/d	5.2	3.8	5.7	3.9

Table 5.4 Summary of evaporation data at the study sites during the data collection periods in 2002 and 2004

Evaporation	Gumsalasa		Korir	
	2002	2004	2002	2004
Data collection period	01/04 - 30/09	03/03 – 18/08	01/04 - 30/09	03/03 – 18/08
Total number of days	183	169	183	169
Total evaporation in mm	934	960	886	858
Evaporation days	183	169	183	169
Average in mm/d	5.1	5.7	4.8	5.1
Minimum in mm/d	2.1	1.4	1.4	0.7
Maximum in mm/d	10.5	9.8	9.1	9.8
Standard deviation in mm/d	2.2	2.2	1.9	2.2

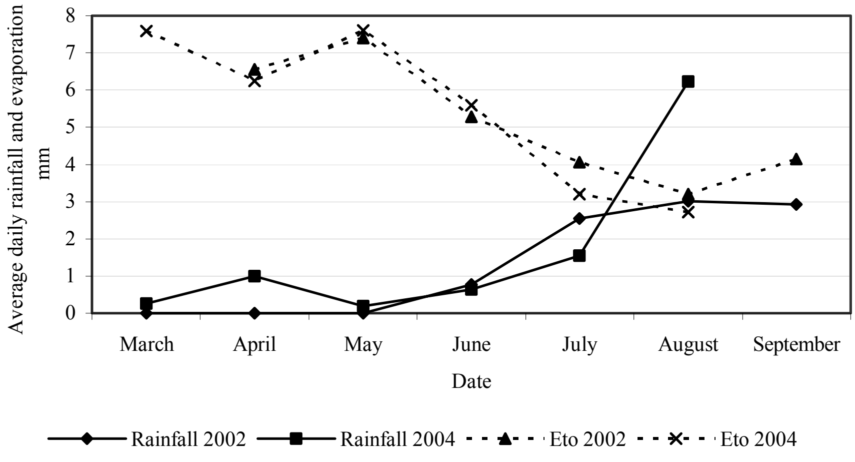


Figure 5.5 Average daily rainfall and evaporation at Gumsalasa in 2002 and 2004

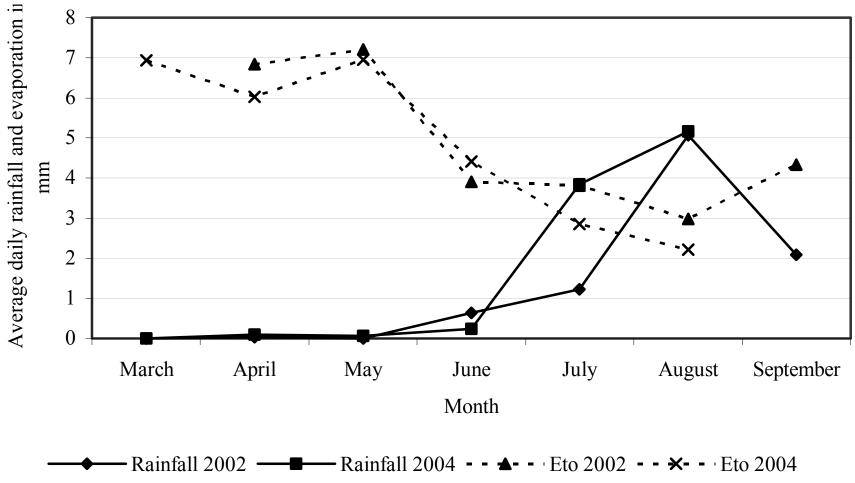


Figure 5.6 Average daily rainfall and evaporation at Korir in 2002 and 2004

The average rainfall and evaporation (per month) figures for the study sites commensurate with daily events (Figure 5.5 and Figure 5.6). Evaporation is high during the 3 months (April – June) prior to the rainy season. The lowest level is recorded in the middle of the rainy season (August) and the evaporation increases again in September. The total reservoir evaporation during the data collection period in 2002 and 2004 was respectively about three-fold and four-fold of the rainfall in both sites (Table 5.3 and Table 5.4).

The number of rainy days during 2002 and 2004 was very low (Table 5.3). Assessment of the data shows that the number of rainfall events decreases dramatically with increase in N-days and minimum threshold rainfall value (Table 5.5 and Table 5.6). For instance, the total number of rainy days in 2002 at Gumsalasa and Korir were 31 and 27, respectively. However, the corresponding number of events with two consecutive days of rainfall drops to 11 and 15. Increasing the threshold rainfall value to "above 4 mm" further reduces the later events to 3 and 9. The situation is more pronounced at Gumsalasa than at Korir.

Table 5.5 Number of N-day rainfall events at Gumsalasa during the data collection periods in 2002 and 2004

N-days[1]	> 0 mm		> 2 mm		>4 mm	
	2002	2004	2002	2004	2002	2004
2	11	7	6	7	3	6
3	3	3	1	3	1	3
4	1	2	0	2	0	2
5	0	1	0	1	0	1

Note:
1 = N is the number of consecutive rainy days

Table 5.6 Number of N-day rainfall events at Korir during the data collection periods in 2002 and 2004

N-days[1]	> 0 mm		> 2 mm		>4 mm	
	2002	2004	2002	2004	2002	2004
2	15	20	15	13	9	8
3	10	11	10	7	7	2
4	9	5	9	3	6	0
5	8	3	8	1	5	0

Note:
1 = N is the number of consecutive rainy days

Correlation is the measure of the strength of association between two factors of a bivariate data set. They are said to be correlated if they tend to either increase or decrease together. The standard measure of this relationship is the correlation coefficient, R, or the coefficient of determination R^2. The coefficient of determination is a number between 0 and 1, where 1 represents a perfect fit. A value closer to 0 is interpreted as indicating that there is no correlation between the variables and suggests that they are independent of each other. However, a look at the bivariate plot is advised in order to confirm this.

Generally, correlation of the monthly data is better than the daily ones (De Laat, 2001). The study sites reveal the same result. No correlation was found for the daily rainfall and evaporation within and between the sites. The only daily data that indicate a relatively good correlation were the 2002 and 2004 daily evaporation at Korir (R^2 = 0.6) and daily evaporation of 2004 at Gumsalasa and Korir (R^2 = 0.7). The correlation between daily rainfall was very poor. This can be due to the presence of high variability in daily rainfall values of both sites.

The monthly data exhibit better correlations. The five monthly data that present best correlation include Gumsalasa 2004 evaporation – Korir 2004 evaporation, Gumsalasa 2002 – 2004 evaporation, Korir 2002 – 2004 evaporation, Gumsalasa 2002 evaporation – Korir 2002 evaporation and Gumsalasa 2002 rainfall – Gumsalasa 2002 evaporation (Figure 5.7- Figure 5.11).

The regression equations indicate that evaporation values decrease with an increase in rainfall at a site. On the other hand, rainfall-rainfall and evaporation-evaporation data relationship between the study sites showed a simultaneously increasing trend.

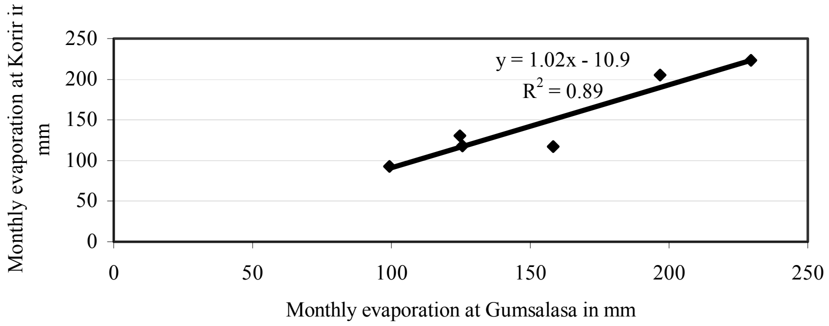


Figure 5.7 Monthly evaporation correlations between Gumsalasa and Korir in 2002

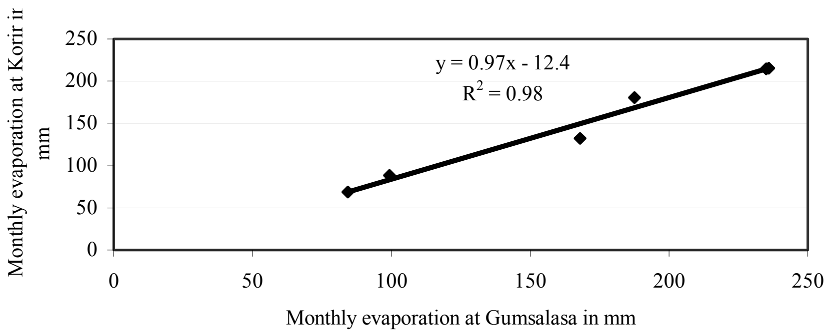


Figure 5.8 Monthly evaporation correlations between Gumsalasa and Korir in 2004

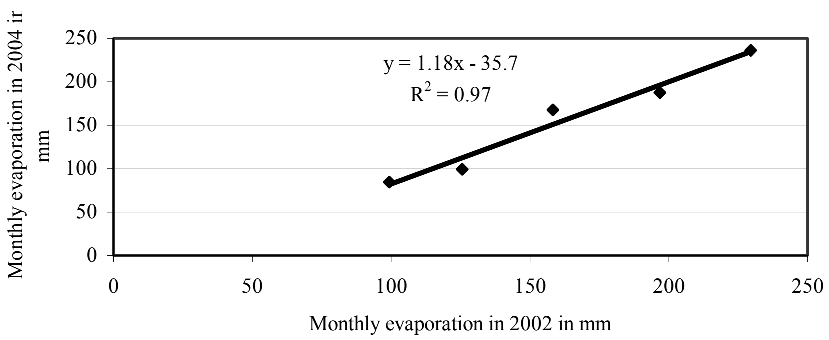


Figure 5.9 Monthly evaporation correlations between 2002 and 2004 at Gumsalasa

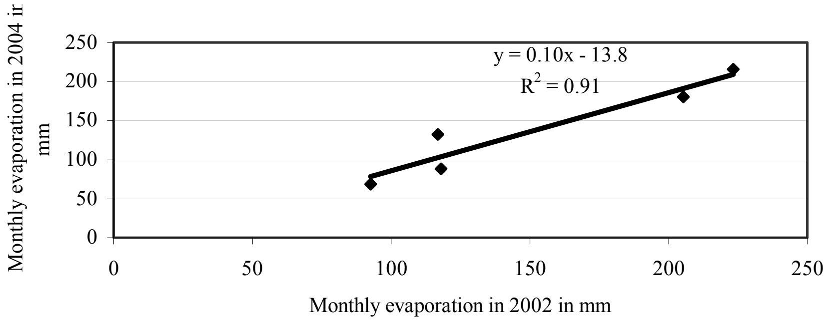


Figure 5.10 Monthly evaporation correlations between 2002 and 2004 at Korir

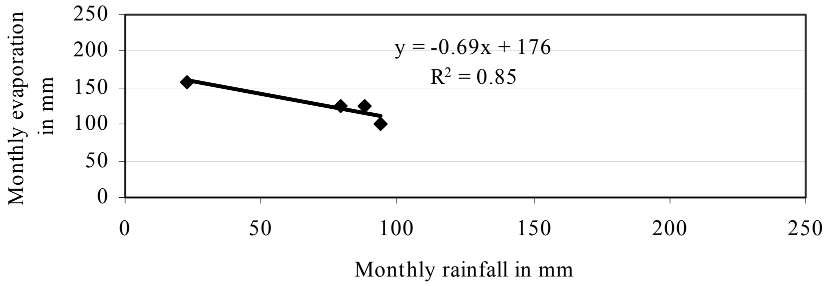


Figure 5.11 Monthly rainfall-evaporation correlations at Gumsalasa in 2002

5.1.2 Discharge

The canal and seepage discharges were determined according to the procedure presented in Chapter 4. The input data and the corresponding discharges for 2002 are presented in Appendix B. The average discharges of the main canal in 2002 were 142 l/s and 86 l/s at Gumsalasa and Korir respectively. The corresponding seepage discharges were 4 l/s and 22 l/s. The seepage discharge at Korir is higher than at Gumsalasa. Observation of the actual situation revealed that the seepage discharge at Gumsalasa emerges at the immediate downstream foot of the dam. This seepage is most likely the result of leakage from the dam through the foundation and/or dam body. At Korir, however, the seepage discharge appears at a distance of more than 100 m downstream of the dam. Furthermore, it was learnt from the farmers that there was a small spring at the point before the construction of the dam. According to the farmers, the dam construction has increased the flow. Besides, unlike Gumsalasa where seepage is diverted directly to a canal, the seepage water at Korir is stored in a pond and released intermittently for irrigation. Taking into account the distance from the reservoir, any increase of the spring discharge is most likely contributed by shallow groundwater flow and night storage, not by surface leakage from the dam. The seepage at Korir is considered as part of the groundwater recharge, not of the surface discharge.

In 2004, three measurements of the main canal discharge were carried out during the data collection period in both sites (Table 5.7). The higher average discharge at Gumsalasa can be due the larger area irrigated. The table indicates a decrease of the canal discharge with the water level in the reservoir. Due to the increase in the outflow, the reservoir water level shows a decreasing trend over the irrigation season. This can cause a lesser piezometric head and subsequent decrease in outlet discharge. The water guard also releases a smaller discharge as the water in the reservoir decreases and crops become well established. According to the water guards the discharge varies with the number of users at a specific time and can vary both from one hour to the next and from one day to the next.

Table 5.7 Main canal discharges at the study sites in 2004

Date	Canal discharge in l/s	
	Gumsalasa	Korir
20/03/04		48
22/03/04	147	
26/04/04		59
29/04/04	131	
18/05/04	89	
19/05/04		34
Average	122	47

Figure 5.12 and Figure 5.13 show the daily operation time of the main canal at Gumsalasa in 2002 and 2004 respectively, while Figure 5.14 and Figure 5.15 present the corresponding operation time at Korir. The figures indicate that the daily canal operation time was longer in 2002 than 2004. This is mainly due to the larger area irrigated in 2002 compared to 2004. The area irrigated at Gumsalasa in 2002 and 2004 was 70 ha and 40.8 ha respectively, while the corresponding area at Korir was 58 ha and 20.6 ha. The total discharge is the sum of the main canal and seepage discharges. When the main canal is closed, the discharge from the reservoir will be only seepage and is about 346 m^3/day at Gumsalasa, while there is no such surface seepage at Korir.

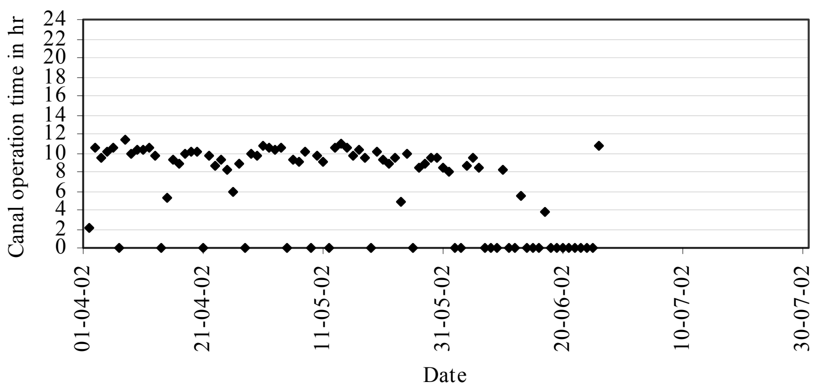


Figure 5.12 Daily operation time of the main canal at Gumsalasa in 2002

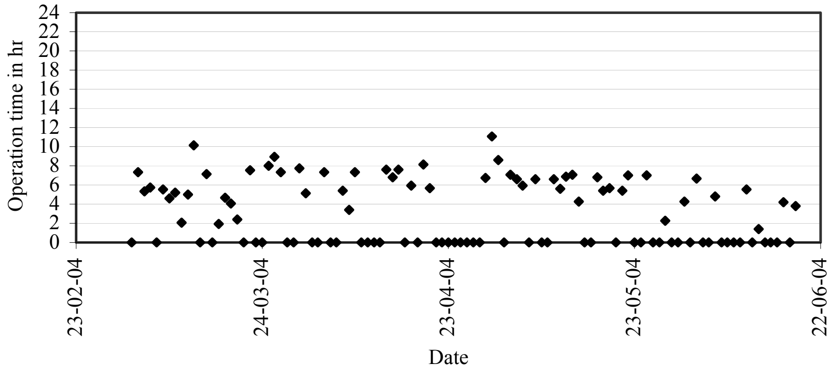


Figure 5.13 Daily operation time of the main canal at Gumsalasa in 2004

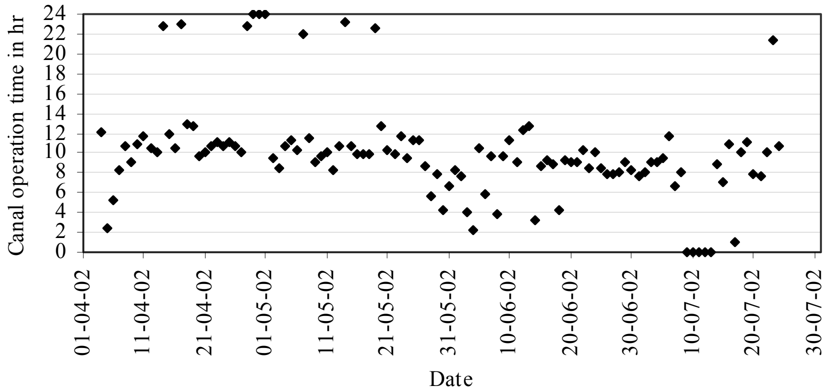


Figure 5.14 Daily operation time of the main canal at Korir in 2002

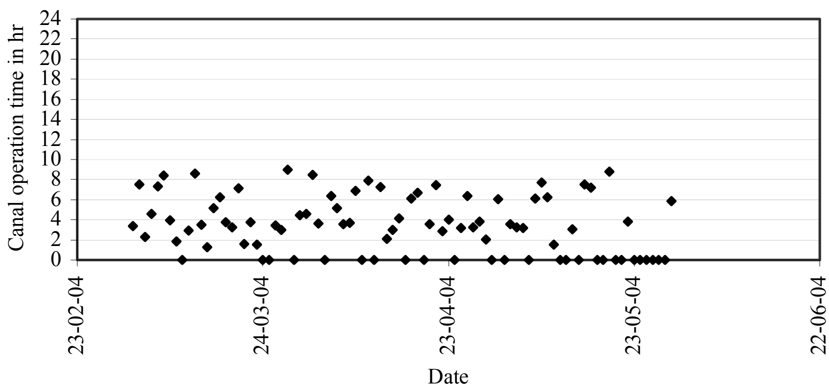


Figure 5.15 Daily operation time of the main canal at Korir in 2004

5.1.3 Livestock consumption

As indicated in Chapter 4, the effect of the water consumption by the livestock on the water balance is insignificant (Table 5.8). The total daily water consumption was only 21 m^3/day and 39 m^3/day at Gumsalasa and Korir respectively.

Table 5.8 Daily livestock water consumption from the reservoirs in 2002

Water consumption	Gumsalasa	Korir
Average number of animals per day		
- Ox/Cow	642	992
- Goat	5	143
- Sheep	15	-
- Donkey	162	93
- Horse/Mule	7	35
- Camel	10	-
- Calf	-	302
Total number of animals per day	841	1,565
Average water consumption in l/head/day	25	25
Total water consumption in l/day	21,025	39,125
Total water consumption in m^3/day	21	39

5.1.4 Groundwater recharge

The available measured data of the water balance during 2002 and 2004 include the daily reservoir evaporation, seepage and livestock consumption as outflow and direct reservoir rainfall as inflow. On the other hand, no daily data is available on the canal discharge. Instead, the data includes an average canal discharge and the daily canal operation time. These data are presented in Eyasu Yazew (2005). This will leave three unknowns: canal discharge (Q_C), groundwater recharge (R_{GW}) and catchment runoff (R_O) (Figure 4.3).

However, since the groundwater is well below the reservoir level, no groundwater inflow into the reservoirs is expected during the dry season. A total dry-up of the reservoir is witnessed in some instances during drought situations. Taking into account the sealing of the reservoir bed due to the deposition of fine sediments over the past few years, the rate of groundwater recharge is generally assumed to be small. As a result, assuming no inflow, the measured average discharge during 2002 and the total reservoir area at design water level was used to estimate the groundwater recharge from the dry period water balance by equation 4.13. The relevant daily data of each water balance parameter during the dry period are summarized in Table 5.9 from Eyasu Yazew (2005).

With all the remaining water balance parameters known, the groundwater recharge can be calculated from the water balance. The groundwater recharge during 02/04/2002 – 03/06/2002 at Gumsalasa will be:

$$\Delta W_D * A_R = -(E_R * A_R + Q_C * T_{op} + V_S * N + V_L * N + R_{GW} * A_R)$$

$$-509 * 10^3 = -(212.1 * 10^3 + 247.1 * 10^3 + 21.8 * 10^3 + 1.3 * 10^3 + R_{GW} * A_R)$$

$R_{GW} * A_R = 27 * 10^3$ m^3 in 63 days (0.9 mm/day)

The groundwater recharge at Korir during 04/04/2002 – 23/05/2002 can similarly be calculated as:

$$-314 * 10^3 = -(112 * 10^3 + 194 * 10^3 + 0 + 2 * 10^3 + R_{GW} * A_R)$$

$$R_{GW} * A_R = 6.2 * 10^3 \text{ m}^3 \text{ in 50 days (0.4 mm/day)}$$

Table 5.9 Data on the dry period water balance of 2002

Data	Gumsalasa	Korir
Duration (t)	02/04 – 03/06	04/04 – 23/05
Total no. of days (N)	63	50
Irrigation days	52	50
Change in water level (ΔW_D) in m	-1.061	-0.982
Total reservoir evaporation (E_R) in m	0.442	0.35
Average canal discharge		
- Discharge (Q_C) in m^3/s	0.142	0.086
- Operation time (T_{op}) in 10^3 s	1,743	2,256
Seepage (V_S) in m^3/d	346	-
Livestock consumption (V_L) in m^3/d	21	39
Reservoir area (A_R) in m^2	480,000	320,000
Total rainfall in m	0	0.001
Rainfall days	0	1
Inflow (I) in m	0	-
Groundwater recharge (R_{GW}) in m	Unknown	Unknown

Note:
Unknown means that there were no direct measurements of the parameters and that they have to be determined from the water balance analysis

5.1.5 *Reservoir water balance*

The elevation-area-capacity curve is an important aspect of reservoir operation. This curve can be developed from a contour map of the reservoir area. Figure 5.16 and Figure 5.17 represent the elevation-area-capacity curves of Gumsalasa and Korir earthen dam respectively. The dead storage level is 1953 m+MSL at Gumsalasa and 1977.5 m+MSL at Korir.

Divers usually measure the reservoir water level with respect to the diver tip. This relative water level should be changed into elevation (m+MSL) in order to convert diver readings to corresponding reservoir area and volume using the elevation-area-capacity curves. Such relationship was not yet available in 2002. In 2004, a Geographical Positioning System (GPS) was used to determine the reservoir area at a particular diver setting. This area was converted to elevation (m+MSL) by using Figure 5.16 and Figure 5.17 for Gumsalasa and Korir respectively. As a result, the reservoir water balance analysis was primarily made based on the 2004 data. Adjustments to the reservoir water balance of 2002 were made based on the results of 2004.

The observation period in both years was categorized into two periods for the water balance analysis, namely, ‘dry period’ and ‘rainy period’. As indicated earlier, the measured canal discharge varies from time to time based on the number of users. As a result, the total discharge was first estimated from the ‘dry period’ reservoir water balance and compared to the measured values. In addition, measurement of runoff from the catchment is also very difficult as it flows into the reservoir in streams and as an overland flow over a large area. The 'rainy period' water balance was, therefore, used to determine the catchment runoff. The classification of the periods was made taking these aspects into account.

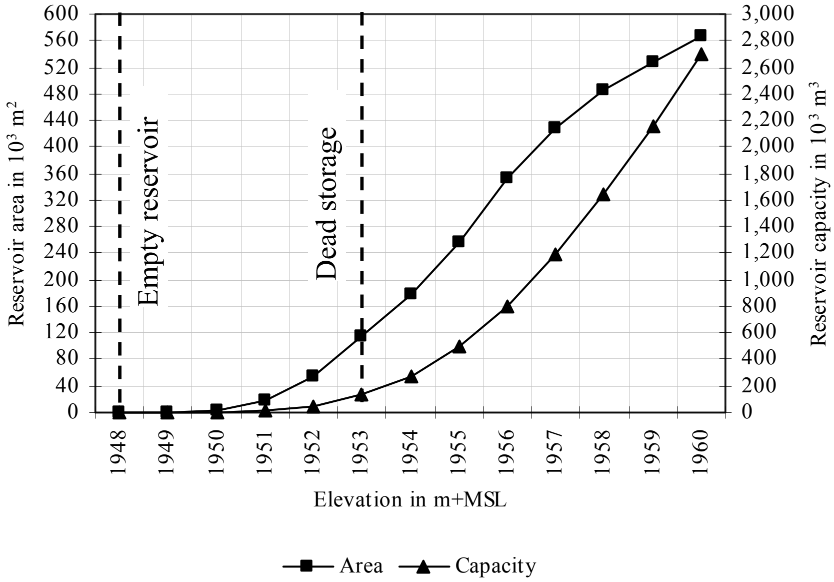


Figure 5.16 Elevation-area-capacity relationship for Gumsalasa earthen dam

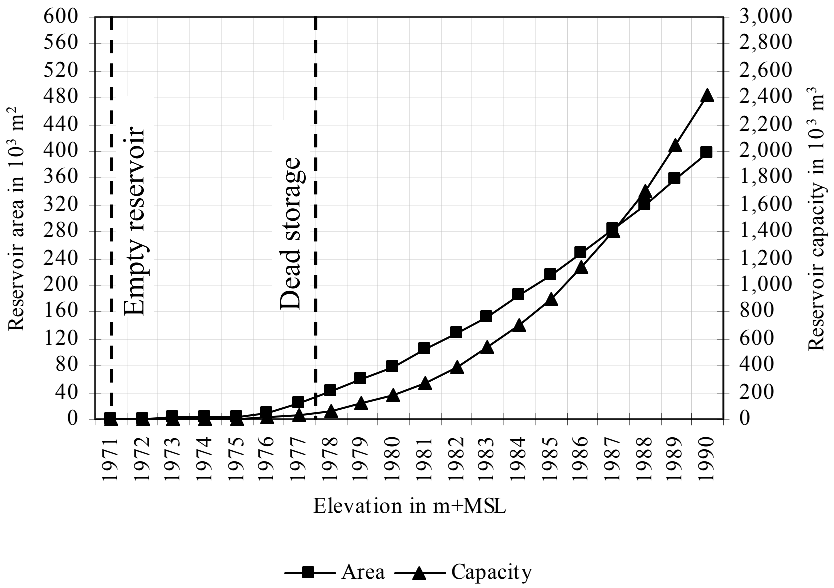


Figure 5.17 Elevation-area-capacity relationship for Korir earthen dam

The 2004 observation period in both sites was divided into two, with the last canal operation day taken as the last day of the first period (dry period). The dry period, which was used to estimate the canal discharge, include 15/03/04 – 02/06/04 and 13/03/04 – 29/05/04 for Gumsalasa and Korir respectively (Figure 5.18 and Figure 5.19). The remaining period, 19/06/04 – 18/08/04 at Gumsalasa and 30/05/04 – 23/07/04 at Korir, has no discharge and was used to estimate the catchment runoff. This period (rainy period) was further divided based on the trend of the reservoir water level. The water level at Gumsalasa continued to decrease during 19/06/04 – 30/07/04 and then increased between 31/07/04 – 18/08/04. The Korir reservoir generally showed a decreasing trend during this period. As a result, the Gumsalasa rainy period was split into two sub-periods: 19/06/04 – 30/07/04 and 31/07/04 – 18/08/04 (Figure 5.20 - Figure 5.22). The daily reservoir water level with reference to the diver tip was calculated using equation 4.10.

The trend of the water level is closely related to the evaporation, discharge and rainfall in both sites (Figure 5.5, Figure 5.6; Eyasu Yazew, 2005). Average daily evaporation increases from March to May and then drops until August (Figure 5.5 and Figure 5.6). The water level shows a very steep decrease during March – May with the increase in evaporation and the high discharge (Eyasu Yazew, 2005, Figure 5.18 and Figure 5.19). The total decrease in level during this period was 1,112 mm at Gumsalasa over 80 days and 758 mm at Korir over 78 days. The higher value at Gumsalasa was due to the larger evaporation and average discharge (Eyasu Yazew, 2005 and Table 5.7).

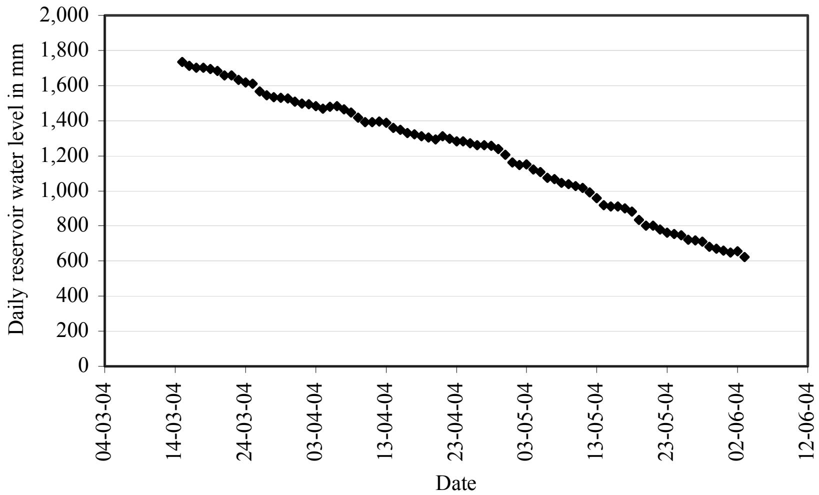


Figure 5.18 Reservoir water level with respect to the diver tip at Gumsalasa during the 2004 ‘dry period’ (15/03/04 – 02/06/04)

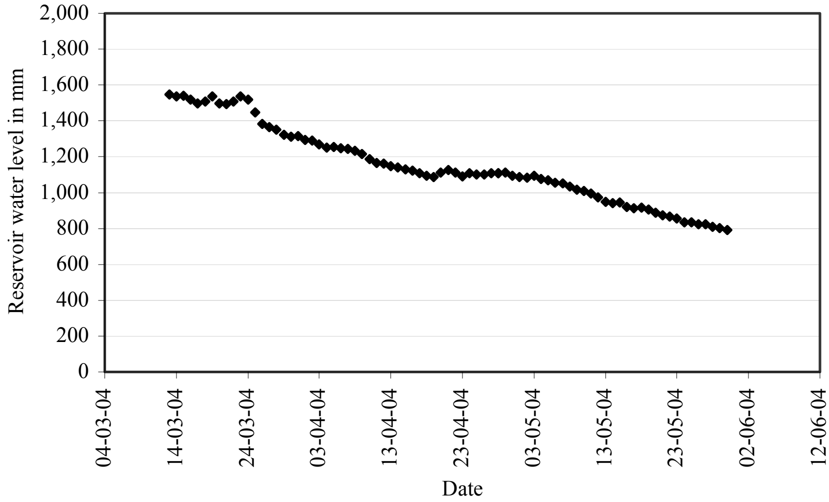


Figure 5.19 Reservoir water level with respect to the diver tip at Korir during the 2004 'dry period' (13/03/04 – 29/05/04)

The steepness of the drop in water level decreases towards the rainy season (Figure 5.20 and Figure 5.21). The reduction in the water level was only 125 mm at Gumsalasa over 42 days and 217 mm at Korir over 55 days. There was no discharge in both sites and the slight variation is related to evaporation. The sharp rise in the water level at Gumsalasa during the main rainy season was contributed by the higher inflow and less outflow (Figure 5.22 and Eyasu Yazew, 2005).

The diver readings and the corresponding elevations (m+MSL) of the two periods are presented in Eyasu Yazew (2005).

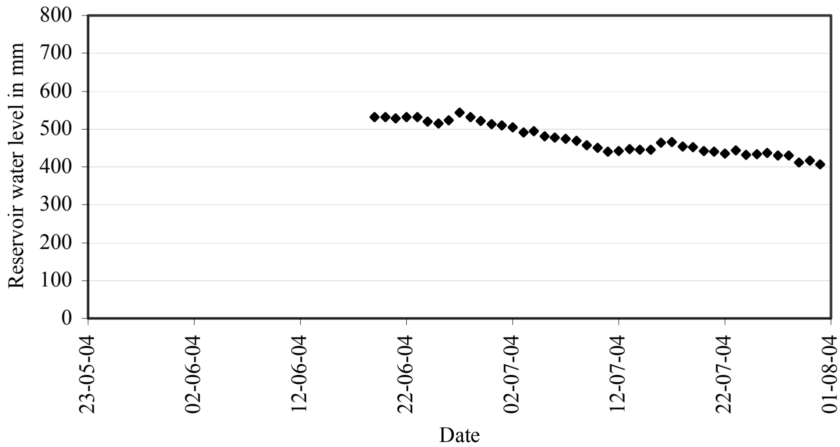


Figure 5.20 Reservoir water level with respect to the diver tip at Gumsalasa during the 2004 'rainy period I' (19/06/04 – 30/07/04)

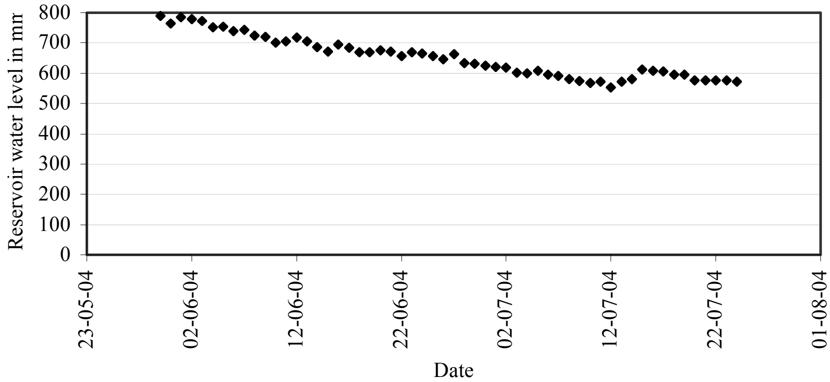


Figure 5.21 Reservoir water level with respect to the diver tip at Korir during the 2004 'rainy period' (30/05/04 – 23/07/04)

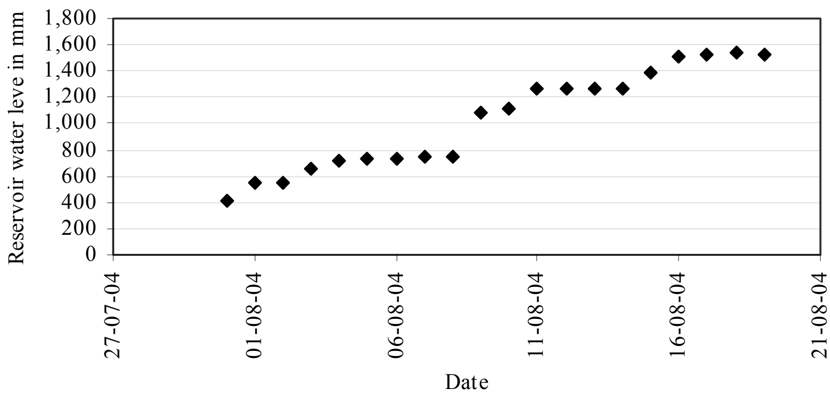


Figure 5.22 Reservoir water level with respect to the diver tip at Gumsalasa during the 2004 'rainy period II' (31/07/04 – 18/08/04)

Figure 5.23 and Figure 5.24 represent the daily water levels in the reservoirs during 2002, with the tip of the diver data logger taken as datum. The divers were shifted to a different location on 18/06/02 and 23/05/02 at Gumsalasa and Korir respectively. While the actual diver readings before and after the shift of position is given in Eyasu Yazew (2005), the figures present an artificially connected water level. This was done by adding the initial water level of the second period to the change in water level of the first period. The gaps at the end of the observation period in both sites were due to a sharp increase in water level.

As in 2004, the decrease in the reservoir water level during the dry period of 2002 (April and May) was very steep due to the high evaporation and discharge (Eyasu Yazew, 2005). The total water level decrease was 1,061 mm at Gumsalasa over 63 days and 982 mm at Korir over 50 days. The steepness then decreases towards the early rainy season due to the reduced outflow and presence of some rainfall. It finally shows a steep increase during the rainy season as a result of the higher inflow and less outflow. For 2002, the duration before and after the shift of the diver location was taken as dry period and rainy period respectively.

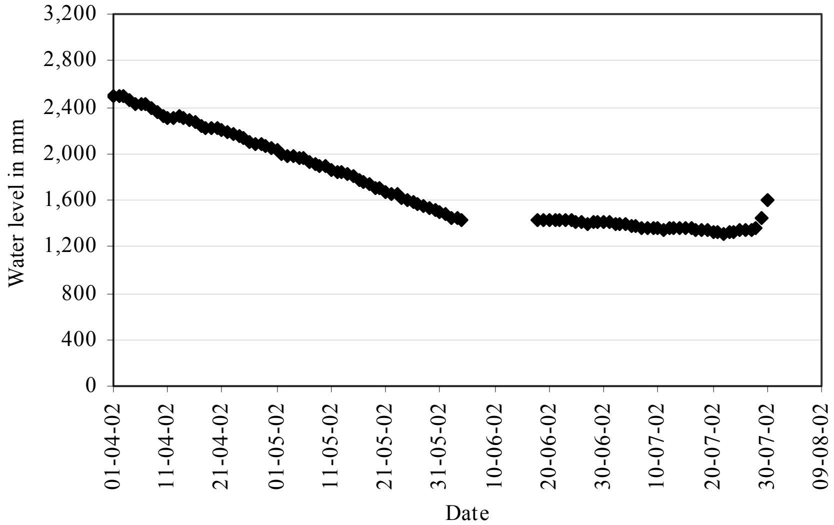


Figure 5.23 Daily water levels of the reservoir at Gumsalasa in 2002

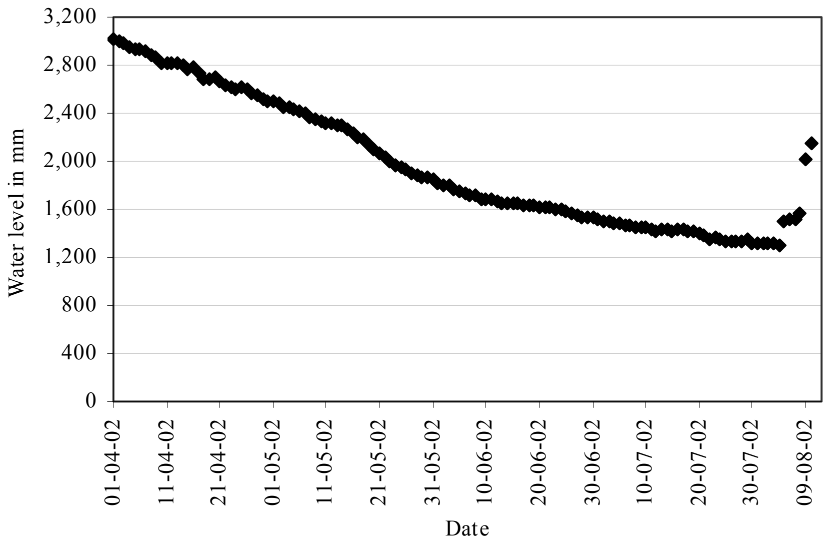


Figure 5.24 Daily water levels of the reservoir at Korir in 2002

Dry period water balance

Table 5.10 presents the summary of the 2002 and 2004 dry period data used for the water balance analysis at Gumsalasa and Korir. The relevant daily data of each parameter over the observation period has been given in Eyasu Yazew (2005).

Table 5.10 Data used for dry period water balance analysis of 2002 and 2004

Data	Gumsalasa		Korir	
	2002	2004	2002	2004
Duration (t)	02/04 – 03/06	15/03–02/06	04/04 – 23/05	13/03-29/05
Total no. of days (N)	63	80	50	78
Irrigation days	52	42	50	53
Initial water level in m+MSL	n.a	1955.19	n.a.	1982.34
Final water level in m+MSL	n.a.	1954.08	n.a.	1981.58
Change in water level (ΔW_D) in m	-1.061	-1.112	-0.982	-0.758
Average reservoir area (A_{Rav})[1] in 10^3 m^2	n.a.	227.5	n.a	127
Change in reservoir water volume (ΔV_R)[1] in 10^3 m^3	Unknown	-250	Unknown	-110
Reservoir evaporation (E_R) in m	0.442	0.563	0.350	0.497
Canal discharge				
- Discharge (V_C) in m^3	Unknown	Unknown	Unknown	Unknown
- Operation time (T_{op}) in 10^3 s	1,743	949	2,256	920
Seepage (V_S) in m^3/d	346	346	-	-
Livestock consumption (V_L) in m^3/d	21	21	39	39
Groundwater recharge (R_{GW}) in m/d	$0.9*10^{-3}$	$0.9*10^{-3}$	$0.4*10^{-3}$	$0.4*10^{-3}$
Inflow (I)				
- Direct reservoir rainfall (P_R) in m	0	0.044	0	0.005
- Catchment runoff (Ro) in m^3	-	-	-	-
- Rainfall days	0	6	0	2
Irrigated area in ha	70	40.8	58	20.6

Note:
Unknown means that there were no direct measurements of the parameters and that they have to be determined from the water balance analysis; while n.a. represents not available
1 = obtained from Table 5.11

The water balance of the various periods can be calculated based upon Equation 4.14. The reservoir area and capacity corresponding to the initial and final reservoir water levels as given in Table 5.11 for 2004 were obtained from Figure 5.16 and Figure 5.17. As it can be seen in Table 5.10, there is only one unknown in each site for 2004. With all the variables known, the canal discharge can be estimated from the water balance. The water balance during the 2004 dry period (15/03/2004 – 02/06/2004) at Gumsalasa will be:

$$\Delta V_R = I - (E_R * A_{Rav} + Q_C * T_{op} + V_S * N + V_L * N + R_{GW} * A_{Rav} * N)$$

$$\Delta V_R = R_O + (P_R * A_{Rav}) - (E_R * A_{Rav} + Q_C * T_{op} + V_S * N + V_L * N + R_{GW} * A_{Rav} * N)$$

$$-250{,}000 = 0 + 10{,}010 - (128{,}100 + Q_C * T_{op} + 27{,}680 + 1{,}680 + 16{,}380)$$

$$Q_C * T_{op} = 86{,}250 \text{ m}^3$$

The water balance for Korir during the dry period (13/03/2004 – 29/05/2004) can be calculated as:

$$-110{,}000 = 0 + 635 - (63{,}120 + Q_C * T_{op} + 0 + 3{,}042 + 3{,}962)$$

$$Q_C * T_{op} = 40{,}510 \text{ m}^3$$

Table 5.11 Reservoir area and capacity for the initial and final water levels of the reservoirs during 2004

Site	Period	Reservoir characteristics			
		Water level in m+MSL	Area in 10^3 m^2	Volume in 10^3 m^3	Change in reservoir volume in 10^3 m^3
Gumsalasa	Dry period				(-)250
	- Initial	1955.19	270	550	
	- Final	1954.08	185	300	
	Rainy period I				(-)15
	- Initial	1953.79	163	240	
	- Final	1953.67	156	225	
	Rainy period II				(+)215
	- Initial	1953.67	156	225	
	- Final	1954.79	235	440	
Korir	Dry period				(-)110
	- Initial	1982.34	136	440	
	- Final	1981.58	118	330	
	Rainy period				(-)20
	- Initial	1981.58	118	330	
	- Final	1981.37	112	310	

The result shows that the total volume of canal discharge in the dry period at Gumsalasa and Korir in 2004 was 86,250 m^3 and 40,510 m^3 respectively. The total canal operation time during the same period was 15,820 minutes at Gumsalasa and 15,330 minutes at Korir (Table 5.10). The corresponding average canal discharge (Q_C) would be 90 l/s and 44 l/s at Gumsalasa and Korir respectively. The measured average discharge of the main canal at Gumsalasa and Korir were 122 l/s and 47 l/s (Table 5.7). Comparing the results show that the canal discharge at Korir is more consistent than at Gumsalasa.

Regarding the water balance of 2002, Table 5.10 reveals two unknowns, namely, change in reservoir water volume and canal discharge. The direct adjustment of the 2002 change in reservoir water volume is difficult due to the unknown reservoir water level in m+MSL. However, the canal discharge of 2002 can be estimated based on the relationship between the canal operation time and irrigated area of the years. Even if the canal operation time and irrigated area in 2002 was greater than 2004 in both sites, a close relationship exists between the ratio of the 2004-2002 irrigated area and canal operation time. The ratio of the 2004-2002 irrigated area at Gumsalasa and Korir was 0.58 and 0.36, while the corresponding ratio of the canal operation time was 0.54 and 0.4. Since the variation of the ratios in both cases was only 4%, it might be fair to assume the canal discharge of 2002 and 2004 to be comparable. Equation 4.14 can be used to calculate the average reservoir area and water balance related to this discharge. The average reservoir area and the change in the reservoir water volume (ΔV_R) during the 2002 dry period (02/04/2002 – 03/06/2002) at Gumsalasa will be:

$-1.061 A_{Rav} = -(0.442\ A_R + 156.6 * 10^3 + 21.8 * 10^3 + 1.3 * 10^3 + 56.7 * 10^{-3} * A_{Rav})$

$A_{Rav} = 320 * 10^3\ m^2$

$\Delta V_R = -1.061 * 320 * 10^3$
$= -340 * 10^3\ m^3$ in 63 days ($5.4 * 10^3\ m^3/d$)

The average reservoir area and the change in the reservoir water volume (ΔV_R) for Korir during the 2002 dry period (04/04/2002 – 23/05/2002) can similarly be calculated as:

$-0.982\ A_{Rav} = -(0.35 A_{Rav} + 99 * 10^3 + 0 + 2 * 10^3 + 20 * 10^{-3} * A_{Rav})$

$A_{Rav} = 165.6 * 10^3\ m^2$

$\Delta V_R = -0.982 * 165.6 * 10^3$
$= -163 * 10^3\ m^3$ in 50 days ($3.3 * 10^3\ m^3/d$)

The calculated change in reservoir water volume during the dry period of 2002 seems acceptable compared to 2004. The decrease in volume at Gumsalasa during the 2002 and 2004 dry period was $340 * 10^3\ m^3$ ($5.4 * 10^3\ m^3/d$) and $250 * 10^3\ m^3$ ($3.1 * 10^3\ m^3/d$) respectively. The decrease at Korir was $163 * 10^3\ m^3$ ($3.3 * 10^3\ m^3/d$) in 2002 and $110 * 10^3\ m^3$ ($1.4 * 10^3\ m^3/d$) in 2004. The higher average decrease in 2002 was due to the larger irrigated area and corresponding discharge. Compared to the 2002, the irrigated area in 2004 was reduced to about 58% and 36% at Gumsalasa and Korir respectively. The corresponding decrease in the daily discharges was 55% at Gumsalasa and 40% at Korir (Table 5.12 and Table 5.13).

The summary of the water balance during the 2002 and 2004 dry period is given in Table 5.12 and Table 5.13. The trend of the decrease in reservoir water volume of the dry period during 2004 is the same as in 2002. In both years, the total decrease in reservoir water volume is higher at Gumsalasa than Korir. This is due to the larger irrigated area and the corresponding canal discharge at Gumsalasa than Korir. In addition, the reservoir evaporation at Gumsalasa was higher during the observation period in both years (Table 5.10). Table 5.12 and Table 5.13 also show that the decrease in reservoir volume is mainly the result of canal discharge and reservoir evaporation in both sites. The reservoir evaporation holds the largest part in both sites in 2004, while the canal discharge was the highest value in 2002. The reason may be the larger number of evaporation days in the dry period and the smaller canal operation times and discharge in 2004 (Table 5.10).

The variation in the total decrease of the reservoir water volume between the study sites was mainly related to the difference in reservoir area and irrigated area (Table 5.12 and Table 5.13). The average daily values in mm of individual water balance variables were comparable. The slightly high canal discharge at Gumsalasa can be the result of the evaporation.

Table 5.12 Summary of the dry period water balance at Gumsalasa in 2002 and 2004

Water balance variable	2002				2004			
	Total	Daily average		% (3)	Total	Daily average		% (3)
	in 10^3 m^3	in m^3 (1)	in mm(2)		in 10^3 m^3	in m^3 (1)	in mm(2)	
Change in reservoir water volume	(-)339.6				(-)250			
Outflow								
- Reservoir evaporation	(-)141.5	2,246	7.00	41.7	(-)128.1	1,600	7.00	49.2
- Canal discharge	(-)156.6	3,011	4.30	46.1	(-)86.2	2,050	5.00	33.2
- Seepage discharge	(-)21.8	346	1.10	6.4	(-)27.7	346	1.50	10.6
- Livestock consumption	(-)1.3	21	0.06	0.4	(-)1.7	21	0.09	0.7
- Groundwater recharge	(-)18.1	287	0.90	5.3	(-)16.4	204	0.90	6.3
Inflow								
- Direct reservoir rainfall	-				(+)10.0			
- Catchment runoff	-			-	-			-
Sum				100.0				100.0

Note:

1 = all average values except canal discharge are calculated based on the total number of days in the period, which were 63 and 80 for 2002 and 2004 respectively. The average canal discharges were estimated from the operation days, which were 52 in 2002 and 42 in 2004

2 = all the values except the canal discharge were determined using the average reservoir area of the period ($320 * 10^3$ m^2 for 2002 and $227.5 * 10^3$ m^2 for 2004). The average for the canal discharge was calculated based on the area irrigated, which was 70 ha in 2002 and 40.8 ha in 2004

3 = this indicates the percentage of each water balance variable with respect to the total outflow. It also represents the same in Table 5.13.

Table 5.13 Summary of the dry period water balance at Korir in 2002 and 2004

Water balance variable	2002				2004			
	Total	Daily average		% (3)	Total	Daily average		% (3)
	in 10^3 m^3	in m^3 (1)	in mm(2)		in 10^3 m^3	in m^3 (1)	in mm(2)	
Change in reservoir water volume	(-)162.6				(-)110.0			
Outflow								
- Reservoir evaporation	(-)58.0	1,160	7.0	35.7	(-)63.1	809	6.4	57.0
- Canal discharge	(-)99.0	1,980	3.4	60.9	(-)40.5	764	3.7	36.7
- Seepage discharge	-	-	-	-	-	-	-	-
- Livestock consumption	(-)2.0	39	0.2	1.2	(-)3.0	39	0.3	2.7
- Groundwater recharge	(-)3.3	66	0.4	2.0	(-)4.0	51	0.4	3.6
Inflow								
- Direct reservoir rainfall	-				0.6			
- Catchment runoff	-			-	-			-
Sum				100.0				100.0

Note:

1 = all average values except canal discharge are calculated based on the total number of days in the period, which were 50 and 78 for 2002 and 2004 respectively. The average canal discharges were estimated from the operation days, which were 50 in 2002 and 53 in 2004

2 = all the values except the canal discharge were determined using the average reservoir area of the period ($165.6 * 10^3$ m^2 for 2002 and $127 * 10^3$ m^2 for 2004). The average for the canal discharge was calculated based on the area irrigated, which was 58 ha in 2002 and 20.6 ha in 2004

Rainy period water balance

The summary of the 2002 and 2004 rainy period data used for the water balance analysis at Gumsalasa and Korir is presented in Table 5.14. The relevant daily data of each parameter over the observation period have been given in Eyasu Yazew (2005).

The table indicates that catchment runoff (R_O) is the only unknown in both sites in 2004. The runoff from the catchment to the reservoirs can, therefore, be estimated from the water balance analysis of the rainy periods. The rainy period water balance of Gumsalasa is divided into two, rainy period I and rainy period II, the sum of which will give the total water balance.

Table 5.14 Data used for rainy period water balance analysis of 2002 and 2004

Data	Gumsalasa			Korir	
	2002	2004		2002	2004
		I	II		
Duration (t)	18/06 – 29/07	19/06– 30/07	31/07- 18/08	24//05 – 09/08	30/05- 23/07
Total no. of days (N)	42	42	19	78	55
Irrigation days	1	-	-	57	-
Initial water level in m+MSL	n.a	1953.79	1953.67	n.a.	1981.58
Final water level in m+MSL	n.a.	1953.67	1954.79	n.a.	1981.37
Change in water level (ΔW_D) in m	0.16	-0.125	1.118	0.188	-0.217
Average reservoir area (A_{Rav})[1] in 10^3 m^2	n.a.	159.5	195.5	n.a	115
Change in reservoir water volume (ΔV_R)[1] in 10^3 m^3	Unknown	-15	+215	Unknown	-20
Total reservoir evaporation (E_R) in m	0.17	0.141	0.052	0.31	0.216
Canal discharge					
- Discharge (Q_C) in m^3/s	0.09	-	-	0.044	-
- Operation time (T_{op}) in 10^3 s	39	-	-	1,760	-
Seepage (V_S) in m^3/d	346	346	346	-	-
Livestock consumption (V_L) in m^3/d	21	21	21	39	39
Groundwater recharge (R_{GW}) in m/d	$0.9*10^{-3}$	$0.9*10^{-3}$	$0.9*10^{-3}$	$0.4*10^{-3}$	$0.4*10^{-3}$
Inflow (I)					
- Direct reservoir rainfall (P_R) in m	0.102	0.06	0.119	0.169	0.054
- Catchment runoff (Ro) in m^3	Unknown	Unknown	Unknown	Unknown	Unknown
- Rainfall days	13	8	10	17	14

Note:
Unknown means that there were no direct measurements of the parameters and that they have to be determined from the water balance analysis; while n.a. represents not available
1 = obtained from Table 5.11

The water balance during the first part of the rainy period (19/06/2004 – 30/07/2004) is given below:

$$- 15{,}000 = R_O + 9{,}570 – (22{,}490 + 0 + 14{,}532 + 882 + 6{,}029)$$

$$R_O = 19{,}360 \text{ m}^3$$

The water balance during the second phase of the rainy period at Gumsalasa (31/07/2004 - 18/08/2004) was:

$$215{,}000 = R_O + 23{,}265 – (10{,}166 + 0 + 6{,}574 + 399 + 3{,}343)$$

$$R_O = 212{,}200 \text{ m}^3$$

The water balance of Korir in the rainy period (30/05/2004 – 23/07/2004) follows the same procedure:

$$-20{,}000 = R_O + 6{,}120 – (24{,}840 + 0 + 0 + 2{,}145 + 2{,}530)$$

$$R_O = 3{,}400 \text{ m}^3$$

Similar to the case of the dry period, there are two unknowns for the rainy season water balance of 2002. These are the change in reservoir water volume and the catchment runoff (Table 5.14). Since most of the water would be released, the reservoir area towards the end of the irrigation season is generally small. Considering the little variation in the change of the water level, it might be reasonable to assume that the reservoir area of 2002 was comparable to 2004. The total inflow in 2002 was determined based on the rainy period reservoir area of 2004.

The inflow during the 2002 rainy period (18/06/2002 – 29/07/2002) at Gumsalasa will be:

$$25.5 * 10^3 = R_O + 16.3 *10^3 - (27.1 * 10^3 + 3.5 * 10^3 + 14.5 * 10^3 + 0.9 * 10^3 + 6 * 10^3)$$

$$R_O = 61.2 * 10^3 \text{ m}^3$$

Similarly, the inflow at Korir during the 2002 rainy period (24/05/2002 – 09/08/2002) can be calculated as:

$$21.6 * 10^3 = R_O + 19.4 *10^3 - (35.6 * 10^3 + 77.4 * 10^3 + 0 + 3 * 10^3 + 3.6 * 10^3)$$

$$R_O = 121.8 * 10^3 \text{ m}^3$$

The summary of the 2002 and 2004 rainy season water balance is presented in Table 5.15 and Table 5.16. In both years, the diver was removed from the reservoir before the end of the rainy season (before it submerges in the reservoir). As a result, the rainy period water balance represents only part of the rainy season. The results show that the inflow at Gumsalasa was larger in 2004 than 2002, while the reverse was true for Korir. The main reason was the variation in rainfall situation during the observation period (Table 5.14). For example, the amount of rainfall at Gumsalasa during the 2002 and 2004 rainy period was 102 mm and 179 mm respectively.

The reservoir water balance during the entire observation period in both years is summarized in Table 5.17. The inflow during the data collection period (before the removal of the diver from the reservoir) in both sites was generally small. A relatively high inflow was recorded at Gumsalasa in 2004. In this case, out of the

274 * 10^3 m^3 inflow, about 84% and 16% was contributed by the catchment runoff and direct reservoir rainfall respectively.

Table 5.15 Summary of the rainy period water balance of Gumsalasa in 2002 and 2004

Water balance variable	2002			2004				
	Total in 10^3 m^3	in mm/d[1]	in %[2]	Period I in 10^3 m^3	Period II in 10^3 m^3	Total in 10^3 m^3	in mm/d[1]	in %[2]
Change in reservoir water volume	(+)25.5		33.0	(-)15.00	(+)215.00	(+)200.0		75.6
Outflow								
- Reservoir evaporation	(-)27.1	4.0	35.0	(-)22.49	(-)10.17	(-)32.7	3.0	12.4
- Canal discharge	(-)3.5	-	4.5	-	-	-	-	0.0
- Seepage discharge	(-)14.5	2.1	18.7	(-)14.53	(-)6.57	(-)21.1	2.0	8.0
- Livestock consumption	(-)0.9	0.1	1.1	(-)0.88	(-)0.40	(-)1.3	0.1	0.5
- Groundwater recharge	(-)6.0	0.9	7.7	(-)6.03	(-)3.34	(-)9.4	0.9	3.5
Inflow								
- Direct reservoir rainfall	(+)16.3			(+)9.57	(+)23.27	(+)32.8		
- Catchment runoff	(+)61.2			(+)19.36	(+)212.22	(+)231.6		
Sum			100.0					100.0

Note:

1= all average values are calculated based on the total number of days in the period and the average reservoir area. The total number of days were 42 in 2002 and 61 in 2004, while the corresponding reservoir area were 159.5 * 10^3 m^2 and 177.5 * 10^3 m^2

2 = this indicates the percentage of the individual water balance variables with respect to the total inflow, which was 77.5 * 10^3 m^3 during 2002 and 264.4 * 10^3 m^3 during 2004

Table 5.16 Summary of the rainy period water balance of Korir in 2002 and 2004

Water balance variable	2002			2004		
	Total in 10^3 m^3	in mm/d[1]	in %[2]	Total in 10^3 m^3	in mm/d[1]	in %[3]
Change in reservoir water volume	(+)21.6		15.3	(-)20.0		
Outflow						
- Reservoir evaporation	(-)35.6	4.0	25.2	(-)24.8	4.0	84.1
- Canal discharge	(-)77.4	2.3	54.8	-	-	0.0
- Seepage discharge	-	-	-	-	-	-
- Livestock consumption	(-)3.0	0.3	2.1	(-)2.2	0.3	7.3
- Groundwater recharge	(-)3.6	0.4	2.5	(-)2.5	0.4	8.6
Inflow						
- Direct reservoir rainfall	(+)19.4			(+)6.1		
- Catchment runoff	(+)121.8			(+)3.4		
Sum			100.0			100.0

Note:

1 = all average values except the canal discharge in 2002 are calculated based on the total number of days in the period and the average reservoir area. The total number of days was 78 in 2002 and 55 in 2004, while the reservoir area of both years was 115 * 10^3 m^2. The average for the canal discharge for 2002 was determined based on the operation days (57) and the area irrigated (58 ha)

2 = this indicates the percentage of the individual water balance variables with respect to the total inflow (141.2 * 10^3 m^3)

3 = this indicates the percentage of the individual water balance variables with respect to the total outflow (29.5 * 10^3 m^3)

Table 5.17 Water balance of the study sites during the observation periods in 2002 and 2004

Water balance variable	2002				2004			
	Dry period in 10^3 m^3	Rainy period in 10^3 m^3	Total in 10^3 m^3	Total in %[1]	Dry period in 10^3 m^3	Rainy period in 10^3 m^3	Total in 10^3 m^3	Total in %[1]
Gumsalasa								
Outflow			(-)391.3	100.0			(-)324.6	100.0
-Reservoir evaporation	(-)141.5	(-)27.1	(-)168.6	43.1	(-)128.1	(-)32.7	(-)160.8	49.5
-Canal discharge	(-)156.6	(-)3.5	(-)160.1	40.9	(-)86.2	-	(-)86.2	26.6
-Seepage discharge	(-)21.8	(-)14.5	(-)36.3	9.3	(-)27.7	(-)21.1	(-)48.8	15.0
-Livestock consumption	(-)1.3	(-)0.9	(-)2.2	0.6	(-)1.7	(-)1.3	(-)3.0	0.9
-Groundwater recharge	(-)18.1	(-)6.0	(-)24.1	6.1	(-)16.4	(-)9.4	(-)25.8	7.9
Inflow			(+)77.5	100.0			(+)274.4	100.0
-Direct reservoir rainfall	-	(+)16.3	(+)16.3	21.0	(+)10.0	(+)32.8	(+)42.8	15.6
-Catchment runoff	-	(+)61.2	(+)61.2	79.0	-	(+)231.6	(+)231.6	84.4
Korir								
Outflow			(-)281.9	100.0			(-)140.1	100.0
-Reservoir evaporation	(-)58.0	(-)35.6	(-)93.6	33.2	(-)63.1	(-)24.8	(-)88.0	62.8
-Canal discharge	(-)99.0	(-)77.4	(-)176.4	62.6	(-)40.5	-	(-)40.5	28.9
-Seepage discharge	-	-	-	-	-	-	-	0
-Livestock consumption	(-)2.0	(-)3.0	(-)5.0	1.8	(-)3.0	(-)2.2	(-)5.2	3.7
-Groundwater recharge	(-)3.3	(-)3.6	(-)6.9	2.4	(-)4.0	(-)2.5	(-)6.5	4.6
Inflow			(+)141.2	100.0			(+)10.1	100.0
-Direct reservoir rainfall	-	(+)19.4	(+)19.4	13.7	(+)0.6	(+)6.1	(+)6.7	66.3
-Catchment runoff	-	(+)121.8	(+)121.8	86.6	-	(+)3.4	(+)3.4	33.7

Note:
1 = percentage of the individual outflow or inflow variable with respect to the total
(-) = indicates withdrawal or decrease, (+) = indicates inflow or increase

As indicated in Chapter 1, the pattern of utilization of the reservoir water is as important as, or even more than, how much is stored. Figure 5.25 gives the percentage of the individual outflow variables with respect to the total during the observation periods. As it can be seen from the figure, reservoir evaporation constitutes the highest percentage at Gumsalasa in both years. At Korir, however, the canal discharge and reservoir evaporation took the largest part in 2002 and 2004 respectively. The high percentage of canal discharge in 2002 at Korir was due to the extended irrigation period (Table 5.14). The outflow values in Figure 5.25 represent only the irrigation period and the rainy season. The percentage of reservoir evaporation would have been larger if the duration between September and December, when the reservoirs are exposed to evaporation loss without any canal discharge, is taken into account. It can generally be summarized that a considerable amount of water is being lost as reservoir evaporation by the existing operational plan. The limited water stored in the reservoirs does not seem to be utilized effectively and would have to be amended. In view of this, evaluation of an alternative scenario for a more productive use of the available water is presented in Chapter 7.

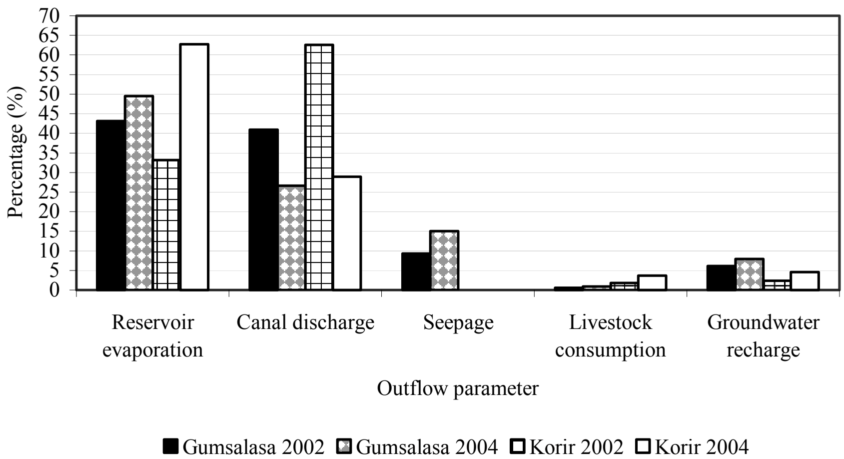


Figure 5.25 Present reservoir outflow patterns of the study sites

5.2 Reservoir sedimentation

5.2.1 Runoff plot method

Statistical analysis of the annual rainfall of the study sites shows that the rainfall of the year 2002 has a probability of exceedance of about 80% (Figure 5.26 and Figure 5.27). This means that there is an 80% probability for a rainfall equal or greater than in the year 2002 to occur every year. The most severe drought situation in the history of Ethiopia that affected about 12.5 million people coincided with the dry year 2002 (Table 5.18).

Table 5.18 Monthly rainfall of the study sites

Month	Rainfall at Gumsalasa in mm		Rainfall at Korir in mm	
	Year 2002	Average of previous 27 years	Year 2002	Average of previous 9 years
January	0	0.4	0	2.1
February	0	2.1	0	2.9
March	0	8.2	0	25.3
April	0	20.8	1.0	28.7
May	0	20.5	0	15.2
June	13.0	39.1	14.0	39.6
July	89.0	170.4	38.0	174.2
August	93.5	203.3	162.3	209
September	88.0	42.5	62.8	41.5
October	0	4.1	0	6.0
November	0	1.4	0	2.6
December	0	0.2	0	3.5
Total	283.5	513.0	278.1	543.0

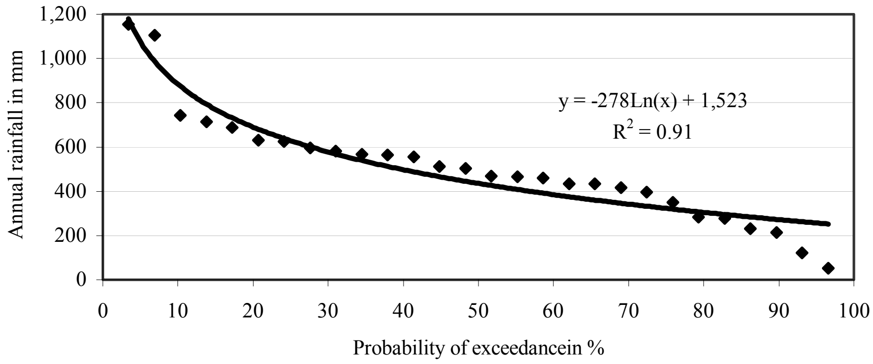


Figure 5.26 Graph of the probability of exceedance of annual rainfall at Gumsalasa

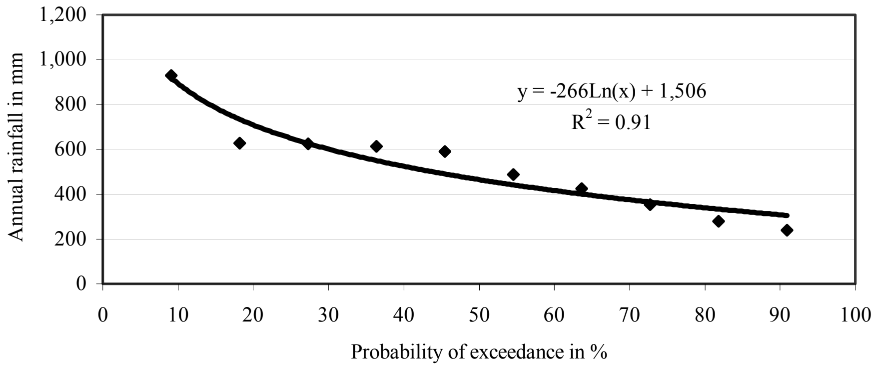


Figure 5.27 Graph of probability of exceedance of annual rainfall at Korir

The runoff plots were constructed during the main rainy season for assessment of the rainfall-runoff-erosion relationships. However, the rainfall events in general and the one's that caused runoff in particular were very few (Table 5.19). The factors affecting runoff can be grouped into two, namely, rainfall characteristics and watershed characteristics (Schwab, *et al.*, 1993). The major rainfall characteristics governing runoff are the amount, intensity, duration, and temporal and spatial distribution while those related to watershed include the type, erosion condition and physical nature of the soil, degree and length of slope, distribution and kind of vegetation, and size and shape of the drainage area (Ayres, 1972). The antecedent moisture condition of the soil also plays an important role.

Table 5.19 Rainfall, runoff and sediment load from runoff plots in the study sites in 2002

Month	Date	Rainfall in mm	Total runoff depth in mm	Total runoff volume in l[1]	Sediment load in gm/l	Total sediment load in gm/plot
Gumsalasa						
August	15	3.5	0	0	0	0
	18	4.0	0	0	0	0
	19	4.0	0	0	0	0
	21	4.0	0	0	0	0
	25	5.0	0	0	0	0
	28	0.5	0	0	0	0
	29	0.5	0	0	0	0
September	3	5.0	0	0	0	0
	5	18.0	130	25.5	6.0	153
	7	48.0	330	64.8	11.5	745
	8	4.0	0	0	0	0
	11	3.0	0	0	0	0
	12	32.0	410	80.5	19.5	1,569
Total rainfall that caused runoff (mm)						98
Total sediment load from the runoff plot area of 23.23 m^2 (kg)						2.5
Equivalent erosion rate (t/ha.yr)						1.1
Korir						
August	8	5.2	40	7.9	37.1	291
	9	14.0	1,024	201.0	20.1	4,039
	11	7.5	68	13.3	12.0	160
	13	10.0	0	0	0	0
	15	12.0	294	57.7	13.0	750
	16	3.1	37	7.3	2.4	17
	22	4.0	0	0	0	0
	25	8.5	654	128.3	14.6	1,874
September	2	3.0	21	4.1	5.7	23
	3	2.5	0	0	0	0
	6	56.0	3,014	591.5	4.4	2,603
Total rainfall that caused runoff (mm)						111.8
Total sediment load from the runoff plot area of 25.15 m^2 (kg)						9.8
Equivalent erosion rate (t/ha.yr)						3.9

Note: 1 = total runoff volume was calculated using Equation 4.16

The results in both of the study sites show a direct relationship between the amount of rainfall and runoff (Table 5.19, Figure 5.28 and Figure 5.29). However, the rainfall-runoff-sediment load relationships and patterns within and between the study sites over the whole rainy season vary depending on the plot and rainfall characteristics. The major factors identified include the slope, soil type, vegetation, antecedent moisture, and the number, amount, duration and intensity of rainfall.

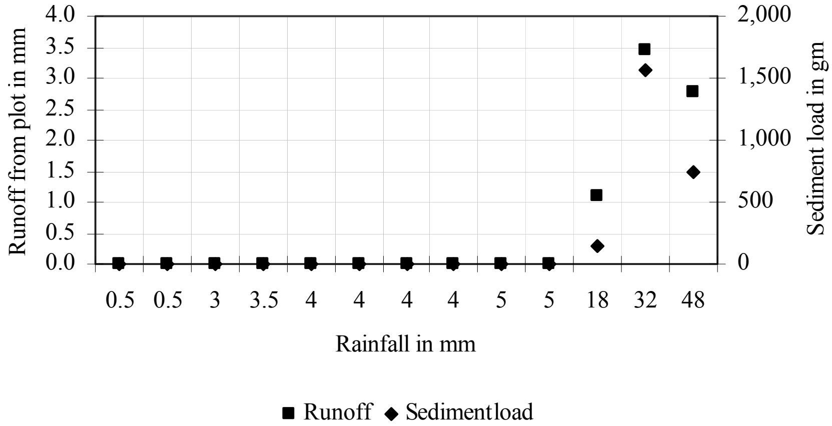


Figure 5.28 Rainfall-runoff-sediment load relationship at Gumsalasa in 2002

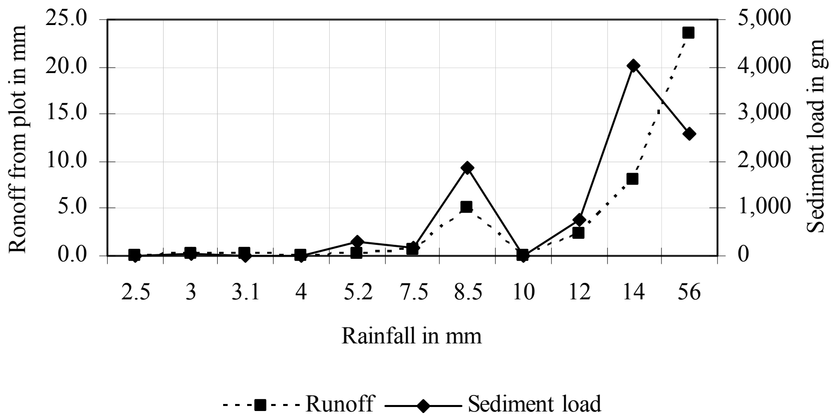


Figure 5.29 Rainfall-runoff-sediment load relationship at Korir in 2002

The antecedent moisture, and the amount, duration, and intensity of rainfall mainly affect the runoff within a plot. For instance there were conditions where smaller but intense rainfall events caused higher runoff. There were no intensity measuring devices in the study sites and observation was used for qualitative comparison. A good example here are the rainfall events on 7 and 12 September 2002 at Gumsalasa where the smaller but intense rainfall caused high runoff. The effect of antecedent moisture on increasing runoff is demonstrated by the 9 August 2002 rainfall at Korir.

The runoff plots of both study sites were almost similar in area and soil type (medium). However, the runoff generated per unit of rainfall is generally higher at Korir. This means that the fraction of rainfall that becomes runoff, known as runoff coefficient, is higher at Korir than at Gumsalasa (Table 5.20). The slope played an important role in this case and Korir, which has a steeper slope (27%), generated a higher runoff.

Table 5.20 Runoff coefficients of the plots in the study sites in 2002

Month	Date	Plot rainfall		Equivalent (potential) runoff in the barrel[2]	Actual runoff in the barrel[3]	Runoff coefficient[4]
		Depth in mm	Volume[1] in 10^6 mm^3	Depth in mm	Depth in mm	
Gumsalasa						
August	15	3.5	88	449	0	0
	18	4.0	101	513	0	0
	19	4.0	101	513	0	0
	21	4.0	101	513	0	0
	25	5.0	126	641	0	0
	28	0.5	13	64	0	0
	29	0.5	13	64	0	0
September	3	5.0	126	641	0	0
	5	18.0	453	2,307	130	0.06
	7	48.0	1,207	6,151	330	0.05
	8	4.0	101	513	0	0
	11	3.0	75	384	0	0
	12	32.0	805	4,101	410	0.10
Korir						
August	8	5.2	131	666	40	0.06
	9	14.0	352	1,794	1,024	0.57
	11	7.5	189	961	68	0.07
	13	10.0	252	1,282	0	0
	15	12.0	302	1,538	294	0.19
	16	3.1	78	397	37	0.09
	22	4.0	101	513	0	0
	25	8.5	214	1,089	654	0.60
September	2	3.0	75	384	21	0.05
	3	2.5	63	320	0	0
	6	56.0	1,408	7,177	3,014	0.42

Note:
1 = plot areas of 23.23 m^2 and 25.15 m^2 taken for Gumsalasa and Korir respectively
2 = assumes all rainfall in the plot as runoff and is the ratio of the plot rainfall volume to the barrel area (barrel area = 196.25 * 10^3 mm^2)
3 = actually measured values as recorded in Table 5.19
4 = the ratio of actual to potential runoff depth in the barrel

The two study sites vary not only in runoff coefficient but also in the pattern of the erosion rate. As indicated in Table 5.19, the sediment concentration at Korir generally decreases over the rainy season while it shows an increasing trend at

Gumsalasa. The main sources of variation may be the vegetation, and number, amount and intensity of rainfall events that caused runoff from the plots. Korir has more runoff events (8) than Gumsalasa (3). Hence, the erosion rate decreases with time due to less detachment of the soil particles as the topsoil is already eroded by early runoff events. Besides, the change caused by rainfall to the moisture condition and the vegetation cover, and the small variation in the daily rainfall amounts may also contribute to the smaller erosion rate at Korir. The situation at Gumsalasa was different from Korir. The rainfall events that caused runoff were very few, the variation in amount between them was high and the effect of antecedent moisture and vegetation cover was minimal.

Table 5.21 Rainfall, runoff and sediment load from runoff plots at Gumsalasa in 2004

Month	Date	Rainfall in mm	Total runoff depth in mm	Total runoff volume in l[1]	Sediment load in gm/l	Total sediment load in gm/plot
July	13	7	0	0	0	0
	15	17	120	23.6	4	94.4
	16	3	0	0	0	0
	25	5	0	0	0	0
	28	6	0	0	0	0
	31	7	15	2.9	2	5.8
August	02	17	150	29.4	8	235.2
	04	5	12	2.4	2	4.8
	06	10	120	23.6	4	94.4
	07	5	25	4.9	2	9.8
	08	21	605	118.7	14	1661.8
	09	15	505	99.1	8	792.8
	10	17	730	143.3	14	2006.2
	14	6	20	3.9	2	7.8
	15	16	470	92.2	6	553.2
	21	16	280	55.0	4	220.0
	22	10	170	33.4	4	133.6
	24	15	480	94.2	8	753.6
	25	5	0	0	0	0
	27	7	10	2.0	2	4.0
September	02	6	0	0	0	0
	05	5	0	0	0	0
	07	6	0	0	0	0
	14	5	0	0	0	0
	22	5	0	0	0	0
Total rainfall that caused runoff (mm)						177
Total sediment load from the runoff plot of area 23.23 m^2 (kg)						6.6
Equivalent erosion rate (t/ha.yr)						2.8

Note:

1 = total runoff volume was calculated using Equation 4.16

Like in 2002, the total rainfall amount in 2004 was small compared to the average annual value. However, there was a better rainfall and runoff situation at Gumsalasa in 2004 than 2002. The number of rainfall events that caused runoff in 2004 was 14, while there were only 3 in 2002. The amount of rainfall that caused runoff was 177 mm in 2004 and 98 mm in 2002 (Table 5.19 and Table 5.21). The distribution of rainfall in 2004 has also contributed to a better antecedent moisture condition. The continuous rainfall events in August 2004 have caused a high runoff (Table 5.21). As a result the total sediment load from the runoff plot was higher during 2004 (2.8 t/ha.yr) than 2002 (1.1 t/ha.yr)

The result of 2002 and 2004 indicate that the annual erosion rate in the study sites is very low compared to the regional average mentioned in Chapter 2. It ranges from about 6.5% at Gumsalasa to 23% at Korir. Owing to the few rainfall events and the limitations of runoff plots, a comprehensive conclusion cannot be made at this stage over the erosion processes of the study sites. This indicates the need for further investigation of the situation using other approaches.

5.2.2 HR Wallingford method

The main objective of this research is to develop an integrated approach for sustainable land and water development and management in Tigray. A simple method that can allow the rapid identification of highly erosive catchments is very important in this regard. One such method as explained in Chapter 4 is the HR Wallingford (2003) method.

Figure 5.30 and Figure 5.31 represent the topography of the catchment area of the study sites (Poesen, *et al.*, 2001). The catchment area and all the necessary information for the estimation of the sediment yield were derived from topographic maps, field observations and measurements. The summary of the most important catchment characteristics is given in Table 5.22.

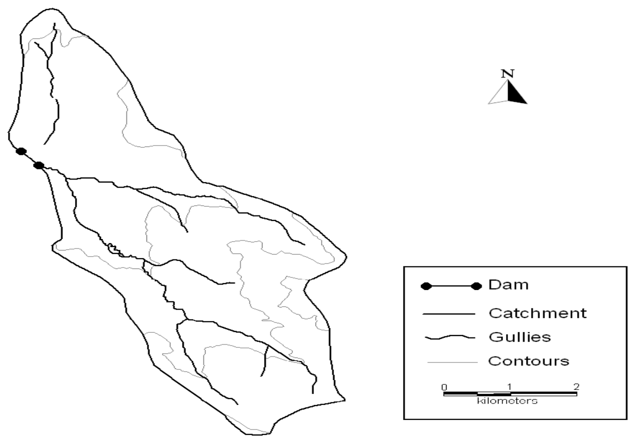


Figure 5.30 Catchment area of the Gumsalasa earthen dam (Poesen, *et al.*, 2001)

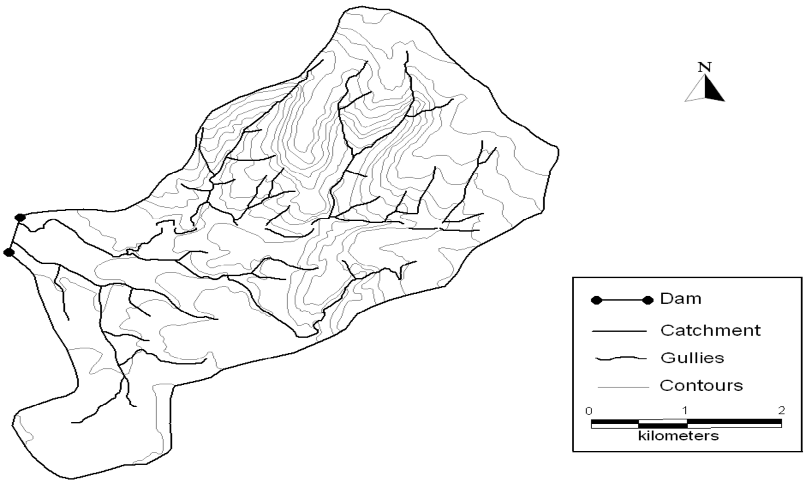


Figure 5.31 Catchment area of the Korir earthen dam (Poesen, *et al.*, 2001)

Table 5.22 Summary of scores for sediment yield estimation by HR Wallingford method

Catchment characteristics	Value/score		Remark
	Gumsalasa	Korir	
Catchment area (A) in km^2	18.6	15.5	Table 2.11
Mean annual precipitation (P) in mm	513	543	
River slope (S)	0.02	0.1	Poesen, *et al.*, 2001
Signs of active erosion (E)	20	10	Table 4.7
Soil type and drainage (SD)	20	20	Table 4.7
Vegetation cover (V)	40	40	Table 4.7

The sediment yield was estimated using Equation 4.17. The sediment yield at Gumsalasa is given below.

$$S_y = 0.0194 * A^{-0.2} * P^{0.7} * S^{0.3} * E^{1.2} * SD^{0.7} * V^{0.5}$$

$S_y = 0.0194 * 18.6^{-0.2} * 513^{0.7} * 0.02^{0.3} * 20^{1.2} * 20^{0.7} * 40^{0.5}$

$S_y = 495$ t/km^2.yr (5 t/ha.yr)

The sediment yield at Korir was estimated in the same manner:

$S_y = 0.0194 * 15.5^{-0.2} * 543^{0.7} * 0.1^{0.3} * 10^{1.2} * 20^{0.7} * 40^{0.5}$

$S_y = 377$ t/km^2.yr (3.8 t/ha.yr)

5.2.3 Verstraeten, et. al,. and the Pacific Southwest Inter Agency Commission (PSIAC) methods

The Verstraeten, *et. al*,. and the Pacific Southwest Inter Agency Commission (PSIAC) methods were applied by Poesen, *et al.,* (2001) to estimate the sedimentation of reservoirs in Tigray. Table 5.23 and Table 5.24 give the estimated sediment yield of the study sites based on the two methods. The data included in the tables were taken from Poesen, *et al,. (*2001).

Table 5.23 Estimation of catchment sediment yield by the Verstraeten, *et al,.* method[1] (Poesen, *et al.,* 2001)

Site	T	G	V	L	S	I	A in km^2	SSY[1] in $t/km^2.yr$
Gumsalasa	1	2	3	3	1	18	22.22	890
Korir	2	2	3	3	2	72	18.08	1,390

Note:
T = topography, G = gullies, V = vegetation cover, L = lithology, S = catchment shape, A = catchment area, I = catchment index, SSY = specific sediment yield
1 = I and SSY are calculated by using Equation 4.18. The scores of T, G, V, L and S were obtained from Table 4.8.

Table 5.24 Estimation of catchment sediment yield by PSIAC method[1] (Poesen, *et al.,* 2001)

Site	SG	S	C	R	T	GC	LU	UE	CE	Sum	SSY in $t/km^2.yr$
Gumsalasa	10	5	10	5	0	5	10	15	10	70.0	357-714
Korir	7	5.5	10	0	4	0	5	10	10	51.5	357-714

Note:
SG = surface geology; S = soils; C = climate; R = runoff; T = topography; GC = ground cover; LU = land use; UE = upland erosion; CE = channel erosion and sediment transport, SSY = specific sediment yield
1 = the scores of SG, S, C, R, T, GC, LU, UE and CE were obtained from Table 4.9. Table 4.10 was used to convert the sum of scores to the corresponding SSY

Referring to the results, the HR Wallingford shows a closer relationship with the runoff plots followed by PSIAC method. The Verstraeten, *et al.,* method, on the other hand, gives a very high estimate compared to the others. In order to select a suitable rapid assessment tool for catchment sediment yield, an evaluation of the results of the four methods based on the situations of the reservoirs is presented in Chapter 7.

6 Water management, socio-economics and salinity at Gumsalasa and Korir

6.1 Management of the irrigation schemes

6.1.1 Institutional set-up and irrigation policy

The Regional, Zonal and Wereda Bureau of Agriculture and Natural Resources plays a major role in the operation and maintenance of the various irrigation schemes in Tigray. However, there is no regionally formulated institutional set-up and irrigation policy for the management of the irrigated lands. As a result, community established 'Water Users Associations' or co-operatives play a major role in water allocation and distribution, conflict management, and operation and maintenance of the irrigation systems. The existing operation and maintenance rules are based on local by-laws (*'Serit laws'*) developed by the users in consultation with the Wereda Bureau of Agriculture and Natural Resources. In most irrigation systems the water committees and/or elected irrigation leaders, locally known as 'Abo Mai', are responsible for the implementation of the irrigation rotations, enforcement of penalties and other operation and maintenance related issues (Girmay, *et al.,* 2000).

The situation in the study sites corresponds with the above presented reality. The organizational structure of the irrigation schemes includes:

- General Assembly;
- management committee;
- 'Abo Mai';
- irrigation unit leaders;
- development agent;
- social court.

The General Assembly consists of all the beneficiary farmers of the irrigation scheme. The General Assembly and the Wereda Bureau of Agriculture and Natural Resources defined the local operation and maintenance rules at the beginning of the irrigation. The major aspects of the 'Serit law' are summarized below:

- a management committee of the irrigation schemes is elected at the start of each irrigation season;
- the total area that can be irrigated during every irrigation season is determined by the Wereda Bureau of Agriculture and Natural Resources and the General Assembly based on the water available in the reservoir;
- maintenance of the canal networks is the duty of the beneficiary farmers. The Wereda Bureau of Agriculture and Natural Resources takes a leading role in heavier maintenance activities such as breached culverts;
- maintenance of canals must be carried out during early September every year. Each beneficiary farmer has to contribute equal labour (3 – 5 days);

- every beneficiary should contribute 22 days of free labour for soil and water activities in the watershed. Additional labour contribution would be on food-for-work basis;
- the Wereda Bureau of Agriculture and Natural Resources has to provide the necessary technical support for the proper management of the irrigation scheme.

The management committee, consisting of 5 members, is responsible for the overall operation and maintenance of the irrigation scheme. An agricultural development agent assigned by the Wereda Bureau of Agriculture and Natural Resources offers technical assistance to the management committee. He/she also monitors the proper implementation of the operation and maintenance activities and rules. The irrigated area is divided into a number of irrigation units, locally known as 'Gujile'. Each unit holds an average of 20 – 25 farmers and has its own group leader. The irrigation unit leaders are responsible for the organization of all water management and maintenance issues within their block. In consultation with the management committee, the development agent and the 'Gujile' leaders, the Abo Mai' runs the day-to-day distribution of the irrigation water. The management committee, Abo Mai, development agent and irrigation unit leaders are also mandated to implement proper penalties for misconducts as indicated in Table 6.1. A farmer who breaks the operation and maintenance rules for a third time appears before the local social court.

Table 6.1 Summary of punishment measures against breaking the operation and maintenance rules

Misconduct	Primary penalty in Birr[1]	Secondary penalty in Birr	Final measure
Absence from general meetings without permission	10	10	-
Taking excess delivery time	10	20	Appears before social court
Water theft	100	500	Appears before social court
Sowing irrigated field by broadcasting	10	30	Appears before social court
Absence from maintenance activities	10	30	Appears before social court
Letting animals into the irrigated area	30	60	Appears before social court
Quarrel among farmers	-	-	Appears before Wereda judiciaries
'Abo Mai' not opening water on time	10	-	Appears before social court

Note:
1 = 1US$ is equivalent to 8.6 Birr (May, 2005)

6.1.2 Operation and maintenance

Present operation and maintenance practices

Furrow irrigation is the common practice in the study areas. The preliminary design by the CoSAERT recommended a gross application of 2.5 l/s.ha regardless of the soil type, crop type, growth stage, and the change in potential evapotranspiration. The design assumed about 11 – 12 hours of irrigation per day and the recommended delivery time was about 2 hours for each holding of 0.2 ha. This assumes rotational distribution among plots and the whole discharge (2.5 l/s) is allocated to each plot during the delivery time. A total of 10 hours is required to irrigate all the plots within a hectare, and the remaining 1 – 2 hours is needed during transfer of water from one plot to the other. This would provide 18,000 l of irrigation water for each 0.2 ha plot, which is equivalent to applying a gross irrigation depth of 9 mm/d.

The practice of the water distribution in Tigray in general and in the study areas in particular is generally not optimal. No consideration seems to be given to the recommended discharge and delivery time. Water is distributed among the farmers based on direct observations of the soil and plant conditions. The actual supply going to a field is not monitored. The preliminary plan was to use sluice gates at the outlet and the various division boxes to estimate the discharge. However, no sluice gate has been fitted so far.

The existing practice in the two schemes is that the ‘Abo Mai’ distributes water among the farmers in a rotational way. The irrigation interval varies based on soil and crop type and on the growing stage. For vegetables, the interval of the first irrigation is 3 days. Afterwards the interval varies from 5 – 15 days on light soils and 5 – 20 days on heavier soils. Similarly, the interval for maize ranges from 7 days at the very beginning to 21 days towards the end. The interval can be extended to 30 days in heavier soils. The common irrigation interval pattern is 3, 5, 7, 12, 15 and 20 days for vegetables and 7, 12, 15, 21 and 30 days for maize. According to the development agents, the average number of supplies over the irrigation season is given in Table 6.2.

Table 6.2 Average number of growing days and irrigation for the major crops in the study areas

Crop development stage	Vegetables		Maize	
	Number of days	Number of supplies	Number of days	Number of supplies
Initial	20	4	25	2
Crop development	30	2	40	4
Mid season	30	2	40	4
Late season	15	-	30	1

Water is distributed among the farmers on a rotational basis. However, the individual farmer decides the delivery time. The 2 hour delivery time per 0.2 ha does not work and the common practice is that a farmer passes the water to the next user only after he/she feels that his/her farm is well irrigated. As a result, wastage of irrigation water by runoff and over-watering is a common practice. The runoff loss was observed to be severe especially in short furrows where the farm discharge reaches the bottom end very quickly. Furrow lengths of as short as 6 m were found at Gumsalasa irrigation scheme. The over-watering, on the other hand, mostly occurs in fields that don not have furrows but are irrigated by spreading (Figure 6.1). Such way of irrigation allows the farmers to store more water in a form of ponds. The interviews with the farmers revealed the same result. According to them the present arrangement creates a sense of competition and selfishness resulting in excessive water applications. The rules and regulations developed by the Water Users Association have clearly set misconducts, such as excessive water applications, subject to punishment (Table 6.1). It seems that little attention is given to an effective implementation of the rules. Since the present practice allows individual farmers to directly communicate with the Abo Mai, the role of the irrigation unit leaders is no more functional.

Figure 6.1 A farm irrigated by spreading at Korir irrigation scheme

In times of dry-spells, restrictive measures are implemented in the schemes in order to efficiently utilize the limited water supply. In such events the types of restrictive measures are decided through negotiation/consultation among the beneficiaries and the Wereda Bureau of Agriculture and Natural Resources. The most commonly implemented restrictive measure is a reduction of the irrigated area. In this case, the area that can be irrigated by the available water in the reservoir will be estimated first. Then, the water will be distributed from upstream to downstream till the planned area is irrigated. The development agents do have neither the reservoir elevation-capacity curves nor the instrument to determine the elevation (m+MSL) of the reservoir water. As a result, the estimation of the irrigable area is based on the best guess of the agricultural expert. The victims of the restrictive measures are always the downstream, lower reach farmers.

The area irrigated in the study sites during the research period was less than the preceding years. The rainfall of the year 2002 was one of the dry-spell events in the study areas in particular and in the whole region in general (Table 5.19). As a result, the area irrigated by the proper canal in 2003 has been reduced to 20 ha at Gumsalasa and 19 ha at Korir. With 440 mm at Gumsalasa and 320 mm at Korir, the rainfall in 2003 was still less than the average annual rainfall but higher than the 2002. The corresponding irrigated area in 2004 was 40.8 ha and 20.6 ha at Gumsalasa and Korir respectively. The area irrigated by the proper canal in 2003 and 2004 at Gumsalasa has been 30% and 61% of the average of the earlier years respectively. Similarly, the irrigated area during 2003 and 2004 at Korir was only 35% and 37% of the previous average (Table 2.15).

The basic principle followed in implementing the restrictive measures in 2003 and 2004 was the same as the above (top to tail water distribution). However, the Wereda Bureau of Agriculture and Natural Resources included a second criterion that aimed at increasing the productivity of the scarce water, namely the right to irrigation water was determined by the will to use fertilizers. Even if located at the top of the command area, no water was allocated to farmers who did not use fertilizers.

Maintenance of the irrigation infrastructure is carried out at the beginning of each irrigation season. All the beneficiaries collectively repair and clean the irrigation infrastructure. Every farmer provides labour in equal measure regardless of the size of his or her land holding. On average, a household contributes 3 – 4 man-days for the maintenance work.

Field assessment of the present water management

Evaluation of field irrigation methods is an important aspect of water management and design. It can be used as a tool to characterize the water management, identify problems and develop alternative mechanisms for improving the system.

The major parameters in the field evaluation of furrow irrigation can be summarised as infiltration characteristics of the soil, farm discharge, advance and recession, furrow length and slope, delivery time and irrigated area.

The irrigated land holding at Gumsalasa is uniform (2,000 m^2/household). However, assessment of the farmers' practice revealed that the delivery time ranges between 3 hours and 5 hours. Discussion with the development agent has revealed that there are also cases where the delivery time exceeds 5 hours. The farm discharge and furrow lengths were also variable. The farm discharge, measured using a small parshall flume at different times and locations, was 2 – 3.5 l/s, while the furrow length varied between 6 – 12 m.

Infiltration is a very important process in surface irrigation and refers to the vertical movement of water into a soil. It controls the amount of water entering the soil reservoir and the advance and recession of the overland flow (Walker, 1989). Two infiltration tests were carried out at Gumsalasa with a double ring infiltrometer. Table 6.3 presents the mean particle size distribution of the soil over a profile of 1.2 m. According to the USDA soil classification system, the texture was classified as clay over the whole profile.

Table 6.3 Average particle size distribution over the various layers (Mintesinot, 2002)

Layer in cm	Sand in %	Silt in %	Clay in %
0 – 25	20	21	59
25 – 75	18	21	61
75 – 120	20	19	61
Average	19	21	60

Figure 6.2 presents the infiltration rate and cumulative infiltration of the two tests over 120 minutes. The figure shows that the results of the two tests were comparable. The final infiltration rate, usually known as basic infiltration rate, in both cases was about 0.1 mm/min (6 mm/hr).

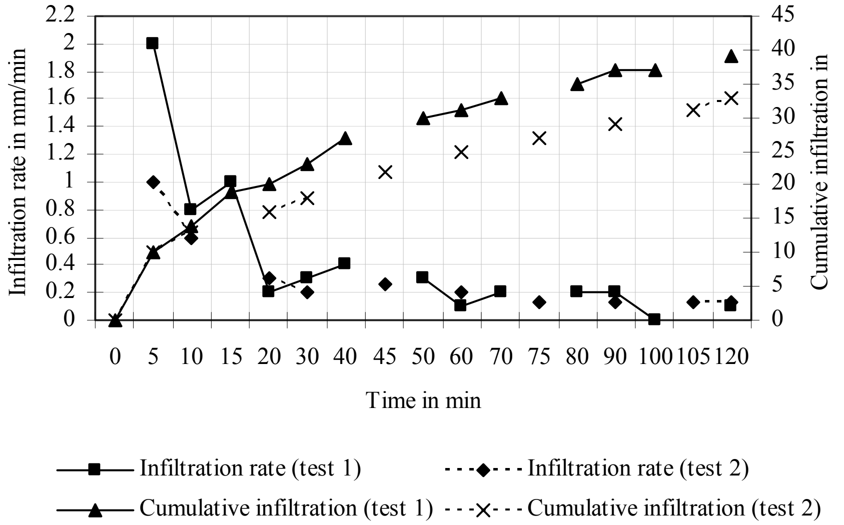


Figure 6.2 Infiltration rate and cumulative infiltration at Gumsalasa for two tests

Based on Jensen, *et al,*. (1993), the furrow advance coefficients of the soil would be about 0.853, 0.711, 7, 7.52, 1.74E-04 for a, b, c, f, and g respectively (Table 6.4).

Table 6.4 Intake family and furrow advance coefficients (Jensen, *et al.,* 1993)

Intake family	Soil type	Coefficients				
		a	b	c	f	g
0.05	very heavy clay	0.533	0.618	7	7.16	1.09E-04
0.10	heavy clay	0.620	0.661	7	7.25	1.25E-04
0.15	moderately heavy clay	0.711	0.683	7	7.34	1.41E-04
0.20	very heavy clay-loam	0.777	0.699	7	7.43	1.58E-04
0.25	heavy clay-loam	0.853	0.711	7	7.52	1.74E-04
0.30	moderately heavy/light clay-loam	0.925	0.720	7	7.61	1.90E-04
0.35	light clay-loam	0.996	0.729	7	7.70	2.07E-04
0.40	very light clay-loam	1.064	0.736	7	7.79	2.23E-04
0.45	very fine silty-loam	1.130	0.742	7	7.88	2.39E-04
0.50	fine silty-loam	1.196	0.748	7	7.97	2.56E-04
0.60	moderately fine-coarse silty-loam	1.321	0.757	7	8.15	2.88E-04
0.70	coarse silty-loam	1.443	0.766	7	8.33	3.21E-04
0.80	very coarse silty-loam	1.560	0.773	7	8.50	3.54E-04
0.90	fine sandy loam	1.674	0.779	7	8.68	3.86E-04
1.00	coarse sandy loam	1.786	0.785	7	8.86	4.19E-04
1.50	fine sand	2.284	0.799	7	9.76	5.82E-04
2.00	coarse sand	2.753	0.808	7	10.65	7.45E-04

The infiltration equation of the tests was also closely related. The cumulative infiltration of the soils was calculated based on the Kostiakov (1932) relationship. The Kostiakov equation is a simple power function of the form:

$$F = a * T_O^b \qquad 6.1$$

Where:
F = cumulative infiltration during opportunity time in mm
T_O = intake opportunity time in min
a and b = empirical constants

The constants were determined directly from the graph of the cumulative infiltration (F) and intake opportunity time (T_O) plotted on a log-log scale (Figure 6.3). The figures indicate that empirical constants and the cumulative infiltration equations of the tests are almost similar. The empirical values based on the two tests are 5.4 and 5.3 for ‘a’ and 0.42 and 0.37 for ‘b’. The following equation was used for the analysis:

$$F = 5.4 * T_O^{0.42}$$

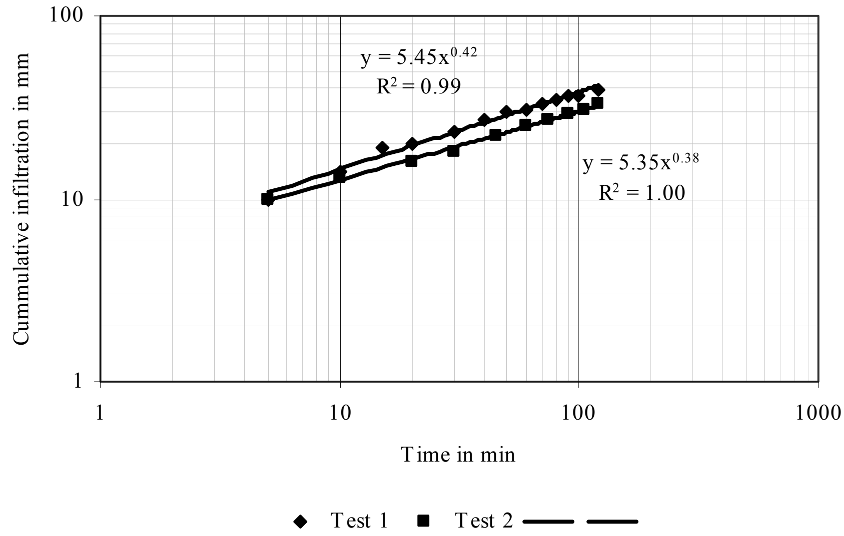


Figure 6.3 Cumulative infiltration over time for the two tests on a log-log scale

Field evaluation of the furrow irrigation was made on three different furrow lengths, namely, 6.3 m, 7.9 m and 12 m. The furrows were marked at various intervals and the advance and recession time of the flow was recorded. The advance and recession time refer to the time the water arrives at and disappears from a particular location respectively along the furrow. The difference between the two at the same location is the contact time and presents the opportunity time (T_O) (Figure 6.4).

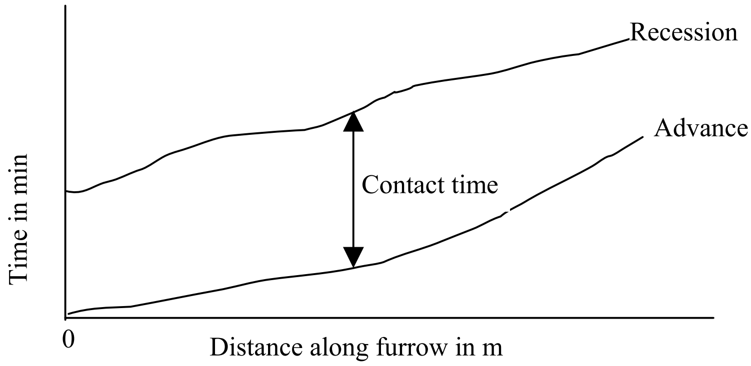


Figure 6.4 Advance, recession and contact time along a furrow

Two furrow evaluation trials were carried out for each furrow. Table 6.5 and Figure 6.5 show the average infiltration of irrigation water along the furrows, while the contact time and the corresponding infiltration of individual tests is given in Appendix C. The irrigated fields are characterized by short furrow lengths. Furrows are built on sloping land and, on short furrows, the advance front arrives at the end very quickly. Since furrows have very small space to store water, the water supply has to be cut off before sufficient water infiltrates at the top to avoid runoff. As a result, the contact time (and infiltration) generally increases with furrow length due to the accumulation of water down the slope (Appendix C).

Table 6.5 Average infiltration of irrigation water at various intervals along the furrows

Trial 1 (6.3 m furrow length)		Trial 2 (7.9 m furrow length)		Trial 3 (12 m furrow length)	
Distance along furrow in m	Average infiltration[1] in mm	Distance along furrow in m	Average infiltration[1] in mm	Distance along furrow in m	Average infiltration[1] in mm
0	16.1	0.0	12.8	0	10.8
2	17.0	3.0	15.6	2	10.8
4	17.1	6.0	17.4	4	11.6
6.3	17.1	7.9	14.8	6	14.7
				8	19.9
				10	22.6
				12	25.5
Average[2]	17.1		15.2		16.5

Note:
1 = this is the average of the two furrow evaluation trials (Appendix C)
2 = this is the average value over the whole length of the furrow

The average depth of infiltration of the furrows varies between 15 mm and 17 mm (Table 6.5). These infiltration values are much less than the water holding capacity of the soil. Table 6.6 gives the readily available moisture (RAM) of the soil for the two most common irrigated crops, maize and onion. The readily available moisture, which is equivalent to the net irrigation depth, was calculated using equation 6.2.

$$RAM = p * AM * D \qquad 6.2$$

Where:
RAM = readily available moisture of the soil in mm
p = fraction of the total available soil water which can be used by the crop without affecting its growth
AM = total available soil moisture in mm/m
D = depth of root zone of the crop in m

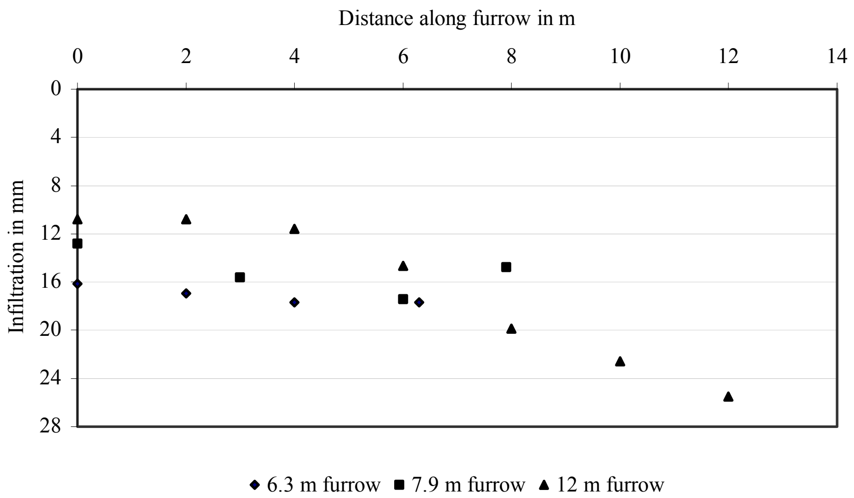


Figure 6.5 Average infiltration of irrigation water at various intervals along the furrows

Table 6.6 Readily available moisture (RAM) content of the soil under maize and onion at different growth stages

Soil and crop data	Maize				Onion				Source
Crop growth stage	I	CD	M	L	I	CD	M	L	CropWat
Root depth (D) in m	0.3	0.5	1	1	0.25	0.4	0.6	0.6	
AM in mm/m	180	180	180	180	180	180	180	180	Mintesinot (2002)
Depletion factor (p)	0.5	0.5	0.5	0.5	0.3	0.3	0.45	0.5	CropWat
RAM in mm	27	45	90	90	13.5	21.6	48.6	54	

Note:
AM = total available soil moisture, RAM = readily available moisture, I = initial stage, CD = crop development stage, M = mid season stage, L = late season stage

Table 6.6 reveals that the present furrow length and irrigation application fills only a small part of the soil moisture holding capacity. This can have a negative impact on the yield of the scheme. Evaluation of the present water management practice on the yield of maize and onion will be presented in Chapter 7. Figure 6.5 also indicates the possibility of better infiltration on longer furrows.

6.2 Socio-economic aspects

As indicated in Chapter 4, the major socio-economic issues investigated in the study sites were:

- land tenure issues including beneficiary selection, displacement, compensation, resettlement and farm size;
- water rights and charges;
- marketing and impact on household income;
- users participation and role of women.

6.2.1 Land tenure

Tenure issues with regard to irrigation development are related to beneficiary selection, determination of the farm size and compensation of farmers displaced by the change in land use. Generally, in a newly developed scheme in Tigray land is equitably allocated to legible farmers. Farmers who have land in the command area and those who lost their land for the scheme development get priority. However, due to limitation in capacity of the scheme and topographic barriers some individuals can be excluded. Investigation in the study sites has revealed that farmers displaced by the reservoir have been compensated for both the loss of production and loss of land. The loss of production that could have been achieved from the rainfed agriculture during the year the land is submerged by the reservoir was compensated by wheat. The original plan was to provide about 1,200 kg of wheat per hectare but there was some inconsistency during implementation. The compensation varied from 266 – 600 kg/ha at Gumsalasa to 933 – 1,200 kg/ha at Korir. The compensation for loss of land was addressed mostly by offering irrigated plots and, as deemed necessary, rainfed plots even if the policy prohibited further reallocation.

Due to the increased population, rural farmland was redistributed in Tigray in 1997. As a result, the rainfed landholding per household has decreased and the average rainfed landholding at Gumsalasa has reduced from 2.2 ha per household before 1997 to 1.2 ha per household afterwards. The rainfed landholding at Korir decreased from 1.5 ha to 1.2 ha per household. The average family size per household in both sites is about 6.

Concerning the irrigated farm size determination, more weight was given to achieving equity in income distribution and spreading the benefits. Accordingly, the current size of average irrigable landholding in Tigray was determined to be 0.2 ha regardless of the agroecology, family size, soil type and access to market.

Results from the study sites indicate that the irrigated land holding at Gumsalasa is 0.2 ha per household irrespective of the family size. On the other hand, the irrigated land holding at Korir takes into account the family size; with an average landholding of 0.32 ha per household, it varies between 0.125 ha to 0.75 ha per household based on the family size. As a result, farmers at Korir are more satisfied with their plot size than at Gumsalasa. About 58% of the respondents at Gumsalasa and 41% at Korir are not satisfied with their farm size while about 42% at Gumsalasa and 59% at Korir expressed their approval. The major reasons mentioned by the unsatisfied farmers were the lack of taking into account the variations in family size and soil types in the allocation process.

6.2.2 Water rights and charges

In Tigray, water rights are in principle related to land ownership in the command area. Accordingly, farmers are entitled to get water equitably. However, the practice in the study sites has revealed a different situation. As indicated in the previous section, distribution of irrigation water is done from head to tail, the irrigation interval is determined by field observation of the soil moisture status and physical conditions of plant and the delivery time is determined by the individual farmers. As a result, there is as such no equity and the downstream, lower reach farmers are mostly exposed to shortage or total lack of irrigation water. CoSAERT has at the planning phase foreseen the possible burden on the lower reach farmers during periods of water shortage (CoSAERT, 1994). The solution suggested for the equitable allocation of irrigation water to all beneficiaries in such situations was related to the landholding arrangement and the water users association. According to CoSAERT, the irrigated fields should be divided into two or three blocks starting from the head to the tail of the canal. All the beneficiary farmers are then provided a plot in each block and should collectively decide the block(s) that may not be irrigated during water shortage. This arrangement allows a proportional decrease of the irrigated area for each farmer and creates a more equitable access to water. CoSAERT also recommended the establishment of a strong water users association that has a regulatory and decision making power. However, neither of the two recommendations is operational in the study sites.

The earthen dam irrigation schemes have a limited service life and need to be reconstructed. This would require large investment. The routine and periodic maintenance activities may also need funds for purchase of materials and other inputs. To this effect, CoSAERT recommended from the beginning the importance of introducing water charge for the maintenance and reconstruction activities. The rural land tenure policy (1997) has also set the need for introduction of water charges in the earthen dam irrigation projects. However, irrigation water is so far provided freely in Tigray including the study sites. The only charge revealed was the 10 Birr annual contribution by each farmer at Gumsalasa to cover the salary of the water guard. The water guard at Korir is still paid by the Wereda Bureau of Agriculture and Natural Resources.

6.2.3 Community participation and role of women

Community participation in the development and management of earthen dam irrigation schemes is encouraging in Tigray. The development strategy adopted by CoSAERT in 1994 seems to have achieved its target in this regard. The strategy aims:

"To consistently observe the support and voluntary participation of the people in every aspect and phase of the project unlike the previous rigid, over-bureaucratized and imposed working mechanisms".

The development strategy emphasized on the importance of incorporating the wishes, ideas and aspirations of the farming community and the need for enhancing participation of women as a basis for sustainability.

Farmers actively participate in the construction of the earthen dam irrigation projects and the rehabilitation of catchments. They are generally represented either individually or through their representatives in all decisions made with respect to the operation and maintenance of the irrigation schemes. Rural women of Tigray, both the household heads and housewives, participate actively in all farming activities. The male household members play the major role in ploughing, sowing, cultivation, irrigating, harvesting, threshing and transportation of agricultural products. In addition to the household duty, the female members also assist during sowing, cultivation, harvesting and transporting.

According to CoSAERT (1994), 40% of the rural households of Tigray are headed by women. They are, however, traditionally among the most disadvantaged of the rural poor both socially and economically. Some promising developments have been witnessed in the study sites with regard to access to irrigated land and other basic resources and services such as credit. An assessment in 2002 has revealed that female heads at Korir and Gumsalasa owned about 41% and 21% of the total irrigated land respectively.

6.2.4 Impact of irrigation on livelihood of farmers

The contribution of rainfed agriculture towards the household food security at the study sites is very low (Table 6.7).

Table 6.7 Status of rainfed agriculture in the study areas

Rainfed yield and household (hh) food demand	Gumsalasa	Korir
Total rainfed production:		
Average cereal production in kg/ha	693	628
Average landholding in ha/hh	1.2	1.2
Total production in kg/hh	831	753
Food demand:		
Average family size in number/hh	6	6
Average food requirement in kg/person	173	173
Total annual food requirement in kg/hh	1,038	1,038
Food deficit in kg/hh	207	285

Irrigated farming in Tigray is also mainly subsistence and the extent of nearby markets is very small to encourage farmers to commercialise and diversify their production systems to high value crops. Although there is currently massive rural road construction in Tigray, the effect of this may not be realised in the immediate future. The original plan of CoSAERT was to establish marketing cooperatives that could create a strong network for the irrigation schemes. Even if the idea is still alive, no action has been taken so far. As a result, marketing is an individual responsibility and most of the yield of the irrigated agriculture is sold locally.

Irrespective of the marketing problems, results have shown that irrigated agriculture is the major source of income for the farmers. Since the introduction of irrigation, the cropping pattern has changed from small grains to maize and vegetables. The yield, the market prices and subsequently the household income generated from the irrigated fields are nowadays higher than in the rainfed situation.

Prices of major crops and vegetables in the study areas are summarized in Table 6.8. The market prices vary throughout the year and the average price is based on the monthly average market prices over the years. The table shows that the unit price of the irrigated crops is generally higher.

Table 6.8 Average prices of irrigated and rainfed crops in the study areas (Compiled from Wereda BoANR)

Crop type	Average price in Birr[1]/kg		Remark
	Gumsalasa	Korir	
Onion	3.82	3.53	Irrigated
Tomato	2.58	2.60	Irrigated
Maize	1.00	1.52	Irrigated
Wheat	1.69	2.23	Rainfed
Teff	1.90	2.61	Rainfed
Barley	1.65	1.74	Rainfed

Note:
1 = 1 US$ is equivalent to 8.6 Birr

Table 6.9 presents the average yields and the corresponding income that could be generated from the rainfed and irrigated fields. The table indicates that the average income from irrigated agriculture ranges from 5,848 Birr per ha for maize to 40,712 Birr per ha for tomato at Gumsalasa. Taking into account the average irrigated landholding of 0.2 ha, a household will be able to generate an average income of 1,170 Birr from maize to 8,142 from tomato per irrigation season. Similarly, an average irrigated landholding of 0.32 ha at Korir might generate an average income of 2,445 Birr from maize to 19,410 from tomato per irrigation season. Unlike the larger rainfed landholding per household in both sites, the income that can be generated is very small due to the low level of rainfed yield and market price. This clearly shows the important role of irrigated agriculture on the improvement of the livelihood of the region's poor farmers. It can be noted that the increase in income from irrigated maize is still low compared to the increase from vegetables.

Table 6.9 Average yield and income of rainfed and irrigated crops in the study sites

Crop	Average yield in kg/ha	Market prices in Br[1]/kg	Average income in Br/ha	Average income in Br/farmer[2]	Crop	Average yield in kg/ha	Market prices in Br[1]/kg	Average income in Br/ha	Average income in Br/farmer[3]
Rainfed					Irrigated				
Gumsalasa									
Barley	770	1.65	1,271	1,525	Maize	5,085	1.15	5,848	1,170
Wheat	840	1.69	1,420	1,704	Tomato	15,780	2.58	40,712	8,142
Teff	470	1.90	893	1,071	Onion	9,397	3.82	35,896	7,179
Korir									
Barley	625	1.74	1,088	1,305	Maize	5,028	1.52	7,642	2,445
Wheat	725	2.23	1,617	1,940	Tomato	23,330	2.60	60,658	19,410
Teff	533	2.61	1,391	1,669	Onion	8,637	3.53	30,488	9,756

Note:
1 = 1 US$ is equivalent to 8.6 Br (birr)
2 = calculated for the average rainfed landholding of the study sites per household, which is 1.2 ha
3 = calculated for the average irrigated landholding of the study sites per household, which is 0.2 ha at Gumsalasa and 0.32 ha at Korir

Table 6.10 Average prices of major production inputs in the study sites

Input type	Input price per unit in Birr	
	Gumsalasa	Korir
DAP fertilizer in kg	2.65	2.62
UREA fertilizer in kg	1.95	1.99
Labour in pd	10.00	10.00
Draft power in od	20.00	20.00
Seed		
Maize in kg	2.12	2.22
Onion in kg	100.00	100.00
Teff in kg	2.70	2.70
Wheat in kg	2.00	2.00
Barley in kg	2.00	2.00

Note:
pd = person day, od = oxen day

Irrigation generally requires more production inputs per unit area than rainfed agriculture. However, the irrigated landholding is much less than the rainfed in the study sites. As a result, the total cost per holding of the rainfed production is higher than the irrigated (Table 6.11 and Table 6.12). Table 6.10 gives the prices of the major production inputs in the study areas, while Table 6.11 and Table 6.12 present the cost of production of the rainfed and irrigated crops respectively based on interviews with farmers.

Table 6.11 Average input requirement and production cost of rainfed agriculture in the study sites[1]

Input type	Ave. landholding	Input requirement and cost by rainfed crops							Average farmer's expense[4]
		Teff		Wheat		Barley		Average input cost[3]	
	in ha	Required input	Cost[2] in Birr	Required input	Cost[2] in Birr	Required input	Cost[2] in Birr	in Birr	in Birr
Gumsalasa									
Seed in kg	1.2	33.6	90.7	153.6	307.2	177.6	355.2	251	251
Labour in pd	1.2	187.0	1,870.0	57.0	570.0	57.0	570.0	1,003	610
Draft power in od	1.2	72.0	1,440.0	57.0	1,140.0	57.0	1,140.0	1,240	0
Total			3,401.0		2,017.0		2,065.0	2,494	861
Korir									
Seed in kg	1.2	43.2	116.6	134.4	268.8	172.8	345.6	244	244
Labour in pd	1.2	144.0	1,440.0	57.0	570.0	57.0	570.0	860	160
Draft power in od	1.2	72.0	1,440.0	57.0	1,140.0	52.0	1,040.0	1,207	0
Total			2,997.0		1,979.0		1,956.0	2,310	404

Note:
1 = the result is based on interviews with farmers
2 = required input multiplied by the corresponding input price from Table 6.10
3 = the average cost of production of rainfed crops
4 = this is the cost covered by the farmer in monetary terms

Table 6.11 and Table 6.12 show that the farmers of the study sites only apply fertilizer on irrigated crops. This is mainly for fear of crop failure in rainfed production due to the erratic and unreliable nature of rainfall. The total cost of crop production of both sites is comparable. The average cost of rainfed production at Gumsalasa and Korir is about 2,494 Birr/1.2 ha and 2,310 Birr/1.2 ha respectively. Similarly, the total cost of irrigated production is about 903 Birr/0.2 ha at Gumsalasa and 842 Birr/0.32 ha at Korir.

Referring to Table 6.9, it can be summarized that, unlike the irrigated agriculture, the cost of the rainfed production is higher than the income that can be generated. The income that can be generated from the rainfed landholding ranges from 1,071 Birr for Teff to 1,704 Birr for Wheat at Gumsalasa and 1,305 Birr for Barley to 1,940 Birr for Wheat at Korir (Table 6.9). The corresponding total cost of production, on the other hand, is 2,017 Birr – 3,410 Birr and 1,965 Birr – 1,979 Birr at Gumsalasa and Korir respectively (Table 6.11). The income from the irrigated fields is higher than the cost in both sites for all crop types (Table 6.9 and Table 6.12).

Table 6.12 Average input requirement and production cost of irrigated agriculture in the study sites[1]

Input	Average landholding	Input requirement and cost by irrigated crops					Average farmer's expense[4]
		Maize		Onion		Average input cost[3]	
		Required input	Cost[2] in Birr	Required input	Cost[2] in Birr		
	in ha					in Birr	in Birr
Gumsalasa							
Seed in kg	0.20	6	12.72	0.7	70	41	41
DAP in kg	0.20	20	53.00	20.0	53	53	53
UREA in kg	0.20	20	39.00	20.0	39	39	39
Labour in pd	0.20	48	480.00	64.0	560	560	79
Draft power in od	0.20	9	180.00	10.0	200	190	0
Chemical in Birr	0.20	-	-		40	20	20
Total			765		1,042	903	232
Korir							
Seed in kg	0.32	6.9	15	0.9	90	52	52
DAP in kg	0.32	28.8	75	44.8	117	96	96
UREA in kg	0.32	28.8	57	44.8	89	73	73
Labour in pd	0.32	33.0	330	47.0	470	400	54
Draft power in od	0.32	10.0	200	12.0	240	220	0
Total			678		1,006	842	275

Note:
1 = the result is based on interviews with farmers
2 = required input multiplied by the corresponding input price from Table 6.10
3 = the average cost of production of irrigated crops
4 = this is the cost covered by the farmer in monetary terms

However, Table 6.11 and Table 6.12 also reveal that the actual money spent by the farmers on production inputs is less than the required amount in both cases (rainfed and irrigated). This is because of the fact that either the household members or a special arrangement locally known as '*Ofera*' supplies all of the draft power and most of the labour requirement. '*Ofera'* is an arrangement where a group of willing farmers provide free labour to each other on rotational basis. *'Ofera'* is mostly common during harvesting and threshing activities. Table 6.11 shows that the average amount of money invested for rainfed production of 1.2 ha was 861 Birr and 404 Birr at Gumsalasa and Korir respectively. Generally, the farmers at Gumsalasa employ more paid labours and spend more money. The cost incurred on the irrigated land was 232 Birr for 0.2 ha at Gumsalasa and 275 Birr for 0.32 ha at Korir. Even if most of the labour and all of the draft power cost is not considered, the result shows that the income from a rainfed field is not far from the money spent on it. This reveals the inadequacy of rainfed production in Tigray. Farmers are engaged in the rainfed agriculture mainly due to lack of other options of livelihood such as off-farm employment. The hope that the rainfall situation will be better year after year also keeps them in the business.

6.3 Waterlogging and salinity

6.3.1 Surface water and soil qualities

The surface water quality during 2002 and 2004 is presented in Table 6.13, Figure 6.6 and Figure 6.7. The soil and water sampling locations are shown in Figure 4.2. The reservoir water is released to the canal by a steel pipe buried in the dam body. As a result, the quality of the canal water of the irrigation schemes is the same as the reservoir in both years.

Table 6.13 Irrigation water quality of the study sites during 2002 and 2004

Area[1]	Sample location	Sample code[2]	Electrical conductivity in dS/m			
			Gumsalasa[3]		Korir[3]	
			April	June	April	June
2002						
Reservoir	Reservoir	W_1	0.30	0.35	0.26	0.26
Primary command	Canal	W_2	0.30	0.35	0.26	0.27
	Irrigated field	W_3	0.32	0.36	0.27	0.29
Secondary command	Source	W_4	0.51	0.75	1.30	1.36
	Irrigated field	W_5	0.77	1.11	1.71	1.72
Downstream	Main drain	W_6	0.88	1.06	1.74	1.74
2004						
Reservoir	Reservoir	W_1	0.29	0.37	0.33	0.34
Primary command	Canal	W_2	0.29	0.38	0.33	0.34
	Irrigated field	W_3	0.31	0.39	0.33	0.35
Secondary command	Source	W_4	0.73	0.85	1.20	1.20
	Irrigated field	W_5	0.73	0.88	1.20	1.20
Downstream	Main drain	W_6	0.96	1.20	1.75	1.77

Note:

1 = primary and secondary command refer to the area irrigated by the canal network and seepage water respectively

2 = W_1 to W_6 refer respectively to the water sampling locations indicated in Figure 4.2. These codes are used in Figure 6.6 and Figure 6.7

3 = April and June refer to the middle and end of the irrigation season

The reservoir water of Gumsalasa and Korir is generally of good quality and is categorized as suitable for irrigation of all soils and crop types (Table 6.13 and Table 4.2). This agrees with the low salinity level of the catchment areas (Table 6.14). The results clearly show that there is no significant difference between the salinity of the years and the sites in the primary command area.

The case of the secondary command is, however, different. Unlike the canal water, the seepage from the reservoir passes through the dam body leaching available soluble salts on its way. As indicated in Chapter 4, this seepage is used downstream for irrigation. Figure 6.8 and Figure 6.9 present the temporary diversion structures constructed at Gumsalasa and Korir respectively. The quality of the seepage water is poor compared to the canal water and varies between locations in the irrigation scheme and irrigation seasons. As it can be seen from the results, the seepage water is categorized as high saline and allows only the growth of salt tolerant crops (Table 6.13 and Table 4.2).

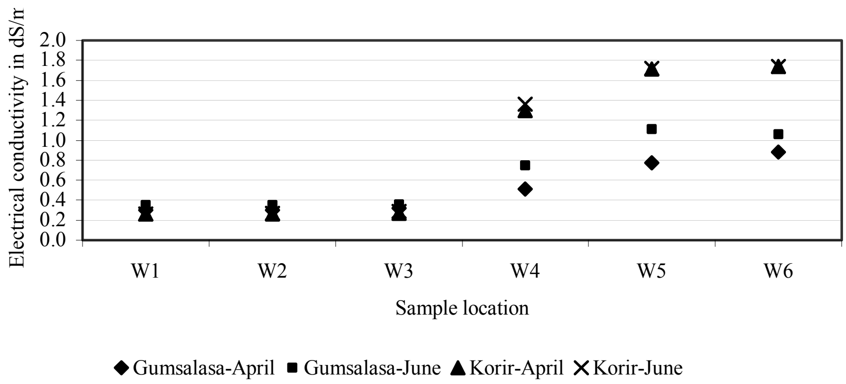


Figure 6.6 Salinity of irrigation water at different locations in the irrigation schemes during 2002

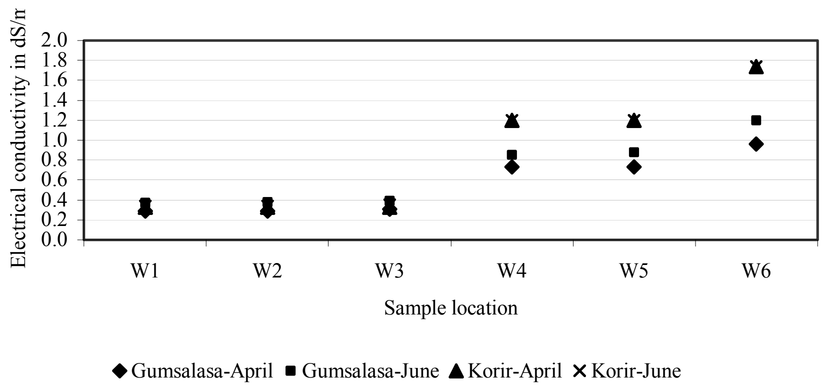


Figure 6.7 Salinity of irrigation water at different locations in the irrigation schemes during 2004

Even if the source of the seepage water is mainly the reservoir, it is further supplemented by seepage from adjacent irrigation canals and drainage from irrigated fields. This may contribute to the increase in salinity level due to the leaching effect. As a result, unlike the canal water, the quality of the seepage water shows a high variation and decreases from top to bottom (i.e., salinity increases from the source to the irrigated field and the downstream area). The seepage salinity at Korir was higher than at Gumsalasa in both years. This can be due to the variation in soil type, which plays a very important role in leaching. The irrigated areas of Gumsalasa are dominated by heavy soils (Vertisos) while Korir is dominated by medium soils (Cambisols). The leaching efficiency depends on the soil type and is generally higher in medium soils than in heavy soils (Arar, 1971). This indicates that medium soils have higher capacity to leach the salt available in the soil profile. The infiltration of the medium soils may also favour a better leaching. The infiltration tests have given a basic infiltration rate of 6 mm/hr and 12 mm/hr for the heavy and medium soils respectively. There was almost no seasonal variation of seepage water salinity at Korir while Gumsalasa showed a slight increase towards the end of the irrigation season. This is possibly due to the gradual increase in leaching effect as more irrigation water is added during the irrigation season.

The 2004 salinity of the seepage at the diversion point was higher than the 2002 at Gumsalasa, but lower at Korir (Table 6.13, Figure 6.6 and Figure 6.7). This can be the effect of the Halophyte grass, locally known as '*Gassa*', which has grown at Korir during the last two years (Figure 6.9). Halophytes are salt resistant plants that can either excrete the salt they absorb or store it in their leaves.

Figure 6.8 Temporary seepage diversion structure at Gumsalasa

Figure 6.9 Temporary seepage diversion structure at Korir

The electrical conductivity of the soils was measured from a 1:5 soil:water extract (EC_5) by filtration. A conversion factor of EC_5 to the electrical conductivity of the saturated extract (EC_e) was derived through correlation based on the measured EC_5 and EC_e value of some samples (Smedema and Rycroft, 1983). A strong correlation was achieved in both sites with a conversion factor of about 1.7 (Figure 6.10 and Figure 6.11).

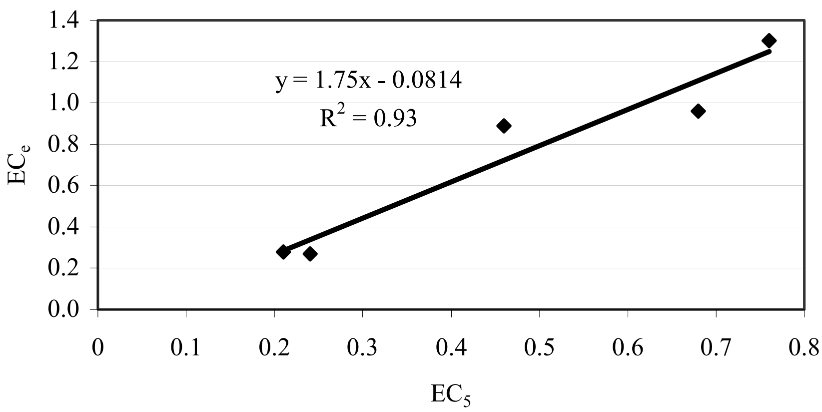


Figure 6.10 Correlation between EC_e and EC_5 at Gumsalasa

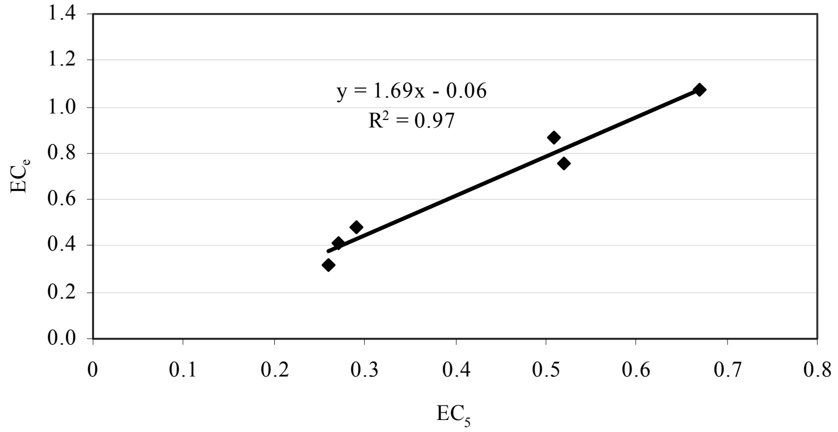


Figure 6.11 Correlation between EC_e and EC_5 at Korir

The surface soil salinity of the irrigation schemes in 2002 and 2004 is given in Table 6.14 and Figure 6.12 -Figure 6.15. The results reveal that the soils of both sites are salt free (Table 6.14 and Table 4.3). Salinity is relatively higher at Gumsalasa than Korir. In both schemes, the salinity increases over the irrigation season due to the higher evapo(transpi)ration that leaves salt in the root zone. Salinity of the secondary command area is also higher than the primary due to the high salinity of the seepage water used for irrigation. The danger of using the seepage water is well illustrated at Korir where the water supply of an area was shifted from canal water in 2002 to seepage water in 2003. The 2004 secondary command was part of the primary command in 2002 (Table 6.14). The farmers started to use seepage water in 2003 when they were cut off from the canal due to the shortage of water in the reservoir.

Figure 6.15 reveals how the use of seepage water has caused a dramatic increase in the salinity of the area over two years. Compared to the rainfed field, which is used as a control, the salinity of the study sites has generally shown a high increase. For instance, taking into account the average values, the increase in salinity at Gumsalasa ranges from about 73% in September to 300% in June at the primary command and from 110% - 460% at the secondary. The increase at Korir was about 29% - 150% at the primary and 40% - 310% at the secondary. The soil salinity of the schemes drops immediately after the rainy season because of the leaching of the soluble salts. The soil salinity of the schemes generally commensurate with the water quality trend.

Previous studies (1997 – 1999) at Gumsalasa by Mitiku, *et al*., (2002) have indicated soil salinity of 0.15, 0.29 and 0.15 dS/m for the top, middle and bottom of the command area respectively during the irrigation season. A comparison with the current results shows an increase of the salinity by a factor two or more. This indicates that salinity may become a major problem threatening the sustainability of land and water development in Tigray in general and the study sites in particular in the years to come.

Table 6.14 Surface soil (0 – 20 cm) quality of the study sites during 2002 and 2004

Area[1]	Sample location	Sample code[2]	Electrical conductivity in dS/m					
			Gumsalasa[3]			Korir[3]		
			April	June	Sept.	April	June	Sept.
			2002					
Rainfed	Rainfed	S_1	0.22	0.22	0.22	0.24	0.24	0.24
Catchment	Catchment	S_2	0.40	0.40	0.40	0.29	0.29	0.29
Primary command	Top	S_3	0.83	1.10	0.32	0.42	0.56	0.26
	Middle	S_4	0.77	0.83	0.51	0.66	0.73	0.41
	Bottom	S_5	0.63	0.78	0.32	0.46	0.51	0.26
Secondary command[4]	Top	S_6	0.87	1.16	0.48	1.56	0.83	0.34
	Middle	S_7	0.90	1.10	0.49	-	-	-
	Bottom	S_8	1.24	1.43	0.44	0.61	0.54	-
			2004					
Rainfed	Rainfed	S_1	0.22	0.22	0.22	0.24	0.24	0.24
Catchment	Catchment	S_2	0.40	0.40	0.40	0.29	0.29	0.29
Primary command	Top	S_3	0.95	1.17	0.51	0.36	0.34	0.27
	Middle	S_4	0.48	0.83	0.54	0.24	0.54	0.36
	Bottom	S_5	0.46	0.71	0.70	0.26	0.71	0.59
Secondary command[4]	Top	S_6	0.83	0.83	0.73	0.48	0.78	0.68
	Middle	S_7	0.71	1.00	0.88	0.82	1.10	0.95
	Bottom	S_8	-	-	-	1.10	1.16	0.65

Note:

1 = primary and secondary command refer to the area irrigated by the proper canal network and seepage water respectively

2 = S_1 to S_8 refer respectively to the surface soil sampling locations indicated in Figure 4.2. These codes are used in Figure 6.12 - Figure 6.15

3 = April refers to the middle of the irrigation season, June to the end of the irrigation season and September end of the rainy season

4 = the bottom of the secondary command at Gumsalasa was not irrigated in 2004. The 2004 secondary command at Korir was part of the primary command in 2002

Soil pH indicates whether the soil is acid, neutral or alkaline. Crops show a marked response to soil reaction since it has a major influence on the soil chemical environment and on the availability of essential nutrients. Crops prefer a soil pH just below to just above neutral (pH = 7). When the soil becomes too acid or too alkaline, a range of problems such as deficiency of nutrient availability and toxicity may occur.

The soils of the irrigation schemes show a soil reaction ranging from 8 to 8.5, indicating slight to moderate alkalinity (Table 6.15). The present results commensurate with findings of previous studies (Mitiku, *et al.,* 2002 and Mintesinot, 2002). Soils of arid and semi-arid regions are commonly alkaline due to an accumulation of carbonates in the soil. The pH of the study sites is slightly high for optimal crop growth. The effect of a high pH is evident in both irrigation schemes in general and at Gumsalasa in particular. Some of the effects observed were localized black oily surfaces, white crystal formation, low aggregation and dispersion impending water movement.

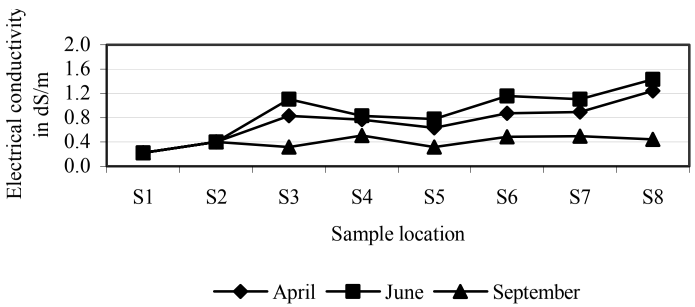


Figure 6.12 Soil salinity of different locations at Gumsalasa irrigation scheme in 2002

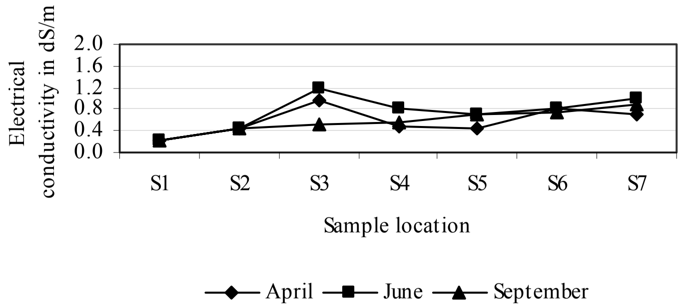


Figure 6.14 Soil salinity of different locations at Gumsalasa irrigation scheme in 2004

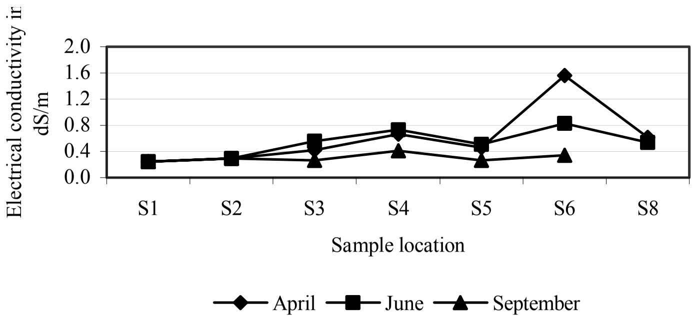


Figure 6.13 Soil salinity of different locations at Korir irrigation scheme in 2002

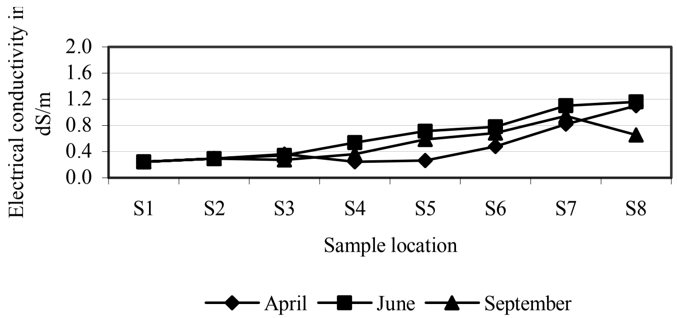


Figure 6.15 Soil salinity of different locations at Korir irrigation scheme in 2004

Table 6.15 pH values of soils in the study sites

Sample location	Sample location	Gumsalasa		Korir	
		During irrigation	After rainy season	During irrigation	After rainy season
Primary command area	Top	8.3	8.5	8.2	8.4
	Middle	8.3	8.4	8.2	8.4
	Bottom	8.3	8.2	8.1	8.1
Secondary command area	Top	8.3	8.6	8.3	8.4
	Middle	8.4	8.4	8.1	8.1
	Bottom	-	-	7.8	8

The results in Table 6.14 give the general condition of the salinity in the study sites. However, observation of the schemes shows the presence of a high level of salinity especially at Gumsalasa. These localized saline areas were sampled and assessed separately. The results generally exhibit the presence of slightly saline to extremely saline conditions (Figure 6.16 and Figure 6.17). The first 9 samples were taken from the primary command area while the rest belong to the secondary. The peak value in Figure 6.16 corresponds to the field shown in Figure 6.17. This field is at the moment abandoned from agriculture.

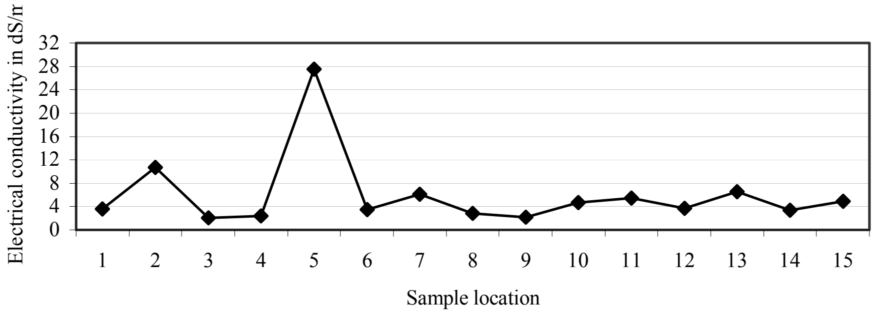


Figure 6.16 Localized soil salinity at Gumsalasa at different locations

Figure 6.17 A salinized irrigated field at Gumsalasa

6.3.2 *Groundwater and subsurface soil qualities*

The monitoring wells (profile pits) excavated in the command areas were 2 m deep. No groundwater was observed in the pits at Korir during 2002 and 2004 irrigation seasons. At Gumsalasa, on the other hand, groundwater levels of 0.24 – 1.75 m-surface and 1.2 – 1.8 m-surface were observed during 2002 and 2004 respectively. The major factors controlling the occurrence of shallow groundwater may be the soil type and depth of the natural drainage (Figure 4.2). Unlike the heavy black soils at Gumsalasa, the command area of Korir is dominated by medium soils. Moreover, the main drain at Korir is relatively deeper than the one of Gumsalasa. These conditions might facilitate the removal of excess water from the soil profiles at Korir to the natural drain.

Table 6.16 Groundwater depth and quality at Gumsalasa during 2002 and 2004 irrigation season

Pit location	Pit code[1]	Electrical conductivity[2] in dS/m			
		2002		2004	
		April	June	April	June
Catchment	P_1	NW	NW	NW	NW
Rainfed	P_2	NW	NW	5.26(1.8)	NW
Primary command	P_3[3]	1.15(1.75)	NW	1.27(1.7)	1.4(1.6)
Primary command	P_4	4.73(0.24)	6.35(0.67)	4.46(1.25)	5.7(1.2)
Secondary command	P_5	NW	NW	NW	NW
Secondary command	P_6	10(1.25)	11.45(1.34)	-	-

Note:
1 = the codes refer to the pit locations in Figure 4.2. P_6 was not irrigated in 2004
2 = the values in brackets are the water levels in the pits in meter below the surface
3 = this pit is located close to the dam
NW = No water in the profile at 2 m depth

The groundwater depth and quality of Gumsalasa in 2002 and 2004 are comparable (Table 6.16). The quality of the groundwater, which varies between 1.15 – 11.54 dS/m, is highly saline and poses a danger to crop yields. The salinity increases over the irrigation season due to evapo(transpi)ration that leaves the soluble salts behind. It also increases from top to bottom of the command area and is coherent to the water management practices. As indicated earlier, downstream fields use drainage water from upper fields and/or seepage water for irrigation. The lowering in groundwater level of P_4 in 2004 might be related to the reduction in the amount of water applied. The field is highly saline and most of the seeds do not emerge. As a result, except for some runoff from adjacent farms, no water was supplied to this field after the initial stage in 2004. It was also learnt that the condition in 2003 was the same.

The subsoil quality of the study sites reflects the groundwater situation. The analysis was carried out during June 2002, June 2004 and September 2004. The soil salinity at Gumsalasa was higher than Korir in both years (Table 6.17, Table 6.18 and Figure 6.18 - Figure 6.23).

The quality of the subsoil at Gumsalasa is presented in Table 6.17 and Figure 6.18 - Figure 6.20. The salinity of the irrigated area is higher than of the rainfed area and increases with the increase in groundwater salinity (Table 6.16 and Table 6.17). The category varies from non-saline to strongly saline. The pit of the rainfed plot is located close to the natural drainage. The presence of groundwater at a depth of 1.8 m-surface in 2004 and the relatively higher subsurface salinity might be the result of seepage.

Table 6.17 Quality of the subsoil at Gumsalasa in 2002 and 2004

Pit location	Pit code[1]	Electrical conductivity in dS/m							
		June				September			
		Depth ranges in m				Depth ranges in m			
		0.3	0.6	1.2	1.8	0.3	0.6	1.2	1.8
2002									
Catchment	P_1	0.47	0.45	0.53	-	-	-	-	-
Rainfed	P_2	0.24	0.28	1.56	1.84	-	-	-	-
Primary command	P_3[2]	0.46	0.47	0.51	0.12	-	-	-	-
Primary command	P_4	4.35	1.86	3.00	-	-	-	-	-
Secondary command	P_5	0.80	0.96	0.98	2.18	-	-	-	-
Secondary command	P_6	0.86	0.80	3.99	3.57	-	-	-	-
2004									
Catchment	P_1	0.47	0.45	0.53	-	0.47	0.45	0.53	-
Rainfed	P_2	0.28	0.41	1.72	1.72	0.26	0.52	1.83	1.83
Primary command	P_3[2]	0.33	0.44	0.85	0.64	0.35	0.40	0.78	0.56
Primary command	P_4	4.00	2.85	4.50	3.00	2.60	5.14	5.52	4.12
Secondary command	P_5	0.31	0.66	1.05	2.53	0.27	0.24	0.81	2.92
Secondary command	P_6	-	-	-	-	-	-	-	-

Note:
1 = the codes refer to the pit locations in Figure 4.2. These codes are used in Figure 6.18 - Figure 6.20. P_6 was not irrigated in 2004
2 = this pit is located close to the dam

The soil salinity generally increases with depth in both years. Except for the case of P_4, the salinity of the profile pits is very low in the top 0.6 m and increases downwards. In addition to the effect of the groundwater, this might be related to the soil type and the poor leaching practices. As indicated in 6.1, the amount of water applied per irrigation is small compared to the moisture holding capacity of the root zone. Besides, no water is supplied for leaching and the drainage facilities are poor. These reasons coupled with the low infiltration characteristics of the clay soil may have contributed to the insufficient leaching and subsequent accumulation of salt at shallow depths.

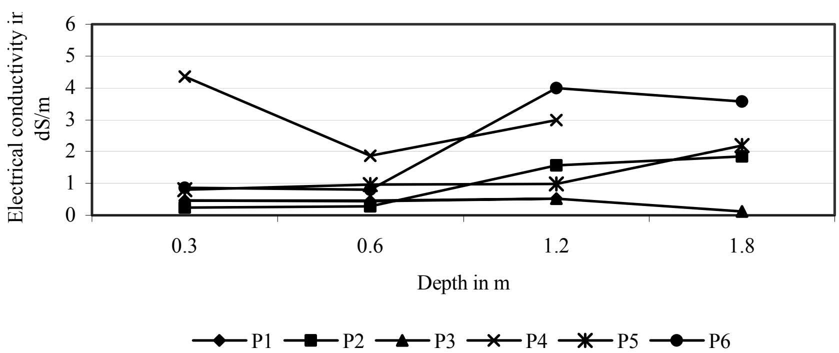


Figure 6.18 Salinity of the subsoil at different locations at Gumsalasa in June 2002

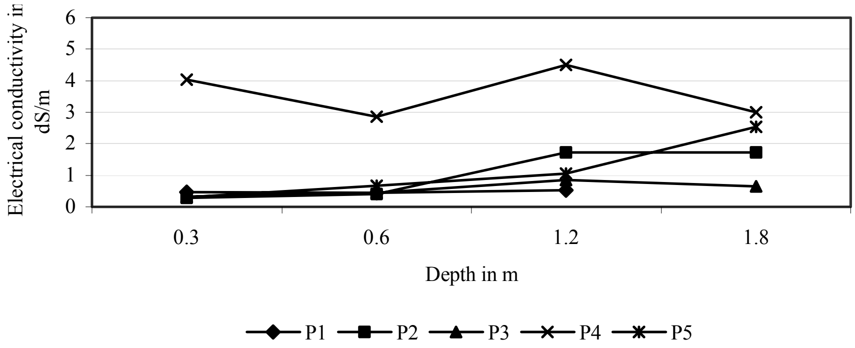


Figure 6.19 Salinity of the subsoil at different locations at Gumsalasa in June 2004

The salinity of the profile pits after the rainy season seems to support the above statement concerning the leaching process. Table 6.17, Figure 6.19 and Figure 6.20 reveal that the trend of salinity before (June 2004) and after (September 2004) the rainy season remains similar. The major crops that grow at Gumsalasa are onion and maize. The present average root zone salinity, which generally ranges from 0.39 – 0.88 dS/m for onion and 0.54 – 0.91 dS/m for maize, does not pose any danger. It could, however, threaten the sustainability of the scheme in the long term if the salt continues to accumulate at shallow depths without being leached. The higher average salinity level of P_4 (3.1 dS/m) and P_6 (1.9 dS/m) within the top 1.2 m indicates the potential problem.

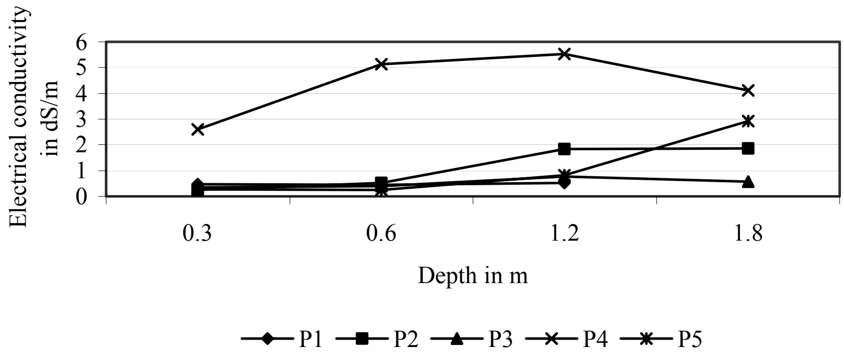


Figure 6.20 Salinity of the subsoil at different locations at Gumsalasa in September 2004

The situation at Korir is totally different from Gumsalasa (Table 6.18 and Figure 6.21 - Figure 6.23). As indicated earlier, the natural drainage is deeper and the infiltration characteristic of the soil is better than at Gumsalasa. As a result, the soils of the profiles are generally salt free and no significant variation is observed among the pits of the catchment, rainfed and irrigated areas (Figure 6.21 - Figure 6.23). Unlike at Gumsalasa, the salinity at Korir shows a decrease over the whole profile after the rainy season (September 2004). This indicates a better leaching condition at Korir.

Table 6.18 Quality of the subsoil at Korir in 2002 and 2004

Pit location	Pit code[1]	Electrical conductivity in dS/m							
		June				September			
		Depth ranges in m				Depth ranges in m			
		0.3	0.6	1.2	1.8	0.3	0.6	1.2	1.8
2002									
Catchment	P_1	0.43	0.45	0.44	0.37	-	-	-	-
Rainfed	P_2	0.39	0.26	0.4	0.25	-	-	-	-
Primary command	P_3[2]	0.44	0.39	1.63	2.57	-	-	-	-
Primary command	P_4	0.35	0.29	0.28	0.21	-	-	-	-
Secondary command	P_5	0.52	0.55	0.53	0.47	-	-	-	-
2004									
Catchment	P_1	0.43	0.45	0.44	0.37	0.43	0.45	0.44	0.37
Rainfed	P_2	0.35	0.32	0.19	0.21	0.35	0.32	0.19	0.21
Primary command	P_3[2]	0.19	0.21	1.15	3.58	0.18	0.18	1.00	-
Primary command	P_4	0.16	0.28	0.27	0.27	0.12	0.19	0.19	0.10
Secondary command	P_5	-	-	-	-	-	-	-	-

Note:

1 = the codes refer to the pit locations in Figure 4.2. These codes are used in Figure 6.21 - Figure 6.23. P_5 was not irrigated in 2004

2 = this pit is located close to the dam

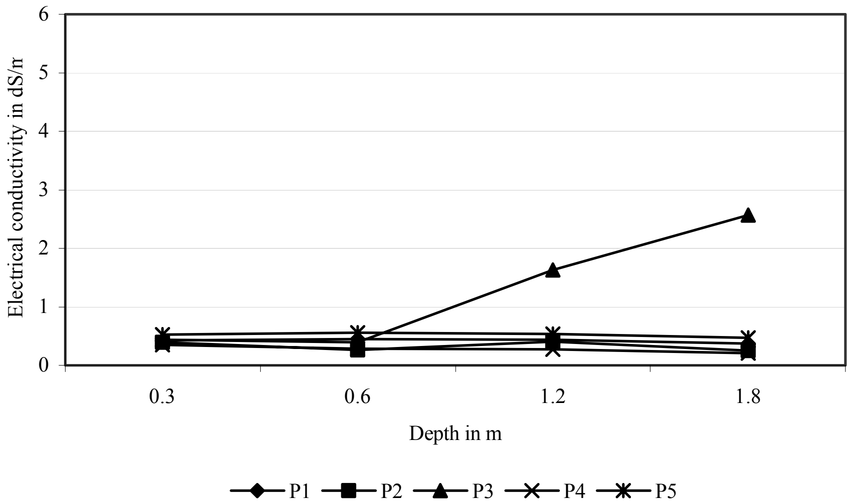


Figure 6.21 Salinity of the subsoil at different locations at Korir in June 2002

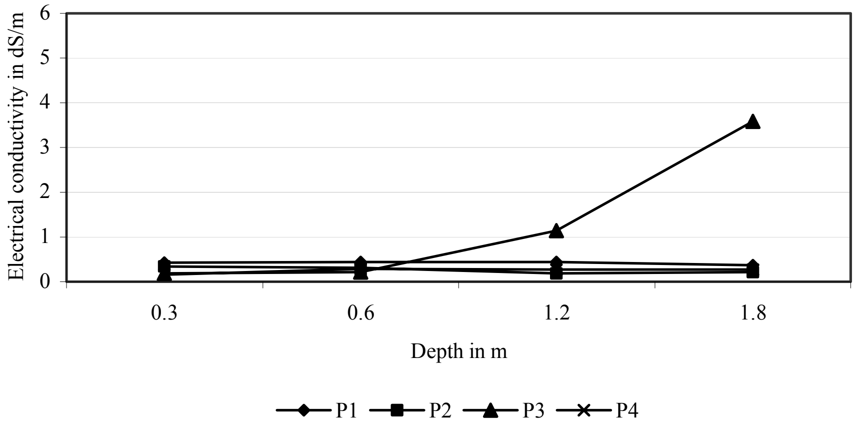


Figure 6.22 Salinity of the subsoil at different locations at Korir in June 2004

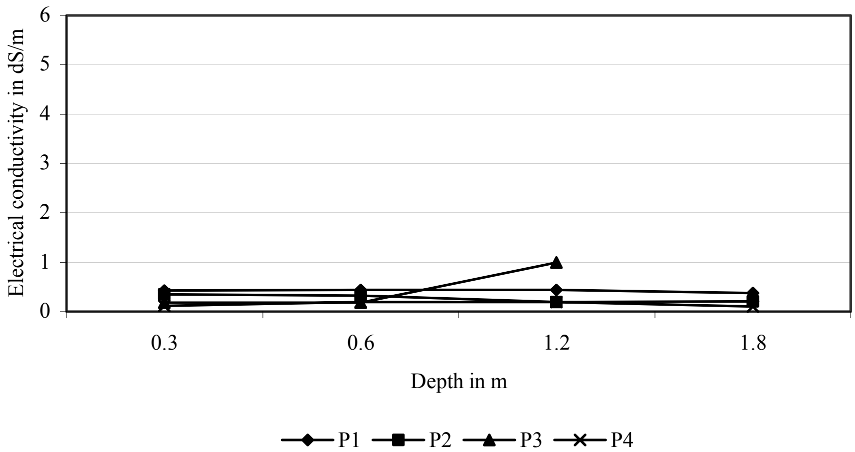


Figure 6.23 Salinity of the subsoil at different locations at Korir in September 2004

Waterlogging and salinity are two important environmental aspects in irrigated lands. According to the results in the study sites, the reservoir and canal irrigation water is suitable for irrigation of all soils and crops. On the other hand, the seepage water is highly saline and allows only the growth of salt tolerant crops.

The surface soil (0-20 cm) salinity in both sites was generally found to have low electrical conductivity indicating a low salinity level. Salinity is generally higher at Gumsalasa than at Korir. In both schemes, salinity increases over the irrigation season due to the higher evapo(transpi)ration that leaves salt in the root zone of the crops. Salinity in the secondary command area is also higher than in the primary. This is due to the high salinity of the seepage water used for irrigating the secondary command area.

There was no shallow groundwater at Korir during the irrigation season, while groundwater levels of 0.24 – 1.8 m below the surface were observed at Gumsalasa. The groundwater at Gumsalasa is highly saline, increases from top to bottom of the command area and is categorised as very dangerous to crop growth and yield. The subsurface soil quality is also poorer at Gumsalasa than at Korir. The subsurface soil at Korir is generally salt free, while it varies from non-saline in the primary command to strongly saline in the secondary.

The soil salinity of the schemes generally commensurate with the water quality trend. The current salinity level is generally not harmful to crop production. However, a comparison of the present salinity with previous studies and the rainfed land shows an increase of the salinity by a factor two or more. The presence of localized highly saline spots reinforces the seriousness of the problem. This indicates that salinity could be a major problem threatening the sustainability of land and water development in Tigray in general and the study sites in particular in the years to come. The major factors that contribute to the salinity development in the study sites include:

- inadequate water management;
- inadequate leaching and drainage facilities;
- inappropriate irrigation timing;
- use of seepage water for irrigation;
- lack of salinity monitoring and follow-up.

In Tigray in general and in the study sites in particular, irrigation scheduling is not based on the crop water and leaching requirements. Water is distributed based on direct observation of soil and plant conditions. The discharge going to the irrigated fields and the delivery time are not monitored. The schemes are not equipped with well designed drainage ditches and irrigation water from one field is mostly transferred to the next. Owing to the semi-arid nature of Tigray, the inadequate water management coupled to the poor drainage facilities would obviously aggravate the salinity situation.

According to the farmers the salinity problem is further aggravated due to the change in irrigation time. During the initial phase of the development, irrigation water was available only during the early morning, the late afternoon and the early evening hours. At the moment, irrigation water is available the whole day including the hot hours that would cause high evapotranspiration leaving the salt on the surface of the soil.

The other factor aggravating the salinity problem is the use of seepage water for irrigation with no attention given to its quality. The assessment in the study sites has clearly shown a very high salinity of the seepage water compared to the reservoir and canal system. This has in turn caused higher soil salinity in the secondary command areas compared to the primary.

The last but most important factor contributing to the worsening of salinity is the lack of monitoring of the situation. The least that could be done is to carry out regular physical observations (such as white crust formation) for incidences of salinity and to take mitigation measures in time. The increasing trend of the salinity problems in the schemes, the loss of a farmland at Gumsalasa and the development of localized high salinity areas indicate the lack of it.

7 Evaluation

As indicated earlier, water harvesting is taken as a major pillar of the food security strategy of Ethiopia in general and in Tigray in particular. The realization of this objective largely depends on the sustainability and efficiency of the present and future land and water development. The study focused on the major issues that have to be considered in the implementation of sustainable earthen dam irrigation schemes. These include:

- reservoir sedimentation;
- reservoir operation;
- operation and maintenance of the schemes;
- institutional, social and economic issues;
- salinity hazard;
- impact on downstream users.

This chapter presents an evaluation and discussion of the research results of the above aspects. Recommendations are also presented as a basis for the formulation of an integrated approach for the development and management of irrigated lands in Tigray.

7.1 Reservoir sedimentation and operation

7.1.1 Sedimentation and service life

With an average life span of 26 years, most of the earthen dam irrigation schemes were designed to serve for about 10 – 40 years (Table 7.1). The reservoir service life is determined by the annual sediment yield of the catchment area and the capacity of the dead storage. However, no detailed catchment sediment yield studies were carried out for the design of the earthen dam irrigation schemes in Tigray. The procedure mostly involves a rough estimation of the sediment yield from available regional secondary data. According to Yigzaw (1994), the sediment yield of catchments around Mekelle ranges between 1,100 $m^3/km^2.yr$ and 2,200 $m^3/km^2.yr$ (1.1 – 2.2 mm/yr). The estimation was made by visual inspection of the catchment area. Nyssen (2001), on the other hand, estimated an average soil loss of 1,000 $m^3/km^2.yr$ (1 mm/yr) for the general situation in the highlands of Ethiopia (Table 7.2).

However, calculation of the design sediment yield based on the catchment area, dead storage capacity and the life span of the various earthen dams revealed a very high variation (Table 7.1). With an average rate of 0.6 mm/yr, the sediment yield varies from 0.2 mm/yr to 1.2 mm/yr. It seems that only about half of the earthen dams have a sediment yield close to the above values mentioned by Yigzaw and Nyssen (Figure 7.1). The figure shows that about 50% of the dams were designed using a sediment yield of above 0.8 mm/yr, while less than 0.6 mm/yr was used for the remaining. A high variation of sediment yield is also observed for catchments with the same area.

Table 7.1 Calculated sediment yield of catchments based on the catchment area, service life and dead storage size of various dams in Tigray (based on Poesen, *et al.*, 2001 and various CoSAERT reports)

Code	Name of dam	Reservoir		Dead storage	Life span	Catchment area	Specific sediment yield		
		Capacity in 10^6 m^3	Area in ha	in m^3	in years	in km^2	in $m^3/km^2.yr$	in $t/km^2.yr$[1]	in mm/yr
1	Adi Amharay	0.96	31.5	175,000	33	6	884	1,061	0.9
2	Adi Gela	1.25	18.5	62,500	40	8.78	178	214	0.2
3	Adi Kenafiz	0.67	12.9	60,953	31	8.8	223	268	0.2
4	Betqua	0.61	11.7	133,267	23	6.13	945	1,134	0.9
5	Dur Anbessa	0.90	14.0	115,598	36	10.07	319	383	0.3
6	Emabgedo	1.78	36.0	360,000	24	12.4	1,210	1,452	1.2
7	Endazeoy	0.18	4.1	20,000	25	1.65	485	582	0.5
8	Filiglig	0.28	6.6	20,832	30	3.2	217	260	0.2
9	Gereb Mihiz	1.30	30.0	325,000	21	17.27	896	1,075	0.9
10	Gereb Segen	0.34	11.7	22,400	25	4.79	187	224	0.2
11	Gindae	0.73	13.5	142,405	20	12	593	712	0.6
12	Gra Shito	0.17	6.7	17,936	20	2.88	311	374	0.3
13	Gumsalasa	1.90	48.0	475,500	30	18.55	854	1,025	0.9
14	Hashenge	2.23	38.0	277,988	25	25.7	433	519	0.4
15	Laelay Wukro	0.93	20.6	220,000	20	9.16	1,201	1,441	1.2
16	Mai Delle	1.57	35.0	270,000	27	10.1	990	1,188	1
17	Mai Haidi	0.15	5.7	15,133	31	1.96	249	299	0.2
18	Mai Serakit	0.49	11.0	129,169	30	4.48	961	1,153	1
19	Sewhimeda	0.36	7.8	40,000	10	4.7	851	1,021	0.9
20	Shilanat 1	1.61	19.3	65,628	20	3.42	959	1,151	1
21	Shilanat 4	2.86	31.5	76,524	35	3.3	663	795	0.7
	Total	21.27	413.9	3,025,833		175	13,610	16,332	13.7
	Minimum	0.15	4.05	15,133	10	2	178	214	0.2
	Maximum	2.86	48.0	475,500	40	26	1,210	1,452	1.2
	Average	1.01	19.7	144,087	26	8	648	778	0.7
	STD	0.75	12.8	131,130	7	6	352	422	0.4

Note: 1 = bulk density of 1,200 kg/m^3 was used for conversion (Nyssen, 2001)

Table 7.2 Estimated rates of soil loss by sheet and rill erosion on slopes, for various land uses in Ethiopia (after Nyssen,(2001)

Land cover	Area	Soil loss		
	in %	in t/ha.yr	in $m^3/km^2.yr$	in mm/yr
Grazing	47	5	4,000	4
Uncultivable	19	5	4,000	4
Cropland	13	42	35,000	35
Woodland/bushland	8	5	4,000	4
Swampy land	4	0	0	0
Former cropland	4	70	58,000	58
Forests	4	1	900	0.9
Perennial crops	2	8	6,700	6.7
Total for the highlands	100	12	1,000	1

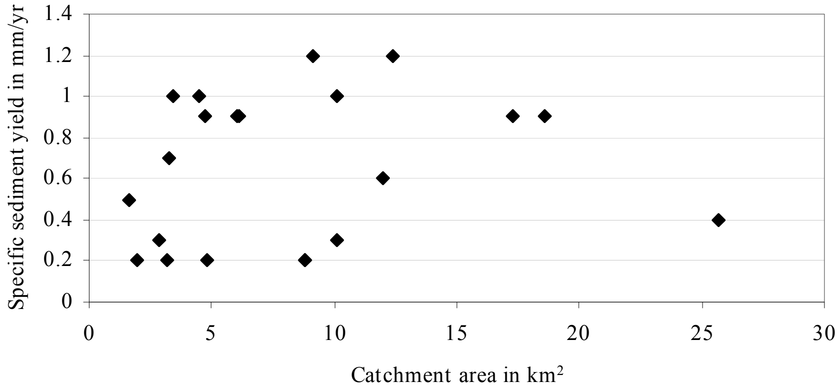


Figure 7.1 Design sediment yield of some of the earthen dams in Tigray

In addition to the difference in catchment characteristics such as soil type, slope and vegetation cover, the major source of the variation is the subjectivity of the estimation procedure. Such approach can result in either an under-estimated or over-estimated sediment yield. As a result, it is not known if the earthen dams will serve for the number of years they are designed. For instance, the Mejae earthen dam that was constructed in 1997/1998 with a reservoir capacity of 0.3 million m^3 was already silted up in 2001 (Figure 7.2) (Poesen, *et al.*, 2001). Similarly, the design sediment yield of Adi Amharay dam is very high compared to Adi Gela (Table 7.1). However, assessment of the catchment characteristics indicated a higher erosion risk at Adi Gela than Adi Amharay (Table 7.3). Consequently, the Adi Gela earthen dam may not serve for 40 years.

Figure 7.2 Mejae reservoir totally silted up by sediment (Poesen, *et al.*, 2001)

Table 7.3 Specific sediment yield estimation by HR Wallingford method for different earthen dams in Tigray

Code	Site	Catchment area (A) in km^2	Mean annual rainfall (P) in mm	River slope (S)	Active erosion (E)	Soil and drainage (SD)	Vegetation cover (V)	Specific sediment yield in t/km^2.yr
1	Adi Amharay	6.00	565	0.03	20	20	40	749
2	Adi Gela	8.78	507	0.09	40	20	20	1,454
3	Adi Kenafiz	8.80	463	0.12	20	20	40	915
4	Betqua	6.13	427	0.09	40	20	30	1,697
5	Endazeoy	1.65	577	0.9	40	20	40	6,275
6	Filiglig	3.20	462	0.08	40	20	20	1,609
7	Gereb Mihiz	17.27	477	0.13	40	20	40	1,922
8	Gereb Segen	4.79	463	0.03	10	20	20	210
9	Gumsalasa	18.55	513	0.02	20	20	40	495
10	Hashenge	25.70	581	0.05	40	20	40	1,530
11	Laelay Wukro	9.16	570	0.12	20	20	40	1,050
12	Mai Delle	10.10	478	0.05	10	20	30	264
13	Mai Haidi	1.96	463	0.1	20	20	40	1,170
14	Sewhimeda	4.70	593	0.05	20	20	20	671
15	Korir	15.50	543	0.1	10	20	40	377

Note:

A, P and S were obtained from Poesen, *et al.,* (2001) and various CoSAERT reports, while E, SD and V were obtained from Table 4.7. Specific sediment yield was calculated using Equation 4.19.

The runoff plot and HR Wallingford approaches were employed at Gumsalasa and Korir in order to present a general assessment of the catchment sediment yield. These were compared with the results of two other empirical methods used by Poesen, *et al.,* (2001), namely, the Verstraeten, *et al.,* and the Pacific Southwest Inter Agency Commission (PSIAC) methods.

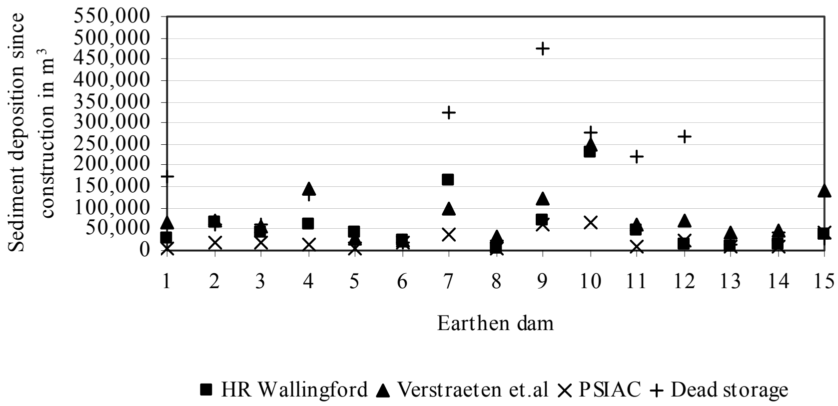
Table 7.4 presents the summary of the reservoir sedimentation of the study sites based on the various empirical approaches. The table reveals that the Verstraeten, *et al.,* method gives the highest sediment yield. If such sediment yield was possible, the Korir reservoir would have been totally silted up about 6 years back. The dead storage of Gumsalasa and Korir earthen dam is 132,000 m^3 and 30,000 m^3 respectively (Figure 5.16 and Figure 5.17). However, the Gumsalasa inlet box was constructed to allow sediment accumulation of 475,500 m^3. Comparing the dead storage values with Table 7.4 clearly indicates the high estimate of the sediment yield by the Verstraeten, *et al.,* method. Taking into account the existing situation at Korir, the runoff plot, the HR Wallingford and PSIAC methods seem to give more uniform and acceptable values. The dead storage at Korir is nearly silted up because, towards the end of the irrigation season, the farmers have to excavate the sediment at the inlet box to allow the flow of water. There is no such problem at Gumsalasa so far.

Table 7.4 Total expected reservoir sedimentation of the study sites since construction based on the various methods

Method	SSY[1] in t/km^2.yr	Catchment area in km^2	Years since construction in year	Total in 10^3 ton	in 10^3 m$^{3\,(2)}$
Gumsalasa					
Runoff plot	280	18.6	9	47	39
HR Wallingford	495	18.6	9	83	69
Verstraeten, *et al.,*	890	18.6	9	149	124
PSIAC	357 - 714	18.6	9	60 – 119	40 – 79
Korir					
Runoff plot	390	15.5	8	48	40
HR Wallingford	377	15.5	8	47	40
Verstraeten, *et al.,*	1,390	15.5	8	170	141
PSIAC	357 - 714	15.5	8	44 – 89	30 – 59

Note:
1 = SSY (specific sediment yield) is obtained from the results in chapter 5
2 = bulk density of 1,500 kg/m^3 is considered for PSIAC and 1,200 kg/m^3 for the remaining methods

A comparative assessment of the empirical approaches on the other operational earthen dams in the region supports the results of the study sites (Table 7.5 and Figure 7.3). The results show that, similar to the case of Korir, some of the operational dams would have already been fully silted at the moment according to the estimate by Verstraeten, *et al.,* method.



Note: the earthen dam codes used correspond to those indicated in Table 7.5

Figure 7.3 Total expected reservoir sedimentation and dead storage capacity of some dams in Tigray based on the different empirical methods

As indicated in chapter 4, the objective of the sedimentation study was to provide a simple empirical tool for rapid assessment of catchments with high risk of erosion. Considering the situation at Korir, the HR Wallingford method gives better estimation of the sediment yield and can be used for preliminary assessment.

Table 7.5 Total expected reservoir sedimentation and dead storage capacity of some dams in Tigray based on the different empirical methods

Code	Name of dam	Life span	Catchment area	Age	Specific sediment yield				Total sedimentation since construction[3]					Dead storage[4]
					HR Wallingford[1]	Verstraeten *et al.*[2]	PSIAC[3]		HR Wallingford	Verstraeten *et al.*	PSIAC			
							Minimum	Maximum			Minimum	Maximum	Average	
		in years	in km^2	in years	in $t/km^2.yr$	in $t/km^2.yr$	in $t/km^2.yr$	in $t/km^2.yr$	in m^3	in m^3	in m^3	in m^3	in m^3	in m^3
1	Adi Amharay	33	6.00	7	749	1,843	143	357	26,230	64,505	4,004	9,996	7,000	175,000
2	Adi Gela	40	8.78	6	1,454	1,600	357	714	63,834	70,240	12,538	25,076	18,807	62,500
3	Adi Kenafiz	31	8.80	6	915	1,248	357	714	40,272	54,912	12,566	25,133	18,850	60,953
4	Betqua	23	6.13	7	1,697	4,074	357	714	60,675	145,679	10,213	20,425	15,319	133,267
5	Endazeoy	25	1.65	5	6,275	4,292	357	714	43,142	29,508	1,964	3,927	2,945	20,000
6	Filiglig	30	3.20	6	1,609	1,608	714	2,143	25,750	25,728	9,139	27,430	18,285	20,832
7	Gereb Mihiz	21	17.27	6	1,922	1,144	357	714	165,949	98,784	24,662	49,323	36,992	325,000
8	Gereb Segen	25	4.79	4	210	2,142	357	714	3,351	34,201	4,560	9,120	6,840	22,400
9	Gumsalasa	30	18.55	9	495	890	357	714	68,852	123,821	39,734	79,468	59,601	475,500
10	Hashenge	25	25.70	7	1,530	1,647	357	714	229,352	246,913	42,816	85,632	64,224	277,988
11	Laelay wukro	20	9.16	6	1,050	1,341	143	357	48,100	61,418	5,240	13,080	9,160	220,000
12	Mai Delle	27	10.10	6	264	1,350	357	714	13,329	68,175	14,423	28,846	21,634	270,000
13	Mai Haidi	31	1.96	6	1,170	4,162	714	2,143	11,468	40,788	5,598	16,801	11,199	15,133
14	Sewhimeda	10	4.70	6	671	1,917	357	714	15,767	45,050	6,712	13,423	10,067	40,000
15	Korir	-	15.50	8	377	1,369	357	714	38,957	141,463	29,512	59,024	44,268	30,000

Note:
1 = obtained from Table 7.3
2 = obtained from Poesen, *et al.,* (2001)
3 = a bulk density of 1,200 kg/m^3 is used (Nyssen, 2001)
4 = obtained from Table 7.1

7.1.2 Reservoir operation

Proper planning and implementation of the reservoir operation is very important for the success of the earthen dam irrigation projects in Tigray. However, analysis of the reservoir water balance during the irrigation season in 2002 and 2004 revealed a loss of a large quantity of water as evaporation from the reservoir (Table 7.6). The table shows that the reservoir evaporation in 2002 was about 42% and 36% at Gumsalasa and Korir respectively, while the corresponding discharge to the command area was about 46% and 57%. As a result of the longer observation period and the decrease in the number of irrigation days in 2004, the percentage of reservoir evaporation was 49% at Gumsalasa and 57% at Korir.

Table 7.6 Percentage of the reservoir evaporation of the study sites during the irrigation season in 2002 and 2004[1]

Water balance parameter	Gumsalasa		Korir	
	2002	2004	2002	2004
Period	02/04 – 03/06	15/03 – 02/06	04/04 – 23/05	13/03 – 29/05
Total number of days	63	80	50	78
Irrigation days	52	42	50	53
Outflow in %				
- reservoir evaporation	41.6	49.2	35.7	57
- canal discharge	46.2	33.2	61	36.7
- seepage discharge	6.4	10.6	0	0
- livestock consumption	0.4	0.7	1.2	2.7
- groundwater recharge	5.3	6.3	2	3.6
Total	100	100	100	100

Note:
1 = data compiled from the water balance results in chapter 5

The high loss of water as reservoir evaporation is caused by the existing operational plan that starts irrigation 4 months after the end of the rainy season (Figure 7.4). The irrigated fields of the schemes are also used for rainfed agriculture. The rainfed crops are sown in June/July and harvested in December. Except for 1 – 2 possible supplementary irrigation water supplies for moisture stressed crops, water is not released from the reservoir during this period. The main irrigation season and reservoir operation starts in January and extends till June. This period, however, coincides with the highest evaporation rates (Table 7.7).

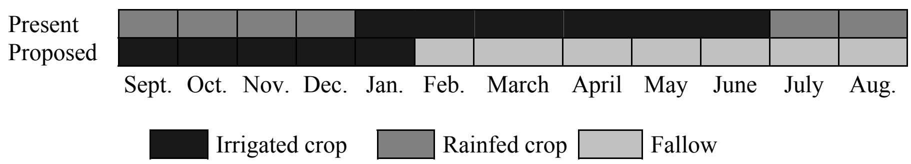


Figure 7.4 Present and proposed cropping schedules

The percentage of reservoir evaporation mentioned above represents the irrigation season only. The amount will be even much higher if the period between

September to December, when there is only reservoir evaporation without any discharge, is taken into account. It can, therefore, generally be summarized that the existing operation is not effective in utilizing the limited water stored in the reservoir. This demands the formulation and implementation of an operational plan that can reduce the loss of water due to reservoir evaporation. Starting irrigation immediately after the rainy season (in September) seems to be a good option in this regard (Table 7.7).This can increase the efficiency of the reservoir operation in two ways compared to the present plan, namely, by reducing the reservoir evaporation loss and the water requirement of the crops. The amount of water that can be saved by the proposed plan is presented underneath.

Table 7.7 Comparative assessment of reservoir evaporation based on the present and proposed operation plan

Month	Days	Gumsalasa			Korir		
		ETo[1]	Reservoir evaporation		ETo[1]	Reservoir evaporation	
			Present operation[2]	Proposed operation[3]		Present operation[2]	Proposed operation[3]
		in mm/d	in mm/month	in mm/month	in mm/d	in mm/month	in mm/month
September	30	4.5	135.0	135.0	4.5	135.0	135.0
October	31	4.3	133.3	133.3	4.4	136.4	136.4
November	30	4.0	120.0	120.0	3.9	117.0	117.0
December	31	3.8	117.8	117.8	3.8	117.8	117.8
January	31	4.3	133.3	133.3	4.1	127.1	127.1
February	28	4.9	137.2	[4]	4.8	134.4	[4]
March	31	5.3	164.3	[4]	5.2	161.2	[4]
April	30	5.4	162.0	[4]	5.4	162.0	[4]
May	31	5.4	167.4	[4]	5.5	170.5	[4]
June	30	5.4	162.0	[4]	5.5	165.0	[4]
July	31	4.1	127.1	127.1	4.1	127.1	127.1
August	31	4.0	124.0	124.0	3.9	120.9	120.9
Total			1,683.4	890.5		1674.4	881.3

Note:

1 = potential evapotranspiration data obtained from the International Water Management Institute (2005)

2 = present operation is during January – June

3 = proposed operation starts in September and assumes growing period of 150 days

4 = this is dependent on the depth of water available in the dead storage

Reservoir evaporation

The reservoir is generally filled with water to a certain level during the main rainy season, which is from late June to early September. The irrigation then starts in January for the present operational plan and in September for the proposed. The water level is generally expected to be utilized up to the dead storage level at the end of the irrigation season, which is June and January for the present and proposed plans respectively. Figure 7.5 presents the schematic diagram of the reservoir water level and the corresponding capacity for the present and proposed operations. The pattern of outflow from the reservoir for the two scenarios can be summarized as follows:

- *present operation*. The outflow during September – end of December (1) includes reservoir evaporation, seepage, livestock consumption and groundwater recharge. Since irrigation starts at the beginning of January, discharge becomes an additional outflow component during January – June (2) resulting in a steeper outflow curve. The reservoir water level is expected to be at the dead storage at the end of the irrigation period (June) and the refilling continues during the rainy season;

- *proposed operation*. Irrigation starts in September and the outflow during September – January (3) includes discharge, reservoir evaporation, seepage, livestock consumption and groundwater recharge. Since the live storage is assumed to be utilized during the irrigation period, the reservoir water level is expected to reach at the dead storage by the end of January. The rainfall and subsequent inflow and refill of the reservoir generally occur during the main rainy season between late June and early September. The water in the dead storage will, therefore, continue to be released in the form of reservoir evaporation, seepage, livestock consumption and groundwater recharge during February – June.

Table 7.7 and Figure 7.5 reveal that the depth of reservoir evaporation loss during the present scheduling depends only on the climatic conditions and occurs while the reservoir water covers a larger area. Under the proposed plan, however, the depth of the evaporation loss is limited by the available water in the dead storage and occurs over a smaller reservoir area (the dead storage). As a result, the total volume of reservoir evaporation loss by the present arrangement would be higher than the proposed. This indicates the potential of the proposed plan to save water and to irrigate a larger area than the present.

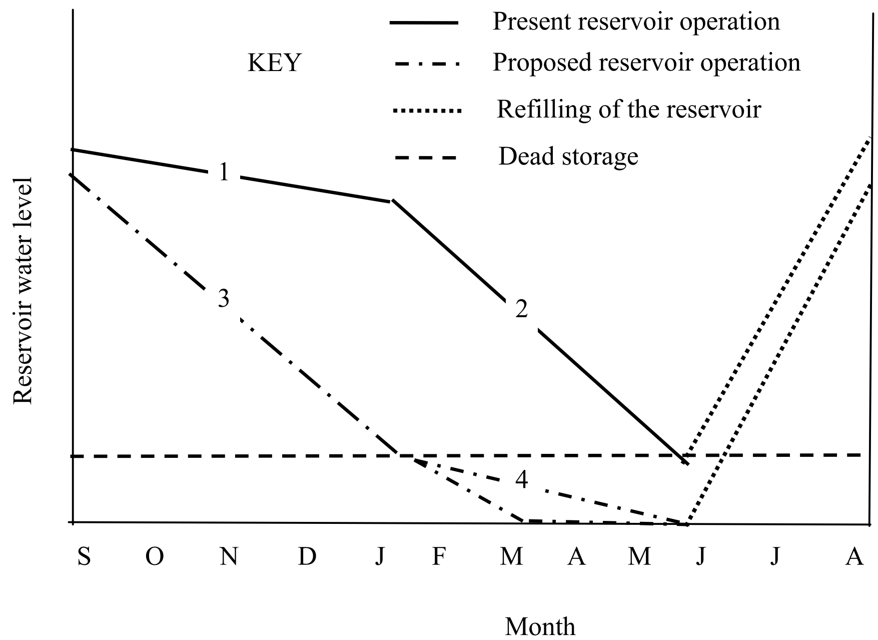


Figure 7.5 Schematic presentations of the reservoir water level for the present and proposed operations

The amount of water available in the reservoir at the beginning of the proposed irrigation season is generally higher than the present (Figure 7.5). On the other hand, unlike the present scheduling, the dead storage is exposed for losses during the proposed operation in the period between the end of the irrigation season and the beginning of the rainy season (February – June). The extent of this loss determines the level to which the reservoir will be filled at the end of the following rainy season. The total volume of water that can be saved by the proposed plan, therefore, depends on the variation in the initial volume of reservoir water at the start of irrigation of the two scenarios and the dead storage loss of the proposed schedule. Taking into account these factors, Equation 7.1 can be used to estimate the volume of water that can be saved by the proposed scheduling based on the initial reservoir volume, the volume of the design dead storage and the volume of sediment deposition since construction. The dead storage volume of the Gumsalasa dam (132 * 10^3 m^3) is about 7% of the design reservoir capacity (1.9 * 10^6 m^3), while that of Korir is only about 2%. Considering the small design dead storage capacity and the effect of sediment deposition since construction, the equation assumes that the water in the dead storage will be totally evaporated during February – June for the proposed operation. It has to be noted that this represents the worst scenario. Because, the reservoir water level at the end of the rainy season will be higher if some water remains in the dead storage by June.

$$V_{PRO} = (V_{IPRO} - V_{IPRE}) - (V_{DS} - V_{Sed}) \qquad 7.1$$

Where:

V_{PRO} = total volume of water that can be saved by the proposed operation in m^3

V_{IPRO} = initial reservoir volume of the proposed scheduling in m^3 (Figure 5.16, Figure 5.17 and Table 7.8)

V_{IPRE} = initial reservoir volume of the present scheduling in m^3 (Figure 5.16, Figure 5.17 and Table 7.8)

V_{DS} = volume of the dead storage in m^3 (Figure 5.16, Figure 5.17 and Table 7.8)

V_{Sed} = total volume of sediment deposited in the dead storage since construction in m^3 (Table 7.4)

Table 7.8 Initial reservoir capacity, dead storage and sedimentation of the study sites for 2003/2004 irrigation season

Parameter	Elevation in m+MSL	Volume in 10^3 m^3	Remark
Gumsalasa			
Initial reservoir volume of the proposed scheduling (V_{IPRO})[1]	1957.08	1,200	Figure 5.16
Initial reservoir volume of the present scheduling (V_{IPRE})[2]	1956.37	950	Figure 5.16
Volume of dead storage (V_{DS})	1953.00	132	Figure 5.16
Volume of sediment deposited (V_{Sed})	-	69	Table 7.4
Korir			
Initial reservoir volume of the proposed scheduling (V_{IPRO})[1]	1983.64	650	Figure 5.17
Initial reservoir volume of the present scheduling (V_{IPRE})[2]	1983.13	550	Figure 5.17
Volume of dead storage (V_{DS})	1977.50	30	Figure 5.17
Volume of sediment deposited (V_{Sed})	-	40	Table 7.4

Note:
1 = this corresponds to 15/09/2003
2 = this corresponds to 01/01/2004

Table 7.8 presents the initial reservoir capacity of the two scenarios, the volume of dead storage and the sediment deposition for the 2003/2004 irrigation season. The total volume of water that could have been saved by the proposed scheduling would have been about 187 * 10^3 m^3 and 100 * 10^3 m^3 at Gumsalasa and Korir respectively (Equation 7.1). Considering an irrigation efficiency of 48% (Appendix D), the net additional amount of irrigation water that would have been available to the crops is 90 * 10^3 m^3 at Gumsalasa and 48 * 10^3 m^3 at Korir.

Crop water requirement

Table 7.9 Crop water requirements of onion and maize under the present and proposed irrigation schedule at Gumsalasa (Clarke, *et al.,* 1998)[1]

Date	ETo in mm/period	Onion kc	Onion ETcrop in mm/period	Maize kc	Maize ETcrop in mm/period
Present operation					
01/01	42.4	0.70	29.7	0.30	12.7
11/01	44.3	0.70	31.0	0.30	13.3
21/01	46.1	0.76	35.2	0.33	15.4
31/01	47.8	0.88	42.1	0.54	25.6
10/02	49.3	1.00	49.1	0.76	37.5
20/02	50.6	1.05	53.1	0.99	49.9
02/03	51.6	1.05	54.2	1.18	60.8
12/03	52.5	1.05	55.1	1.20	62.9
22/03	53.0	1.01	53.7	1.20	63.6
01/04	53.4[2]	0.96	25.6	1.20	64.0
11/04	53.4	-	-	1.16	62.3
21/04	53.3	-	-	0.96	50.9
01/05	53.0	-	-	0.72	38.2
11/05	26.3	-	-	0.55	14.4
Total			428.8		571.5
Proposed operation					
15/09	41.3	0.70	28.9	0.30	12.4
25/09	40.8	0.70	28.5	0.30	12.2
05/10	40.4	0.76	30.9	0.33	13.5
15/10	40.2	0.88	35.4	0.54	21.5
25/10	40.0	1.00	39.9	0.76	30.5
04/11	40.0	1.05	42.0	0.99	39.5
14/11	40.1	1.05	42.1	1.18	47.2
24/11	40.3	1.05	42.3	1.20	48.3
04/12	40.5	1.01	41.0	1.20	48.6
14/12	40.8[3]	0.96	19.6	1.20	48.9
24/12	41.2	-	-	1.16	48.0
03/01	42.8	-	-	0.96	40.8
13/01	44.6	-	-	0.72	32.2
23/01	23.0	-	-	0.55	12.6
Total			350.6		456.2

Note:
1 = effective rainfall during the present and proposed operation plans is zero; ETcrop = NIR
2 = ETo of onion during this period is 26.7 mm
3 = ETo of onion during this period is 20.4 mm
ETo = potential evapotranspiration, kc = crop coefficient, Etcrop = crop water requirement, NIR. = net irrigation water requirement

Crop water requirement varies with climatic conditions, crop type and growth stage. The potential evapotranspiration of the present irrigation scheduling is higher than of the proposed. As a result, in addition to minimizing the reservoir operation loss, the proposed arrangement demands less irrigation water than the present. The CropWat computer program (Clarke, *et al.,*1998) was used to compare the crop water requirements of the two commonly irrigated crops (onion and maize) under the present and the proposed operational plan for the irrigation schemes (Table 7.9 and Table 7.10). The results show that the proposed plan can save about 78 mm and 77 mm of irrigation water from onion production at Gumsalasa and Korir respectively. The amount increases to 115 mm at Gumsalasa and 118 mm at Korir for maize.

Table 7.10 Crop and irrigation water requirements of onion and maize under the present and proposed irrigation schedule at Korir (Clarke, *et al.*, 1998)[1]

Date	ETo	Onion		Maize	
	in mm/period	kc	ETcrop in mm/period	kc	ETcrop in mm/period
Present operation					
01/01	41.6	0.70	29.1	0.30	12.5
11/01	43.5	0.70	30.5	0.30	13.0
21/01	45.4	0.76	34.7	0.33	15.1
31/01	47.1	0.88	41.8	0.54	25.3
10/02	48.7	1.00	48.5	0.76	37.1
20/02	50.0	1.05	52.5	0.99	49.4
02/03	51.2	1.05	53.7	1.18	60.3
12/03	52.1	1.05	54.7	1.20	62.5
22/03	52.8	1.01	53.5	1.20	63.3
01/04	53.2[2]	0.96	25.6	1.20	63.8
11/04	53.4	-	-	1.16	62.2
21/04	53.3	-	-	0.96	50.9
01/05	53.1	-	-	0.72	38.3
11/05	26.4	-	-	0.55	14.4
Total			424.3		568.2
Proposed operation					
15/09	41.4	0.70	28.9	0.30	12.4
25/09	40.8	0.70	28.5	0.30	12.2
05/10	40.3	0.76	30.8	0.33	13.4
15/10	40.0	0.88	35.2	0.54	21.4
25/10	39.7	1.00	39.6	0.76	30.2
04/11	39.6	1.05	41.6	0.99	39.1
14/11	39.6	1.05	41.6	1.18	46.6
24/11	39.7	1.05	41.6	1.20	47.6
04/12	39.8	1.01	40.3	1.20	47.8
14/12	40.0[3]	0.96	19.2	1.20	48.0
24/12	40.4	-	-	1.16	47.0
03/01	42.0	-	-	0.96	40.1
13/01	43.9	-	-	0.72	31.4
23/01	22.6	-	-	0.55	12.4
Total			347.5		449.9

Note: 1 = effective rainfall during the present and proposed operation plans is zero; ETcrop = NIR

2 = ETo of onion during this period is 26.6 mm

3 = ETo of onion during this period is 20 mm

ETo = potential evapotranspiration, kc = crop coefficient, ETcrop = crop water requirement, NIR. = net irrigation water requirement

The net amount of water that can be saved from the reduced crop water demand of the proposed scheduling is converted to volume using the average irrigated area of Gumsalasa (67 ha) and Korir (55 ha) (Table 2.15). The net additional irrigation water volume that can be saved at Gumsalasa becomes 52 * 10^3 m^3 for onion and 77 * 10^3 m^3 for maize, while the respective amount at Korir is 42 * 10^3 m^3 and 65 * 10^3 m^3.

7.1.3 Recommendations

To be accepted by the government and farmers, a proposed change in reservoir operation plan will have to improve the benefit that can be gained from the irrigation schemes. It has been shown that, as a result of the smaller crop water requirement and the reduced reservoir evaporation loss, the proposed operational plan can provide more water for irrigation than the present arrangement. One of the problems to implement this plan is the presence of rainfed crops in the fields. As shown below, however, the assessment of the situation of the study sites indicates that implementation of the proposed irrigation scheduling by terminating the rainfed production in the irrigated fields seems more beneficial than the existing arrangement. For example, the average rainfed cereal production is 693 kg/ha at Gumsalasa and 628 kg/ha at Korir (Table 6.7). The yield that can be obtained from the average household irrigated landholding, which is 0.2 ha at Gumsalasa and 0.32 ha at Korir, would be 138 kg and 200 kg respectively. This is very low especially taking into account the high cost of production as given in chapter 6. On the other hand, the water that can be saved by the proposed scheduling can irrigate a relatively large area and benefit more of farmers. Table 7.11 reveals that a potential average area of 38 ha at Gumsalasa and 26 ha at Korir can be additionally irrigated by the water that can be saved if the start of the irrigation season is shifted from January to September. Based on the average household irrigated landholding of the schemes, about 190 and 80 more households than the existing ones can benefit from the irrigation at Gumsalasa and Korir respectively. Besides, the average annual yield from the irrigation per household is about ten-fold of the production that can be obtained from rainfed agriculture. The increased yield combined with the higher market price of the irrigated production will generally improve the equitable income distribution and livelihood of the poor farmers. In addition, utilizing the land during both the rainfed and irrigation seasons may over-exploit the soil nutrients and reduce the productivity. On the other hand, fallowing of the fields during the rainfed season can contribute to the improvement of the soil fertility. It would, therefore, be beneficial to implement the proposed operational plan primarily in the study sites and adopt it regionally afterwards following evaluation. The farmers can concentrate the rainfed agriculture on their rainfed fields, which is about 1.2 ha per household in Tigray.

The success of the above proposition, however, depends on the proper determination of the total reservoir water at the beginning of the irrigation season, the part that will be available for irrigation and the corresponding area that can be irrigated. As indicated in chapter 6, the development agents of the irrigation schemes do not have a mechanism to estimate the amount of water in the reservoir and the corresponding area that can be irrigated. The reservoir elevation-area-capacity curves are not available at the irrigation schemes. Even if they are available, there are no marks on the upstream slope of the dams that indicate the elevation (m+MSL). As a result, the area to be irrigated is decided by best guess which needs to be improved. In this regard, the elevations (m+MSL) would have to be marked on the upstream slope of the dams so that the development agents can easily read the levels and determine the corresponding reservoir capacity from the elevation-area-capacity curves (Figure 5.16 and 5.17).

Table 7.11 Additional area that can be irrigated and corresponding yield achieved by the proposed irrigation schedule[1]

Crop	Amount of net water saved from			Additional area that can be irrigated		Yield that could be obtained		
	Reservoir[2]	Irrigated field	Total	NIR[3]	Area	Average		Total
	in 10^3 m^3	in 10^3 m^3	in 10^3 m^3	in mm	in ha	in kg/ha[4]	in kg/holding[5]	in tons
Gumsalasa								
Onion	90	52	142	350	41	9,397	1,879	385
Maize	90	77	167	456	36	5,085	1,017	182
Average[6]	90	65	155	403	38	7,241	1,448	277
Korir								
Onion	48	42	90	347	26	8,637	2,764	224
Maize	48	65	113	450	25	5,028	1,609	126
Average[6]	48	54	102	399	26	6,833	2,186	175

Note:
1 = irrigation starts September 15
2 = an irrigation efficiency of 48% is assumed (Appendix D)
3 = net irrigation water requirement during the growing period (Table 7.9 and Table 7.10)
4 = obtained from Table 6.9
5 = the yield that could be harvested per the average household irrigated landholding of 0.2 ha at Gumsalasa and 0.32 at Korir
6 = the average value represents a situation where half of the irrigated land is under maize production and the other half under onion, which is common in the study sites

Once the total reservoir water is known by using the above approach, the amount that will be available for irrigation can be estimated by Equation 7.2. The input values of the equation can be obtained either from the elevation-area-capacity curves or the water balance analysis in chapter 5.

$$V_{IR} = V_{Ri} - (V_{DS} + E_R * A_{Rav} + V_S * N + V_L * N + R_{GW} * A_{Rav} * N)$$

and

$$A_{Rav} = \frac{A_{Ri} + A_{DS}}{2} \qquad 7.2$$

Where:
V_{IR} = total volume of water available for irrigation in m^3
V_{DS} = volume of the dead storage in m^3 (from Table 7.1)
V_{Ri} = total reservoir water volume at the beginning of the irrigation season in m^3 (from elevation-area-capacity curves, Figure 5.16 and Figure 5.17)
E_R = evaporation from the reservoir during the irrigation season in m (from Table 7.9 and Table 7.10)
A_{Rav} = average reservoir area during the irrigation season in m^2

V_S = seepage in m^3/d (from Table 5.10)
V_L = water consumed by livestock in m^3/d (from Table 5.8)
R_{GW} = groundwater recharge in m/d (from Table 5.10)
A_{Ri} = reservoir area at the beginning of the irrigation season in m^2 (from elevation-area-capacity curves)
A_{DS} = area of the dead storage in m^2 (from elevation-area-capacity curves)
N = number of days during the irrigation season (the crop growing period)

The area that can be irrigated is then determined based on the available irrigation water, the net irrigation water requirement and the irrigation efficiency (Equation 7.3).

$$A = \frac{V_{IR}}{10 * D * E_i} \tag{7.3}$$

Where:
A = area that can be irrigated in ha
V_{IR} = total volume of water available for irrigation in m^3
D = the net irrigation water depth required over the growing period in mm (Table 7.9 and Table 7.10)
E_i = irrigation efficiency (Appendix D)

7.2 Water management and crop production

It is mentioned in chapter 6 that the water management practice at the study sites is based on direct observation of the soil and plant conditions and allows individual farmers to decide the delivery time. As a result, wastage of irrigation water by runoff and over-watering is a common practice. The runoff loss was observed to be severe especially in short furrows where the farm discharge reaches the bottom end very quickly. Furrow lengths of as short as 6 m were found at Gumsalasa irrigation scheme. The over-watering, on the other hand, mostly occurs in fields that do not have furrows but are irrigated by spreading. This arrangement may have a negative implication on the food security and environment of the irrigation schemes. In this section, the potential yield that can be obtained at Gumsalasa under the present and proposed irrigation scheduling is presented for the main crops. In addition, the effect of the existing water management on the crop production and recommendations for improvement are provided.

7.2.1 Maximum yield

The maximum crop yield (Ym) is defined as the harvested yield of a high-producing variety, well-adapted to the given environment where water, nutrients, pests and disease do not limit the yield. The level of the maximum yield is primarily determined by its genetic characteristics and the adaptation to the prevailing environment. Environmental requirements of climate, soil and water for optimum growth and yield vary with crop and variety. Selection of a crop and variety most suited to the given environment is very crucial for obtaining high production (Doorenbos, *et al.*, 1996).

In addition to any specific temperature and day-length requirements for crop development, the major climatic factors that determine the maximum yield are temperature, radiation and length of the total growing season. In general, temperature controls the rate of crop development and consequently affects the length of the total growing period of a crop. For example, a maize variety that reaches maturity in 100 days at a mean daily temperature of 25 – 30 ^{0}C may take 150 days at 20 ^{0}C.

Some crops have specific temperature and/or day-length requirements for initiation of certain growth and development. For instance, a night temperature of below 15 ^{0}C is required for tuber initiation of potato, while flowering of some sorghum varieties is sensitive to short day-length (Doorenbos, *et al.*, 1996).

Crop growth and yield are also affected by the total radiation received during the growing period. At given radiation and temperature, crops differ in their response to how much of the received radiation can be converted into growth and yield. This variation in response has a very important implication in the efficient utilization of water for crop production. A good maize crop can convert 1 – 2% of the total radiation it receives into growth. Crop selection should, therefore, consider the radiation requirement and response in addition to temperature and day-length.

Most crops offer varieties that differ in their general and specific climatic requirements and length of total growing period. This allows the crop to be adapted to a wide range of climatic conditions and time available for crop production.

In addition to climate, the available growing season is also determined by the duration of an assured water supply of good quality. The available water supply and crop water requirements should be taken into account in crop selection. Other aspects include such factors as farmers' preference, marketing and storage.

The maximum yield can be calculated for different climatic conditions. This would allow the quantification of production potential of different areas and identify the most suitable areas for production of a given crop. The agro-ecological method developed by Kassam (1977) for Africa was used to determine the maximum yield for Gumsalasa. The method involves the estimation of the possible potential yield of a standard crop for a given climate using radiation data, followed by corrections for genetically-controlled growth process of a particular agricultural crop (Doorenbos, *et al.*, 1996). The procedure includes:

- calculation of gross dry matter production of a standard crop (Yo);
- application of corrections for crop species and temperature, crop development over time and leaf area (cL), net dry matter production (cN) and harvested part (cH).

Calculation of gross dry matter production of a standard crop (Yo)

The gross dry matter production of a standard crop (Yo) for a given location can be calculated by the De Wit method (1965). The method is based on the level of incoming active shortwave radiation for standard conditions (Equation 7.4).

$$Yo = F * yo + (1 - F)yc \qquad 7.4$$

Where:

Yo = gross dry matter production of a standard crop in kg/ha.d

F = fraction of the day time the sky is clouded

Table 7.12 Maximum active incoming shortwave radiation and gross dry matter production on overcast and clear days for standard crop (after De Wit, 1965)

North South		January July	February August	March September	April October	May November	June December	July January	August February	September March	October April	November May	December June
0^0	Rse in $J/cm^2.d^1$	1,435	1,506	1,544	1,523	1,460	1,410	1,435	1,494	1,540	1,527	1,460	1,410
	yc in kg/ha.d	413	424	429	426	417	410	413	422	429	427	418	410
	yo in kg/ha.d	219	226	230	228	221	216	218	225	230	228	222	216
10^0	Rse in $J/cm^2.d^1$	1,251	1,389	1,502	1,569	1,577	1,565	1,569	1,577	1,544	1,443	1,301	1,218
	yc in kg/ha.d	376	401	422	437	440	440	440	439	431	411	385	370
	yo in kg/ha.d	197	212	225	234	236	235	236	235	230	218	203	193
20^0	Rse in $J/cm^2.d^1$	1,402	1,226	1,410	1,569	1,648	1,674	1,669	1,615	1,494	1,310	1,105	996
	yc in kg/ha.d	334	371	407	439	460	468	465	451	425	387	348	325
	yo in kg/ha.d	170	193	215	235	246	250	249	242	226	203	178	164
30^0	Rse in $J/cm^2.d^1$	799	1,025	1,268	1,519	1,674	1,745	1,720	1,607	1,393	1,130	879	749
	yc in kg/ha.d	281	333	385	437	471	489	483	456	412	356	299	269
	yo in kg/ha.d	137	168	200	232	251	261	258	243	216	182	148	130
40^0	Rse in $J/cm^2.d^1$	548	795	1,088	1,418	1,657	1,766	1,728	1,544	1,274	920	632	494
	yc in kg/ha.d	219	283	353	427	480	506	497	455	390	314	241	204
	yo in kg/ha.d	99	137	178	223	253	268	263	239	200	155	112	91

Note:
1 = 4.184 was used to convert Calorie to Joule

Rse = maximum active incoming shortwave radiation, yc = gross dry matter production on clear days, yo = gross dry matter production on overcast days

yo = gross dry matter production rate of a standard crop for a given location on a completely overcast day in kg/ha.d (Table 7.12)
yc = gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day in kg/ha.d (Table 7.12)

The fraction of the day time the sky is clouded (F) can be calculated by equation 7.5.

$$F = \frac{Rse - 0.5Rs}{0.8Rse} \qquad 7.5$$

Where:
Rse = maximum active incoming shortwave radiation on clear days in J/cm^2.d (Table 7.12)
Rs = actual measured incoming shortwave radiation in J/cm^2.d

When only sunshine data are available, the actual incoming shortwave radiation (Rs) can be estimated using equation 7.6.

$$Rs = Ra * (0.25 + 0.5n / N) \qquad 7.6$$

Where:
Ra = extra-terrestrial radiation in mm/d
N = maximum possible sunshine duration in hr/d
n = actual measured sunshine duration in hr/d

Correction for crop species and temperature

The gross dry matter production (Yo) depends on crop species and temperature. A production rate (ym) of either larger or smaller than 20 kg/ha.hr is assumed as a threshold value for a standard crop. Table 7.13 presents the production rates for various crop groups.

Table 7.13 Production rates (ym) for various crop groups and mean temperatures (Doorenbos, *et al.*, 1996)

	Mean temperature in ^{0}C								
	5	10	15	20	25	30	35	40	45
Production rate by crop group (in kg/ha.hr)									
- Cool-I	5	15	20	20	15	5	0	0	0
- Warm-I	0	0	15	32.5	35	35	32.5	5	0
- Cool-II	0	5	45	65	65	65	45	5	0
- Warm-II	0	0	5	45	65	65	65	45	5

Note:
Cool-I = alfalfa, bean, cabbage, pea, potato, tomato, sugarbeet, wheat (optimal 15 – 20 ^{0}C); Warm-I = alfalfa, citrus, cotton, groundnut, pepper, rice, safflower, soybean, tobacco, tomato (optimal 25 – 30 ^{0}C); Cool-II = some maize and sorghum varieties (optimal 20 – 30 ^{0}C); Warm-II = maize, sorghum, sugarcane (optimal 25 – 35 ^{0}C)

Adjustment of the gross dry matter production for crop species and temperature can be made by equation 7.7 for production rates greater than 20 kg/ha.hr and by equation 7.8 for production rates less than 20 kg/ha.hr.

$$Yo = F*(0.8+0.01ym)*yo+(1-F)*(0.5+0.025ym)*yc \quad (ym > 20) \qquad 7.7$$

$$Yo = F*(0.8+0.01ym)*yo+(1-F)*(0.5+0.025ym)*yc \quad (ym < 20) \qquad 7.8$$

Correction for crop development over time and leaf area (cL)

Table 7.14 gives the correction factor for crop development over time and leaf area (cL). With the highest rate during the middle of the total growing season, crop growth is generally small at the beginning and end of the growing period. The average growth rate over the growing period is about 50% of the maximum. In addition, the active leaf area index (LAI) of the standard crop is assumed to be five times the ground surface. Correction should be applied for smaller leaf area, whereas the effect of larger leaf area is insignificant.

Table 7.14 Correction for crop development over the growing period and leaf area (Doorenbos, *et al.*, 1996)

Leaf area index (LAI)	1	2	3	4	≥5
Correction cL	0.2	0.3	0.4	0.5	0.5

Correction for net dry matter production (cN)

In addition to the dry matter production, the crop also needs energy for the respiration process. The fraction of energy that can be used for dry matter production (cN) is about 0.6 for cool (mean temperature lower than 20 ^{0}C) and 0.5 for warm (mean temperature higher than 20 ^{0}C) conditions.

Correction for harvested part (cH)

In general, part of the total dry matter, such as grain and sugar, is harvested in crop production. The harvest index (cH) (Table 7.15), which is the ratio of the net total dry matter and the harvested yield, is usually used for the correction of the harvested part.

Table 7.15 Harvest index (cH) of high-producing varieties under irrigation on dry weight basis (Doorenbos, *et al.*, 1996)

Crop	Product type	cH	Crop	Product type	cH
Bean	grain	0.25-0.35	Potato	tuber	0.55-0.65
Cabbage	head	0.6-0.7	Rice	grain	0.4-0.5
Cotton	lint	0.08-0.12	Sorghum	grain	0.3-0.4
Groundnut	grain	0.25-0.35	Soybean	grain	0.3-0.4
Maize	grain	0.35-0.45	Sugarbeet	sugar	0.35-0.45
Onion	bulb	0.7-0.8	Sugarcane	sugar	0.2-0.3
Pea	grain	0.3-0.4	Sunflower	seed	0.2-0.3
Pepper	fruit	0.2-0.4	Tobacco	leaf	0.5-0.6
Pineapple	fruit	0.5-0.6	Tomato	fruit	0.25-0.35
Alfalfa	hay		Wheat	grain	0.35-0.45
- year 1		0.4-0.5			
- year 2		0.8-0.9			

Summarizing the above presented climatic and crop aspects give equations 7.9 and 7.10 that can be used for the calculation of the maximum yield (Ym) for production rates (ym) of greater than and less than 20 kg/ha.hr respectively.

$$Ym = cL * cN * cH * G * F * (0.8 + 0.01ym) * yo + (1 - F) * (0.5 + 0.025ym) * yc \qquad 7.9$$

$$Ym = cL * cN * cH * G * F * (0.8 + 0.01ym) * yo + (1 - F) * (0.5 + 0.025ym) * yc \qquad 7.10$$

Where:

Ym = potential yield of high-producing, climatically adapted variety grown under constraint-free conditions over the growing period in kg/ha.period

cL = correction for crop development and leaf area (Table 7.14)

cN = correction for dry matter production, 0.6 for cool and 0.5 for warm conditions

cH = correction for harvested part (Table 7.15)

G = total number of days of growing period in days

F = fraction of the day time the sky is clouded

yo = gross dry matter production rate of a standard crop for a given location on a completely overcast day in kg/ha.d (Table 7.12)

yc = gross dry matter production rate of a standard crop for a given location on a clear (cloudless) dayin (kg/ha.d (Table 7.12)

ym = maximum gross dry matter production rate for a given climate in kg/ha.hr (Table 7.13)

According to Doorenbos, *et al.*, (1996), the maximum yield of onion is about 35,000 kg/ha – 45,000 kg/ha in all climatic regions and temperatures. On the other hand, the maximum yield of maize varies with agro-ecology and temperature. As a result, the afore-mentioned approach was used to determine the potential yield of maize at Gumsalasa under the present and proposed irrigation scheduling. Table 7.16 presents the summary of the input data used for the calculation. The mean actual incoming shortwave radiation (Rs), calculated by equation 7.6 based on the data in Table 7.17, was 2,483 J/cm^2.d and 2,309 J/cm^2.d for the present and proposed scheduling respectively.

Table 7.16 Input data for the calculation of potential yield of maize at Gumsalasa

Input data			Remark
	Present scheduling	Proposed scheduling	
Latitude	13 ^{0}N	13 ^{0}N	
Growing period	01/01 - 16/05	15/09 - 28/01	CropWat
No. of growing days (G) in days	135	135	CropWat
Mean temperature in ^{0}C[1]	19.1	17.5	IWMI (2005)[2]
Mean yo in kg/ha.d[1]	218	202	Table 7.12
Mean yc in kg/ha.d[1]	411	385	Table 7.12
Mean Rse in J/cm^2. d[1]	1,435	1,301	Table 7.12
ym in kg/ha.hr	61	55	Table 7.13
cL at LAI 5	0.5	0.5	Table 7.14
cN	0.6	0.6	
cH	0.4	0.4	Table 7.15

Note:

1 = this represents the mean value over the growing period

2 = International Water Management Institute

With all the necessary data available in Table 7.16 and Table 7.17, equations 7.5 and 7.9 were used for the estimation of the fraction of the day time the sky is clouded (F) and the potential yield (Ym) of maize at Gumsalasa. The result reveals that the maximum yield of maize that could be obtained at Gumsalasa under constraint-free condition is about 12,000 kg/ha under the present scheduling and 10,700 kg/ha for the proposed.

The potential yield per unit area of the present arrangement is slightly higher than the proposed. However, as shown in 7.1, the additional area that can be irrigated by the water saved due to the change in scheduling is about 38 ha. The gross potential yield that can be harvested from the total irrigated land under the proposed plan will, therefore, be higher than the present (Table 7.18). It has also to be noted that achieving the potential yield is generally difficult. Under actual farming conditions, yield loss usually occurs due to limited water and nutrient supply, and problematic farm operations including land preparation, weeding and harvesting. However, when compared to the actual farmers' yields, the potential yield will give an indication of the efficiency in agricultural production (Doorenbos, *et al.*, 1996).

Table 7.17 Actual incoming shortwave radiation (Rs) at Gumsalasa for maize

Radiation data	Present irrigation scheduling					
	January	February	March	April	May	Mean
n in hr/d[1]	10.6	10.6	10.5	10.4	11.1	
N in hr/d[2]	11.5	11.7	12.0	12.4	12.7	
Ra in mm/d[3]	12.6	13.8	15.0	15.7	15.7	
Rs in mm/d[4]	9.0	9.7	10.3	10.5	10.8	10.1
Rs in J/cm^2.d[5]						2,483.0
	Proposed irrigation scheduling					
	September	October	November	December	January	Mean
n in hr/d[1]	10.1	10.5	10.2	10.7	10.6	
N in hr/d[2]	12.2	11.8	11.5	11.3	11.4	
Ra in mm/d[3]	15.1	14.2	13.0	12.2	12.6	
Rs in mm/d[4]	10.0	9.9	9.0	8.8	9.0	9.3
Rs in J/cm^2.d[5]						2,309.0

Note :

1 = actual measured sunshine duration obtained from Table 3.3 of this document

2 = maximum possible sunshine duration obtained from Table 11 in Doorenbos, *et al.*, (1996) based on the latitude of the study site

3 = extra-terrestrial radiation obtained from Table 10 in Doorenbos, *et al.,* (1996) based on the latitude of the study site

4 = actual incoming shortwave radiation calculated using equation 7.6

5 = mm/d actual incoming shortwave radiation converted to equivalent J/cm^2.d (1 mm/d = 247 J/cm^2.d, based on Doorenbos, *et al.*, 1996)

Table 7.18 Average gross potential yield of maize that can be obtained from the present and proposed irrigation scheduling at Gumsalasa

Yield variable	Present scheduling	Proposed scheduling
Average irrigated area in ha[1]	X	X + 38
Potential yield in kg/ha	12,000	10,700
Gross potential yield in 10^3 kg[2]	12X	(10.7X + 406.6)

Note:

1= assuming the average area that can be properly irrigated based on the present arrangement as “X ha”, the area that will be irrigated by the proposed scheduling is taken as (X + 38 ha) where 38 ha is the additional area that can be irrigated by the water that will be saved (Table 7.11),

2 = for instance assuming the present average irrigated area of 67 ha (X) (Table 2.15), the increase in the gross potential yield of the proposed plan as a result of the additional irrigated area will be 319 * 10^3 kg

7.2.2 *Effect of the present water application on yield*

The average net infiltration depth per furrow per irrigation at Gumsalasa is about 16 mm (Table 6.5). Considering the irrigation interval that ranges from 5 days to 15 days (Table 6.2), the current water application would be equivalent to 1 – 3 mm/d. This is, however, insufficient compared to the water requirement of the crops during the irrigation season (Table 7.9) and affects the yield. The impact of water supply on crop yield can be determined when crop water requirements and crop water deficits, on the one hand, and maximum and actual crop yield on the other can be quantified. Water deficits in crops, and the resulting water stress on the plant, have an effect on the crop evapotranspiration and yield. Water stress in the plant can be quantified by the rate of actual evapotranspiration (ETa) in relation to the rate of maximum evapotranspiration (ETm). ETa = ETm if crop water requirements are fully met from the available water supply, while ETa < ETm when water supply is insufficient (Doorenbos, *et al.*, 1996).

When the full water requirements are not met, water deficit in the plant can reach to a point where crop growth and yield are affected. The manner in which water deficit affects crop growth and yield varies with crop species and crop growth stage. The impact of the water stress on yield decrease generally depends on the relative evapotranspiration (ETa/ETm). According to Doorenbos, *et al.*, (1996), the relative yield loss can be estimated if information is available on actual yield (Ya) in relation to maximum yield (Ym) under different water supply regimes. Where economic conditions do not restrict production and in a constraint-free environment, Ya = Ym when full water requirements are met. On the other hand, Ya < Ym if the water requirements are not met by the available water supply.

The effect of water stress can be quantified based on the relationship between the relative yield decrease and relative evapotranspiration deficit given by the empirically-derived yield response factor (ky) (Equation 7.11).

$$(1-\frac{Ya}{Ym}) = ky*(1-\frac{ETa}{ETm}) \qquad 7.11$$

Where:

Ya = actual harvested yield in kg/ha

Ym = maximum harvested yield in kg/ha

ky = yield response factor

ETa = actual evapotranspiration in mm/growing period
ETm = maximum evapotranspiration in mm/growing period

This relationship was used to evaluate the effect of the existing water supply on the yield of the major irrigated crops at Gumsalasa. The CropWat model was used to determine the water requirement and the yield response factor of the crops. The crop water requirement has already been presented in Table 7.9, while Table 7.19 gives the basic crop and irrigation data used in the simulation.

The total number of irrigations under the existing traditional practice at Gumsalasa is about 8 and 11 times for onion and maize respectively (Table 6.2). Taking the average infiltration of 16 mm per irrigation, the total depth of water applied during the irrigation season would be 128 mm for onion and 176 mm for maize. However, the net irrigation water requirement of onion and maize calculated using the CropWat model for a maximum yield (100% yield level) is about 429 mm and 571 mm respectively (Table 7.9). The effect of the water deficit on the relative yield reduction calculated by equation 7.11 is summarized in Table 7.20. The table clearly indicates that the yield reduction ranges from about 60% for maize to 70% for onion.

Table 7.19 Simulation data of onion and maize for the present crop calendar at Gumsalasa

Crop data	Onion (01/01 - 06/04)					Maize (01/01 - 16/05)				
Crop growth stage	I	CD	MS	LS	Total	I	CD	MS	LS	Total
No. of days	20	30	30	15	95	25	40	40	30	135
kc value	0.7	1.05	1.05	0.95		0.3	1.2	1.2	0.5	
Depletion factor	0.3	0.3	0.45	0.5		0.5	0.5	0.5	0.8	
Yield response factor (ky)	0.8	0.4	1.2	1.2		0.4	0.4	1.3	0.5	

Note:
I = initial, CD = crop development, MS = mid season, LS = late season

Table 7.20 Effect of the present water application practice on the yield of irrigated crops at Gumsalasa

Yield response factor	Crop										Remark
	Onion					Maize					
Crop growth stage	I	CD	MS	LS	Total	I	CD	MS	LS	Total	
ETa in mm	64	32	32	0		32	64	64	16		Table 6.2
ETm in mm	60.7	126.5	162.4	79.4		41.4	173.8	252.9	103.6		Table 7.9
ky	0.8	0.4	1.2	1.2		0.4	0.4	1.3	0.5		Table 7.19
Ya/Ym	1	0.7	0.04	0		0.91	0.75	0.03	0.58		
Yield reduction in %	0	30	96	100		9	25	97	42		
Weighted yield reduction in %[1]	0	3.3	32	33.3	68.7	1.4	3.8	48.5	8.1	61.8	

Note:
1 = this is calculated as a weighted value based on the ratio of the individual and the total yield reduction factor (ky). The total ky is the sum of the individual ky, which is 3.6 for onion and 2.6 for maize

The present average yield data of the irrigation scheme also generally reflect the same trend (Table 7.21). Even if water is the most limiting element, it has to be noted that other factors also contribute to the yield reduction.

Table 7.21 Level of the present actual average yield of irrigated crops with respect to the calculated maximum yield at Gumsalasa

Yield response variable	Crop		Remark
	Onion	Maize	
Average actual yield (Ya) in kg/ha	9,397	5,085	Table 6.9
Maximum yield (Ym) in kg/ha	40,000	12,000	
Relative yield decrease (Ya/Ym)	0.23	0.42	
Yield reduction %	77	58	

7.2.3 Recommendations

Water management plays a major role in the efficiency, productivity and sustainability of irrigation schemes. However, as already mentioned, it generally is inadequately administered in the study sites. The Regional Government of Tigray in general and the Bureau of Agriculture and Natural Resources in particular would, therefore, have to implement necessary measures to improve the situation. Based on the results of the study, the measures have to focus especially on planning and implementation of effective irrigation scheduling and improving the field irrigation method.

Planning and implementation of effective irrigation scheduling

It has been demonstrated that shifting the irrigation scheduling from the present (January – June) to the proposed (September – January) is more effective. The proposed scheduling would generally minimize the evaporation loss from the reservoirs, demand less irrigation water, increase the total irrigated area and the subsequent total production. The irrigation scheduling plan proposed in Table 7.9 and Table 7.10 is, therefore, recommended for the study sites. Based on the results at Gumsalasa and Korir, the new plan can further be adapted to the other operational earthen dam irrigation schemes and future developments.

However, proper implementation remains a key factor in the success of an effective irrigation scheduling. The current water management practice is a good example in this regard. Section 6.1.2 stated that the actual practice is totally different from the scheduling recommended by CoSAERT. Future operation of the irrigation schemes would have to give due attention to this aspect. To this effect, the following four variables, which are important for proper planning and operation of surface irrigation have to be known (Jensen, 1980 and Kay, 1986):

- irrigated area (A): the area to be irrigated in ha;
- irrigation depth (d): the amount of irrigation water that must infiltrate into the root zone in mm;
- stream size (Q): the amount of water per unit time needed to supply the required irrigation depth in l/s;
- irrigation time (t): the time required to supply the irrigation depth in hr.

From the agricultural water balance, the required amount of water needs be equal to the amount supplied. This means:

irrigation depth * irrigated area = irrigation time * stream size

The delivery time (t) required to apply an irrigation depth (d) to the crop root zone can then be calculated by using equation 7.12.

$$t = \frac{2.78 * d * A}{Q} \qquad 7.12$$

The main problem here is that almost all the earthen dam irrigation schemes in Tigray, including the study sites, have no mechanism to monitor the discharge passing through canals. As indicated in 6.1.2, the dam outlet and the various division boxes in the study sites are constructed with provisions to use sluice gates for discharge measurement. But, no sluice gate has been fitted so far and the discharge monitoring will remain to be one of the obstacles for improving the water management. In addition to the preparation of a proper cropping calendar and irrigation scheduling, effort needs to be made to provide the division boxes with the required discharge measurement and monitoring devices.

Improving the field irrigation method

The furrow lengths used in the irrigation schemes, especially at Gumsalasa, are generally short. As a result, the irrigation water reaches the furrow end quickly and causes runoff if the supply is not cutoff. On the other hand, the amount of water that infiltrates into the root zone becomes less than required when the discharge is cutoff early. It is, therefore, recommended to improve the design of the furrows of the irrigation schemes. In this regard, a user-friendly spreadsheet furrow evaluation and design program based on the equations for open-end furrows developed by the Soil Conservation Service (SCS) of the US Department of Agriculture was assessed based on the field test results and can be used for the situations in the study sites (Catholic University of Leuven, 2005 and Depeweg, 2000)

Model description

The variables involved in surface irrigation modeling are classified into field parameters and decision variables. The field parameters for furrow irrigation include the infiltration characteristics, the surface roughness, the required irrigation depth, the required irrigation depth and the gradient, shape and spacing of furrows. The decision variables are those parameters the designer can manipulate to obtain the best irrigation performance for given selected field conditions. These are mostly the field size (length and width) and the discharge. The main equations used in the SCS approach are summarized in Table 7.22.

The spreadsheet program contains two categories, namely, the input and the results sections (Table 7.23).

The input data include (Catholic University of Leuven, 2005 and Depeweg, 2000):

- Manning's roughness coefficient (n);
- furrow length (L) in m;
- furrow spacing (W) in m;
- furrow slope (S) in m/m;
- net irrigation depth (Fn) in mm;
- inflow rate (Q) in I/s;
- furrow intake family.

Table 7.22 Summary of equations for evaluation and design of furrows by SCS approach (Catholic University of Leuven, 2005)

Equation	Remark
To = Ti - Tt + Tr	To = opportunity time in min
Fn = RAM	Tt = advance time in min
$F = a\ T^b + c$	Tr = recession time in min
$Fx = (a\ T^b + c) * (P/W)$	Ti = inflow time in min
$P = 0.265\ (Q*n/S^{0.5})^{0.425} + 0.227$	T(T) = total travel time in min
$Tn = \{[Fn * (W/P) - c]/a\}^{(1/b)}$	Tn = required opportunity time in min
$Tt = (x/f) * e^{\beta}$	RAM = readily available moisture in root zone in mm
$\beta = (g * x)/(Q * S^{0.5})$	F = cumulative infiltration depth in mm
Tr = 0 (assumption)	Fx = adjusted cumulative infiltration depth in mm
Fg = (60 * Q * Ti)/(W * L)	T = infiltration time in min
RO = Fg - Fav	a, b and c = constants
DP = Fav - Fn	P = wetted perimeter in m
	W = furrow spacing in m
	Q = flow rate in l/s
	n = roughness coefficient
	S = slope in m/m
	β = advance coefficient
	f = constant (function of soil type) for x = L, Tt = T(T), with T(T) = the total travel time (As a rule of thumb, T(T) =< 1/4 * Tn)
	g = constant (function of soil type)
	Fg = gross application depth in mm
	RO = runoff in mm
	Fav = average infiltrated depth between 0 and L in mm
	DP = deep percolation loss in mm
Ea = 100 * (Fn/Fg)	Ea = application efficiency in %

The results of the program are:

- advance time T_t in mm, the time required for the water to flow from the inlet to the end of the furrow (based on L, intake family and β);
- design inflow time T_i in min, being the advance time T_t plus the net opportunity time $T_{n;}$
- total travel time T(T) in min;
- net opportunity time T_n inmin, the time that the water is available at the end of the furrow (field) to infiltrate the required net irrigation depth; depending on the intake family;
- cumulative infiltration depth Fx in mm;
- area of infiltrated water per section Ai in m^2;
- advance coefficient β, used in the SCS equations;
- adjusted wetted perimeter P in m according to the SCS equations;
- average intake depth F_{av} in mm over the furrow length L, ΣAi/L;
- gross application depth F_g in min, being the inflow per furrow times the inflow time divided by the area of the furrow (furrow length times wetted furrow perimeter);
- surface runoff RO in mm, the difference between the gross application depth F_g and the average intake depth $F_{av;}$
- deep percolation DP in mm, the difference between the average application depth F_{av} and the net application depth $F_{n;}$
- total application efficiency E_a %, being the ratio of the net application depth F_n and the gross application depth $F_{g.}$

Table 7.23 The input and output sections of the spreadsheet SCS furrow design (Catholic University of Leuven, 2005)

FURROW IRRIGATION DESIGN BASED ON SCS EQUATIONS								
INPUT VALUES								
Length (L)			125	m				
Furrow spacing (W)			0.75	m				
Slope (S)			0.004	m/m				
Net irrigation depth (Fn)			75	mm				
Irrigation depth at end of furrow			75	mm				
Inflow rate (Q)			1	l/s				
Roughness coefficient			0.04					
Furrow intake family			1					
a	1.786	(Vlookup from table on worksheet explanation)						
b	0.785	(Vlookup from table)						
c	7.000	(Vlookup from table)						
f	8.860	(Vlookup from table)						
g	4.188E-04	(Vlookup from table)						
RESULTS								
Required application time at end furrow				211minutes to deliver 75 mm at the bottom end				
Time to travel to the end		32 minutes to reach 125 m at the bottom of the furrow						
Total time required		244 min.						
P	0.45	m						
Tn	211	min						
Li/L	Li	β	Tt	To	Ti	Fn	Fx	Ai
Ti	244	min						
T(T)	32	min						
Tn	211	min						
Fn	75	mm						
Fav	80	mm						
Fg	156	mm						
RO	76	mm						
DP	5.1	mm						
Ea	48.1	%						

Evaluation of Program

Programs should usually be tested based on field data before they are applied at a particular location. As indicated in chapter 6, field infiltration assessment of the furrow irrigation was carried out on 6.3 m, 7.9 m and 12 m long furrows and the average infiltration of the furrows per irrigation was about 17 mm, 15 mm and 16 mm respectively (Table 6.5). The SCS spreadsheet program was run for evaluating the three furrows based on the existing field data of the scheme. Table 7.24 and Table 7.25 present the input data and the summary of the simulation for the present furrow irrigation at Gumsalasa. Table 7.25 shows that the average intake depths of the simulation are similar to the field infiltration test data. As a result of the high surface runoff at the end of furrows, efficiencies are very low in all furrow lengths. Since part of the runoff is mostly used for irrigating other furrows downstream, the actual application efficiency might be a little higher. However, improvement of the furrow design remains to be the main option to increase the efficiency.

Table 7.24 Field data of the furrow irrigation at Gumsalasa used in simulation of the spreadsheet program

Data	Value	Remark
manning's roughness coefficient (n)	0.1	
furrow length (L) in m	6.3, 7.9, 12	
average opportunity time (Tn) in min	15, 12, 16	for the furrow lengths respectively
furrow spacing (W) in m	0.4	
furrow slope (S) in m/m	0.01	
net irrigation depth (Fn) in mm	30	assumed
inflow rate per furrow (Q) in I/s	0.9	
furrow intake family	0.25	Table 6.4

Table 7.25 Summary of the SCS furrow design results of the present furrow irrigation at Gumsalasa

Parameter	Furrow lengths in m		
	6.3	7.98	12
Advance coefficient (ß)	0.0	0.0	0.0
Adjusted perimeter (P) in m	0.5	0.5	0.5
Advance time (Tt) in min	0.8	1.1	1.6
Net opportunity time (Tn) in min	15.0	12.0	16.0
Design inflow time (Ti) in min	15.8	13.1	17.6
Average intake depth (Fav) in mm	15.6	14.7	16.2
Gross application depth (Fg) in mm	339.6	223.3	198.4
Surface runoff (RO) in mm	324.0	208.6	182.2
Deep percolation (DP) in mm	-	-	-
Total application efficiency (Ea) %	8.8	13.4	15.1

Application of the program

The SCS approach can generally be used for evaluation and design of furrows in the study sites. The design should involve selection of suitable decision variables, especially furrow length and discharge, based on the situation of the irrigation schemes. For instance, the irrigation landholdings at Gumsalasa are 40 m * 50 m. It is, therefore, recommended to use the maximum furrow length of 50 m to improve the application efficiency of the irrigation scheme. Two options are generally available for improving the furrow design, namely, adjusting the furrow discharge for the present slope or adjusting both the furrow discharge and slope. Table 7.26 gives the result of the spreadsheet program for two scenarios. The table reveals that the application efficiency of the furrow irrigation increases with a decrease in the furrow discharge and slope. A suitable slope and furrow discharge combination would have to be implemented for the irrigated fields in the study sites. In future developments, however, the field layouts need to be designed to attain the maximum possible application efficiency within the prevailing field conditions. If field situations such as soil type and slope permit, a shift can also be made to other field application methods such as basin.

Table 7.26 Application of the SCS furrow design procedure at Gumsalasa

Furrow discharge in l/s	Ti in min	Fn in mm	Fav in mm	Fg in mm	RO in mm	DP in mm	Ea in %
Present slope (0.01 m/m)							
0.5	100	30	31	150	119	0.7	20.0
0.4	108	30	31	130	99	0.7	23.1
0.3	119	30	31	107	76	0.7	28.1
0.2	134	30	31	81	50	0.8	37.3
0.1	163	30	31	49	18	1.1	61.2
Reduced slope (0.005 m/m)							
0.5	89	30	30	134	103	0.9	22.5
0.4	97	30	30	116	86	0.9	25.8
0.3	108	30	30	97	66	0.9	30.9
0.2	124	30	30	74	43	1.1	40.3
0.1	159	30	31	48	16	1.8	63.0

7.3 Water management and salinity

7.3.1 Present water management and salinity

The salinity of the irrigation water used at the primary command area is about 0.3 dS/m in both irrigation schemes. On the other hand, the seepage water used for irrigating the secondary command is about 0.8 dS/m at Gumsalasa and 1.2 dS/m at Korir (Table 6.13). According to Table 4.2, the salinity hazard of the irrigation water can be classified as moderate at primary and high at the secondary command. Leaching is generally recommended in such situations to keep the salinity level of the root zone within a suitable range for crop growth and production.

The reality in the study sites is that the leaching requirement is not taken into account in the operational plan and the soil salinity is not monitored. As a result, the soil salinity of the schemes has shown an increase over the last few years. Assuming the salinity level of the irrigated fields before the introduction of irrigation to be the same as in the rainfed fields, the salinity during the irrigation season has increased by more than two-fold since the start of full irrigation in 1999 (Table 7.27).

There seems to be a slight leaching activity during the rainy season. The soil salinity shows a decrease after the rainy season but still remains high compared to salinity in the rainfed land. This is due to the poor rainfall situation both in amount and distribution.

Table 7.27 Increase in soil salinity of the irrigated fields compared to the rainfed fields[1]

Location	Gumsalasa		Korir		Gumsalasa		Korir	
	During the 2002 irrigation season				During the 2004 irrigation season			
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Electrical conductivity in dS/m								
Primary command	0.63	1.10	0.42	0.73	0.46	1.17	0.24	0.71
Secondary command	0.87	1.43	0.61	0.83	0.71	1.00	0.48	1.16
Rainfed	0.22	0.22	0.24	0.24	0.22	0.22	0.24	0.24
Increase of salinity (ratio of irrigated area salinity to rainfed land salinity)								
Primary command	2.9	5.0	1.8	3.0	2.1	5.3	1	3.0
Secondary command	4.0	6.5	2.5	3.5	3.2	4.5	2	4.8
	After the 2002 rainy season				After the 2004 rainy season			
Electrical conductivity in dS/m								
Primary command	0.32	0.51	0.26	0.41	0.51	0.7	0.27	0.59
Secondary command	0.44	0.49	-	0.34	0.73	0.88	0.65	0.95
Rainfed	0.22	0.22	-	0.24	0.22	0.22	0.24	0.24
Increase of salinity (ratio of irrigated area salinity to rainfed land salinity)								
Primary command	1.5	2.3	-	1.7	2.3	3.2	1.1	2.5
Secondary command	2.0	2.2	-	1.4	3.3	4.0	2.7	4.0

Note:

1 = the electrical conductivity values were obtained from Table 6.14

Figure 7.6 A stunted growth of maize at Gumsalasa due to salinity

Even if there is an increase, the present average soil electrical conductivity is categorized as non-saline and does not yet pose any danger to the yield of the irrigated crops (Table 4.3 and Table3 4.4). It has, however, to be noted that the effect of localized salinity is evident in the irrigation schemes. Figure 6.17 presents a totally abandoned field, while Figure 7.6 shows a stunted growth of maize due to salinity.

7.3.2 *Proposed water management and salinity*

Implementation of an improved and proper irrigation scheduling has been recommended in 7.2.3 as a means to increase crop production. However, the success of the proposed plan depends on maintaining the salinity level at least at its current level through leaching. However, if the leaching practice continues to be inadequate as is the case at the moment, the salt concentration may develop to a point where crop production might be greatly reduced or even impossible. In order to demonstrate the danger, this section simulates the long-term impact of poor leaching on the salinity and crop yield of the Gumsalasa irrigation scheme.

The change in salt content over a particular period can be determined based on the salt storage equation (Equation 7.18) (van Hoorn and van Alphen, 1994). If the quantity of salt in the root zone at the beginning of the period (Z_1) differs from that at the end (Z_2), the change in salt content (ΔZ) can be written as:

$$\Delta Z = Z_2 - Z_1 \qquad 7.13$$

Where:
ΔZ = change in salt concentration in the root zone in dS/m
Z_2 = salt concentration in the root zone at the end of the period in dS/m
Z_1 = salt concentration in the root zone at the beginning of the period in dS/m

Generally, the downward movement of water and salt takes place at water content near field capacity. As a result, the salt in the root zone can be considered to be dissolved in the amount of soil water at field capacity in the root zone (Wfc). Wfc can be estimated by using equation 7.14.

$$Wfc = Qfc * D \qquad 7.14$$

Where:
Wfc = water content of the root zone in mm
Qfc = soil water content in mm/m
D = depth of the root zone in m

The salt concentration of the soil water in the root zone at field capacity (Cfc) is:

$$Cfc = \frac{Z}{Wfc} \qquad 7.15$$

Considering a period in which Z changes from Z_1 to Z_2, the average salt concentration of the soil water at field capacity (Cfc_{av}) during the period can be computed by equation 7.16.

$$Cfc_{av} = \frac{Z_1 + Z_2}{2Wfc} = \frac{Z_1}{Wfc} + \frac{\Delta Z}{2Wfc} \qquad 7.16$$

Assuming $C_g = C_p = Cfc$ (see below), the change in salt content of the root zone can also be written as:

$$\Delta Z = IC_i - P^x Cfc_{av} \qquad 7.17$$

Combining equation 7.16 and 7.17 yields the salt storage equation (Equation 7.18). Taking the present root zone salinity as initial value, this equation is used to predict the salinity accumulation in the root zone at Gumsalasa if leaching is not practiced.

$$\Delta Z = \frac{IC_i - \frac{P^x Z_1}{Wfc}}{1 + \frac{P^x}{2Wfc}} \qquad 7.18$$

Where:

C = salt concentration in dS/m

i = suffix denoting irrigation water

g = suffix denoting groundwater

p = suffix denoting percolation water

I = irrigation in mm

P^x = net percolation, which is the difference between deep percolation and capillary rise in mm

Z_1 = salt quantity in the root zone at the beginning of the period in ECmm or dS/m*mm

Wfc = water content of the root zone at field capacity in mm

The following basic assumptions are considered for the present situation at Gumsalasa:

- as indicated in chapter 6, the electrical conductivity of the saturated paste (ECe) of the root zone during the irrigation season ranges from 0.4 dS/m – 0.9 dS/m for onion and 0.54 dS/m – 0.9 dS/m for maize. However, since the water content of the saturated paste is about twice that of the field capacity, ECe = 0.5 ECfc (van Hoorn and van Alphen, 1994). The equivalent ECfc will be 0.8 dS/m – 1.8 dS/m and 1.1 dS/m – 1.8 dS/m for onion and maize respectively. An average ECfc of 1.5 dS/m and the root zone of maize is used for the simulation;
- since no leaching water is available from the reservoir, the only source of leaching is rainfall. The summary of the monthly effective rainfall and evaporation is given in Table 7.28. The table reveals that the effective rainfall exceeds the evaporation only during August. This excess amount, which is about 30 mm, is assumed to go to deep percolation;
- the groundwater is generally deep and capillary rise into the root zone is assumed negligible;
- the change in water storage (ΔS) for a complete year period is assumed zero.

The major data used for the simulation of the salinity process is given in Table 7.29. Taking maize into account, the change in salt quantity of the primary command area at the end of the first year can be calculated by equation 7.18:

$$\Delta Z = \frac{456 * 0.3 - \frac{30 * 270}{180}}{1 + \frac{30}{2 * 180}}$$

$\Delta Z = 85$

The salt quantity at the end of the first year (Z_2) can be determined as follows based on equation 7.13 and 7.15:

$Z_2 = Z_1 + \Delta Z = 355$

$ECfc = Z_2/Wfc = 2$ dS/m

Table 7.28 Monthly effective rainfall and evaporation at Gumsalasa

Month	Mean rainfall[1] in mm	Effective rainfall (P_{eff})[2] in mm	Evapotransration (E)[3] in mm	P_{eff}-E in mm
January	0.4	0	132	-
February	2.1	0	136	-
March	8.2	2	163	-
April	20.8	9	162	-
May	20.5	9	168	-
June	39.1	20	161	-
July	170.4	128	129	-
August	203.3	155	123	32
September	42.5	22	135	-
October	4.1	0	134	-
November	1.4	0	119	-
December	0.2	0	118	-

Note:
1 = obtained from Table 2.8, with 80% probability of occurrence (i.e 4 out of 5 years)
2 = calculated using Equation 3.2 and 3.3
3 = obtained from International Water Management Institute (2005)

Table 7.29 Data used in the simulation of salinity accumulation at Gumsalasa irrigation scheme

Component	Value				Remark
	Primary command area		Secondary command area		
	Onion	Maize	Onion	Maize	
Amount of irrigation water (I) in mm	351	456	351	456	Table 7.9
Salinity of the irrigation water (Ci) in dS/m	0.3	0.3	0.8	0.8	Table 6.13
Net percolation (P^x) in mm	30	30	30	30	
Present soil water salinity at field capacity (ECfc) in dS/m	1.5	1.5	1.5	1.5	
Soil water at field capacity (Qfc) in mm/m	180	180	180	180	Table 6.6
Root zone depth (D) in m	0.6	1	0.6	1	Table 6.6
Soil water in root zone at filed capacity (Wfc) in mm	108	180	108	180	Equation 7.14
Salt quantity in the root zone at the beginning of the period (Z_1)	162	270	162	270	Equation 7.15

Following the above given procedure, Table 7.30 presents the simulation of the long-term salinity accumulation at the primary and secondary command areas of the Gumsalasa earthen dam irrigation scheme. The maximum permissible ECe that does not affect the yield of onion and maize is 1 dS/m and 2 dS/m respectively (Table 4.4). Referring to the simulation results (Table 7.30 and Figure 7.7), it can be summarized that the impact of salinity on crop yield is evident as of the second year of the implementation of the proposed irrigation scheduling.

Table 7.30 Simulation of effect of poor leaching on the long-term salinization at Gumsalasa irrigation scheme using the salt storage equation (van Hoorn and van Alphen, 1994)[1]

Component	Unit	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14
Initial ECfc	dS/m	1.5 (ECe = 0.75 dS/m)													
Primary command area															
I	mm	456	456	456	456	456	456	456	456	456	456	456	456	456	456
ECi	dS/m	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
ΔS	mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P^x	mm	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Wfc	mm	180	180	180	180	180	180	180	180	180	180	180	180	180	180
Z1	-	270	355	427	488	539	582	619	650	676	698	717	733	747	758
ΔZ	-	85	72	61	51	43	37	31	26	22	19	16	14	11	10
Z2	-	355	427	488	539	582	619	650	676	698	717	733	747	758	768
ECfc	dS/m	1.97	2.37	2.71	3.00	3.24	3.44	3.61	3.76	3.88	3.98	4.07	4.15	4.21	4.26
ECe	dS/m	0.99	1.19	1.35	1.50	1.62	1.72	1.81	1.88	1.94	1.99	2.04	2.07	2.11	2.13
Secondary command area															
I	mm	456	456	456	456	456	456	456	456	456	456	456	456	456	456
ECi	dS/m	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
ΔS	mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P^x	mm	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Wfc	mm	180	180	180	180	180	180	180	180	180	180	180	180	180	180
Z1	-	270	355	427	488	539	582	619	650	676	698	717	733	747	758
ΔZ	-	295	565	920	1,347	1,835	2,374	2,956	3,575	4,225	4,901	5,599	6,316	7,049	7,796
Z2	-	565	920	1,347	1,835	2,374	2,956	3,575	4,225	4,901	5,599	6,316	7,049	7,796	8,554
ECfc	dS/m	3.14	5.11	7.48	10.19	13.19	16.42	19.86	23.47	27.23	31.11	35.09	39.16	43.31	47.52
ECe	dS/m	1.57	2.56	3.74	5.10	6.59	8.21	9.93	11.74	13.61	15.55	17.54	19.58	21.66	23.76

Note:
1 = the root zone considered is for maize; primary and secondary command area refer to the area irrigated by the proper canal network and the seepage water respectively

For instance, the yield of onion will start to be affected as of the third year and the second year at the primary and secondary command area respectively. On the other hand, the impact of salinity on the yield of maize can start after 10 years in the primary and just after the first year in the secondary command.

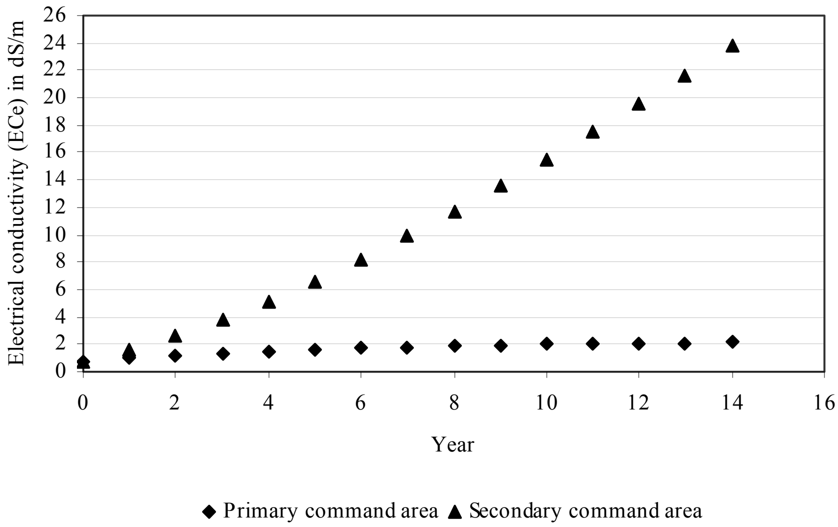


Figure 7.7 Simulation of effect of poor leaching on the long-term salinization progress at Gumsalasa irrigation scheme

The simulated results clearly indicate that the sustainability of the earthen dam irrigation schemes in Tigray can be at risk if the operation continues without leaching the irrigation induced salts. In this regard, the movement of water and salt in the soil profile should be studied in combination to determine the amount of percolation (leaching) water required to ensure that the salt content of the soil does not exceed a yield reducing value.

The water balance of the root zone (Figure 7.8) over a certain period of time, taking the beginning and end of the period soon after irrigation when the soil profile is at field capacity, can be given by equation 7.19 (van Hoorn and van Alphen, 1994, Smedema and Rycroft, 1983 and Arar, 1971):

$$I + R + G = E + P \tag{7.19}$$

Where:

I = net irrigation in mm
R = effective rainfall in mm
G = capillary rise in mm
E = evapotranspiration in mm
P = percolation in mm

The salt balance can be derived from equation 7.19 as follows:

$$IC_i + RC_r + GC_g = PC_p \tag{7.20}$$

Where:
C = salt concentration in dS/m
i = suffix denoting irrigation water
r = suffix denoting rainwater
g = suffix denoting groundwater
p = suffix denoting percolation water

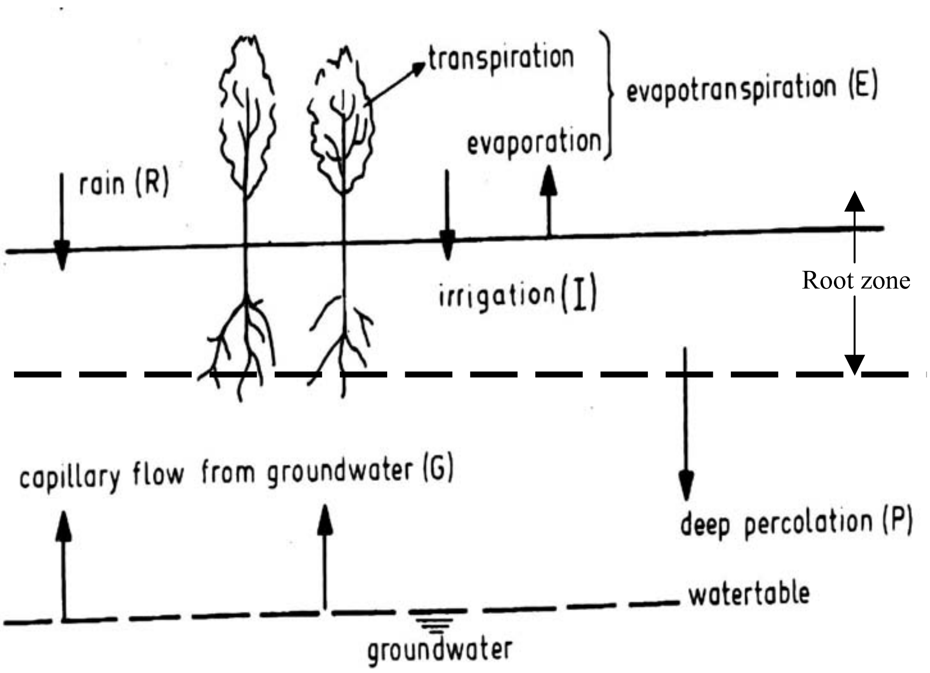


Figure 7.8 Water balance of irrigated land (Smedema and Rycroft, 1983)

As in most normal rain, the salinity of the rainwater in Tigray is negligible and equation 7.20 can be rewritten as:

$$IC_i + GC_g = PC_p \quad 7.21$$

Combining equation 7.19 and 7.21 will give the basic equation (7.22) in which no assumption has been made about the salt concentration of the upward capillary flow.

$$P = \frac{(E - R)C_i + G(C_g - C_i)}{C_p - C_i} \quad 7.22$$

Introducing the net deep percolation (P^x), which is the excess of deep percolation (P) over capillary rise (G) (i.e. $P^x = P - G$), we get equation 7.23. This equation represents the leaching requirement (LR) which is defined as the fraction of the irrigation water that must be leached through the root zone to control the salinity at a specified level.

$$P^x = (E - R)\frac{C_i}{C_p - C_i} + \frac{C_g - C_p}{C_p - C_i} \tag{7.23}$$

$$I = E - R + P^x \tag{7.24}$$

If the groundwater in the area is fed by seepage from elsewhere, the salt concentration of capillary water, C_g, will be different from the salt concentration of the percolation water, C_p. In such cases, equation 7.23 can be used to calculate the amount of leaching requirement, LR, and equation 7.24 to obtain the amount of irrigation water, I.

If there is no seepage and capillary rise, then the percolation water will in the long run create a belt of water below the root zone and the salt concentration of the capillary flow will be equal to the salt concentration of the percolation water ($C_g = C_p$). Moreover, if the irrigation water is mixing thoroughly with the soil water in the root zone, the salt concentration of the soil water at field capacity will equal the salt concentration of the water percolating from the root zone ($Cf_c = C_p$). Taking the above assumption into account will yield the following formula (Equation 7.25).

$$P^x = (E - R)\frac{C_i}{Cf_c - C_i} \tag{7.25}$$

Equation 7.25 can be used in most cases of dryland areas to calculate the leaching requirement. Because, though it is less valid for short periods, it is generally a reasonable assumption to take $C_g = C_p$ for averages over annual periods (van Hoorn and van Alphen, 1994). Besides, in non-saline soils with a stable groundwater table, there is equilibrium between the salt concentration of seepage and percolation water, i.e. $C_g = C_p$ (Arar, 1971). Moreover, the risk of rise of the groundwater table to the extent of causing capillary movement of water is very minimal and, hence, capillary rise may be disregarded in such areas.

Combining equation 7.24 and 7.25 will give the total amount of irrigation water required to cover both the consumptive use of the crop and the leaching of the soil (Equation 7.26).

$$I = (E - R)\frac{Cf_c}{Cf_c - C_i} \tag{7.26}$$

However, taking into account the leaching efficiency, f, equation 7.25 and 7.26 will become:

$$P^x = (E - R)\frac{C_i}{fCf_c + C_i} \tag{7.27}$$

$$I = (E - R)\frac{fCf_c}{fCf_c - C_i} \tag{7.28}$$

Where f denotes the ratio between the salt concentration of the water draining from a soil layer to the salt concentration of the soil solution in that layer (Arar, 1971). According to Arar, the leaching efficiency f varies with soil texture and usually is taken to be 0.5 for heavy soils and 0.6 for medium and light soils. This indicates that not all of the deep percolation is equally effective in contributing to the leaching of salts from the root zone. The most effective leaching results from water that moves through the mass of the soil. The water that moves downward rapidly through large pores and cracks picks up very little salt and has a minimal leaching effect (Smedema and Rycroft, 1983).

In these equations, (E – R) represents the influence of climate on the amount of irrigation water needed, Ci the influence of water quality and Cfc the agronomic criterion which takes into account the influence of salinity on crop yield (van Hoorn and van Alphen, 1994).

7.3.3 Recommendations

In order to minimize the effect of salinity on the food security and environment of the irrigated land, the following measures are suggested to be considered in the present and future development and management of earthen dam irrigation projects in Tigray.

Leaching of accumulated salts from the root zone

For the situation in the study sites in particular and the other irrigation schemes in general, the salinity level should be maintained at its current level so as to guarantee sustainable crop production. This requires the removal of the soluble salts that will be accumulated during each irrigation season. The amount of water available determines whether to adopt frequent or seasonal leaching. The frequent leaching, for example at every watering or every month, is applied if there is no shortage of water supply and keeps the salinity level low at every time. Seasonal leaching, on the other hand, reduces the quantity of water to the amount required for the consumptive use of the crop and postpones leaching until a period of lower demand or off-peak period. Though it tends to increase the salinity, the latter method saves water and is generally recommended for semi-arid areas with continual monitoring of the salinity level (Van Hoorn, 1971). In line with this, leaching for the earthen dam irrigation schemes is recommended to be carried out following the rainy season. Since no rainfed crops are expected according to the newly proposed irrigation scheduling, this season coincides with no crop consumptive period. Besides, the contribution of the rainfall in leaching some part of the accumulated salt will reduce the amount of leaching water that has to be transported by the irrigation canals. Equation 7.27 can be used to estimate the total amount of water required to remove the extra salt from the soil root zone. The part of the rainfall that might deep percolate can be subtracted from this total amount to determine the amount that has to be supplied from the irrigation source. The annual leaching requirement of Gumsalasa is presented in Table 7.31. In order to maintain the salinity level at its current level, about 100 mm and 200 mm of leaching water has to be applied from the reservoir for the primary and secondary command areas respectively. This will be about 20% of the irrigation water requirement at the primary and 40% at secondary. The percentage at the secondary command area is high but covers a small area. The same approach can be used for all the earthen dam irrigation schemes in the region.

Table 7.31 Annual leaching requirement of the Gumsalasa irrigated fields to maintain the salinity at its current level

Leaching parameters	Primary command area	Secondary command area	Remark
Amount of irrigation water (I) in mm	456	456	Table 7.29
Salinity of the irrigation water (Ci) in dS/m	0.3	0.8	
Present soil water salinity at field capacity (ECfc) in dS/m	1.5	1.5	
Leaching efficiency (f)	0.5	0.5	Clay soil (Arar, 1971)
Total annual leaching requirement in mm	130	235	Equation 7.27
Contribution of rainfall to leaching in mm	32	32	Table 7.28
Leaching requirement from reservoir in mm	100	200	

Irrigation timing and salinity monitoring

During the initial phase of the development, irrigation water was available only during the early morning, the late afternoon and the early evening hours. At the moment, irrigation water is available the whole day including the hot hours that will cause high evapotranspiration leaving the salt on the surface of the soil. According to the farmers the salinity problem is further aggravated due to the change in the irrigation time. Even if the salt accumulation generally depends on the amount and salinity of irrigation water applied and the leaching conditions, irrigation during hot periods of the day would have to be avoided as much as possible.

The other most important factor contributing to the worsening of salinity is the lack of monitoring of the situation. The increasing trend of the salinity problems in the schemes, the loss of a farmland at Gumsalasa and the development of localized high saline areas indicate the lack of it. The least that could be done is to carry out regular observations (such as white crust formation) for incidences of salinity and to take mitigation measures in time. Measuring the salinity of few soil samples using an electrical conductivity meter at the beginning and end of each irrigation season would be more effective.

7.4 Institutional and socio-economic aspects

The major objective of the earthen dam irrigation schemes is to improve the livelihood of the poor farmers of Tigray. In line with this, the farmers in the study sites have benefited from the irrigation.

It has been mentioned in 6.2.4 that rainfed production in Tigray is inadequate to supply the household food demand. Since the introduction of irrigation, the cropping pattern has changed from small grains to maize and vegetables. The yield, the market prices and subsequently the household income generated from the irrigated fields are much higher than in the rainfed situation.

The average family size in both areas is 6 and the total population in 2002 was 7,834 and 4,761 at Gumsalasa and Korir respectively. The average household rainfed land holding in the study sites is 1.2 ha, while the irrigated land holding is 0.2 ha at Gumsalasa and 0.3 ha at Korir. The average number of households benefiting from irrigation is 425 and 330 at Gumsalasa and Korir respectively. The number of beneficiary households could increase to about 600 at Gumsalasa and 400 at Korir if the proposed irrigation scheduling is implemented properly.

Community participation in the development and management of earthen dam irrigation schemes is very encouraging in Tigray. The development strategy emphasized on the importance of incorporating the wishes, ideas and aspirations of the farming community and the need for enhancing participation of women as a basis for sustainability.

Farmers actively participate in the construction of the earthen dam irrigation projects and the rehabilitation of catchments. They are generally involved either individually or through their representatives in all decisions made with respect to the operation and maintenance of the irrigation schemes. Promising developments have also been witnessed with regard to the access of women to irrigated land and other basic resources and services. Female heads at Korir and Gumsalasa own about 41% and 21% of the total irrigated land respectively. The development effort should continue to empower the farmers and facilitate the hand-over of the operation and maintenance of the schemes to the beneficiaries.

However, due attention would have to be given to institutional, water management, socio-economic and salinity aspects if the present and future irrigation development activities are to be successful.

7.4.1 Management of the irrigation schemes

The sustainability of the earthen dam irrigation schemes largely depends on the institutional capacity to manage and maintain the projects. This may include the presence of sufficiently skilled human resources, efficient management tools, and appropriate policy and legal frameworks. But, these aspects are not properly implemented in Tigray in general and in the study sites in particular. The study sites do have local institutional set-up, operational and maintenance policy and legal frameworks in place. But, the role of the institutions in the proper management of the irrigation schemes is inadequate. The traditional operational and maintenance rules and regulations are not functioning properly. The management tools in general and the irrigation scheduling in particular are inadequate. The water management committee only distributes the water among farmers and the individual farmer decides the delivery time. This arrangement might lead to excessive application of irrigation water and threaten the efficiency and sustainability of the schemes. The effect of this is two-fold. On the one hand, irrigation water will be wasted and less area irrigated. On the other, it may cause waterlogging and gradual accumulation of salts on the fields. The lack of training of farmers in areas related to water management and crop agronomy may also play a negative role. The absence of regionally implemented institutional set-up and irrigation policy can be taken as a major factor to the poor performances at the scheme level..

If the institutional and water management issues continue in the same way, the land and water development efforts of the region can be jeopardised. The immediate formulation and implementation of a comprehensive and participatory regional irrigation policy will have to be given priority. Assessment of the strengths and weaknesses of the management of the operational earthen dam irrigation schemes is very important in this regard.

7.4.2 *Socio-economic aspects*

Unlike at Gumsalasa, the irrigated landholding at Korir varies with the family size. The compensation of yield loss to farmers displaced from the reservoir was also better at Korir than Gumsalasa. As a result, more complaints have been expressed by the farmers at Gumsalasa. Effort will have to be made to avoid such disapproval by the farmers in future development activities.

As indicated in chapter 6, none of the recommendations by CoSAERT and the regional Government regarding the equitable distribution of irrigation water, water charges and marketing cooperatives have been implemented so far. As a result, the current practice during water shortage victimizes the downstream, lower reach farmers. This practice is not equitable and socially fair. Therefore, due attention would have to be given to strengthen the institutional capacity and manage the irrigation schemes efficiently so that less water will be wasted. Farmers also need to be trained about the methods and advantages of efficient use of water and the negative impacts of excessive application. The suggestion by CoSAERT to divide the irrigation scheme into two or three blocks may also improve the equity issue.

The beneficiary farmers contribute only labour for the maintenance of the irrigation schemes, while the Wereda Bureau of Agriculture and Natural Resources supplies other necessary resources. The Bureau may, however, not be able to satisfy the material needs of each and every scheme in the district in the long-term. The farmers would have to be able to contribute towards the better operation and maintenance of their scheme. An introduction of a fair and adequate water charge for the services that takes into account the paying capacity of the farmers and the maintenance needs of the schemes is vital.

Establishment of marketing cooperatives based on the interest of the farmers might open better marketing options and increase the income from the irrigated fields. The overall increase in income and household welfare may lead to investment on land thereby contributing positively in reversing the spiral of poverty-induced environmental degradation.

The regional irrigation policy would have to address all the above issues properly.

7.5 The earthen dam irrigation schemes and the Nile basin

Ethiopia contributes about 75 billion m^3 of the 84 billion m^3 Nile river discharge that annually reaches the Aswan dam. The existing earthen dam irrigation development activities in Ethiopia are focused in two of the drainage basins of the Nile river, namely, the Abay (Blue Nile) and the Tekeze basins. The annual runoff of the Abay and Tekeze river basins, located in Amhara and Tigray regions respectively, is about 56 billion m^3 and 8 billion m^3 respectively. The irrigation developments may cause a change in the hydrological regime of the downstream areas including the Nile river basin. Based on the results of the study sites, this section aims to present the general implications of the earthen dam irrigation schemes in Tigray in particular and in the highlands of Ethiopia in general on the Nile basin.

7.5.1 Impacts on the Nile basin

The main impacts of the earthen dam irrigation projects in the highlands of Ethiopia on the downstream areas can be classified into four categories. These include:
- change in water quality;
- change in the groundwater recharge;
- change in the soil erosion and sedimentation;
- change in the amount of annual flow of the Nile river.

The original development plan was to construct about 500 dams in each of Tigray and Amhara regions during 1994 – 2004. However, the number of dams constructed so far is quite small. As a result, the potential impact was assessed first assuming the construction of the total planned dams in the years to come. The potential impact was then compared to the actual situation in Tigray. Table 7.32 gives the summary of the basic information of the dams already constructed in Tigray.

Table 7.32 Various components of the 44 dams constructed in Tigray[1]

Scheme components	Total (44 dams)	Minimum (per dam)	Maximum (per dam)	Average (per dam)
Catchment area in km^2	41,826	36	3,001	950
Reservoir area in 10^3 m^2	7,760	21	950	250
Reservoir capacity in 10^6 m^3	51	0.1	3.1	1.15

Note:
1 = the data was compiled from Table 3.14

Change in water quality

The quality of the groundwater and the drainage water from the earthen dam irrigation schemes is poor compared to the quality of the water in the reservoirs. According to Table 4.2, the drainage water from the irrigated fields (Table 6.13) and the groundwater (Table 7.33) is categorized as highly saline. The impact to the immediate downstream users who depend on the springs resulting from the recharge of the dams may be significant. These farmers will have to generally grow salt tolerant crops along with leaching whenever possible.

Due to its little contribution to the total flow, the effect on the water quality of the Nile river would be very low.

Change in groundwater recharge

The earthen dams will generally play a positive role in recharging the groundwater of the irrigated and the downstream areas. Besides, they can also enhance the subsurface flow and contribute to the streamflows of the downstream areas.

The reservoir water balance analysis of the study sites has revealed that the average groundwater recharge from the reservoirs is about 0.9 mm/d and 0.4 mm/d at Gumsalasa and Korir respectively (Table 5.11). The average value of the two reservoirs ($0.7 * 10^{-3}$ m/d) was used to estimate the annual potential volume of groundwater recharge (V_{GW}) of the earthen dams using equation 7.29. The equation assumes that the water in the reservoir is exploited up to its dead storage over the irrigation season. Since elevation-area-capacity curves of all the dams are not available, the average area of the dead storage was estimated based on the reservoir and dead storage volume relationship. Table 7.1 indicates that the average volume of the dead storage is about 14% of the average reservoir capacity. This relationship was used to estimate the average dead storage area from the average reservoir area.

$$V_{GW} = T * R_{GW} * A_{Rav} * N_d$$

and

$$A_{Rav} = \frac{A_{RM} * A_{DS}}{2} \qquad 7.29$$

Where:

V_{GW} = total annual groundwater recharge in m^3/yr

T = number of days in a year water is available in the reservoir in days
= 365 days for the present practice
= 245 days for the proposed practice, assuming no water in reservoir during mid-February to mid-June

R_{GW} = average depth of daily groundwater recharge in m/d
= $0.7 * 10^{-3}$ m/d

A_{RM} = average maximum (design) reservoir area in m^2/dam (Table 7.32), this is the area that corresponds to the maximum reservoir capacity
= 250,000 m^2

A_{DS} = average area of the dead storage in m^2/dam (14% of A_{RM})
= 35,000 m^2

A_{Rav} = average reservoir area of a dam in m^2/dam

N_d = number of dams

Based on the present reservoir operation practice, the maximum amount of water that can annually percolate into the groundwater from the 1,000 dams would be about 36 million m^3 (Equation 7.29), which is 3% of the design reservoir capacity and only 0.04% of the total Nile flow. On the other hand, the potential groundwater recharge under the proposed plan will be about 24 million m^3. This is due to the fact that irrigation stops by the end of January and, subsequently, the reservoirs are assumed to be without water for about 4 months before the rainy season. However, the real groundwater recharge depends on the actual number of dams and the reservoir area covered by the water. For example, the maximum reservoir area (A_{RM}) of the Gumsalasa and Korir earthen dams is about $480 * 10^3$ m^2 and $320 * 10^3$ m^2 respectively. But, the actual maximum reservoir area covered by the water during the 2004 data collection period was about $270 * 10^3$ m^2 at Gumsalasa and $136 * 10^3$ m^2 at Korir (Table 5.11). Since the data collection was started in March 2004 in both sites, the reservoir area in September 2003 would be slightly larger due to mainly the reservoir evaporation. Taking into account the small number of dams constructed and the reduced reservoir area, the actual impact will be much less than 3% of the design reservoir capacity. It can generally be concluded that the groundwater recharge might be a good source of water supply to the immediate downstream users. Kifle (2000) reported an increase in spring discharge of 5 l/s – 25 l/s in downstream areas after the construction of surface water harvesting structures (Table 7.33). The contribution to the Nile flow, however, will be very little.

Table 7.33 Discharge and quality of spring water before and after the construction of surface water harvesting structures (After Kifle, 2000)

Location		Before the construction		After the construction	
		Discharge in l/s	Electrical conductivity in dS/m	Discharge in l/s	Electrical conductivity in dS/m
Adigudom	Spring 1	Dry	-	5	1.3
	Spring 2	Dry	-	7	1.6
	Spring 3	Dry	-	10	1.3
	Spring 4	0.5	1.6	13	1.5
	Spring 5	1	1.4	15	1.4
Agula	Spring 1	Dry	-	Dry	-
	Spring 2	0.5	1.5	Dry	-
	Spring 3	0.2	1.8	Dry	-
Negash	Spring 1	0.3	1.4	Dry	-
	Spring 2	Dry	-	Dry	-
Feleg-Waero	Spring 1	Dry	-	13	1.5
	Spring 2	0.8	2	10	1.7
	Spring 3	0.5	2	25	1.6
Aba'ala	Spring 1	Dry	2.3	11	2
	Spring 2	5	2.1	15	1.9
	Spring 3	Dry	-	10	1.3
	Spring 4	2.5	1.7	17	1.6

Change in soil erosion and sedimentation

It has been mentioned in chapter 2 that about 1.5 billion tons of soil is annually eroded from the highlands of Ethiopia, of which about 140 million tons is transported towards Sudan and Egypt by the Blue Nile river (Moushid, *et al.*, 1997). The rapid siltation of the reservoirs in Sudan is the direct consequence of this high erosion (Figure 7.9).

Figure 7.9 Little Abay (Gilgel Abay) river laden with silt (Rämi, 2003)

The construction of earthen dams in this part of Ethiopia can play an important role in minimizing this problem. The impact was estimated in two ways, namely:

- the total sediment that can be retained by the dams during their service life based on the average dead storage capacity;
- the average annual sediment that can be retained by the dams based on the HR Wallingford method.

The average dead storage capacity of a dam in Tigray is about 144 * 10^3 m^3 (Table 7.1). The 44 dams constructed in Tigray will store about 6.3 million m^3 of sediment during their service life which, considering a bulk density of 1.2 t/m^3 (Nyssen, 2001), is equivalent to 7.6 million tons of soil. Similarly, the maximum amount of soil that will be retained by the dead storage of the 1,000 planned dams is about 173 million tons during their service life. With an average of 26 years, the design service life of the dams already constructed in Tigray varies between 10 years and 40 years (Table 7.1).

The average annual sediment that will be collected by the reservoirs depends on the number of reservoirs, the sediment yield and the catchment area (Equation 7.30). The average catchment area of a reservoir is about 9.5 km^2 (Table 7.32), while the average annual sediment yield based on HR Wallingford method is 1,359 t/km^2.yr (Table 7.5). The average annual sediment deposit in the existing reservoirs in Tigray and the total planned dams in the highlands of Ethiopia would be about 0.6 million tons and 13 million tons respectively. It can be clearly seen that the maximum annual sediment that can be retained by the planned dams (13 million tons) is about 9% of the sediment transported by the Blue Nile (140 million tons).

$$S_D = A_{Cav} * SSY_{av} * N_d \qquad 7.30$$

Where:

S_D = total annual sediment deposited in all earthen dams in t/yr
A_{Cav} = average catchment area of a dam in km^2
SSY_{av} = average annual sediment yield in t/km^2.yr
N_d = number of dams

Change in the amount of the Nile flow

By storing part of the watershed runoff in the reservoir, the earthen dam irrigation schemes will reduce the flow to the downstream areas. The potential impact of the dams on the annual discharge of the Nile river can be estimated based on the total number of dams to be constructed and their corresponding design capacity.

Taking into account the average design reservoir capacity of 1.15 million m^3 (Table 7.32), the maximum amount of runoff that can be retained annually by the 1,000 earthen dams would be about 1.15 billion m^3. The potential reduction in the Nile flow will, therefore, be only about 1.5% of the total contribution of Ethiopia. The real impact, however, depends on the actual number of dams constructed and the water stored in the reservoirs. For instance, out of the 500 planned dams, only 44 are constructed in Tigray so far. Besides, the results from the study sites indicate that the actual amount of water stored in the reservoirs is less than the amount used in the design. The Gumsalasa and Korir earthen dams were designed with annual reservoir capacity of 1.9 million m^3 and 1.6 million m^3 respectively. As indicated in chapter 5, the inflow from the watershed to the reservoirs during the 2002 data collection period was about 78 * 10^3 m^3 at Gumsalasa and 141 * 10^3 m^3 at Korir. However, since data were collected till 29 July 2002 at Gumsalasa and 09 August 2002 at Korir, the total inflow would be slightly higher due to the rainfall during August. Considering both the potential and actual impacts, it can be summarized that the effect of the earthen dam irrigation developments on the annual discharge of the Nile is at maximum about 1.5% of the annual flow.

7.5.2 Recommendations

With a projected population rise from 246 million in 1994 to 800 million by mid of the twenty first century, the Nile riparian countries are facing the problem of satisfying the increasing food demand. In line with this, the population of Ethiopia has raised from 22 million in 1961 to about 69 million at the moment with an average annual growth rate of 3%. Besides, the country is characterized by famine as a result of high population pressure, resource base degradation, and insufficient rainfall for rainfed production. With 22 major drought occurrences in the past 40 years, the country generally faces an annual cereal food deficit of 0.03 - 3.3 million tons. To the contrary, it is endowed with huge annual surface water potentials, large potential irrigable land and sufficient productive manpower. However, only about 5.2% of the 3.6 million ha irrigable land and 2.7% of the 110 billion m^3 water resource is utilized annually. The 2.2 million ha of the potential irrigable land is located in the Nile basin of which 23,000 ha is currently under irrigation.

Since 1995, small-scale irrigation development has been taken as a major pillar to increase the food production and improve the food security of the country. The earthen dam irrigation projects were launched as part of this strategy. While these irrigation schemes have improved the livelihood of the poor farmers, the effect of the existing dams on the Nile flow is so far marginal. Even after the construction of the planned 1,000 dams, the impact would at maximum become 1.5% of the annual flow originating in Ethiopia.

However, as a major contributor to the total Nile flow, developments in the highlands of Ethiopia will always have to take into account the impacts on the downstream riparian countries. In this regard, a basin–wide effective cooperation for the benefit and welfare of the riparian societies remains a major task. The riparian countries should work jointly for a more equitable and increased productivity of the Nile water through (Molden, *et al.*, 1998 and Waterbury and Whittington, 1999):

- a sensible revision of the Nile Waters Agreement;
- further reduction of the drainage outflow and convert it into a productive use. Here attention should be given to the amount of downstream environmental outflow requirements (environmental maintenance);
- recovering part of the non-process depletion water for productive use;
- increasing efficiency of water use at local level;
- growing high value crops or high yielding, less water demanding crops.

Ignorance to each other and subsequent unilateral development planning and activity in the basin could lead to a dangerous conflict among the riparian countries in general and the three most downstream countries in particular. Because, changes in water use in one area in a river basin will affect the water balance and water use in another (Molden, *et al.,* 1998).

8 Future outlook

The research results, analysis, discussions, evaluations and recommendations have been presented in the previous chapters. This section aims at describing the writer's views about the general future direction of the development and management of irrigated lands in Tigray based on the findings of the study.

8.1 Major findings

The existing few earthen dam irrigation schemes implemented so far have made important contribution in improving the livelihood of the poor farmers of Tigray. The results from the study sites have generally demonstrated the potential contribution of the CoSAERT irrigation development plan to the regional food security in the long term.

However, the research has also identified problems that may affect the sustainability and ultimately the food security effort of the regional Government. Any large scale development plan such as the earthen dam irrigation launched by the CoSAERT needs practical policy, strategy and an agency capable of implementing it. As indicated in Chapter 3, one of the main reasons for the low level of achievement of CoSAERT was the inadequate strategy. Almost all of the assumptions set as corner stones for the success of the plan were not available as required. Besides, the mandate of CoSAERT was to construct the earthen dams and irrigation networks and design the agronomic, water management and catchment management plans of the schemes. The mandate to carry out the planned catchment treatment and to deliver the necessary extension services to the farmers was given to the Bureau of Agriculture and Natural Resources. However, the absence of a binding irrigation policy with clear duties and obligations and insufficient coordination seem to have affected the proper implementation of activities.

If a clear, effective and participatory irrigation policy was implemented in time, most of the existing problems could have at least been minimized. The main problems that are threatening the sustainability of the earthen dam irrigation schemes are summarized below:

- *sedimentation of reservoirs.* Problems related to sedimentation are three-fold. Primarily, the catchment sediment yield used for the design of the dead storage is based on a rough estimation. Secondary, catchment rehabilitation starts either simultaneously or after the construction of the dams. However, the biological measures in particular need few years before they can effectively minimize the detachment, erosion and transportation process of soil particles by rainfall. Finally, the catchment treatment is generally inadequate in view of the recommendations by CoSAERT;
- *less water storage in the reservoirs*. Most of the existing dams have not been filled to their designed capacity. This may be mainly due to the lack of adequate design data, especially rainfall. The design approach may have also contributed to the problem. The reservoir capacity is determined based on a dependable rainfall of 75% of the long-term average annual rainfall. However, taking into account the unreliable rainfall condition of the region, this estimation may not

represent the most probable scenario. For instance, the dependable rainfall of Gumsalasa and Korir based on the above approach is about 385 mm and 407 mm respectively. But, the total annual rainfall during the data collection period in 2002 and 2004 was not beyond 300 mm in both sites. In addition, the runoff coefficient seems to be determined for the actual land use with out considering future conservation activities;

- *inadequate reservoir operation plan*. There are two major problems related to the existing operational plan. On the one hand, considerable amount of water is being lost as evaporation from the reservoirs. On the other, the extent of the area irrigated per irrigation season is mostly decided by 'best guess', not based on reservoir elevation-area-capacity curves. The ultimate effect might be an inefficient utilization of the limited water supply;
- *inadequate water management*. The major indicators of inadequate water management include lack of proper irrigation scheduling, short furrow lengths and poor leaching. This seem to have contributed to a low level of yield and an increase in soil salinity;
- *lack of sufficient skilled manpower*. One of the problems facing CoSAERT and the Bureau of Agriculture and Natural Resources was the limited number of skilled personnel for the study, design, construction and management of the earthen dam irrigation schemes. At the moment, however, the regional Government is providing in-service training to upgrade the development and management skills of the human resource. Besides, the Government has also opened a number of technical colleges aiming at producing diploma graduates that could take part in improving the agricultural development activities at grass root level;
- *inadequate institutional and socio-economic performance*. Positive initiatives have been scored with respect to establishment of Water Users Associations, participation of beneficiaries, involvement of women and compensation and resettlement. However, improvement of these aspects and addressing other aspects still remain a major task. This may include, strengthening the capacity of the Water Users Associations and farmers to properly plan, implement and monitor the operation, maintenance and legal aspects, improving the marketing of high value irrigated crops, introduction of cost recovery for the maintenance and reconstruction activities, etc;
- *inadequate research input, coordination and dissemination*. The researches carried out so far on the earthen dam irrigation schemes are few and segmented. But, more important is that the results of the undertaken researches have neither been tested nor disseminated, the main reason being the absence of a responsible agency and a mechanism to coordinate the effort.

8.2 The way forward

8.2.1 Integrated approach

The policy of the regional Government still maintains irrigation development as a major pillar of the food security strategy of Tigray. However, the future development and management of irrigated lands would have to be improved in view of the issues discussed above. The Government needs to give due attention to the lessons learnt from this research and various other sources. The main outcome of this study was that the sustainability of the irrigation schemes depends on the level of integrated approach in the development and management. The integrated approach takes the whole irrigation schemes as one entity, including the catchment, the reservoir and dam, the command area and the beneficiaries. Failure or weakness in one of the links will affect the entire system. For example, a high catchment sediment yield and subsequent rapid siltation of reservoirs will minimize the service life of the dams. Similarly, a salinized command area may lead to a reduced yield or, in worst scenario, to abandonment of irrigated agriculture. In addition, the impact of the earthen dams on the regime of downstream areas including the Nile river would have to be accounted and monitored. Accordingly, the integrated approach given in Figure 8.1 is suggested as a general framework for Tigray based on the results of the research on the main issues that play an important role in the success and sustainability of the irrigation schemes. The figure presents the outlines, while details of the main issues are given in the preceding section and chapters.

8.2.2 Development strategy

As indicated earlier, the development strategy of CoSAERT was ambitiously formulated especially with regard to the availability of human, financial, material and physical resources. An adoption of a new and practical development strategy that considers the proposed integrated approach and the experiences learnt from previous interventions will be a key step. In line with this, it would have to take into account the available resources and follow a participatory approach involving the relevant stakeholders. In line with the Water Resource Policy of the country, the strategy need also to consider the possible impacts of the developments on the regime of the downstream areas including the Nile river.

The strategy of the regional Government has recently been changed from high-cost, abutment-centered earthen dams to low-cost, household-centered land and water development activities. These include interventions that could be implemented using household labour as the major input and include in-situ moisture conservation, flood diversion (spate irrigation), small pond construction (*Horoye)*, and river diversions. The construction of feasible earthen dams, the management of the operational dams and rehabilitation of the failed dams is also considered. According to the new strategy, water harvesting using ponds at the village or household level is proposed as a practical and effective alternative to improve the lives of rural people at little cost and with minimal outside inputs. The shift made from small dams towards the construction of small ponds as part of the food security strategy is in principle acceptable. However, the experiences learnt from the previous interventions should be given special attention, so as not to repeat the same mistakes.

As indicated in Chapter 3, the total capacity of the ponds is at maximum 180 m^3, with top surface area of 144 m^2 and depth of 3 m. Taking into account the possible evaporation from the open water surface, the net amount of water that will be available for irrigation will be very small. It has to be noted that the ponds may only supplement, but not replace, the efforts of the earthen dam irrigation schemes in securing the food demand of the region. This recent shift should, therefore, not over shadow the development of feasible earthen dam irrigation schemes.

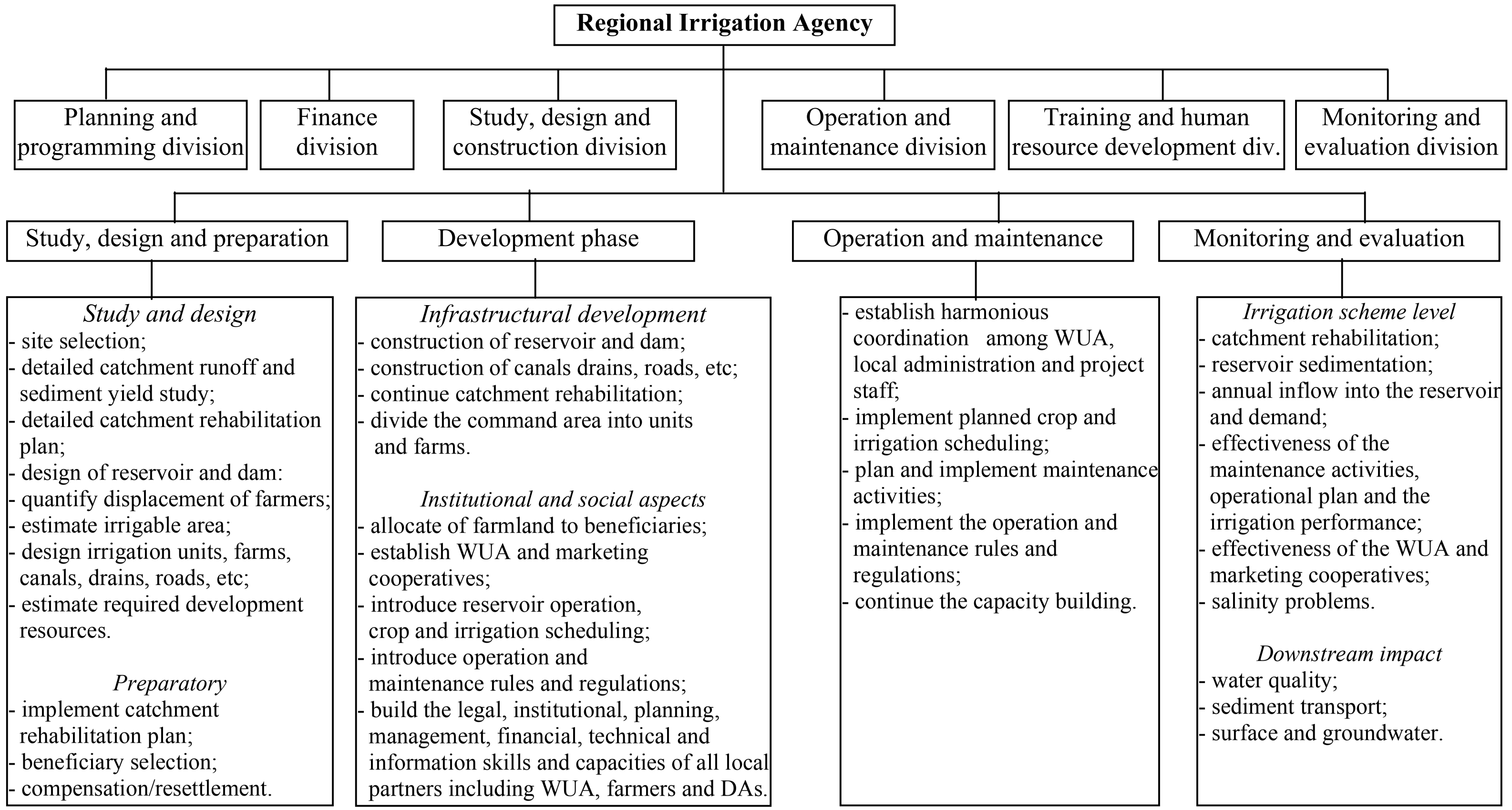


Figure 8.1 General framework of integrated land and water development and management for Tigray

8.2.3 Institutional set-up and irrigation policy

The proper implementation of the development strategy and the integrated approach largely depends on the presence of an agency with clear policy and sufficient human, financial, legal, monitoring and evaluation mechanisms and capacities.

The measure taken by the regional Government to merge the various institutes involved in land and water development under one umbrella is a good initiative in this regard. Three organizations (the CoSAERT, Raya Valley and the Water sector of the previous Water, Energy and Mines Bureau) which were separately engaged in land and water development activities have now formed the Regional Water Resource Development Bureau. This bureau can be used as a focal point to establish the institutional set-up at regional, district (Wereda) and irrigation scheme levels. It has also to be equipped with a participatory irrigation policy within the framework of the integrated approach and based on the strengths and drawbacks of past experiences. For example, the institutional conceptual framework and organizational structure formulated by CoSAERT (1994) was based on sound development directions. It focused on participatory and decentralized approach, human resource development, establishment of the planning process at grassroots level with the Wereda administrative structure as focal point for participation, the intimate involvement of rural people's organizations and representative political bodies and the local administrations ('Baitos'). The results from the study sites also show the presence of local Water Users Associations and operation and maintenance rules and regulations.

The main problem is the lack of smooth transfer of projects from CoSAERT to the Bureau of Agriculture and Natural Resources and the inadequate functioning of local agencies and laws. The proper implementation of organizational structures and policies need to be given focus in the future land and water development efforts of the region.

8.2.4 Summary

The low level of achievement of the earthen dam irrigation projects in Tigray is due to the inadequate development and management strategies. The future outlook need, therefore, to follow a clear and practical development strategy and irrigation policy along with a strong institution capable of implementing them. Some of the main aspects that need to be considered in the future development and management of irrigated lands in Tigray are summarized underneath based on the experiences of CoSAERT and the situations in the study sites.

Primarily, the available data on the existing dams would have to be compiled as a basis for the formulation of comprehensive development strategy, irrigation policy and institutional set-up. These may include researches carried out on various issues such as erosion and sedimentation, salinity, reservoir water balance, socio-economics, etc. In addition, annual reports of the individual dams on the institutional arrangements, local operation and maintenance rules and regulations, reservoir water volume, irrigated area, irrigation scheduling, cropping pattern, yield, number of beneficiaries, etc need to be compiled from respective Wereda Bureau of Agriculture and Natural Resources. Creation of a forum where relevant stakeholders, involved in the funding, research, development, operation and maintenance of the irrigation projects, can discuss the status of irrigated agriculture in the region based on the compiled data will also be important in setting the right and participatory direction, strategy and policy of the future land and water development and management.

If irrigation is expected to play a major role in reducing poverty and improving the food-security of Tigray, the earthen dam irrigation schemes need to remain to be at the center of the development strategy. However, the planning and implementation would have to be based on an integrated approach and the capital, human and material resources that can practically be available. Besides, the construction of the dams should commence following a detailed feasibility study, design and rehabilitation of the catchment. Existing information on the dams need to be used in the development and management of future schemes. For instance, available catchment sediment yield studies and tools can be used for detailed catchment study of future dams. Data on annual inflow into reservoirs may be used to adjust the existing dam capacity design approach. Evaluation results of current field irrigation practices can also be used in the improvement of present and future designs. The furrow layout of irrigated fields would have to be designed to give the maximum possible application efficiency under the prevailing soil and topography.

The establishment and proper functioning of the Water Users Associations and the operation and maintenance rules and regulations need to be given due emphasis in the regional strategy, organizational structure and irrigation policy. The institutional arrangement need to aim at gradual transfer of the operation and maintenance of the irrigation schemes to the farmers with the necessary support from relevant partners. In this regard, preparation of the Water Users Associations, farmers, local administrations, development agents and other local partners for this responsibility would have to be carried out simultaneously with the development of the schemes. This may include building and strengthening the legal, institutional, planning, management, financial, technical and information skills and capacities. This approach can contribute to the smooth transfer and improved management of the irrigation schemes. The formation of strong and voluntary based marketing cooperatives may also assist in improving the marketing and financial situations.

Water is a scarce resource in arid and semi-arid areas like Tigray. The amount of water available for irrigation in reservoirs varies from year to year due to the erratic and unreliable nature of rainfall. The wise and efficient use of what is available at the end of each rainy season would, therefore, be very vital for maximizing the benefit of the irrigation schemes. In this regard, a change in reservoir operation plan from the present (January – June) to the proposed (September – January) has shown the possibility of increasing the irrigated area and the number of beneficiary households by as much as 56% and 45% respectively of the existing for the 2003/2004 irrigation season at Gumsalasa. The corresponding increase at Korir was estimated to be 48% and 24%. This result, however, represents only one year. The increase in the extent of the irrigated area in other years may vary based on the rainfall situations and the corresponding amount of water in the reservoir at the beginning of the irrigation season. For instance, the 2003 annual rainfall at Gumsalasa (443 mm), an input to the reservoir inflow for the 2003/2004 irrigation season, was about 88% of the average annual value and has a probability of exceedance of 60%. This may generally indicate a higher chance of occurrence of at least the 2003 inflow situation in the years to come. The reservoir was filled to about 63% of the design capacity at the beginning of the 2003/2004 irrigation season. The additional area that can be irrigated by shifting to the proposed scheduling will, therefore, be larger if the rainfall and the corresponding reservoir water volume at the end of the rainy season of other years is higher than the 2003. If the reservoir volume is rather lower than in 2003, the proposed change in scheduling becomes even much more important. Because, starting irrigation in September will allow the use of the limited water for irrigation as opposed to the present arrangement that would expose the reservoir only for a loss during September – December.

This thesis describes the benefit of the proposed change for only two earthen dam irrigation schemes. The result, however, indicates the potential of the new operational plan to contribute towards the regional food security if it is practiced at the existing and future earthen dam irrigation projects in Tigray. The Government is advised to discuss the implications of the change with the farmers and implement it in the schemes starting with the study sites. In addition, the operational plan need to be made based on the crop water requirement, soil type and leaching requirements.

Last but not least, monitoring and evaluation would have to be an integral and compulsory process of the integrated development and management of the irrigated lands in Tigray. This can be carried out at two levels, namely, the irrigation schemes and the Nile river basin. The issues discussed above need to be monitored and evaluated at irrigation scheme level.

As a major contributor to the total Nile flow, developments in the highlands of Ethiopia such as Tigray should also monitor the impacts on the downstream riparian countries. This may include impacts on water quality, sedimentation and amount of flow. In this regard, a basin–wide effective cooperation for the benefit and welfare of the riparian societies is a major task ahead. The riparian countries need to work jointly for a more equitable and increased productivity of the Nile water. The ongoing negotiations and agreements among the three major players, Egypt, Sudan and Ethiopia, in particular and the whole riparian countries in general to cooperate in irrigation development, conservation works and hydropower development is a vital step forward and would have to be strengthened.

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Appendix A

Data collection questionnaire

Introduction

This part aims to provide information on farming system, socio-economic, institutional and management aspects that can be used for the development of an integrated approach for sustainable irrigation development and management in Tigray.

Data will be collected from individual farmers, group discussions, development agents and Wereda Bureau of Agriculture and Natural Resources as deemed necessary.

1. Respondent information

a. Name of the household head ________________________________
Sex ________________ Age ______________________

b. Family size and composition

Sex	1 – 15 years	16 – 45 years	46 – 64 years	> 64 years
Male				
Female				

2. Landholding by soil type per household

a. Landholding pattern prior to irrigation introduction (the recent five years)

Year	Landholding in ha	Soil type
1997		
1998		
1999		
2000		
2001		

b. Current landholding

Irrigated		Rainfed	
Land size in ha	Soil type	Land size in ha	Soil type

c. What is your perception of the irrigated plot size? Why?

3. Crop production

a. Average yield of major crops

	Soil type	Crop	Yield in kg/ha	Crop calendar		
				Seedbed preparation	Planting	harvesting
Irrigated		Maize				
		Onion				
		Tomato				
Rainfed		Barley				
		Wheat				
		Teff				

b. Monthly prices of major crops

Month	Price of crops in Birr/kg							
	Barley	Wheat	Teff	Maize	Onion	Tomato		
January								
February								
March								
April								
May								
June								
July								
August								
September								
October								
November								
December								

4. Production input

a. Input type and price

Input type	Unit	Unit price in Birr		
		Minimum	Maximum	Average
Seed Maize Onion Tomato Barley Wheat Teff	 kg kg kg kg kg kg			
Fertilizer DAP UREA	 kg kg			
Labour	pd			
Animal power oxen pack animal	 od ad			
Chemicals				

Note:
pd = person-day, od = oxen day, ad = pack animal-day

b. Input requirement by crop type

Irrigated crop production

Input type	Unit	Farm size in ha	Input requirement		
			Maize	Onion	Tomato
Seed	kg				
Fertilizer DAP *UREA*	 kg kg				
Labour[1] seedbed preparation sawing and fertilizing cultivation harvesting and threshing transporting and storing	 pd pd pd pd pd				
Animal power oxen seedbed preparation sawing and fertilizing cultivation threshing pack animal threshing transaporting	 od od od od ad ad				
Chemicals					

Note:
1 = includes labour of the household involved in the work

Rainfed crop production

Input type	Unit	Farm size in ha	Input requirement		
			Barley	Wheat	Teff
Seed	kg				
Fertilizer DAP UREA	 kg kg				
Labour[1] seedbed preparation sawing and fertilizing cultivation harvesting and threshing transporting and storing	 pd pd pd pd pd				
Animal power oxen seedbed preparation sawing and fertilizing cultivation threshing pack animal threshing transaporting	 od od od od ad ad				
Chemicals					

Note:
1 = includes labour of the household involved in the work

5. Perception of farmers about the key socio-economic, institutional, operation and maintenance aspects

a. Community participation
b. Women's role
c. Resettlement/compensation
d. Water rights and charges
e. Economic impacts
f. Institutional set up and the role played in operation and maintenance

6. Water allocation and management

a. The irrigation interval and period
b. The use of seepage, drainage and/or groundwater to supplement their irrigation need and their perception about the suitability of using such water for irrigation
c. The copping mechanism during water shortage
d. The environmental problems in the area due to the introduction of the irrigation and the view of the farmers on the causes and the solutions of the hazards
e. Water management training given to farmers and the benefits achieved

Appendix B

Determination of canal discharges

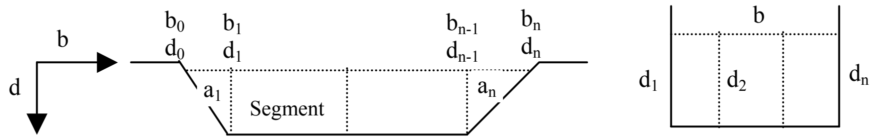

Figure B.1 Typical canal cross-sections

The cross-sectional area of the trapezoidal canals was determined by Equation 1.

$$A_i = \sum_{i=1}^{n} a_i \text{ and}$$

$$a_i = (b_i - b_{i-1}) * \frac{d_i + d_{i-1}}{2} \qquad 1$$

The cross-sectional area of the rectangular canals was calculated by Equation 2.

$$A_i = b * \sum_{i=1}^{n} \frac{d_i}{n} \qquad 2$$

Where:

A_i = cross-sectional area of the canal at location (m^2)
a_i = area of segment i (m^2)
b = width (m)
d = depth (m)

Table B.1 Discharge estimation for trapezoidal canals (and rectangular canal at Korir[1]) in the study sites

		Gumsalasa main canal 1				Korir main canal				Korir seepage (rectangular)[1]			
Velocity	Length (m)	9				9				6			
	Time (s)												
	t_1	10				7				15			
	t_2	9				6				15			
	t_3	11				5				15			
	t_4	8				5				15			
	t_5	9				6				15			
	t_6	8				7				15			
	Average time (s)	9.17				6				15			
	Surface velocity (m/s)	0.98				1.5				0.4			
	Velocity coefficient	0.6				0.5				0.5			
	Average velocity (m/s)	0.59				0.75				0.2			
Area	Location	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4
	Width (m)									0.83	0.73	0.94	0.87
	b_0	0	0	0	0	0	0	0	0				
	b_1	0.3	0.3	0.3	0.3	0.3	0.25	0.25	0.3				
	b_2	0.6	0.6	0.6	0.6	0.6	0.50	0.5	0.6				
	b_3	0.91	0.905	0.94	0.91	0.9	0.75	0.75	0.9				
	b_4					1.13	1	1					
	Depth (m)												
	d_0	0	0	0	0	0	0	0	0	0.11	0.06	0.125	0.13
	d_1	0.37	0.36	0.365	0.36	0.11	0.13	0.15	0.15	0.143	0.147	0.13	0.186
	d_2	0.38	0.36	0.37	0.36	0.175	0.17	0.18	0.18	0.13	0.115	0.139	0.174
	d_3	0	0	0	0	0.12	0.15	0.18	0	0.086	0.1	0.121	0.132
	d_4					0	0	0		0.11725	0.1055	0.12875	0.1555
	Average depth (m)[1]												
	Area (m^2)	0.227	0.217	0.228	0.218	0.117	0.113	0.128	0.099	0.097	0.077	0.121	0.135
	Average area (m^2)	0.222				0.114				0.108			
Discharge	Average discharge (m^3/s)	0.130				0.0855				0.0216			

Note: 1 = this canal is a rectangular canal and the procedure followed is similar to Table B.2.

Table B.2 Discharge estimation for rectangular canals in the study sites

		Gumsalasa main canal 2				Gumsalasa seepage1				Gumsalasa seepage2			
Velocity	Length (m)	10				6				9			
	Time (s)												
	t_1	11				61				40			
	t_2	11				78				36			
	t_3	10				70				36			
	t_4	10				62				39			
	t_5	9.5				66				41			
	t_6	10				72				41			
	Average time (s)	10.25				68.17				38.83			
	Surface velocity (m/s)	0.98				0.088				0.232			
	Velocity coefficient	0.6				0.5				0.5			
	Average velocity (m/s)	0.59				0.044				0.116			
Area	Location	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4
	Width (m)	0.73	0.7	0.67	0.72	0.87	0.83	0.85	0.9	0.66	0.65	0.66	0.75
	Depth (m)												
	d_0	0.37	0.37	0.37	0.37	0.1	0.108	0.114	0.119	0.027	0.027	0.03	0.043
	d_1	0.37	0.37	0.37	0.37	0.15	0.166	0.158	0.14	0.048	0.051	0.045	0.06
	d_2	0.37	0.37	0.37	0.37	0.114	0.18	0.16	0.162	0.03	0.03	0.06	0.047
	d_3	0.37	0.37	0.37	0.37	0.106	0.101	0.133	0.154				
	Average depth (m)	0.37	0.37	0.37	0.37	0.1175	0.139	0.141	0.144	0.035	0.036	0.045	0.05
	Area (m^2)	0.27	0.26	0.25	0.27	0.102	0.115	0.12	0.129	0.023	0.023	0.03	0.038
	Average area (m^2)	0.263				0.117				0.028			
Discharge	Average discharge (m^3/s)	0.154				$5 * 10^{-3}$				$3 * 10^{-3}$			

Appendix C

Field evaluation of furrow irrigation at Gumsalasa

Table C Advance time, recession time, contact time and corresponding infiltration of irrigation water along furrows

Distance in m	Advance time[1] in hh:mm:ss	Recession time[1] in hh:mm:ss	Contact time in min	Infiltration[2] in mm
Trial 1 (6.3 m furrow length)				
Test 1				
0	10:45:55	11:01:00	15	17.2
2	10:46:05	11:01:11	15	17.2
4	10:46:15	11:03:17	17	18.1
6.3	10:46:31	11:03:17	17	18.1
Test 2				
0	10:46:45	10:57:22	11	15.1
2	10:47:04	11:01:11	14	16.7
4	10:47:24	11:02:14	15	17.2
6.3	10:47:45	11:02:14	15	17.2
Trial 2 (7.9 m furrow length)				
Test 1				
0	11:01:57	11:08:24	7	12.5
3	11:02:10	11:15:42	14	16.7
6	11:02:26	11:16:47	15	17.2
7.9	11:02:40	11:14:30	12	15.6
Test 2				
0	11:00:38	11:08:26	8	13.2
3	11:00:50	11:10:20	10	14.5
6	11:01:11	11:17:09	16	17.7
7.9	11:01:39	11:10:20	9	13.9
Trial 3 (12 m furrow length)				
Test 1				
0	0	5	5	10.8
2	1.5	7	5.5	11.2
4	4	13	9	13.9
6	6	24	18	18.6
8	10	37	27	22.1
10	12	48	36	24.9
12	16	63	47	27.9
Test 2				
0	0	5	5	10.8
2	2	6.5	4.5	10.3
4	6	9.5	3.5	9.3
6	7.5	12.5	5	10.8
8	13	29	16	17.7
10	19	41	22	20.2
12	29	59	30	23.1

Note:
1 = the time for the 12 m long furrow was measured in minute
2 = the equation used to calculate filtration was $F = 5.45*T_O^{0.42}$

Appendix D

Irrigation efficiency values

Table D.1 Indicative values of the conveyance efficiency (Ec) for adequately maintained canals (Brouwer and Prins, 1989)

Canal length	Conveyance efficiency in %			
	Earthen canals by soil type			Lined canals
	Sand	Loam	Clay	
Long (> 2000 m)	60	70	80	95
Medium (200 – 2000 m)	70	75	85	95
Short (< 200 m)	80	85	90	95

Table D.2 Indicative values of field application efficiency (Ea) (Brouwer and Prins, 1989)

Irrigation methods	Field application efficiency in %
Surface irrigation (border, furrow, basin)	60
Sprinkler irrigation	75
Drip irrigation	90

List of symbols

ΔS	change in storage in m or m^3
ΔV_R	change in reservoir water volume during the observation period in m^3
ΔW_D	water level variation in the reservoir in m
ΔZ	change in salt concentration in the root zone in dS/m
A	catchment area in km^2
A	irrigated area in ha
a, b & c	intake family coefficients
A_{av}	average cross-sectional area of the canal in m^2
A_{Cav}	average catchment area of a dam in km^2
A_{DS}	area of the dead storage in m^2
A_i	cross-sectional area of a canal at location i in m^2
AM	total available soil moisture in mm/m
A_{Rav}	average reservoir area during the observation period in m^2
A_{Rf}	reservoir area at the end of the observation period in m^2
A_{Ri}	reservoir area at the beginning of the observation period in m^2
A_{RM}	average maximum (design) reservoir area in m^2/dam
C	salt concentration in dS/m
cH	correction for harvested part
cL	correction for crop development and leaf area
cN	correction for dry matter production, 0.6 for cool and 0.5 for warm conditions
D	depth of the root zone of the crop in m
d	irrigation depth in mm
DP	percolation loss in mm
E	evapotranspiration in mm
E	signs of active erosion
Ea	application efficiency in %
ECe	salt concentration of a saturated extract in dS/m
ECfc	salt concentration of the soil water in the root zone at field capacity in dS/m
E_i	irrigation efficiency
E_{Pan}	pan evaporation in mm/d
E_R	evaporation from the reservoir during the irrigation season in m
ETa	actual evapotranspiration in mm/growing period
ETcrop	consumptive crop water requirement in mm/day
ETm	maximum evapotranspiration in mm/growing period
ETo	potential evapotranspiration in mm/day
f and g	advance coefficient for furrow design, varying with intake family
F	cumulative infiltration during opportunity time in mm
F	fraction of the day time the sky is clouded
Fav	average infiltrated depth between 0 and L in mm
Fg	gross application depth in mm
G	capillary rise in mm
G	gullies
H	total depth of runoff in barrel in m
I	catchment index
I	inflow in m or m^3
I	net irrigation in mm

kc	crop coefficient
K_{Pan}	pan coefficient
K_V	velocity correction factor
ky	yield response factor
L	distance traveled by the float in m
L	lithology
n	roughness coefficient
n	actual measured sunshine duration in hr/d
N	maximum possible sunshine duration in hr/d
N	number of days in the observation period
N_d	number of dams
O	outflow in m or m^3
p	fraction of the total available soil water which can be used by the crop without affecting its growth
P	wetted perimeter in m
P	percolation in mm
P_A	atmospheric pressure at time t in mm
P_{dep}	dependable rainfall of a decade in mm/decade
P_{eff}	effective rainfall in mm
P_R	direct reservoir rainfall during the observation period in m
P_T	piezometric head at time t in mm
P^x	net percolation, which is the difference between deep percolation and capillary rise in mm
Q	discharge in m^3/s
Qfc	soil water content in mm/m
R	effective rainfall in mm
r	radius of the barrel in m
Ra	extra-terrestrial radiation in mm/d
RAM	readily available moisture of the soil in mm
R_{GW}	groundwater recharge in m/d
RO	runoff in mm
Rs	actual measured incoming shortwave radiation in $J/cm^2.d$
Rse	maximum active incoming shortwave radiation on clear days in $J/cm^2.d$
S	slope in m/m
S	catchment shape
SD	soil type and drainage
S_D	total annual sediment deposited in all earthen dams in t/yr
SSY_{av}	average annual sediment yield in $t/km^2.yr$
S_y	sediment yield in $t/km^2.yr$
T	irrigation interval (frequency of irrigation) in days
T	topography
T(T)	total travel time in min
t_{av}	average time elapsed in s
Ti	inflow time in min
Tn	required opportunity time in min
T_O	intake opportunity time in min
T_{op}	canal operation time during the observation period in s
Tr	recession time in min
Tt	advance time in min
V	vegetation cover
V	volume of runoff in the barrel(s) in m^3

V_1	inflow from other sources in m^3
V_2	non-irrigation deliveries from the conveyance system in m^3
V_3	non-irrigation deliveries from the distribution system in m^3
V_{av}	average velocity in m/s
V_c	volume diverted or pumped from the source in m^3
V_d	volume delivered to the distribution system in m^3
V_{DS}	volume of the dead storage in m^3
V_f	volume of water furnished to the fields in m^3
V_{GW}	total annual groundwater recharge in m^3/yr
V_{IPRE}	initial reservoir volume of the present scheduling in m^3
V_{IPRO}	initial reservoir volume of the proposed scheduling in m^3
V_{IR}	total volume of water available for irrigation in m^3
V_L	water consumed by livestock in m^3/d
V_m	volume of water needed, and made available, for evapotranspiration by the crops to avoid undesirable water stress in the plants throughout the growing cycle in m^3
V_{PRO}	total volume of water that can be saved by the proposed operation in m^3
V_{Rf}	reservoir volume at the end of the observation period in m^3
V_{Ri}	reservoir volume at the beginning of the observation period in m^3
V_S	seepage in m^3/d
V_S	surface velocity in m/s
V_{Sed}	total volume of sediment deposited in the dead storage since construction in m^3
W	furrow spacing in m
Wfc	water content of the root zone at field capacity in mm
W_{t1}	water level at time 0.0 hours in relation to a datum in mm
W_{t2}	water level at time 24.0 hours in relation to a datum in mm
Ya	actual harvested yield in kg/ha
yc	gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day in kg/ha.d
yc	gross dry matter production rate of a standard crop for a given location on a clear (cloudless) dayin (kg/ha.d
ym	maximum gross dry matter production rate for a given climate in kg/ha.hr
Ym	maximum harvested yield in kg/ha
Yo	gross dry matter production of a standard crop in kg/ha.d
Z_1	salt concentration in the root zone at the beginning of the period in dS/m
Z_2	salt concentration in the root zone at the end of the period in dS/m
β	advance coefficient

Samenvatting

Ethiopië is een door land omgeven staat in Oost Afrika. De agrarische sector is met een betrokkenheid van 90% van de bevolking de voornaamste bron van werkgelegenheid, inkomen en export. Het totale oppervlak van Ethiopië bedraagt ongeveer 110 miljoen ha, waarvan 67% een aride of semi-aride klimaat heeft. De bevolking van Ethiopië, waarvan 90% in landelijke gebieden leeft, is gegroeid van 22 miljoen in 1961 tot ongeveer 69 miljoen tegenwoordig, met een gemiddelde jaarlijkse bevolkingsaanwas van 3%.

Ethiopië wordt gekenmerkt door honger als gevolg van de grote bevolkingsdruk, uitputting van natuurlijke hulpbronnen en onvoldoende regenval voor de productie die afhankelijk is van regenval. Met 22 grote droogteperioden in de afgelopen 40 jaar alleen al, heeft het land te maken met een jaarlijks graantekort van 0,03 – 3,3 miljoen ton. Aan de andere kant beschikt het land over een jaarlijkse watervoorraad van ongeveer 110 miljard m^3, een te bevloeien landoppervlak van 3,6 miljoen ha en een arbeidspotentieel van ca 48% van de totale bevolking. Tot op heden is echter slechts ongeveer 3 miljard m^3 van de watervoorraad en 190.000 ha van het potentieel beschikbare te irrigeren land in gebruik.

Gezien de beschikbare voorraad aan water en land, het gebrek aan voedsel, de bevolkingstoename en de beperkte regenval, heeft de nieuwe regering van Ethiopië al sinds 1991 voorrang gegeven aan de agrarische ontwikkeling. De in 1992 aanvaarde door agrarische ontwikkeling gestuurde industriële ontwikkelingsstrategie (ADLI) stelt irrigatie als voornaamste pijler om de voedsel productie te vergroten en te bereiken dat het land in haar eigen voedselproductie kan voorzien.

Met een oppervlakte van 8 miljoen ha is Tigray een van de meest achtergebleven en droogste gebieden van Ethiopië. De huidige bevolking bedraagt 3,7 miljoen, met een jaarlijkse groei van 3,3%. Het jaarlijkse tekort aan graan wordt geschat op ongeveer 180.000 ton. Van de vele oorzaken voor het voedseltekort speelt het vochttekort een belangrijke rol. Het klimaat van Tigray is voornamelijk semi-aride en het merendeel van de regio ontvangt een beperkte hoeveelheid neerslag die te gering is voor een goede groei van gewassen. Aan de andere kant vloeit er jaarlijks 9 miljard m^3 water weg uit de regio. Als bijvoorbeeld 50% van deze afvoer gebruikt zou worden voor irrigatie dan zou een half miljoen ha land kunnen worden geïrrigeerd wat voldoende zou zijn om driemaal de huidige bevolking van Tigray van voedsel te voorzien. Het geschatte potentiële gebied voor irrigatie is ongeveer 325.000 ha waarvan slechts ongeveer 15.000 ha op de traditionele manier wordt geïrrigeerd.

Bewust van deze problematiek en dit potentieel is de regionale regering gedurende de laatste jaren betrokken bij activiteiten met betrekking tot irrigatie met behulp van aarden dammen. In 1994 is de Commissie voor Duurzame Landbouw en Milieukundige Herinrichting in Tigray (CoSAERT) opgericht om in een periode van 10 jaar 500 dammen te bouwen en om 50.000 ha te irrigeren. De voornaamste doelstellingen waren om het landbouwkundige systeem te veranderen in wijdverspreide kleinschalige geïrrigeerde landbouw en om geleidelijk zelf te kunnen voorzien in de voedselproductie.

Tot dusverre zijn er 44 aarden dammen met de bijbehorende irrigatievoorzieningen gebouwd en wordt gemiddeld per jaar ongeveer 1.418 ha geïrrigeerd. De aarden dam irrigatie systemen bestaan uit een stroomgebied, een

reservoir, een aarden dam en een beheersgebied. Het beheersgebied van de meeste van deze systemen is vervolgens verdeeld in een primair en een secundair beheersgebied. Het primaire beheersgebied is het gebied dat irrigatiewater ontvangt uit het reservoir door de uitlaat via leidingen, terwijl kwelwater door de dam van het reservoir het secundaire beheersgebied bevloeit. De gemiddelde oppervlakte van een stroomgebied, reservoir oppervlakte, reservoir capaciteit, dam hoogte, lengte van de kruin, mogelijk en werkelijk bevloeibaar gebied per dam zijn achtereenvolgens 950 ha, 1.1 miljoen m^3, 15,5 m, 67 ha en 32 ha. Er zijn echter behoorlijke verschillen tussen de verschillende systemen.

Het succes van de huidige en toekomstige kleinschalige irrigatiesystemen om de armoede te verminderen en om geleidelijk de voedselvoorziening in de regio te garanderen hangt af van hun duurzaamheid. Het algemene beginsel van duurzaamheid gaat uit van een zodanige ontwikkeling, gebruik en beheer van land en watervoorraden dat toekomstige generaties niet aan risico's worden blootgesteld. Volgens Savenije (1997) zijn de voornaamste aspecten van duurzaamheid:

- duurzaamheid van het milieu (geen negatieve effecten op de lange duur of onomkeerbare effecten);
- technische duurzaamheid (evenwicht in vraag en aanbod, geen uitputting);
- economische duurzaamheid (duurzame economische ontwikkeling, ofwel welvaart en productie);
- financiële duurzaamheid (terugverdienen van de kosten);
- maatschappelijke duurzaamheid (stabiliteit van de bevolking, stabiliteit van de vraag, bereidheid om te betalen).

De aandacht van de uitgevoerde studies over de aarden dam irrigatiesystemen in Tigray is altijd uitgegaan naar een enkel onderdeel zoals sedimentatie in de reservoirs en de verzilting van de geïrrigeerde velden. Tot dusver is geen poging ondernomen om het gehele systeem als een geïntegreerde eenheid te bestuderen, rekening houdend met het stroomgebied, het reservoir, de dam en het beheersgebied.

Dit onderzoek is geïnitieerd en uitgevoerd in twee aarden dam irrigatiesystemen, Gumsalasa en Korir met als voornaamste doelstelling een geïntegreerde benadering van duurzame ontwikkeling en beheer van geïrrigeerde gebieden in Tigray. De aarden dam in Gumsalasa is gebouwd in 1995 met een reservoirinhoud van 1,9 miljoen m^3. De aarden dam in Korir is een jaar later gebouwd met een reservoirinhoud van 1,6 miljoen m^3. Met meer dan 85% van de totale jaarlijkse neerslag vallend in een periode van vier maanden ,van juni tot september, heeft de neerslag in beide systemen een zelfde patroon. De gemiddelde jaarlijkse neerslag is 513 mm in Gumsalasa en 543 mm in Korir. De dammen zijn gebouwd door CoSAERT, terwijl het beheer en onderhoud in handen is van het Bureau Landbouw en Natuurlijke Hulpbronnen en van de boeren.

Primaire en secundaire meetgegevens zijn verzameld en geanalyseerd op basis van de voornaamste duurzaamheidkwesties die betrekking hebben op het stroomgebied, het reservoir en de dam, het beheersgebied, en de gebruikers, voor de formulering en de waardering van de geïntegreerde aanpak. Deze omvatten het klimaat, institutionele aspecten en waterbeheer, erosie en sedimentatie, met water verzadigde grond en verzilting, de waterbalans van het reservoir, en socio-economische aspecten. De mogelijke effecten van de irrigatiesystemen met aarden dammen op het regime van de rivier de Nijl is ook in algemene zin onderzocht.

Langjarige klimaatsgegevens in Gumsalasa zijn gebruikt om de betrouwbaarheid van de neerslag afhankelijke landbouw in het gebied te toetsen. Meteorologische meetgegevens van het gebied, twee dominante bodemsoorten, klei en leem, en het meest voorkomende gewas, tarwe, zijn gebruikt voor de beoordeling van de irrigatie systematiek en de droogteperiodes gedurende het groeiseizoen. De Penmann-Monteith methode is gebruikt voor de berekening van het irrigatie interval voor tarwe onder de meest voorkomende condities in Gumsalasa. Op basis van analyse van droogteperioden in 26 jaar dagelijkse neerslaggegevens is de kans bepaald dat in het groeiseizoen een droogteperiode voorkomt die langer duurt dan of gelijk is aan dit interval.

Meetgegevens betreffende landbouwkundige exploitatie, sociale en institutioneel aspecten, alsmede betreffende het waterbeheer zijn met behulp van een vragenlijst verzameld bij de boeren, vertegenwoordigers van organisaties voor ontwikkelingssamenwerking, en het Wereda Bureau van Landbouw en Natuurlijke Hulpbronnen.

De methoden van het afvoer verzamelgebied en HR Wallingford zijn onderzocht teneinde een algemene beoordeling te presenteren van de sedimentatie in het stroomgebied. De resultaten zijn vergeleken met de resultaten van twee andere empirische benaderingen die gebruikt zijn voor het schatten van de sedimentatie in reservoirs in Tigray door Poesen *et al.* (2001), namelijk de methoden van Verstaeten *et al.* en van de Pacific Southwest Inter Agency Commission (PSIAC).

Neerslag, verandering van het waterpeil in het reservoir, evapotranspiratie, afvoer in de watergangen, kwel, aanvulling van het grondwater en de consumptie van vee zijn gemeten over een bepaalde periode om de waterbalans van het reservoir te benaderen. Regenmeter, duiker, data-logger en barometergegevens, klasse A verdampingspannen en drijvende verdampingspannen zijn gebruikt om achtereenvolgens de neerslag, het waterpeil in het reservoir, de verdamping en de afvoer te meten. De schatting van het watergebruik door het vee is gebaseerd op het gemiddelde aantal stuks vee dat uit het reservoir drinkt. De aanvulling van het grondwater is indirect geschat met behulp van de waterbalans formule voor de droge periode.

Beoordeling in het veld van de toepassing van irrigatiewater werd gedaan op basis van verscheidene greppellengten om de huidige praktijk van het waterbeheer en de invloed op gewasopbrengsten en de verzilting te schatten.

Voor het onderzoek naar de verzilting, zijn de irrigatiesystemen verdeeld in het door neerslag gevoede stroomgebied, reservoirs, primaire en secundaire beheersgebieden en zijn er profielkuilen op diverse relevante plaatsen gegraven. Het gebied dat gevoed wordt door neerslag is erbij inbegrepen als controle op de invloed van de ontwikkeling van irrigatie op de verzilting. De grond aan de oppervlakte, het oppervlaktewater, de grond onder de oppervlakte en grondwatermonsters zijn verzameld en onderzocht op verschillende tijdstippen en locaties.

Tenslotte is er op twee niveaus een evaluatie uitgevoerd van de gevolgen van de voornaamste resultaten van het onderzoek naar duurzaamheid, namelijk, het niveau van het irrigatie systeem en het benedenstroomse gebied, de Nijl inbegrepen. Alternatieve scenario's ten opzichte van de bestaande praktijk zijn ook gepresenteerd en gesimuleerd met het doel om het gebruik van de beperkte watertoevoer te verbeteren, om de opbrengst van het gewas te vergroten en om de verziltingproblemen te verkleinen. De verkregen resultaten zijn hieronder samengevat.

Het irrigatie-interval voor tarwe in Gumsalasa ligt tussen 13 en 28 dagen. De analyse van de resultaten van de droogteperioden laten zien dat er tenminste een keer per groeiseizoen een kans van bijna 100% bestaat op een droge periode die langer is dan de genoemde intervallen. Dit betekent dat door neerslag gevoede landbouw in de regio praktisch onmogelijk is zonder aanvullende irrigatie.

De voornaamste doelstelling van de aarden dam irrigatiesystemen is om het welzijn van de arme boeren in Tigray te verbeteren. De situatie in het studiegebied heeft dit bevestigd. In vergelijking tot de door neerslag gevoede landbouw is een toename van de oogst van 170 - 285% waargenomen. Het gemiddelde aantal huishoudens die voordeel hebben van irrigatie is respectievelijk 425 and 330 te Gumsalasa en Korir. Sinds de invoering van de irrigatie is het gewaspatroon veranderd van kleinkorrelige gewassen naar maïs en groenten. De opbrengst, de marktprijzen en dientengevolge het huishoudelijk inkomen voortvloeiend uit de geïrrigeerde gebieden zijn tegenwoordig hoger dan in de situatie van de door neerslag gevoede landbouw.

Weldoordachte planning en toepassing van het reservoirbeheer zijn zeer belangrijk voor het succes van de aarden dam irrigatie systemen. Twee scenario's, het huidige beheer (januari – juni) en een alternatief beheersplan (september - januari) zijn in dit verband beoordeeld. Omdat de geïrrigeerde velden van de systemen ook gebruikt worden voor neerslag gevoede landbouw gedurende juni - december, begint het voornaamste irrigatieseizoen en het reservoirbeheer tegenwoordig over het algemeen in januari en duurt het tot juni. Deze periode valt echter samen met het hoogste verdampingsniveau van het jaar. Dit heeft als resultaat dat meer dan 40% van het beschikbare water bij het begin van het irrigatieseizoen verloren gaat door verdamping uit het reservoir. Het percentage zou zelfs veel hoger zijn dan de periode tussen september en december, als er alleen reservoirbeheer zonder enige afvoer in beschouwing wordt genomen. De kleine afmetingen van het geïrrigeerde grondbezit in aanmerking genomen (0.2 - 0.3 ha per huishouden), de onbetrouwbaarheid en lage kwaliteit van de opbrengst uit de door neerslag gevoede landbouw en het feit dat elke gebruiker ongeveer 1.2 ha land bezit voor de neerslagafhankelijke landbouw, wijzen er op dat beëindiging van neerslagafhankelijke productie op de geïrrigeerde velden en het starten met irrigatie onmiddellijk na het regenseizoen (in september) een betere optie is. Deze werkwijze kan vergeleken met de huidige praktijk de doelmatigheid van het reservoirbeheer op twee manieren verhogen, te weten door de vermindering van de verdampingsverliezen in het reservoir en de gewenste hoeveelheid water voor de gewassen. De evaluatie toont aan dat een potentieel gemiddeld gebied van 38 ha in Gumsalasa en 26 ha in Korir extra kan worden geïrrigeerd met water dat bespaart kan worden door het begin van het irrigatieseizoen te verplaatsen van januari naar september. Uitgaande van het gemiddelde huishouden per geïrrigeerd stuk land, kunnen er in respectievelijk Gumsalasa en Korir 190 en 80 meer huishoudens dan de bestaande van de irrigatie profiteren. Bovendien zal dan de jaarlijks opbrengst van de irrigatie ongeveer het tienvoudige bedragen van de opbrengst die kan worden verkregen van door neerslag gevoede landbouw.

De bestaande praktijk van het waterbeheer beval een leveringsduur aan van 2 uur voor iedere 0,2 ha, bij een afvoer naar de velden van 2,5 l/s. Tegenwoordig wordt het water onder de boeren verdeeld op basis van directe waarneming van bodem en gewas condities en wordt de afvoer naar de velden niet gecontroleerd. Watertoewijzing gebeurt bij toerbeurt, maar de individuele boer beslist over de leveringsduur. De leveringsduur van 2 uur schijnt niet te worden toegepast en de praktijk van alledag is dat een boer het water alleen door laat naar de volgende gebruiker nadat hij/zij het gevoel heeft dat zijn/haar land goed geïrrigeerd is. Het resultaat is dat verspilling van water door wegvloeien en over-irrigatie gebruikelijk is. Onderzoek in het veld naar de irrigatiepraktijk in Gumsalasa wijst drie hoofdproblemen aan: korte greppellengten, onvoldoende watertoevoer naar de wortelzone van de gewassen en slechte uitspoeling. Op basis van de resultaten van het veldonderzoek bedroeg de totale hoogte van de toegepaste waterschijf tijdens het irrigatieseizoen ongeveer 128 mm voor uien en 176 mm voor maïs. De netto irrigatiewaterbehoefte voor uien en maïs bij toepassing van het CROPWAT model voor een maximale opbrengst (100% opbrengst) is echter respectievelijk ongeveer 429 mm en 571 mm. Het effect van het watertekort op de reductie in opbrengst was geschat te variëren tussen ongeveer 60% voor maïs en tot 70% voor uien. Vergelijking van de huidige werkelijke gemiddelde opbrengst laat dezelfde ontwikkeling zien. In dit verband wordt een juiste toepassing van het voorgestelde irrigatierooster aanbevolen. Een gebruikersvriendelijk spreadsheet ter berekening van greppels en een ontwerpprogramma gebaseerd op de vergelijkingen voor greppels met een open einde, ontwikkeld door de Soil Conservation Service (SCS) van het departement voor Landbouw van de Verenigde Staten was geëvalueerd op basis van de resultaten van de veldproeven en kan gebruikt worden voor de situaties in de studiegebieden.

Resultaten van de studie naar het zoutgehalte tonen aan dat het zoutgehalte van het irrigatiewater van het hoofdbeheersgebied in beide irrigatiesystemen 0,3 dS/m bevat. Aan de andere kant bevat het kwelwater dat gebruikt wordt om het secundaire beheersgebied te irrigeren ongeveer 0,8 dS/m te Gumsalasa en 1,2 dS/m te Korir. Het gevaar van verzilting van irrigatiewater kan worden gerangschikt als gematigd in het primaire beheersgebied en hoog in het secundaire beheersgebied. Uitspoeling wordt in het algemeen aanbevolen in zulke situaties om het verziltingniveau van de wortelzone binnen geschikte grenzen voor de gewasgroei en productie te houden. In de studiegebieden is de uitspoelbehoefte bij het uitvoeringsplan niet in aanmerking genomen en wordt de verzilting van de grond niet gecontroleerd. Dit had als resultaat dat het zoutgehalte van de bodem in de systemen sinds het begin van de volledige irrigatie in 1999 meer dan verdubbeld is. Echter het huidige gemiddelde zoutgehalte in de wortelzone is ongeveer 0,75 dS/m en vormt geen gevaar voor de opbrengst van de voornaamste geïrrigeerde gewassen. Indien echter het ontziltende vermogen onvoldoende blijft, zoals thans het geval is, dan kan de zoutconcentratie verder oplopen tot een punt waarbij de gewasproductie sterk kan afnemen of zelfs onmogelijk wordt. Simulatie van het effect op de lange duur van slechte uitspoeling op de opeenhoping van zout in Gumsalasa liet zien dat verzilting de oorzaak is van de vermindering van de gewasopbrengst vanaf het tweede jaar na invoering van het plan. Het succes van het voorgestelde uitvoeringsplan hangt af van het handhaven van het verziltingniveau op tenminste het huidige peil dat door uitspoeling bereikt is. De jaarlijkse uitspoelbehoefte van het irrigatiesysteem was geschat op 100 mm en 200 mm voor respectievelijk het primaire en secundaire beheersgebied. Dit zal ongeveer 20% bedragen van het benodigde irrigatiewater in het primaire beheersgebied en 40% in het secundaire. Het percentage in het secundaire gebied is hoog maar behelsd een klein gebied.

De inspraak van de gemeenschap in de ontwikkeling en het beheer van aarden dam irrigatiesystemen is in Tigray veelbelovend. De ontwikkelingsstrategie benadrukt het belang van het betrekken van de wensen, ideeën, en verwachtingen van de landbouwgemeenschap en de noodzaak om de deelname van vrouwen als basis voor de duurzaamheid te bevorderen. Boeren nemen deel aan de bouw van de aarden dam irrigatie projecten en de herinrichting van de stroomgebieden. Zij zijn in het algemeen of individueel of door vertegenwoordigers betrokken bij alle beslissingen die met betrekking tot het beheer en onderhoud van de irrigatiesystemen genomen worden. Ook is zijn veelbelovende ontwikkelingen gesignaleerd betreffende te toegang van vrouwen tot geïrrigeerd land, alsmede tot andere basisvoorzieningen en diensten. Ongeveer 41% en 21% van het totaal geïrrigeerde land in respectievelijk Korir en Gumsalasa is in eigendom van vrouwen. De ontwikkelingsinspanning zou moeten worden voortgezet om de boeren te versterken en om het beheer en het onderhoud van de systemen over te dragen aan de belanghebbenden.

Het lijkt er echter op dat tot dusver zeer belangrijke beleids-, institutionele en sociaal-ecomonische aspecten, die de belangrijkste rol in het succes van de irrigatie systemen kunnen spelen, nog niet de nodige aandacht krijgen. Dit heeft tot resultaat dat de door de gemeenschap aangestelde organisaties van watergebruikers de belangrijkste rol spelen in de toewijzing en verdeling van het water, conflictbeheersing en het beheer en onderhoud van de irrigatiesystemen. De bestaande beheers- en onderhoudsregels zijn gebaseerd op plaatselijke verordeningen (*'Serit laws')* opgesteld door de gebruikers met raadpleging van het Wereda Bureau van Landbouw en Natuurlijke Hulpbronnen. De verenigingen van watergebruikers en het plaatselijke wettelijke gezag passen echter de traditionele beheers en onderhoudsvoorschriften en regelingen om op een juiste manier het beheer, het onderhoud en de juridische zaken uit te voeren niet toe. Daarom zou - op basis van deelname van belanghebbenden - voorrang moeten worden gegeven aan het formuleren en invoeren van een veelomvattend en regionaal irrigatiebeleid. CoSAERT en de regionale overheid stelden de belangrijkste aanbevelingen voor met betrekking tot de verdeling van water onder de belanghebbenden, de tarieven voor water en de verkoop. Deze waren: verdeling van de geïrrigeerde kavels in twee of drie blokken en het toewijzen in elk blok van een kavel aan alle belanghebbenden om de eerlijke verdeling van water te verbeteren, invoering van water tarieven voor onderhoud en herstelwerkzaamheden en het oprichten van marktcoöperaties die een sterk netwerk kunnen vormen ter verkrijging van de nodige kredieten en markten. Geen enkele hiervan is tot dusverre uitgevoerd. Dit heeft tot resultaat dat de huidige praktijk is dat tijdens een tekort aan water de benedenstroomse - aan de lagere uiteinden gelegen - boeren benadeeld worden. De plaatselijke marktprijzen zijn eveneens laag.

De doelstelling van de sedimentatiestudie was om een eenvoudig hulpmiddel te verschaffen om stroomgebieden met een hoog risico van erosie snel te kunnen beoordelen. De situatie in Korir in aanmerking genomen kan met behulp van de HR Wallingford methode een goede schatting gedaan worden van de hoeveelheid sedimentatie en kan dit gebruikt worden voor een eerste beoordeling.

Ethiopië draagt ongeveer 75 miljard m^3 bij aan de 84 miljard m^3 van de afvoer van de rivier de Nijl die jaarlijks de Aswan dam bereikt. Het plan van de overheid is om 100 aarden dammen te bouwen in twee van de belangrijkste stroomgebieden, Abay (Blauwe Nijl) in de regio Amhara en Tekeze in de regio Tigray. De invloed van deze ontwikkelingen op het regime van de rivier de Nijl kunnen bestaan uit verandering van waterkwaliteit, verandering van aanvulling van grondwater, verandering van bodemerosie en verandering van de jaarlijkse afvoer. Het mogelijke gevolg is hieronder in algemene bewoordingen weergegeven, gebaseerd op de ontwerp capaciteiten van de bestaande dammen in Tigray. Gevonden is dat de kwaliteit van het grondwater en het drainagewater van de aarden dam irrigatiesystemen zeer zout is. Dit kan van belang zijn voor de onmiddellijk benedenstroomse gebruikers die afhankelijk zijn van bronnen die ontstaan door de aanvulling die door de dammen wordt veroorzaakt. Deze boeren moeten zoutbestendige gewassen telen en zorgen voor uitspoeling wanneer dat mogelijk is. Vanwege de geringe bijdrage tot de totale afvoer zal het effect op de waterkwaliteit van de rivier de Nijl echter marginaal zijn. De aarden dammen kunnen in het algemeen het grondwater aanvullen en de kwel in de benedenstrooms gebieden verbeteren. De maximum hoeveelheid water van al de reservoirs dat jaarlijks tot het grondwater doordringt (percoleert) is geschat op ongeveer 36 miljoen m^3, hetgeen 3% bedraagt van de ontwerp reservoir capaciteit en slechts 0,04% van de totale Nijl afvoer. Er is derhalve gevonden dat de bijdrage tot de aanvulling van het grondwater alleen van belang is voor de direct benedenstrooms gebruikers. Nadat spaarbekken constructies voor oppervlaktewater zijn gebouwd is in de benedenstroomse gebieden een toename van een hoeveelheid kwelwater geregistreerd van 5 l/s tot 25 l/s. Er wordt door de Nijl ongeveer 140 miljoen ton sediment per jaar naar Soedan en Egypte getransporteerd. De snelle dichtslibbing van de reservoirs in Soedan is een direct gevolg van deze erosie. Als alle geplande dammen in het hooggebergte van Ethiopië gebouwd zouden worden, zouden zij in staat zijn om ongeveer 13 miljoen ton sediment per jaar op te slaan, hetgeen een maximum van 9% van het totale sediment transport van de Nijl bedraagt. Het proces van aanslibbing in aanmerking genomen, kan niet al het sediment worden getransporteerd en dientengevolge zou de werkelijke bijdrage van de dammen minder bedragen dan 9%. Omdat het aantal dammen dat tot dusverre is gebouwd zeer klein is vergeleken met het oorspronkelijke plan, is het effect op de totale Nijl afvoer marginaal. Indien alle voorgestelde dammen zouden worden gebouwd in de komende jaren, dan zou de potentiële impact maximaal ongeveer 1,5% zijn van de totale afvoer naar de Nijl.

Als een belangrijke contribuant in de totale Nijl afvoer, moet Ethiopië bij de ontwikkelingen in het hoogland de gevolgen voor de benedenstroomse Nijloever staten in ogenschouw nemen. In dit verband is een effectieve samenwerking in het hele stroomgebied voor de welvaart en het welzijn van de Nijloever staten een belangrijke toekomstige taak. De Nijloever staten moeten samenwerken aan een billijker verdeling en toenemende productiviteit van het Nijlwater. De onderhandelingen die thans plaatsvinden en de overeenkomsten die er zijn tussen de Nijloever staten in het algemeen en de belangrijkste spelers: Egypte, Soedan en Ethiopië in het bijzonder om samen te werken in de ontwikkeling van irrigatie, aanleg van reservoirs en ontwikkeling van waterkracht vormen een essentiële stap voorwaarts en zouden moeten worden geïntensiveerd.

ማጠቃለያ

ኢትዮጵያ የባህር በር የሌላት የምስራቅ አፍሪካ አገር ናት፡፡ ግብርና ዘጠና ከመቶ የሚሆነውን ህዝብ የሚያሳትፍ ዋና የስራ መስክ፣ የገቢና የውጭ ምንዛሪ ምንጭ ነው፡፡ የኢትዮጵያ ጠቅላላ የቆዳ ስፋቷ 110 ሚሊዮን ሄክታር የሚጠጋ ሲሆን ከዚህ ውስጥ 67% ያህሉ በረሃማ ወይም ከፊል በረሃማ ነው፡፡ 90% የሚሆነው የኢትዮጵያ ህዝብ የሚኖረው በገጠር ሲሆን አጠቃላይ የህዝብ ብዛት በ1953 ዓ.ም ከነበረው 22 ሚሊዮን በአሁኑ ጊዜ ወደ 69 ሚሊዮን አድጓል፡፡ አማካይ አመታዊ የእድገት መጠንም 3% ነው፡፡

ኢትዮጵያ በድርቅ የምትታወቅ አገር ስትሆን ለዚህም ከፍተኛ የህዝብ ብዛት፣ የተፈጥሮ ሀብት መመናመንና ለሰብል ምርት በቂ የሆነ የዝናብ መጠን ያለመኖር ዋናዎቹ ተጠቃሽ ምክንያቶች ናቸው፡፡ ባለፉት አርባ አመታት ውስጥ ብቻ እንኳን 22 ከፍተኛ የድርቅ ክስተቶች የታዩ ሲሆን፤ በአጠቃላይ ግን አገሪቱ ከ0.03 — 3.3 ሚሊዮን ቶን አመታዊ የጥራጥሬ ምግብ እጥረት ያጋጥማታል፡፡ በአንፃሩ ግን ወደ 110 ቢሊዮን ሜትር ኩብ የሚሆን አመታዊ የውሃ ሀብት፣ በመስኖ ሊለማ የሚችል 3.6 ሚሊዮን ሄክታር መሬትና ከጠቅላላው ህዝብ 48% የሚያክል አምራች ሀይል የታደለች አገር ናት፡፡ ይሁን እንጂ እስከ አሁን ጥቅም ላይ የዋለው ወደ 3 ቢሊዮን ሜትር ኩብ የሚሆነው አመታዊ የውሃ ሀብትና 190,000 ሄክታር የመስኖ መሬት ብቻ እንደሆነ ይገመታል፡፡

የአገሪቱን ሊለማ የሚችል መሬትና ውሃ ሀብት አቅም፣ የምግብ ዋስትና አለመኖር፣ የህዝብ ብዛትና የዝናብ ማነስ ችግሮችን ግምት ውስጥ በማስገባት የኢትዮጵያ መንግስት ከ1983 ዓ.ም ጀምሮ የግብርና ምርትን ለማሳደግ ትኩረት ሰጥቶ ሲንቀሳቀስ ቆይቷል፡፡ ከዚህም አኳያ አሁን ያለው የአገሪቱ ግብርና መር የኢንዱስትሪያዊ እድገት ፖሊሲ የመስኖ ልማትን ለምርት መጨመርና የምግብ ዋስትና መሳካት እንደ ዋና ምሰሶ አድርጎ የወሰደ ነው፡፡

ትግራይ 8 ሚሊዮን ሄክታር የቆዳ ስፋት ያላት ሲሆን ለድርቅ በጣም ከተጋለጡት የኢትዮጵያ ክልሎች አንዷ ናት፡፡ የህዝቡ ብዛት 3.7 ሚሊዮን የሚገመት ሲሆን አማካይ አመታዊ የእድገት መጠኑም 3.3% ነው፡፡ አመታዊ የጥራጥሬ ምግብ እጥረት 180,000 ቶን እንደሆነ ይገመታል፡፡ የምግብ እጥረት መንስኤዎች ብዙ ቢሆኑም የውሃ እጥረት ከፍተኛውን ሚና ይጫወታል፡፡ የክልሉ የአየር ንብረት ከፊል በረሃማ ሲሆን አብዘሃኛው ቦታ ለምርት በቂ ያልሆነ ዝናብ ያገኛል፡፡ በሌላ በኩል ግን 9 ቢሊዮን ሜትር ኩብ የሚሆን ውሃ በየአመቱ ከክልሉ ውጭ በጎርፍነት ይፈሳል፡፡ ለምሳሌ ያክል ከዚህ ጎርፍ ውስጥ 50% የሚሆነው እንኳ ለመስኖ አገልግሎት ቢውል ግማሽ ሚሊዮን ሄክታር መሬት ማልማት የሚቻል ሲሆን ይህም አሁን ያለውን የህዝብ ብዛት ሶስት እጥፍ መመገብ ይችላል፡፡ በክልሉ በመስኖ ሊለማ የሚችል መሬት ወደ 325,000 ሄክታር የሚገመት ሲሆን ከዚህ ውስጥ 15,000 ሄክታር የሚሆነው በባህላዊ መንገድ ይለማል፡፡

ከላይ የተጠቀሱትን ችግሮችና አቅሞች በመገንዘብ የክልሉ መንግስት በአነስተኛ ግድቦች የታገዙ የመስኖ ልማቶችን ላለፉት ጥቂት አመታት ሲያካሂድ ቆይቷል። ለዚህም ሲባል በ1986 ዓ.ም የትግራይ ዘላቂ ግብርናና አካባቢያዊ ጥበቃ ኮሚሽን (CoSAERT) በአስር አመት ውስጥ 500 ግድቦችን ለመስራትና 50,000 ሄክታር መሬት ለማልማት ተመሰረተ፡፡ የCoSAERT ዋና አላማ መስኖ በማስፋፋት ክልሉ በምግብ እራሱን የቻለ ማድረግ ነበር፡፡

እስከ አሁን ድረስ 44 አነስተኛ ግድቦች ተሰርተው ጥቅም ላይ የዋሉ ሲሆን በአማካይ ወደ 1,418 ሄክታር በአመት ያለማሉ፡፡ የመስኖ ልማቶቹ ተፋሰስ፣ ውሃ ማከማቻ፣ ግድብና የሚለማ መሬት የያዙ ናቸው፡፡ የአብዘሃኛዎቹ ግድቦች

ለሚ መሬት በሁለት የሚከፈል ሲሆን እነዚህም በቀጥታ ከግድቡ በመስኖ በሚለቀቀው ውሃ የሚለማና ከግድቡ ሰርጎ በሚወጣው ውሃ የሚለማ ናቸው፡፡ የመስኖ ልማቶቹ አማካይ የተፋሰስ ስፋት፣ ውሃ የማከማቸት አቅም፣ የግድብ ቁመት፣ የግድብ ርዝመት፣ ሊለማ የሚችል አጠቃላይ የመሬት ስፋትና እየለማ ያለ መሬት በቅደም ተከተል 950 ሄክታር፣ 25 ሄክታር፣ 1.1 ሚሊዮን ሜትር ኩብ፣ 15.5 ሜትር፣ 378 ሜትር፣ 67 ሄክታርና 32 ሄክታር ናቸው፡፡፡

አሁን ያሉትም ሆነ ወደፊት የሚሰሩት አነስተኛ የመስኖ ልማቶች የክልሉን ድህነት በመቀነስና የምግብ ዋስትናን በማረጋገጥ ረገድ የሚኖራቸው አስተዋፅኦ በዘለቄታማነታቸው ላይ የተመረከዘ ነው፡፡ Savenije (1997) እንዳስቀመጠው ዋና ዋናዎቹ የዘለቄታማነት መግለጫዎች የሚከተሉት ናቸው፡-

- አካባቢያዊ ዘለቄታማነት (አካባቢያዊ ብክለትን የማያመጣ)
- ቴክኒካዊ ዘለቄታማነት (የተመጣጠነ ፍላጎትና አቅርቦት)
- ኢኮኖሚያዊ ዘለቄታማነት
- የፋይናንስ ዘለቄታማነት (ወጪ መተካት)
- ማህበራዊ ዘለቄታማነት (የህዝብ መረጋጋት፣ ፍላጎት መረጋገጥና የመክፈል ፍላጎት)
- ድርጅታዊ ዘለቄታማነት (የማቀድና የመተግበር አቅም)

አብዛሃኛዎቹ እስከ አሁን በመስኖ ልማቶቹ የተደረጉ ጥናቶች በተወሰነ አካል ላይ ያተኮሩ ሲሆኑ ሁሉንም አካላት ማለትም ተፋሰሱን፣ የውሃ ማከማቻውንና ግድቡን እንዲሁም የሚለማውን መሬት አንድ ላይ በመውሰድ ለማጥናት የተደረገ ሙከራ የለም፡፡

ይህ ጥናት በጉምሳላሳና ቆሪር ግድቦቸ ላይ የተካሄደ ሲሆን ዋና አላማውም በትግራይ ውስጥ ዘላቂ የመስኖ ልማት እንዲኖር የሚያስችል የተቀናጀ ስልት መቀየስ ነው፡፡ የጉምሳላሳ ግድብ ውሃ የማከማቸት አቅም 1.9 ሚሊዮን ሜትር ኩብ ሲሆን የቆሪር ደግሞ 1.6 ሚሊዮን ሜትር ኩብ ነው፡፡ አማካይ አመታዊ የዝናብ መጠን ደግሞ 513 ሚሜ በጉምሳላሳና 543 ሚሜ በቆሪር ነው፡፡ ግድቦቹ የተሰሩት በCoSAERT ሲሆን የማንቀሳቀስና የመጠገን ሃላፊነት ደግሞ የገበሬዎችና የግብርናና የተፈትሮ ሃብት ቢሮ ነው፡፡

ይህ ጥናት ያተኮረው ከላይ በተጠቀሱት ዋናዎቹ የዘለቄታማነት መስፈርቶች ላይ ሁኖ ማእከል ያደረገው ደግሞ ተፋሰሱን፣ የውሃ ማቆርያውንና ግድቡን፣ የሚለማውን መሬትና ተጠቃሚውን ህብረተሰብ ነው፡፡ የተቀናጀ የመስኖ ልማት ስልት ለመቀየስ የሚያስችሉ አስፈላጊ መረጃዎች የተሰበሰቡና የተተነተኑ ሲሆኑ እነዚህም የአየር ንብረትን፣ የአደረጃጀትና የውሃ አስተዳደር፣ የግድብ በአፈር መደለልን፣ ጨዋማነትን፣ የግድብ ውሃ አጠቃቀምና ማህበራዊና ኢኮኖሚያዊ ጉዳዮችን ያካትታል፡፡ ትግራይ ውስጥ የተሰሩት ግድቦች በአባይ ተፋሰስ ላይ የሚኖራቸው ተፅእኖም ጠቅለል ባለ ሁኔታ ታይቷል፡፡

የክልሉ ዝናብ ላይ የተመረኮዘ ግብርና (መህር) አስተማማኝነት ለማጥናት የጉምሳላሳ የረጅም ጊዜ የአየር ንብረት መረጃ ጥቅም ላይ ውሏል፡፡ የ "Penman-Monteith" ዘዴን በመጠቀም በአካባቢው አብዛሃኛውን ግዜ በክረምት የሚዘራውን የስንዴን የውሃ ፍላጎት የጊዜ ሰሌዳ የተሰላ ሲሆን የውሃ አቅርቦቱ በተፈለገው ጊዜ ከዝናብ ሊገኝ ስለመቻሉ ደግሞ የ26 ዓመት ዕለታዊ ዝናብ በመጠቀም በ "dry-spell" ምርመራ ተወስኗል፡፡

የእርሻ ዘዴ፣ ማህበራዊ፣ ኢኮኖሚያዊ፣ ድርጅታዊና የውሃ አጠቃቀም በተመለከተ አስፈላጊ የሆኑ መረጃዎች ከገበሬዎች፣ ከልማት ወኪሎችና ከወረዳ የግብርናና የተፈትሮ ሃብት ቢሮ መጠይቅ በመጠቀም ተሰብስቧል፡፡

የተፋሰሱን የአፈር መቦርቦር ጠቅላላ ግምገማ ለማቅረብ "runoff plot" እና "HR Wallingford" ዘዴዎች ጥቅም ላይ የዋሉ ሲሆን የእነዚህም ውጤት ሌሎች ከዚህ በፊት ትግራይ ውስጥ ከተሰራባቸው ሁለት ዘዴዎች ማለትም "the

Verstraeten, *et al.,*" እና "the Pacific Southwest Inter Agency Commission (PSIAC)" ውጤት ጋር ተነፃፅሯል፡፡

በግድቡ ማከማቻ ውስጥ የተጠራቀመውን ውሃ አጠቃቀም ሁኔታ ለማወቅ ደግሞ የዝናብ መጠን፣ የማከማቻው የውሃ ከፍታ፣ የትነት መጠን፣ በመስኖ የሚለቀቀው የውሃ መጠን፣ ከግድቡ በስርገት የሚወጣው የውሃ መጠንና የእንስሳት ፍጆታን በተወሰነ የጊዜ ገደብ ውስጥ በተለያዩ ዘዴዎች ተለክቷል፡፡ በተጨማሪም በሚለሙት መሬቶች ያለው የውሃ አጠቃቀም ሁኔታና በምርትና ጨዋማነት ላይ የሚኖረው ተፅዕኖም ተገምግሟል፡፡

የጨዋማነት ጥናቱ የመስኖ ልማቱን ወደ በዝናብ የሚለማ፣ ተፋሰስ፣ በቀጥታ ከግድቡ በመስኖ በሚለቀቀው ውሃ የሚለማና ከግድቡ ሰርጎ በሚወጣው ውሃ የሚለማ በመከፋፈል የተካሄደ ሲሆን አስፈላጊ የምድርና የከርሰ ምድር የውሃና የአፈር ናሙናዎች ተመርምረዋል፡፡

በመጨረሻም የጥናቱ ዋናዋና ውጤቶች በመስኖ ልማቶቹ ዘለቄታማነት ላይ የሚኖራቸው ተፅዕኖ በሁለት ደረጃዎች ማለትም በግድቦቹ አካባቢና ከግድቦቹ በታች የአባይ ተፋሰስን ጨምሮ ተገምግሟል፡፡ አሁን ካለው አካሄድ በተሻለ ውሱን የሆነውን የውሃ አቅርቦት አጥቃቀም ለማሻሻል፣ ምርትን ለማሳደግና የጨዋማነት ችግሮችን ለመቀነስ የሚረዱ አማራጭ ስልቶችም ቀርበዋል፡፡ ከጥናቱ የተገኙት ውጤቶች እንደሚከተለው ተጠቃልለዋል፡፡

በጉምሳላሳ በመህር ወቅት ስንዴ ውሃ የሚፈልገው በአማካይ በየ 13 እስከ 28 ቀናቶች ጊዜ ሲሆን ዝናብ ከተጠቀሱት ቀናት በላይ ሳይጥል የመቆየት እድሉ ግን ከፍተኛ መሆኑ የ "dry-spell" ምርመራው አረጋግጧል፡፡ ይህ የሚያሳየው በመስኖ ካልታገዘ በስተቀር ዝናብ መገብ ግብርና ብቻውን ማካሄድ እንደማይቻል ነው፡፡

የአነስተኛ ግድቦቹ መስኖ ልማቶች ዋነኛ አላማ የትግራይን ድሃ ገበሬ ህይወት ማሻሻል ነው፡፡ በተጠኑት ቦታዎች ያለው ሁኔታም የሚመሰክረው ይህንኑ ነው፡፡ ከዝናብ መገብ ግብርና ጋር ሲነፃፀር የመስኖ ልማቱ ከ170 — 285% የምርት እድገት አስመዝግቧል፡፡ የሚለሙት አትክልቶችና ፍራፍሬዎችም የገበያ ዋጋቸው በዝናብ ከሚመረቱት ጥራጥሬዎች በላይ ነው፡፡ በእነዚህ ምክንያቶች የመስኖ ተጠቃሚ ገበሬዎች አጠቃላይ የገቢ መሻሻል አሳይተዋል፡፡ በአማካይ ከመስኖው የሚጠቀሙ አባዋራዎች ብዛት በጉምሳላሳ 425 ሲሆኑ በቆሪር ደግሞ 330 ናችው፡፡

የተጠራቀመውን ውሃ አጠቃቀምን በተመለከት ተገቢ እቅድ ማውጣትና መተግበር ለአነስተኛ ግድቦቹ መስኖ ልማቶች መሳካት በጣም አስፈላጊ ነው፡፡ በዚህም መሰረት አሁን ያለው አሰራር (ከጥር - ሰኔ) እና አማራጭ እቅድ (ከመስከረም - ጥር) ተገምግመዋል፡፡ በመስኖ ሚለሙት ማሳዎች በመህር ወቅትም ለእርሻ አገልግሎት ስለሚውሉ (ከሰኔ - ታህሳስ)፣ የመስኖ ወቅቱ በአብዘሃኛው ጊዜ በጥር ጀምሮ እስከ ሰኔ ይዘልቃል፡፡ በአጋጣሚ ይህ ወቅት ከዓመቱ ውስጥ ከፍተኛ የትነት መጠን ያለው ነው፡፡ በመሆኑም ጥር ላይ መስኖው ሲጀመር ግድቡ ውስጥ ከነበረው ውሃ ቢያንስ 40% ያክሉ ከማከማቻው ተኖ ይጠፋል፡፡ ከመስከረም እስከ ታህሳስ ያለምንም የመስኖ ልማት የግድቡ ውሃ ለትነት ብቻ የተጋለጠ እንደመሆኑ አጠቃላይ ብክነቱ ከተገለፀው ከፍ ይላል፡፡

የመስኖ ማሳ ይዞታ ትንሽነት (0.2 - 0.3 ሄክታር በአባዋራ)፣ የመህር ምርት አስተማማኝ ያለመሆንና እንዲሁም እያንዳንዱ አባዋራ በዝናብ የሚለማ ማሳ በአማካይ 1.2 ሄክታር ያለው መሆኑን ግምት ውስጥ በማስገባት በመስኖ ማሳዎች ላይ የሚካሄደውን የመህር ግብርና በማቋረጥ የመስኖ ስራውን ቀደም አድርጎ በመስከረም መጀመር ጥሩ አማራጭ ሁኖ ተገኝቷል፡፡ ይህ አማራጭ የትነት ብክነትን የሚቀንስ ሲሆን ዓዝርእቶችም በዚህ ወቅት የሚፈልጉት የውሃ መጠን አነስተኛ ነው፡፡ በዚህም መሰረት የመስኖው የመጀመርያ ወቅት ከጥር

ወደ መስከረም ቢዛወር ውሃ መቆጠብ የሚቻል ሲሆን የ1996 ዓ.ም መረጃ እንደሚያመለክተው በሚቆጠበው ውሃ አሁን ካለው ጋር ሲነፃፀር ተጨማሪ 38 ሄክታር በጉምሳላሳና 26 ሄክታር በቆሪር ማልማት ይቻላል፡፡ ይህም በጥናት ቦታዎቹ ባለው የመስኖ ማሳ ይዞታ መሰረት በጉምሳላሳ 190ና በቆሪር 80 ተጨማሪ አባዋራዎች ተጥቃሚ ይሆናሉ ማለት ነው፡፡ በተጨማሪም አያንዳንዱ ቤተሰብ ከመስኖ የሚያገኘው አመታዊ ምርት ከዝናብ ከሚያገኘው 10 እጥፍ ድረስ ይሆናል፡፡

አሁን ያለው የውሃ አጠቃቀም ዘይቤ የመስኖውን ዘለቄታማነት አደናቃፊ መስሎ ይታያል፡፡ በአሁኑ ሰዓት ያለው የውሃ ስርጭት የአፈርና የእፅዋት ሁኔታ በማየት እንጂ መቸና ምን ያህል ውሃ እንደሚፈልግ ባገናዘበ መልኩ አይደለም፡፡ ምንም እንኳ በመጀመርያ ለአንድ ማሳ የማጠጫ ግዜ 2 ሰዓት የተመደበ ቢሆንም ባለው አሰራር ግን ግዜውን የሚወስነው ተጠቃሚው ገበሬ ነው፡፡ በዚህም መሰረት ውሃ በተለይ በጎርፍ መልክ ሲባክን ይስተዋላል፡፡ በጉምሳላሳ ማሳዎች ላይ በተደረገው ጥናት መሰረት ዋናዎቹ ችግሮች የመሌ ማጠርና ወደ አዝርእቱ ስር የሚዘልቀው የውሃ መጠን ማነስ ናቸው፡፡ ይህ የውሃ እጥረት ያለው ተፅዕኖ ሲገመገም አሁን ያለው የበቆሎ ምርት መገኘት ከነበረበት በ60% ያነሰ ሲሆን የሽንኩርት ደግሞ በ70% ያነሰ ነው፡፡ ይህን ግምት ውስጥ በማስገባት ጥናቱ ምርታማነትን ማሳደግ እንዲቻል ለአዝርእቶች የሚያስፈልገው የውሃ መጠንና ጥቅም ላይ መዋል ያለባቸው የመሌ ርዝማኔዎችንና አቅርቧል፡፡

የጨዋማነት ጥናቱ እንደሚያመለክተው በሁለቱም የመስኖ ልማቶች በቀጥታ ከግድቡ በመስኖ የሚለቀቀው ውሃ 0.3 dS/m የጨው መጠን ያለው ሲሆን ይህም ለአዝርእቶች ተስማሚ ተብሎ ይመደባል፡፡ በሌላ በኩል ግን ከግድቡ ሰርጎ የሚወጣው ውሃ የጨው መጠን 0.8 dS/m በጉምሳላሳና 1.2 dS/m በቆሪር ነው፡፡ በዚህ ውሃ የሚለማ መሬት በተቻለ መጠን የሚጠራቀመውን ጨው ከልክ ሳያልፍ ማጠብ (Leaching) ያስፈልጋል፡፡ የሚለሙት መሬቶች ሁኔታ እንደሚያሳየው መስኖ ሙሉ ለሙሉ ከተጀመረ ከ1991 ዓ.ም ወዲህ የአፈሩ ጨዋማነት በአማካይ ሁለት እጥፍ ጨምሯል፡፡ ይሁን እንጂ አሁን ያለው አማካይ የአፈር ጨዋማነት (0.75 dS/m) ምርታማነትን የሚጎዳ ደረጃ ላይ አልደረሰም፡፡ ነገር ግን ጨውን የማጠብ ስራ በግዜው ካልተካሄደ የምርቱን መጠን መጉዳት የሚችልበት ብሎም ማምረት የማይቻልበት ደረጃ ላይ ሊደርስ ይችላል፡፡ ለምሳሌ ያህል በዚህ ጥናት የተቀመረው የውሃ አስተዳደር ያለ ምንም Leaching ተግባራዊ ቢሆን ከሁለተኛው ዓመት ጀምሮ ምርት ሊቀንስ እንደሚችል የተደረገው ግምገማ ያሳያል፡፡ ይህን መቆጣጠር ይቻል ዘንድ በየዓመቱ የሚጠራቀመውን ጨው ለማጠብ የሚያስፈልገውን የውሃ መጠን ጥናቱ አቅርቧል፡፡

በትግራይ ያለው ህብረተሰቡን በመስኖ ልማትና አስተዳደር የማሳተፍ እንቅስቃሴ አመርቂ ነው፡፡ ህብረተሰቡ በአጠቃላይ ተፋሰስ በመንከባከብ፣ ግድብ በመስራት፣ በማስተዳደርና በመጠገን ንቁ ተሳትፎ ያደርጋል፡፡ የሴቶች ተሳትፎም ቢሆን እየጎለበተ ሲሆን ለምሳሌ ያህል ከ1994 ዓ.ም የመስኖ ተጠቃሚዎች ውስጥ 41% በቆሪርና 21% በጉምሳላሳ ሴቶች ነበሩ፡፡

በሌላ መልኩ ግን ለመስኖ ልማቶቹ ስኬት የሚረዱና እስከ አሁን ድረስ ተግባራዊ ያልሆኑ የፖሊሲ፣ ድርጅታዊ መዋቅርና ማህበራዊና ኢኮኖሚያዊ ጉዳዮች አሉ፡፡ የመጀመሪያው ክልላዊ የሆነ የመስኖ ፖሊሲና የአስተዳደር ድርጅታዊ መዋቅር ያለመኖር ነው፡፡ በዚህም ምክንያት አብዛሃኛዎቹ የመስኖ ልማቶች አስተዳደር የሚካሄደው ገበሬዎችና የወረዳው ግብርና ቢሮ በመተባበር በሚያወጧቸው መመርያዎች ናቸው፡፡ ዋነኛው ችግር ግን በጥናት ቦታዎቹ የወጡት የስሪት ህጎች ተግባር ላይ ያለመዋል ነው፡፡ ይህን ማሻሻል ይቻል ዘንድ የክልሉን ነባራዊ ሁኔታ ያገናዘበ የመስኖ ፖሊሲና የአስተዳደር

ድርጅታዊ መዋቅር ተግባራዊ ማድረግ ቅድሚያ ሊሰጠው የሚገባ ጉዳይ ነው፡፡ በፖሊሲ ቀረፃውና ተግባራዊነት ላይ ከዚህ በፊት በCoSAERT እና በክልሉ መንግስት ቀርበው የነበሩ ቁልፍ ማሳሰቢያዎች መካተት ይኖርባቸዋል፡፡ ለምሳሌ ያህል ውሃን ፍትሃዊ ብሆነ መልኩ ለማከፋፈል እንዲቻል ሚለማውን መሬት ለሁለት ወይም ሶስት መክፋፈልና እየንዳንዱ ተጠቃሚ ከሁሉም ክፍሎች ማሳ እንዲኖረው ማድረግ፣ ገበሬው ለጥገናና መልሶ መገንቢያ መዋጮ እንዲከፍል ማድረግና የገበያ ማህበራትን ማቋቋም የሚሉት ጥቂቶቹ ናችው፡፡

ኢትዮጵያ ከጠቅላላው 84 ቢሊዮን ሜትር ኩብ የአባይ አመታዊ የፍሰት መጠን 75 ቢሊዮን ሜትር ኩብ ያህሉን ታበረክታለች፡፡ የኢትዮጵያ መንግሰት በትግራይና በአማራ ክልሎች ሊገነባ ያሰባቸው 1,000 አነስተኛ የግድብ መስኖ ልማቶች በአባይ ተፋሰስ ላይ ሊያመጡ የሚችሉት ለውጥ ጠቅለል ባለ መልኩ ሲታይ በውሃ ጥራት፣ በከርሰ ምድር ውሃ ሙላት፣ በአፈር ቡርቦራና በፍሰት መጠን ላይ ተብሎ ሊከፈል ይችላል፡፡ ከግድቦቹ አልፎ ወደ ታች የሚሄደው ውሃ ጨዋማ ሲሆን ከመጠኑ ማነስ የተነሳ የሚኖረው ተፅዕኖ ከግድቦቹ ዝቅ ብለው ለሚገኙ ቦታዎች እንጂ አጠቃላይ የአባይ ተፋሰስ ላይ አይደለም፡፡ ስለዚህ ይህን ውሃ የሚጠቀሙ ከግድቦቹ ዝቅ ብለው የሚገኙ ገበሬዎች ጥንቃቄ ሊያደርጉ ይገባል፡፡

እንኳንና አሁን ያሉት ጥቂት ግድቦች የታለሙት 1,000 እንኳ ቢሰሩ በአባይ ተፋሰስ ላይ የሚኖራቸው ተፅዕኖ በጣም ትንሽ ነው፡፡ ጥናቱ እንደሚያሳየው አጠቃላይ ግድቦቹ ቢሰሩ የሚይዙት አማካይ ዓመታዊ የውሃ መጠን ኢትዮጵያ ከምታበረክተው ውስጥ 1.5% ያህሉን ብቻ ነው፡፡ በሌላ በኩል ደግሞ እነዚሁ ግድቦች በዓመት እየተቦረቦረ ሱዳን ውስጥ ያሉትን ግድቦች የሚሞላውን አፈር እስከ 9% ድረስ ሊቀንሱት ይችላሉ፡፡

ጠቅለል ባለ መልኩ ሲታይ ግን ሁሉም የአባይ ተፋሰስ አገሮች፣ በተለይ ደግሞ ኢትዮጵያ፣ ሱዳንና ግብፅ የአባይን ውሃ ፍትሃዊ በሆነ መልኩ ለመጠቀም በጋራ አብረው ሊሰሩ ይገባል፡፡

Curriculum vitae

The author of this dissertation was born in Alamata, Tigray, Ethiopia on August 24, 1971. He followed both his primary and secondary school in Alamata. In 1994 he graduated with BSC degree in Agricultural Engineering from Alemaya University of Agriculture, Ethiopia.

He worked as Graduate Assistant II at the Department of Soil and Water Conservation, Mekelle University during the 1994/95 academic year. In 1996 he obtained his MSc in Soil and Water Engineering from Silsoe College, Cranfield University, United Kingdom. His thesis was entitled "Procedures for the Development of Small-Scale Micro-Dam Irrigation Projects in Tigray, Ethiopia". From September 1996 till March 2001 he worked as lecturer and researcher at the Mekelle University. He also served as Center Coordinator of the Continuing Education Program and as Head of the Department of Soil and Water Conservation of the University.

In April 2001, he joined the Core Land and Water Development, Department of Water Engineering, UNESCO-IHE Institute for Water Education, Delft, the Netherlands for his PhD study. His PhD research was a sandwich type and deals with “Development and Management of Irrigated Lands in Tigray, Ethiopia”. During his research he carried out field data collection at two earthen dam irrigation schemes in Tigray, Ethiopia.

He has participated and presented papers related to his research at the Sixth Symposium on Water Resources Development, 8 – 9 July, 2002, Arba Minch, Ethiopia and in three conferences of the International Commission on Irrigation and Drainage (ICID) in Montpellier, France, 14 –19 September, 2003, Moscow, Russia, 5 – 11 September, 2004 and Beijing, China, 10 – 18 September 2005.