PERFORMANCE EVALUATION OF AN INDIGENOUS IRRIGATION SYSTEM AT TOWERO VILLAGE, WESTERN ULUGURU MOUNTAINS, TANZANIA

BY

MALONGO JOHN MUSSA KONGOLA

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN AGRICULTURAL ENGINEERING OF SOKOINE UNIVERSITY OF AGRICULTURE, TANZANIA.

2000

ABSTRACT

Indigenous irrigation methods in mountainous areas are a result of people's efforts to survive on limited land resource bases. The adoption of an irrigation method depends on whether it does not affect the soil. While surface methods are common in the Uluguru Mountains, *drag hose* sprinkling is receiving wide use at Towero. *Drag hose* sprinkler irrigation refers to the local use of sprinklers where water pressure is obtained by gravity flow.

Effects of indigenous irrigation systems' practices on soil erosion were evaluated using field data and aerial photographs. Field data were obtained from six slopes, ranging from 6 to 84%. Two versions of aerial photographs were used to produce land-use maps for 1964 and 1992, respectively. Traversing produced the land-use map of 1999.

Land-use analysis revealed that between 1964 and 1999, the area under indigenous irrigation increased by 0.81 ha/year. Between 1964 and 1999 the settlement area increased by 0.83 ha/year. Deforestation rate was 6.48 ha/year.

Mean crop yields for leeks ranged between 9.65 – 13.53 tonne/ha. Mean specific yields ranged between 0.65 - 1.09 kg/m^3. Mean water conveyance, application and storage efficiencies were 83.72%, 86.20% and 99.64%, respectively. All fields were

over-irrigated based on soil moisture data which were taken daily. Over-irrigation caused inequitable water distribution.

Daily sediment load transport in canals A, B and C were 22.2 kg, 187.6 kg and 54.7 kg, respectively. Total sediment loss was 264.6 kg per day. Net downslope splash loss at 84, 70, 65, 24 and 15% slope was 28.9, 19.1, 12.0, 6.0, and 1.0 kg/ha, respectively.

The effects of indigenous irrigation systems' practices at Towero were: soil loss in the form of splash erosion and sediment load transport, and acceleration of deforestation in pursuit for more agricultural land. Hence, efforts to promote soil conservation practices at Towero are essential.

DECLARATION

I, **MALOGO JOHN MUSSA KONGOLA** do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my original work and that it has not been submitted for a degree award in any other University.

Signature: .....

Date: 25/7/2000

COPYRIGHT

ACKNOWLEDGEMENTS

The author is deeply indebted to his supervisors: Dr. A.K.P.R. Tarimo and Dr. P. W. Mtakwa for guidance and valuable suggestions during the study.

Thanks are due to Prof. V. P. Rönick of the Department of Agricultural Engineering and Land Planning, Sokoine University of Agriculture, who made helpful comments and suggestions on the use of GIS techniques in the study.

A special gratitude is expressed to SACCAR/GTZ for financial support provided in the form of scholarship.

Finally, the author wishes to express special appreciation to his wife Zilpa and his son Mtemi for their encouragement and patience throughout the coursework and research period.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ABBREVIATIONS AND SYMBOLS

AIWS	Adequacy of irrigation water supply
ANOVA	Analysis of variance
CSWD	Coefficient of spatial water distribution
CRWS	Cumulative relative water supply
DMRT	Duncan's New Multiple Range Test
EIWS	Equity of irrigation water supply
GLM	General Linear Model
GMAD	Geometric mean aggregate diameter
GTZ	Deutsche Gesselschaft für Technische Zusammenarbeit (German Technical Co-operation)
IQR	Inter-quartile ratio
LOI	Loss on ignition
MAD	Maximum allowable deficiency
M.a.s.l	Metres above sea level
MSS	Multispectral scanner
RWS	Relative water supply
SACCAR	Southern Africa Centre for Co-operation in Agricultural research
SAS	Statistical analysis system (version 608)
SUA	Sokoine University of Agriculture
TM	Thematic Mapper
ULUS	Uluguru land usage scheme

UMISCP	Uluguru Mountain integrated soil conservation
UTM	Universal Transverse Mercator
USGS	United States geological survey
WSA	Water stable aggregate

Symbols

E_a	Application efficiency
E_c	Conveyance efficiency
E_{cu}	Consumptive-use efficiency
E_d	Water-distribution efficiency
E_i	Overall irrigation system efficiency
E_r	Root zone storage efficiency
E_u	Water-use efficiency
ET_C	crop evapotranspiration
ET_O	Reference crop evapotranspiration
ρ_b	Bulk density

1 INTRODUCTION

1.1 An overview of the origins and development of indigenous irrigation systems

Since ancient times land users in mountainous are as have, under widely varying ecological conditions, attempted to cultivate their crops using various indigenous methods, conserve the soil, and maintain fertility at acceptable levels (IFAD, 1992). In order to survive on a limited land resource base, intensive systems of agriculture which included irrigation and terracing often had to be developed on steep slopes (Yoder and Martin, 1985).

The methods of irrigation in mountainous areas were selected based on whether they conserve the soil. For instance, farmers in west Sichuan (China), Himachal Pradesh (India), Pakistan, and the middle hills of Nepal have more than one indigenous method of irrigation in one particular area (Fisher, 1989; Yanhua *et al.*, 1992). In the mountains of Pakistan's Himalayan-Karakoram-Hindu Kush, nearly all irrigation is conveyed through *kuhls* - small, often lengthy canals, usually carrying water directed through a crude intake from mountain stream sources (Vander Velde, 1992). Further south into Baluchistan, the mountains of Pakistan's western borderlands, the indigenous *karez* systems of irrigation are found (Gupta and Ura, 1992). Shafts are normally sunk in the alluvial fans; linked by galleries to form a tunnel that may tap a spring or, more commonly, collect subsoil water, which is then delivered to fields at a lower elevation. Along Tigris and Euphrates rivers, which flow from the Mountains of Turkey through Syria and Iraq, *spate* irrigation and irrigation from the

groundwater via wells and *ghanats* (underground canals dug to intercept the watertable) are common systems (Field, 1990). While surface irrigation ditches – locally known as *mifereji* are common in the rest of the Uluguru mountains, in Towero village *drag hose* sprinklers have started to receive wide use. *Drag hose* sprinkler irrigation refers to the local use of sprinklers where water pressure is obtained by gravity flow.

1.2 Problem statement

Highland areas are characterised by adequate rainfall and relatively fertile soils (Svendsen and Hansen, 1993). However, during the dry season water becomes scarce and a variety of crops are irrigated using indigenous methods (Gupta and Ura, 1992). Overtime, irrigation activities have increased. Consequently, there has always been a conflict between agriculture, land-use and soil conservation (Mulk, 1992; Sharma, 1992; Gupta and Ura, 1992; Shrestha and Katwal, 1992).

Towero village, located on the western side of the Uluguru Mountain range, is also faced with similar problems. Soil erosion (soil loss due to splash erosion + sediment load transport) has also been observed. In the course of establishing new fields for irrigated agriculture, such practices as deforestation and setting of fires have been observed to accompany development of indigenous irrigation systems (Kilasara and Rutatora, 1993).

The prevailing view is that irrigation intensifies the process of water erosion (Lundekvam and Skøien, 1998). Excessive irrigation mainly causes soil erosion through splash, runoff and sediment load transport (Nijman, 1992). In the irrigation canals, sediment load becomes a problem when such canals are located on erodible soils and steep slopes. The effects of irrigation systems' practices on soil erosion have in general been little studied (Kilasara and Rutatora, 1993; Lyamuya *et al.*, 1994)

The urgent need to assess irrigation-induced soil erosion in the Uluguru Mountains is dictated by the rapid development of indigenous irrigation in the area. In the past, irrigated areas had been chosen on comparatively flat, erosion-safe land; the situation today is quite different (Senkondo, 1992).

As a result, in recent years the danger of erosion has become the basic criterion for selecting irrigation methods in the Uluguru Mountains. For example, nowadays farmers of Towero prefer *drag hose* sprinkler irrigation systems to ditch irrigation because the latter causes more soil erosion.

Despite several efforts to study soil erosion in the Uluguru Mountains, there is still a paucity of information on the effects of indigenous irrigation systems' practices on soil erosion at Towero village. Therefore, there was need to study the effects of indigenous irrigation systems.

1.3 Importance of the study

Towero village is an important catchment area for water supplies for domestic use in some parts of the Morogoro township (Lyamuya *et al.*, 1994; Bhatia and Ringia, 1996). Due to this fact, conservation of the Towero catchment is of vital importance. The catchment further secures a stable and good water supply and maintains a humid climate suitable for agriculture. It also has a high value for prevention of erosion and siltation of rivers and streams in other agricultural areas further down the slopes.

Three rivers, which are of importance to people living in Morogoro township, originate from the Towero catchment. These rivers are Kikundi, Mwere and Mlali. They are among the main water sources for the urban and industrial users in the township. Unfortunately, dense woodlands on the slopes have largely been cleared due to the expansion of agricultural land, while cultivated land is seriously being eroded. Clearing of woodlands on the slopes has consequently been associated with frequent water shortages, which have recently been threatening Morogoro township dwellers.

Therefore, when the results of this research are disseminated to the stakeholders they will support farmers, local policy makers, non-governmental organisations (NGOs) and sub-regional planners in their search for strategies to protect the environment.

1.4 Hypothesis

This study and the methodology adopted were based on the hypothesis that: Indigenous irrigation systems' practices cause soil erosion.

1.5 Objectives

The main objective of this study was to evaluate the effects of indigenous irrigation systems practices on soil erosion in Towero village, on the Uluguru Mountains. The specific objectives were:

a) to determine the extent of the area covered under indigenous irrigation systems.

b) to assess the efficiency of indigenous irrigation systems.

c) to determine the rate of soil erosion due to indigenous irrigation.

2 LITERATURE REVIEW

Effects of indigenous irrigation systems' practices on soil erosion are a threat to agricultural sustainability in mountainous areas. They affect both the characteristics of the *in situ* soil and its productive potential (Tengberg *et al.*, 1997). Indicators of the effects of indigenous irrigation systems include runoff, splash erosion, sedimentation rate, and deterioration of soil structure, deforestation and many others. Deforestation, soil erosion and sediment load are the main indicators of the effects of indigenous irrigation systems' practices in mountainous areas (Shrestha and Katwal, 1992).

The effects of deforestation, soil erosion and sedimentation in the Uluguru Mountains are well known (Kilasara and Rutatora, 1993). However, there is no documented data regarding the area affected, the rate at which they occur, the relationships between various forms of land use and losses of productivity (Senkondo, 1992). This chapter reviews the effects of indigenous irrigation systems' practices on these indicators.

2.1 Determination of soil parameters

2.1.1 Soil texture

Determination of the soil textural class is necessary in the irrigation studies because the texture of the soil is related to its water holding capacity (FAO, 1988). It also determines the quantity of water to be applied, the frequency of irrigation as well as

soil's vulnerability to soil erosion. There are several textural classifications. The most commonly used for agronomic purposes is the classification of the U. S. Department of Agriculture (Raes, 1996). There are basically three methods, which are used in the determination of particle-size analysis. These are: the feeling, hydrometer and the pipette methods (Gee and Bauder, 1986).

Among textural properties important for soil resistance to water erosion are clay humus content, and stability of soil aggregates. A high proportion of water-stable aggregates in the 2 – 6 mm fraction is a soil property that facilitates infiltration and affords resistance to erosion (Bryan, 1977). Measuring the water stability aggregates in samples from the surface soil gives a meaningful parameter for describing soil erodibility. The stability is related to clay, humus and biological activity (Tisdall and Oades, 1982). Aggregate stability provides indirect information about soil erodibility, organic matter, permeability and tendency to crust formation. Therefore, aggregate stability is a valuable soil parameter for describing erosion risks. The effect of such properties can be very pronounced. For example, soil losses were 75% less at Øsaker than Bjørnebekk in Norway for the years 1990 – 1995, (Lundekvam and Skøien, 1998). The particle concentration in the surface runoff at Øsaker was 40-60% less than at Bjørnebekk from 1990-1995, which show that the Øsaker soil was less erodible. The greatest erosion differences were found in aggregate stability, organic matter content and infiltration rates.

2.1.1.1 Aggregate stability

Aggregate stability is the resistance of soil aggregates to failure when subjected to disruptive forces. Bryan (1974) and Luk (1979), found indices of water-stable aggregation (WSA) determined from wet sieving to be highly correlated with soil loss from laboratory erosion plot experiments. These correlations suggest that, as aggregate stability increases soil erodibility decreases. Briefly, the two-phase method involved shaking 10g of 2.00-4.00 mm air-dried aggregates with 100 ml of water with a wrist-action shaker. Shaking was followed by gently washing the samples through a nest of sieves to isolate the WSA fractions in the aggregate diameter ranges 2.00-4.00, 1.00-2.00, 0.25-1.00, 0.063-0.25, and < 0.063 mm. From these data three indices of water stable aggregation were computed, the geometric mean aggregate diameter, percent of water-stable aggregates greater than 0.25 mm (WSA fraction $\geq$ 0.25 mm), and WSA fraction < 0.063 mm.

Ziegler and Giambelluca (1998) used aggregate stability as an index for relative strength of the surface soil. They took 5-9 measurements at many locations using a pocket penetrometer. Then they separated soil sampled from the upper 3 cm using a Tyler (Mentor, OH) Ro-tap sieve shaker to estimate the geometric mean aggregate diameter (GMAD) of the material at each site. The samples were shaken through a nest of sieves to isolate fractions into the following aggregate size ranges: 2.00-4.00, 1.00-2.00, 0.25-1.00, 0.063-0.25, and < 0.063 mm. After shaking, they removed visible rock fragments from the two largest sieves prior to massing. They calculated GMAD using the method defined by Kemper and Rosenau (1986). In addition, they

calculated two soil erodibility indices from the sieved samples, the aggregate fraction $\geq$ 1.0 mm and the aggregate fraction < 0.063 mm. Then they determined loss on ignition (LOI) as a proxy for organic matter content. Briefly, for this technique, they oven-dried 30 g of finely ground aggregates at 105 ^{0}C for 24 hours, then it dried in a muffle furnace at 400 ^{0}C overnight. The LOI values were determined as a ratio of the mass lost through 'muffle-drying' to the oven dry mass.

2.1.2 Soil moisture

The gravimetric method is accomplished by collection of soil samples from various depths and locations in a field is the simplest, most widely used and probably the best method for measuring soil moisture (Jensen, 1983; Gardner, 1986; FAO, 1988). In this method, the soil sample has to be placed in an airtight container (such as aluminium, metal can or glass jar) and sealed immediately to prevent the loss of moisture en route to the laboratory. The moist samples are then weighed, dried to constant weight in an oven at 105-110 °C and reweighed (Gardner, 1986). The difference in weight is due to the loss in water and is divided by the oven dry weight of the soil to give the percent of moisture on a dry weight basis. When this method is used, samples are usually taken at several locations in the field and composited, to indicate the average soil moisture content (FAO, 1988). The samples can be obtained by use of a soil tube, which gives soil cores of approximately equal volume, or by one of the many types of augers, which permit sampling at different depths. A shovel or a spade can also be used if proper precautions are taken to ensure a representative sample (Gardner, 1986). This method is laborious and time-consuming unless only

the surface soil is sampled. If the samples are composited, each of the sub-samples making up the composite should be approximately the same size (FAO, 1988).

There are various devices used to measure soil moisture without the drudgery of soil sampling. Some of these devices are the tensiometer, porous electrical resistance blocks and the neutron probe (Jensen, 1983; James, 1988). Tensiometers and gypsum blocks are often used together. Tensiometers characterise wet soil and the gypsum blocks characterise tensions less than about -1 atmosphere (Jensen, 1983; James, 1988). The neutron probe determines water content on a volume basis when a fast radioactive neutron source is lowered down a previously installed access tube (Romwell, 1994). These instruments are commonly used by trained technicians and irrigation scientists as irrigation scheduling tools. Before use, tensiometers, gypsum blocks and neutron probes have to be calibrated by soil moisture sampling. Calibration can be done based on soils with known moisture contents.

2.1.2.1 Field capacity

Field capacity can be determined by securing a moist soil sample 2 to 3 days after the soil has been wetted by a rain or an irrigation (Klute, 1986). Then, the percent moisture can be obtained by drying the sample in an oven and determining the moisture loss. In securing the soil samples, certain precautions are necessary: (a) the soil must have been saturated within 1 to 2 days' duration, (b) the internal drainage must essentially be completed by leaving an allowance of 1 to 2 days depending on the soil type, (c) the water table should not be high such as to hinder real field

capacity to reach, (d) if plants are growing on the soil, the samples should be taken before the roots have absorbed water in sufficient amounts to reduce the moisture level below the field capacity and, (e) if the sample includes the surface soil, no moisture should be lost by evaporation (Jensen, 1983).

One of the laboratory procedures for measuring the water holding properties of a soil is the moisture equivalent (FAO, 1988). With the moisture equivalent method, the moisture held in the soil against gravity may be described in terms of moisture tension (FAO, 1988). Tension values may be expressed in equivalent atmospheres or height of water column in centimetres. In converting soil moisture tensions to equivalent atmospheres one atmosphere is approximately equal to suction or a negative pressure of 1000-cm height of water column. At field capacity a loam or clay soil retains moisture under a tension of about 1/3 atmosphere, or a water column height of 300 cm, whereas sands may be as low as 0.1 atmosphere or a water column height of 100 cm. This procedure is often used to estimate the amount of water a soil holds at field capacity. Moisture equivalent provides a quick and convenient method for estimating the field capacity on a large number of soils where it would not be practical to make direct measurements.

The pressure plate or sand kaolin box, is another laboratory procedure for estimating field capacity and the most favoured procedure at the present time (Gardner, 1986). The pressure or suction, applied to a saturated soil, is one tenth or 0.1 atmospheres for sand, to one third or 0.3 atmospheres for clay, and the moisture remaining in the

soil after equilibrium has been obtained is approximately the field capacity (FAO, 1988). Sometimes soil moisture tension is expressed in pF-value; pF-value is the logarithm to base 10 of the height of water column measured in centimetres (Klute, 1986). Field capacity is in the range of pF 2 to 2.4 (FAO, 1988; James, 1988).

2.1.2.2 Permanent wilting point

Permanent wilting point of the soil can be ascertained under field conditions, but usually the determination is made in the laboratory. According to FAO (1988), permanent wilting point is determined under field conditions by growing plants on soil that has been wetted to field capacity. When the plants have nearly reached their maximum vegetative growth, water is withheld and the plants are allowed to wilt. At this time the soil is sampled and dried in an oven at 105-110 ^{0}C and the moisture determined. Certain precautions must be observed: (a) the soil sample must be within the depth of rooting, (b) plants having poor root system must be avoided and, (c) the upper 15-cm thick soil surface will be below the permanent wilting point because of water lost by evaporation.

With the pressure-membrane apparatus for the determination of the permanent wilting point, the principle is the same as for the pressure plate apparatus for the determination of the field capacity (Romwell, 1994). In determining permanent wilting point much higher pressures are required (14 to 15 atmospheres - equal to a suction or negative pressure of a water column 1.5 x 106 cm high (pF = 4.2)), (Klute, 1986). The pressure for the 15-atmosphere percentage must be maintained for one to

two days, or until hydraulic equilibrium has been approached. For soils high in clay content, a longer pressure time may be required (Romwell, 1994).

2.2 Extent of the area covered under indigenous irrigation systems and methods used for mapping them

2.2.1 Area covered

The 1990s have heralded a period of renewed activity and change for indigenous irrigation systems in Mountainous areas (Shrestha and Katwal, 1992). Primarily, these changes have come in response to the effects of such indigenous systems on land (Shrestha and Katwal, 1992; Verma and Partap, 1992). Although there is evidence of continued vitality of proven ways to solve problems, and of carefully adjusting new systems to fit environmental conditions, it is also clear that there has been both institutional innovation and considerable farmer-initiated experimentation to modify the previous irrigation management practices or techniques (Vander Velde, 1992).

In Tanzania, indigenous irrigation systems in mountainous areas are found in areas such as Meru, Mpwapwa, Lushoto and the Uluguru mountains. In the rest of the Uluguru Mountains field ditches or furrows (*mifereji*) are commonly used, whereby at Towero, *drag hose* sprinkler irrigation systems have started to receive a wide use. Farmers use *drag hose* sprinklers to irrigate their fields by taking advantage of gravitational forces. All sprinklers are normal, but highly localised in use - *drag hose* sprinklers. The *drag hose* sprinkler irrigation system generally requires a smaller

investment because, the farmer buys a sprinkler and a hosepipe only. Water is conveyed to the field through a hosepipe, which is attached to a sprinkler. The entire system can be moved from field to field.

2.2.2 Methods used for mapping and determining extent

In analysing land-cover changes in the Riam Kanan watershed in Indonesia, Indrabudi *et al.* (1998) used panchromatic aerial photographs and digital data of Landsat Multispectral Scanner (MSS) and Landsat Thematic Mapper (TM). They analysed the remotely sensed data using ILWIS software. They made contour composites for Landsat MSS and TM data. Visual interpretation followed by screen digitizing was applied to obtain digital data. The area of each land-cover type was calculated for each data set and individual results integrated to calculate the rates of change.

Omar *et al.* (1998), used aerial photographs to study land degradation of irrigated areas in Kuwait. They used recent aerial photographs at 1:29 000 to prepare a mosaic for the Wafra area of Ethiopia at a scale of about 1:17 000. The photos were of a minimum of about 60% forward and 30% side overlaps. This means that it was possible to use only the central portions of the photos, thereby reducing distortions due to relief and tilt. Printing was done on single-weight papers with 1.7065 time magnification to achieve 1:17 000 scale. The grid co-ordinates used on the map were based on the Universal Transverse Mercator (UTM) grid zone 38, international spheroid with a grid interval of 200 m. They used the hierarchical system, devised by

the US Geological Survey (USGS) (Anderson *et al.*, 1976), in the classification systems for description of land-use and land-cover. The USGS system attempts to meet the need for current overview of land use and land cover on a basis that it is uniform in categorisation at the generalised first and second levels. The categories of land-use and land-cover developed in the USGS classification system can be related to systems for classification of land suitability, vulnerability of certain management practices, potential for any particular activity, or land value, either intrinsic or speculative. The functions of current land-use are usually associated with certain types of cover, e.g. forest, agricultural or urban. Thus, the image interpreter attempts to identify land-cover patterns and shapes as a means of delivering information about land-use.

Duchhart and Povel (1991) used visual materials such as aerial photographs, aerial slides and field observations to examine the landscape of an irrigation scheme in Kano, south – west Kenya. Additional data support was provided through interviews of farmers and relevant literature. Aerial slides played an important role in accurately qualifying and quantifying the data. The accurate statistics of the actual land use, were obtained by categorising all relevant land-use features and calculating their relative areas by sampling. To that end, each slide was projected on a standardised sample grid of very small unit areas. These unit areas were then specified and tallied according to their land use. The land use map, including the settlement pattern, was obtained by projecting the slides on accurate topographical maps (scale 1:10 000).

Slides of one flight line were projected on a scale 1:2 000 (in order to visualise a representative cross-section of the project area in more detail).

Malongo (1997) used aerial photographs and topographical maps as the primary source of information for determination of land use and erosion features of the Usangu irrigation project, in Tanzania. Malongo (1997) delineated the independent unit area of upstream of the project on the topographical map based on natural drainage. Land use and erosion features were then stereoscopically mapped from the central portion of the photographs directly on a piece of transparent overlay. The measurement of areal extent of land use and erosion features of the catchment was then carried out by direct planimetering from the maps and aerial photo interpretation. The area of land use and gully measured in two maps were used to determine the rate of deforestation and gully expansion.

Eweg *et al.* (1998) used geographical information and remote sensing technology to analyse the extent of land degradation and to provide support for rehabilitation planning in the highlands of Ethiopia. Before starting the fieldwork, a topographical map 1:50 000 of the study area had to be generated. SPOT satellite imagery was used to produce the map. The image was then georeferenced with the help of points taken from the topographical map 1:250 000. The drainage network and the outlines of the towns were digitised on screen by interpreting the SPOT imagery. Contour lines, infrastructure and villages were digitized from the 1:250 000 map and transferred to the 1:50 000 scale. This map, combined with a geometrically corrected SPOT

imagery, formed a common base for the fieldwork of all disciplines. In their study, a field inventory and aerial photographs formed the basis for the geomorphologic interpretation. The legend of the geomorphologic map was organised in three groups: geomorphologic units, geomorphologic processes and geomorphologic details.

2.3 Performance indicators of indigenous irrigation systems

2.3.1 Adequacy of irrigation water supply (AIWS)

Adequacy of irrigation water supply is a good indicator of the system's water delivery ability to deliver the amount of water required to meet farmers' irrigation water requirements. One of the parameters that can be used to evaluate AIWS is Relative Water Supply (RWS). RWS is a ratio of water supply to irrigation water requirement that is associated with the crop grown with actual cultural practice (Nihal, 1992). This ratio is the most crucial factor in design, planning, management and operation of irrigation systems, whereby, RWS values are obtained from field measurements (Nihal, 1992; Sakthivadiel *et al*, 1993).

The RWS concept suggested by Nihal (1992) has proved to be a useful tool in monitoring and evaluating irrigation water supply at various field levels. Its world-wide acceptance as a multi-dimensional performance indicator lies in its ability in evaluating satisfactorily productivity, relative equity and adequacy of irrigation water supply and distribution (Nihal, 1992; Sakhivadiel *et al.*, 1993).

The RWS concept however, has proved to be a useful monitoring tool in indicating the behaviour and decision rules that are associated with the system operation of the irrigation management personnel and farmers at different periods within irrigation seasons. For example, according to Gates *et al.* (1991) for most crops RWS values equal to 1 indicate that the irrigation water supply meets irrigation requirement, while RWS greater than 1 implies that irrigated water is in excess of the crop water requirement. RWS values less than 1 or below 0.8 indicate deficiency or inadequate irrigation.

For paddy rice, during the paddy crop growth period RWS values approximating to 2 show the monitoring levels of secondary canals, day time and limited communication between system managers and farmers and relative farmer independence while values greater than or equal to 2.5 indicate system with minimal operational control at the main system distribution level (Sakthivadiel *et al.*, 1993).

Despite its numerous advantages, the RWS concept has some few weaknesses, which may be overcome by the use of Cumulative Relative Water Supply (CRWS) as explained by Sakthivadiel *et al.* (1992). CRWS is the cumulative RWS over a given time interval.

2.3.2 Equity of irrigation water supply (EIWS)

Equity, or spatial uniformity of water distribution, is one of the aims of the farmers organisation in any irrigation scheme (Abernethy, 1986). This is due to the fact that

the inequity problem may occur in any irrigation scheme if measures to avoid it are not taken in advance.

Equity of irrigation water supply can be defined as the delivery of a fair share of irrigation water to all irrigators throughout the system (Bhutta and Vander Velde, 1992). Its concept deals with supply of irrigation water among irrigators in a fairly equal and just manner.

Inequity of water distribution can occur within the field, between users of the same field channel or between the flow issued from the main system to distributaries or to field channels. Some studies carried in Asia and Africa have shown that variation in water supply may be due to the nature of supply, design faults, poor maintenance of canals and drains, construction faults and management faults (Vander Velde, 1992).

According to Abernethy (1986), the degree of inequity is mostly readily demonstrated through the Inter-Quartile Ratio (IQR). This measure compares the performance of the poorest performing quartile and the top quartile along a channel. However, it is preferred to take the average depth of water received by all land in the best quarter divided by the average depth received in the poorest quarter. This is termed as the modified inter-quartile ratio (I_2).

The modified inter-quartile ratio provides a satisfactory measure of equity and facilitates communication among irrigators involved in the inequity problem (Vander

Vclde, 1992). For example, if I=2 it implies that the farmer in the best quarter got 2 times as much water as those in the least favoured quarter. However, the use of this indicator is restricted to variables that have a zero as minimum (Abernethy, 1986).

According to FAO (1989), Uniformity of Christiansen's Coefficient (UCC) is another parameter used to quantify inequity. This parameter has the advantages that it is easy to compute its value range from zero to unity. When UCC is zeroing the degree of inequity is high and there is totally no uniform distribution of water and vice versa when it is unity.

Although IQR and UCC offer simple computations and reveal non-uniformity in water distribution and supply among irrigators, at the farm level the concept of RWS and CRWS give better representation of inequity situation (Abernethy, 1986).

The Coefficient of Spatial Water Distribution (CSWD) is another parameter used to quantify inequity. This parameter has the advantages that it is easy to compute. Its values range from 1 and above. CSWD is computed by dividing the smallest RWS value by other RWS values. Whenever CSWD values are different, the degree of inequity is high and there is totally no uniform distribution of water and vice versa when they are equal.

2.3.3 Crop yield measurements

Yield per cubic volume of water is one of the most useful indicators in assessing the technical efficiency of use of water (Nijman, 1992). This performance indicator reveals farmers' technical efficiency in utility of irrigation water supply. Besides its ability to reveal irrigators' technical efficiency in irrigation water utilisation; it has been reported that specific yield is nowadays widely used in place of yield per irrigated area. The term specific yield means the weight of crop produced per volume of water issued (kg/m^3). In this study, specific yield per unit irrigated area were adopted to indicate the farmers' technical efficiency in irrigation water utilisation.

2.3.4 Determination of irrigation efficiencies

When determining the performance of a farm irrigation system it is often useful to examine the efficiency of each system component. This allows components that are not performing well to be identified. As suggested by FAO (1989), the overall system efficiency is the product of the following efficiencies:

$$E_i = \{(E_r)(E_c)(E_a)(E_w)(E_d)(E_{cu})\}100 \quad (1)$$

Where,

E_i = overall irrigation efficiency in percent;

E_r = root zone storage efficiency in percent;

E_c = conveyance efficiency in percent;

E_a = application efficiency in percent;

E_u = water-use efficiency;

E_d = water-distribution efficiency;

E_{cu} = consumptive-use efficiency,

For practical purposes, when calculating the overall efficiency, some efficiency components can be assumed to be 100% and hence deal with a few of them (James, 1988; FAO, 1988, 1989)

2.3.4.1 Conveyance efficiency (E_c)

Water conveyance (E_c) is the ratio in percent, of the amount of water delivered by a canal or pipeline to the amount of water delivered to the conveyance system. James (1988) suggested the following relationship when computing conveyance efficiency, E_c:

$$E_c = (W_f / W_r)100 \quad (2)$$

Where,

E_c = Conveyance efficiency in percent;

W_f = volume of water delivered by conveyance system (i.e., outflow) (m^3);

W_r = volume of water diverted from the source (i.e., inflow) (m^3).

The rate of flow passing a point in a pipe or open channel is determined by multiplying the cross-sectional area of the flow section at right angles to the direction of flow by the average velocity of water:

$$Q = (A_n)\, V_e \qquad (3)$$

Where:

Q = discharge rate (m^3/s);

A_n = channel cross-sectional area (m^2);

V_e = velocity of flow (m/s).

The cross-sectional area is determined by direct measurements. The velocity is generally measured with a current meter. Approximate values of rate of flow may also be obtained by the float method (Michael, 1978). Details velocity measurements using current meters and float methods are well covered in Linsley *et al.* (1988) and Michael (1978).

In order to determine flow measurement in open canals, James (1988) used a stopwatch and a calibrated container to measure discharge. James (1988) recorded time taken to fill one container and calculated the volume by the following relationship:

$$V_o = Q\Delta t / k \qquad (4)$$

Where,

V_o = volume of flow (m^3),

Q = volumetric flow rate (l/s),

Δt = time interval (min.), and

k = is a unit constant. (k=16.67 for V in m^3 and Q in l/s).

2.3.4.2 Application efficiency (E_a)

FAO (1985) defined water application efficiency for an irrigated area (E_a) as the ratio, expressed in percent, of the volume of water beneficially used by the crop to the volume of water delivered to the area. Application efficiency can be computed for each field of the farm as follows (James, 1988):

$$E_a = (W_s / W_f)\ 100 \qquad (5)$$

Where,

E_a = application efficiency in percent;

W_s = volume of water beneficially used by crop(s) in an area (m^3);

W_f = volume of water applied in an area (m^3);

2.3.4.3 Root zone storage efficiency (E_r)

FAO (1988) defined the adequacy of irrigation as the percent of the field receiving sufficient water to maintain the quantity and quality of crop production at a 'profitable' level. When the desired depth of irrigation fills the soil to field capacity,

storage efficiency is often used as an index to adequacy (James, 1988). FAO (1989) and James (1988) suggested the following equation when computing E_r.

$$E_r = (W_s / W_n)100 \qquad (6)$$

Where,

W_s = amount of water stored in the root zone during irrigation (cm);

W_n = amount of water required to fill the root zone to field capacity (cm);

2.4 The rate of soil erosion due to indigenous irrigation

2.4.1 Sediment load in irrigation canals

Two types of suspended material are carried in irrigation canals at Towero: canal-derived material and material eroded from slopes (Bhatia and Ringia, 1996).

In Tanzania, Rapp (1977) measured suspended material in the Morogoro river using hand operated sediment samplers. Most of the sediment measurements were made with a point integrating, hand operated sampler of the Uppsala type. The device takes a one-litre sample and is easily constructed from readily available materials. During the first minutes of high flood, the samples had about 2 to 3.5 g/L of sediment. Evidently, this washed material was from the streambed which most likely were material washed from slopes of the Uluguru Mountains.

An automatic sampler of the Hayim 7 type, which takes one-litre samples, was installed in the Msalato catchment in Tanzania. This sampler was put on the bed of

the channel whose, which was sandy in nature. The Hayim is primarily designed for desert streams, where floods are violent and short-lived. When checked after two flash floods, the sample bottles contained sediment, ranging from 15 to 75 g/L.

Analysing the sediment samples in the laboratory, Djorovic (1977) and Lundekvam and Skøien (1998) filtered one-litre samples through 'whatman' filter paper No. 40. After drying the filter paper, the concentration of suspended sediment was determined as the difference of filter paper weight before and after filtration. According to Lundekvam and Skøien (1998), this method is rather inaccurate when the sediment concentration is low, but acceptable when the concentration is higher than 1 000 g/m^3.

Since bed silt is static, and suspended silt is dynamic Khushalani (1990) differentiated ways of sampling silt from those of sampling bed load by using bottle samplers to find the quantity of silt content in water. Using silt samplers, samples of water were collected from various depths along several sections in a cross-section. The water was then filtered and the residue dried and weighed.

The use of silt samplers can cause errors if the observer is not experienced. Judgement of the time required to fill the sampler at various depths determines the magnitude of the error. For instance, Khushalani (1990) found that if the silt contents of one litre bottle after 12 minutes was found to be 0.294 g, the quantity of silt increased to 0.518 gm if it was kept open for a total time of 60 minutes. Therefore,

even with the best efforts, the bottle sampler was likely to give erroneous results. Another objection against this sampler was that, it caused turbulence at the point of sampling, which vitiated the results. To counteract this deficiency, an improved type of sampler, that overcomes both these difficulties, was developed by Punjab Rescarch Station in India.

Khushalani (1990) proposed a different method of taking bed silt samples from that of taking suspended silt samples. The apparatus developed by the Punjab Irrigation Research Institute consists of an eccentrically mounted scoop made from an iron sheet which on being rotated digs into the bed and takes a bit of bed material which is protected from being washed by a cowl made of thick iron sheet. Before the sample is taken, the dig has its mouth directed downwards so that when the apparatus is lowered the scoop is ready for digging. A handle at the top attached to a pulley carrying an endless wire is then lifted to the surface and the scoop is turned back to empty its contents.

Djorovic (1977) collected total sediment load (suspended + bed load) using rectangular metal collectors. One portion of the sediments collected remained in suspension and, another portion was deposited (settled) in the bottom of the collector. If the quantity of material deposited was not great and fine-textured, the water in the collector was agitated with a paddle to disperse the material. Three samples of one-litre size were taken, filtered and the residue dried at 105 ^{0}C and weighed. The laboratory technique which he used to analyse the sediment samples was similar the

one described by Rapp (1977). The total amount of suspended sediment in the collector was determined by multiplying the average dry weight of the samples by the volume of water in the collector. In case there was a large quantity of deposited sediment or if it was coarse-textured, the collector was drained and the material weighed. If it was not possible to oven-dry the entire quantity, it was sampled. Three samplers were taken and weighed before and after oven drying at 105 ^{0}C to determine the water content, which was used to convert the total wet weight of the deposited sediment to dry the weight.

2.4.2 Splash erosion

Under sprinkler irrigation, splash erosion predominates. According to Lundekvam and Skøien (1998), soil splash is influenced by many factors including antecedent soil properties, landform, sprinkler characteristics, properties of overland flow and vegetation cover.

2.4.2.1 Soil moisture potential and the wetting process

The collision between dry soil particles and sprinkler drops is essentially a collision between two elastic bodies (Lal, 1990). The energy of the sprinkler drop is transmitted to the aggregate or soil clod, but the clod may still retain its shape (Park *et al.*, 1980, 1982). As the clod progressively gets wet, its soil moisture potential increases, its strength decreases, and its particles are detached and spattered about by drops later impacting on it (Truman *et al.*, 1990). Quick wetting of dry clods affects

their detachability in two ways: through the pressure of air entrapped and by releasing the heat of wetting (Badrashi *et al.*, 1981).

2.4.2.2 Entrapped air

The entrapped air on quick wetting can virtually explode, breaking the clod and spattering soil particles into the air (Bruce-Okine and Lal, 1975; Badrashi *et al.*, 1981). Energy in the form of soil pressure within the soil contributes substantially to detachment at the soil surface. Badrashi *et al.* (1981) showed that entrapped air increased soil detachment by 21%.

2.4.2.3 Heat of wetting

The wetting process also influences soil detachment by altering the energy status of the soil water system (Lal, 1990). In addition to facilitating a gradual escape of air, slow wetting changes the energy status of the soil water system (De Ploey, 1971). The heat of wetting, or the energy released when soil water potential changes from one energy state to another, plays a significant role in detachment of relatively dry soil (Farmer, 1973). The drier the soil the greater the surface area, the more heat of wetting is released, the greater the change in soil strength. Therefore, more soil is detached per unit energy expended by the sprinkler drop impact (Farmer, 1973). In addition to the quantity of heat released, the rate at which it is released and dissipated is important (Farmer, 1973). Fast release causes more soil detachment and splash (Liebenow *et al.*, 1990).

Many researchers have observed that some soils are more easily detached when dry than when moist (Young, 1984; Truman *et al.*, 1990). For example, Bruce-Okine and Lal (1975) observed that fewer drops were required to disrupt a dry clay clod than a wet one. Furthermore, the effect of soil moisture potential on detachment depends on the surface area and hence the particle-size distribution. In general, clayey soils are more easily detached when at low (more negative) than at high (less negative) moisture potential (Maene and Chong, 1979). The high detachability of clayey soils at low moisture potential is attributed partly to the heat of wetting and partly to entrapped air (Badrashi *et al.*, 1981). The amount of heat of wetting can be computed from the changes in entropy and enthalpy of the soil water system (El-Swaify and Dangler, 1977).

2.4.2.4 Shear strength

Soil shear strength is influenced by soil texture and particle-size distribution and differs among soils developed on different parent materials (Ghadiri and Payne, 1977, 1979, 1988). Working on some Japanese soils, Ezaki (1985) reported measurable differences in splash among soils developed on coarse-grained decomposed granite, fine-grained composed granite, and a red soil. Ezaki (1985) proposed sediment yield, soil density and maximum rainfall intensity for a 10-min period to be the parameters influencing splash.

2.4.2.5 Slope gradient

Grosh and Jarrett (1994) measured splash erosion in the laboratory from a 504-mm-square box filled with disturbed Hagerstown silty clay loam under a simulated 20-min, 92-mm/h rainfall at several slopes. They used two splash collectors, one attached to one side of the box, and the other attached to the upslope end of the box. Similar splash collectors were attached to the opposing sides of the box. After analysing the results they concluded that in general terms, soil detachment was independent of slope. Soil splash was, however, affected by slope steepness and the direction of the sprinkler spray vector in relation to the direction of slope.

Soil particles spattered in the air may move horizontally as much as 1.5 m from the original location (Morgan, 1978, 1982). During landing under the force of gravity, the amount of material splashed downslope is often more than that splashed upslope (Poesen, 1984, 1985). This means that soil can move downslope even if there is no runoff (Poesen, 1984). However, in windless spray falling on a flat soil, the net soil movement from an area should be zero (Quansah, 1981). All factors being the same, net splash from an area may increase with increasing slope steepness (van Asch, 1980).

The amount of soil carried downslope depends on many factors including slope steepness, drop size, wind velocity, and soil surface conditions, e.g. vegetation cover or mulch (Lal, 1990; Liebenow *et al.*, 1990). These factors and their interaction are

responsible for a controversy in the literature regarding the effects of slope steepness on the amount of splash carried downslope.

Some researchers have observed increased splash downslope with increasing slope gradient. For example, Lal (1990) established that the amount of splash downhill was approximately equal to fifty percent plus the land slope percentage. Foster and Martin (1979) observed that depending on the soil and its bulk density, downslope splash increased as the slope increased up to 33% but decreased on steeper slopes.

The rate of splash is also time-dependent even during an irrigation event of constant erosivity. De Ploey (1971) observed an increase in the proportion of material landing downslope from drop impact with an increase in slope angle. However, there was a negligible increase between slope angles of 58% and 84%. Bryan (1979) made similar observations and reported that the quantity of splash downslope peaked between 27% and 34% slope angle.

Many other researchers have observed either little or no effect of slope gradient on splash downslope. Farmer (1973) observed only a small effect of slope steepness on splash even with slope ranges of 2, 18, and 32 percent. There was approximately 0.1% increase in creep per unit increase in percentage of slope. Morgan (1978) observed no relationship between percentage of downslope splash and slope steepness because only a small portion of the irrigation energy contributed to splash erosion. He concluded that splash is so small that its major role is to detach soil

particles before overland flow removes them. Quansah (1981) also observed a negligible effect of slope steepness on splash.

2.4.2.6 Sprinkler characteristics

Soil splash due to irrigation is related to irrigation water amount and intensity, i.e. its application rate (FAO, 1988). For a given amount of irrigation water, high intensity spray produces more splash than irrigation at lower intensity (Jensen, 1983). High intensity is related to relatively big dropsize and number per unit area per unit time. Lal *et al.* (1980) reported a significant correlation coefficient between sand splash, intensity and irrigation amount.

2.4.2.7 Drop size distribution and kinetic energy

Soil splash depends on the kinetic energy of the impacting water drop, and hence on its size (Maene and Chong, 1979). The physical characteristics of impacting drops affect the quantity and nature of soil material detached. The drop size and terminal velocity influence the kinetic energy. The size of the soil particle displaced depends on the terminal velocity of the impacting drops. There is a threshold impact velocity below which soil particles are not displaced by drop impact (Lal, 1990).

It is widely accepted that the kinetic energy of impacting drops is the predominant factor responsible for soil splash. Young and Wiersma (1973) reported that decreasing the drop impact energy by 89% without decreasing the intensity, decreased soil losses by 90% or more, indicating that the impact energy of a water

drop is the major factor that initiates soil detachment. Ghadiri and Payne (1977, 1979) also concluded that the breakdown of crumbs was related to the drop diameter and to the square of its velocity, that is, the kinetic energy.

The most suitable expression of the erosivity of a sprinkler spray is an index based on the kinetic energy of the spray (Hudson, 1981). Thus the erosivity of a single sprinkler irrigation event is a function of its intensity and duration, and of the mass, diameter and velocity of the falling drops (Hudson, 1981). Wischmeier and Smith (1978) obtained the following relationship between kinetic energy and rainfall intensity:

$$KE = 11.9 + 8.7 \log_{10} I \qquad (7)$$

Where, I is the intensity (mm/h) and KE is the kinetic energy (J/m^2/mm).

2.4.2.8 Wind-driven sprinkler spray

Soil detachability by a wind driven spray differs from that by a windless spray (Lal *et al.*, 1980). By adding a horizontal component, wind alters the vertical component of the vector. A water drop falling vertically through wind gradually gains horizontal velocity until it reaches a state where its horizontal velocity component is equal to the wind velocity (Wischmeier, 1975; Wischmeier and Smith, 1978). The wind velocity also influences the size and shape of impacting raindrops, as well as their terminal velocity, by altering the resistance of air or by breaking large drops into

smaller droplets (Wischmeier, 1975; Wischmeier and Smith, 1978). Lal *et al.* (1980) showed that 73% more soil detachment occurred at a wind velocity of 13.4 m/s than with windless spray.

Boardman (1991) and Bolline (1978) reported that soil detachment from clods exposed to a wind-driven spray was greater than that caused by similar intensities without wind: Experimenting in clay loam soils, Lyles *et al.* (1974) observed that rainfall waterdrops detached 2.68 times more soil when accompanied by a 25-mil/h wind than by no wind.

2.4.2.9 Sprinkler intensity

The effect of cover on soil splash also depends on the sprinkler intensity and canopy height (McGregor and Mutchler, 1978; Liebenow *et al.*, 1990). For high sprinkler intensities, there may be little differences in drop size distribution between the intercepted and un-intercepted spray. The energy reduction by canopy is, however, proportional to the spray intercepted (Morgan, 1978, 1982). At low intensities, in contrast, the canopy intercepts small drops that coalesce on the leaves and fall to the ground as large drops with much more kinetic energy than the un-intercepted spray (Hudson, 1995).

The erosive force of sprinkler water drops is determined by the drop size, the drop velocity, and the intensity and duration of the irrigation (Hansen *et al.*, 1996). Even light irrigation water drops can cause surface runoff and erosion when water drops

fall on soils with a limited water storage capacity or infiltration capacity (Oad and King, 1991). A research conducted in Norway to determine size and intensity of sprinkler drops revealed typical intensity to be 1-4 mm/h and the mean drop size to be 0.5-2 mm (Lundekvam and Skøien, 1998). The following relationship has been used to determine the application rate and other parameters (James, 1988):

$$A = k(Q / a) \qquad (8)$$

Where,

A = application rate (mm/h)

Q = sprinkler discharge (L/min.),

a = wetted area of the sprinkler (m^2), and

k = unit constant. ($k = 60.0$ for A in mm/h, Q in L/min., and a in m^2).

2.4.2.10 Depth of overland flow

The ability of a water droplet to cause detachment and soil splash differs when overland flow is present or absent (Foster and Meyer, 1975; Lang and McCaffrey, 1984; Hansen *et al.*, 1996; Lundekvam and Skøien, 1998). Walker *et al.* (1978) observed that water drop impact in runoff flow is important in soil detachment. The impacting drops in overland flow increase turbulence, which increases both detachment and spattering of soil particles (Liebenow *et al.*, 1990). Drop impact transforms hydraulic patterns in sheet flow, generates local turbulence, and may even

retard flow velocity (Lal, 1990). There are different types of overland flow depending on the velocity, depth, and changes in flow patterns with time (Truman *et al.*, 1990).

The diameter that causes maximum detachment depends on the depth of overland flow (Park *et al.*, 1980,1982). Lal (1990) reported that soil splash generally increased with increased depth of overland flow up to a threshold approximately equal to the diameter of the impacting water drop. Park *et al.* (1982) used Palmer's (1973) concept and computed splash in reaction to the depth of overland flow. Splash increased slightly with increasing depth of overland flow to a critical water depth approximately equal to one-drop diameter; splash then decreased sharply as water depth increased.

High overland flow and other losses when irrigating encourage waterlogging and soil erosion, while high deep percolation would encourage leaching of nutrients and salinity (Kaufmann, 1995; Miller, 1995; Raes, 1996; Tengberg *et al.*, 1997). All these factors acting on the land for a long time may lead to physical degradation of the land to levels where it would no longer be able to support crops. This is a good indication of poor irrigation efficiency (Kaufmann, 1995; Miller, 1995). The knowledge as to how well an irrigation system is being used (actual application efficiency) is important when evaluating the effects of an irrigation system. This information can only be obtained by field performance measurements (FAO, 1985, 1988. 1989).

2.4.2.11 Vegetation cover

The effect of canopy cover on sprinkler-spray erosivity and splash erosion has long been recognised (Lal, 1990). Vegetation cover may dissipate drop impact and protect the soil against splash. Vegetation cover alters the volume, drop size distribution, impact velocity, and kinetic energy of drops reaching the ground (Ghadiri and Payne, 1977, 1979, 1988). A striking example of the protective effect of a cover in dissipating water-drop energy came from an experiment reported by Lal (1990). Results indicated that, the average soil erosion over an unprotected plot was 123 times higher than that from the plot with a protective cover.

2.4.2.12 Crop canopy

Effects of canopy cover on soil splash vary among crops depending on foliage characteristics, canopy height, and ground cover percentage (Wischmeier, 1975). High rates of soil splash from bare soil and reduced splash by crop cover are reported even from climates of mild erosivity. For example, in Belgium, Bolline (1978) observed splash rates of 9 to 40 kg/m^2 per year on bare soils, 2 to 18 kg/m^2 per year under sugar beet, and 1 to 4 kg/m^2 per year under winter wheat for Brussels Sands Series at Hesbaye. Results indicated that crop cover reduced splash erosion by a factor of 2 to 9. In Poland, splash rates of 2.0 to 8.3 kg/m^2 from a bare soil and 6.2 to 16.2 kg/m^2 from a compacted cart track were reported on a loamy soil over 137 days (Lal, 1990). In the United Kingdom, Morgan (1978) recorded splash rates of 29.0 to 36.5 kg/m^2 per year for bare sandy soil and 18.3 and 22.6 kg/m^2 per year for sandy loam soil under cereals.

The kinetic energy of drops leads to soil compaction and a decrease in its conductivity (Lal, 1990). The compaction effect of the compacting raindrop is, however, modified by the vegetation cover. The vegetation close to the ground surface offers more protection than that high above.

2.4.2.13 Canopy height

When coalesced, drops fall from large trees they often reach terminal velocity and have high kinetic energy (McGregor and Mutchler, 1978; Schottman, 1978). Schottman (1978) observed that the kinetic energy of throughfall under a pine forest was greater than that in an open field. In Malaysia, Maene and Chong (1979) observed that rain falling under oil palm consisted predominantly of large drops 3.0 to 3.5 mm diameters. The large drops fall regardless of rainfall intensity and are obviously formed by small drops' coalescing. At low intensities and high canopy, therefore, the rainfall energy reduced by interception is partly offset by the increased energy from larger drops. McGregor and Mutchler (1978) also have observed relatively large drops under cotton canopy, although fewer drops reached the soil surface.

Various models have been proposed to account for canopy cover effects on throughfall erosivity and soil splash. Wischmeier (1975) proposed a canopy subfactor as the ratio of rainfall erosivity with a crop canopy to rainfall erosivity without a crop canopy. In southern Africa, Elwell (1981) proposed an exponential decrease in the

rate of detachment with an increased percentage of intercepted rainfall energy. The exponential relationship is applicable to all covers in direct contact with the soil surface. Examples of such contacts are, crops residue mulch (Laflen and Colvin, 1981; Hussein and Laflen, 1982), stone cover (van Asch, 1980), pasture (Lang and McCaffrey, 1984), and ponded water on the soil surface (Foster, 1982).

3 MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Extent, location and agro-ecological zones

This study was conducted at Towero village, in the Morogoro river's catchment area, western Uluguru Mountains, in Tanzania. The whole of the Morogoro river's catchment area occupies 19.1 km^2, of which Towero village occupies about 4.4 km^2.

Towero village is located about 7-km south east of Morogoro town. The approximate geographical position of the area is 6° 58' S and 37°41' E, at an average elevation of about 1380 metres above sea level (m.a.s.l), situated on the catchment area of river Morogoro, on the western part of the Uluguru Mountains.

There are generally four main local agricultural zones at Towero: forests (*mwituni*), home gardens (*jalalani*), valley bottoms (*mabondeni*) and lower plain fields (*makondeni*), where different cropping systems are practised.

The study area is essentially mountainous consisting of steep and deep valleys of varying slope gradients ranging from 10% to more than 100% (Kilasara and Rutatora, 1993). The altitude ranges from 700 to 1390 m.a.s.l, at Morningside (Nyingi and Bhatia, 1996). Small narrow valleys, steep hillsides with perennial streams, and intensive farming along the slopes characterise much of the land. Owing to these numerous peaks, streams, ridges and depressions, the total surface area is

probably two to three times that of its plain surface area (Kilasara and Rutatora, 1993).

The area is mostly inhabited by the Waluguru people who depend mainly on subsistence farming of maize, beans and from selling vegetables and fruits to urban markets. In most areas, subsistence agriculture is carried out on steep slopes, right up to the lower forest edge. The population density of Towero village is slightly greater than 150 persons/km^2 while the annual population increase is 2.8% (Kilasara and Rutatora, 1993). Further background information including topography, geology, soils, climate, vegetation, history of land management and previous conservation efforts are given in Lyamuya *et al.* (1994). Figure 3.1 shows the location of Towero village in detail.

3.1.2 Climate

The climate of Towero is generally favourable for growing most of the upland crops and vegetables. During the dry season priority is given to the production of vegetables under indigenous irrigation systems. During this research, only those plots which were planted with leeks (*Allium ampeloprasum* L.) were selected for the study because leek was the dominant vegetable crop grown at that time.

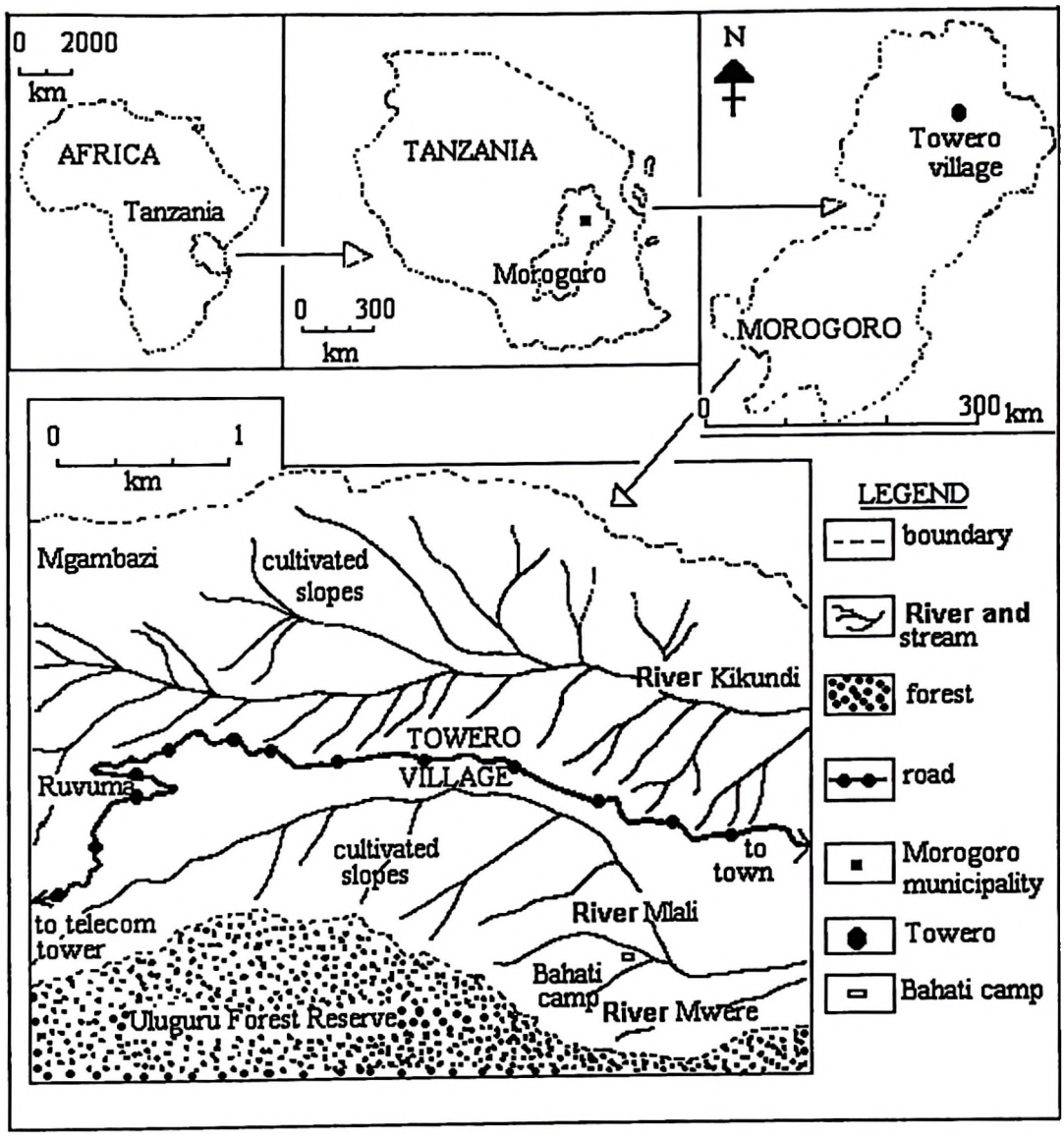

Figure 3.1 Location map of Towero village

Rainfall at Towero varies from 890 to 2392 mm per year (Bhatia and Ringia, 1996). There are generally two rainy seasons punctuated by a dry season, although in the upper parts of Towero there may be some rain every month. The long rains (*Masika*) usually fall in the period February to June the dry season (*Kiangazi*) follows between July and September, and the short rains occur in the period October to January.

3.1.3 Hydrology

The major sources of irrigation water for Towero farmers are the Kikundi, Mlali and Mwere rivers. These are tributaries of River Morogoro, originating from springs scattered in the northern national forest reserve. The characteristic flow of all these rivers is perennial.

3.1.4 Land-use

Agriculture is the main economic activity of the people in Towero village. Much of the area is not well suited for agricultural production because of its mountainous nature. In the flat places, there is potential for a broad diversification of both food and cash crop production which would in turn boost income and employment. Road accessibility is a serious constraint and one which contributes to other problems including the export of agricultural produce. Slash-and-burn, shifting cultivation and reduced fallow periods due to land scarcity are common in Towero village.

The main food crops include maize, bananas, sorghum, cassava, sweet potatoes, beans, pigeon peas, peanuts, cow peas, soybeans and round potatoes. A variety of vegetables such as cabbages, onions, lecks, parsley, beetroots, tomatoes, amaranth and spinach are grown. Fruits grown include avocado, citrus, pineapples and mangoes. Fruits and vegetables serve a dual purpose as both food and cash crops.

As a result of population increase farmers need more land to meet their food and cash demands. Additional land is scarce and this is a major reason why villagers push more and more into marginal lands including forests (Kilasara and Rutatora, 1993).

The system of land ownership and tenure in the village of Towero is based on lineage systems and this often leads to parcelation, inequitable distribution, land scarcity and poor land management (Lyamuya *et al.*, 1994). While some families suffer from a shortage of land, others hold land, which is not in productive use. Some farmers are tenants, paying in cash or kind, and they are restricted from practising permanent land development including the planting of trees (Nyingi and Bhatia, 1996).

3.2 Data collection

Data for this study was collected from *drag hose* sprinkler irrigated leeks fields owned by the farmers. Irrigation was carried out using *drag hose* sprinklers whereby water pressure was obtained from gravitational force. These sprinklers were capable of irrigating an area (swath) ranging between 10-12 m radius per irrigation event. The study field slopes were randomly selected on six slopes as shown in Table 3.1:

Table 3.1 Details of study fields

Block name	Slope (%)	Number of replications[&]
A	84	3
B	70	5
C	65	6
D	24	2
E	15	2
F	6	4

[&] Refers to the number of sprinkler stations or area wetted by one sprinkler.

There were different replications for each block because each block had different numbers of sprinkler stations – hence varying in sizes. In the six blocks, a different farmer owned each block. Despite study blocks being at different slopes and ownership, field conditions were the same: (a) planted only one type of vegetation - leeks (b) all under *drag hose* sprinkler irrigation and (c) all blocks were under the same tillage methods whereby ridges and ladder terraces are used. Farmers' routine programmes like duration and interval of irrigation were not interfered with in order to study real field conditions. Fig 3.2 shows a sketch map of the locations of the fields that were under investigation.

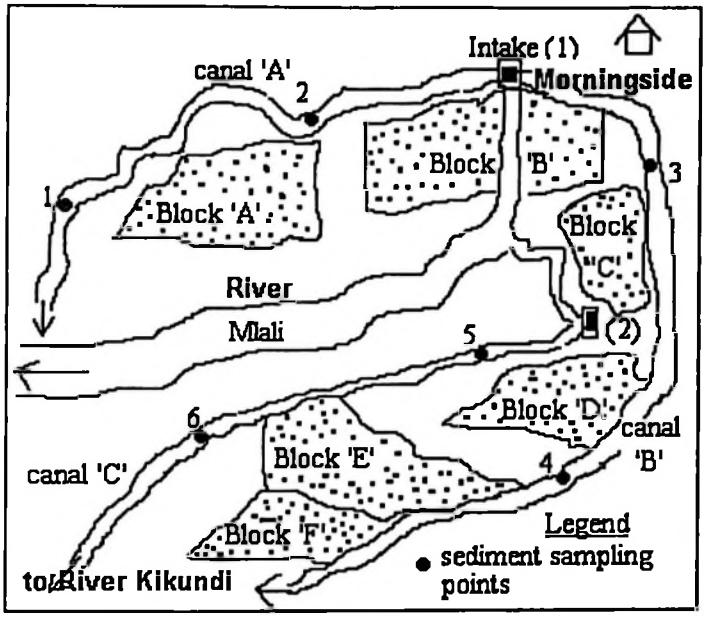

Fig. 3.2: A sketch layout of leek fields in the study area at Towero

3.2.1 Determination of the increase in agricultural area

A field inventory and aerial photographs formed the basis for the land use interpretation of Towero village. Two versions of aerial photographs, which covered the village of Towero, were used to produce land-use/land-cover maps. One version both at a scale of 1:12 500 was photographed in July 1964 and the other in July 1992. The land-use/land-cover maps were then stereoscopically mapped from the central portion of the photographs directly on a piece of transparent overlay.

The land-use/land-cover map of 1999 was produced after conducting a traverse. Features, which could be found both on the map of 1992 and on the actual ground by April, 1999, were used as reference or control points. Whenever there were changes on the ground for the year 1999, distances and direction (angles) were measured and

transferred to the map of 1992 at the same scale. In this way, a complete land cover map of 1999 was finally achieved. The three different land cover maps were then overlaid and the land-use/land-cover changes detected by comparison. Measurement of areal extent of land use was carried out by direct planimetering from the maps.

After drawing land cover maps, the maps were georeferenced with the help of co-ordinate points taken from the field. The grid co-ordinates used on the maps were based on the UTM grid zone 37. Thereafter, the drainage network and the outlines of the settlements were digitized at 1:12500 scale, and mapping units identified by different colouring. Finally, complete land-use/land-cover maps were printed.

3.2.2 Soil sampling and analysis

Random selection of sampling points was done within the leek plots, making sure that the points were representative. Then, grass was removed from the soil surface ready for sampling. Several vertical soil pits were opened and soil samples taken at 10 cm, 20 cm, 30 cm, 60 cm, 80 cm, 100 cm and 120 cm. The reason for sampling soils to a depth of 120 cm was to see whether there were any losses of irrigation water due to deep percolation. This was being done at the start of every irrigation round.

Dry bulk density (ρ_b) of surface soil was determined as the ratio of dry mass to bulk volume of the soil, after oven drying for 24 h at 105 ^{0}C. For determination of soil textural classes, samples were taken at several locations in each particular field, at

different depths (as per the sampling depths indicated), and composited to indicate the average soil texture. Particle size distribution was determined using the hydrometer method (Gee and Bauder, 1986) while aggregate stability was determined by use of the wet-sieving method (Kemper and Rosenau, 1986).

In order to measure soil moisture content, the gravimetric method was used (Gardner, 1986). Soil samples were placed in an airtight aluminium container and sealed immediately to prevent the loss of moisture en route to the laboratory. The moist samples were weighed, dried to constant weight in an oven at 105 °C cooled and re-weighed. The difference in weight, which was due to the loss in water, was divided by the oven dry weight of the soil to give the percent of moisture on a dry - weight basis.

Field capacity and permanent wilting point were determined by laboratory methods using the sand kaolin box and a pressure plate, respectively. For determination of field capacity, soil samples were put in a sand kaolin box and subjected to a pressure of 0.3 bar, equivalent to 2.4 pF-value, then re-weighed and field capacity determined by dividing with initial weight. In order to determine the permanent wilting point, the soil samples were put in a pressure plate at a pressure of 15 bar, equivalent to 4.2 pF-value, then re-weighed and permanent wilting point determined by dividing with initial weight (Klute, 1986). Bulk density was obtained by using the core method (Blake and Hartge, 1986).

3.2.2.1 Determination of soil infiltration capacities

The double ring infiltrometer was used in order to measure infiltration characteristics of the soil. The infiltrometer was driven at least 150 mm into the soil. Enough water was added in the ring and the water level measured periodically. The depth, water level drop, and the time of measurement were recorded for each ring. This method is fully described in James (1983). The data obtained were plotted on a log-log paper and a line of fit through the data points was determined. The following relationship was used to determine infiltration rates of soils using the double ring infiltrometer:

$$f = at^b \qquad (9)$$

where,

f = infiltration rate of the soil (mm/h),

t = time since infiltration began (h), and

a and b are constants.

3.2.3 Determination of adequacy of irrigation

The following relationship was used when evaluating adequacy of irrigation in terms of RWS:

For crop growth period:

$$RWS = (IW + RE)/(ET_c + L) \qquad (10)$$

Where:

RWS = Relative Water Supply

IW = Irrigation Water Delivery (mm)

RE = Effective rainfall (assumed as actual rainfall, mm)

ETc = Crop evapotranspiration (mm)

L = Losses (deep percolation)

The effective rainfall was assumed to be actual rainfall. However, since this study was conducted during the dry season, no rainfall was received throughout the growing season despite setting instruments for rainfall recording.

Evaporation rate data were measured by class A pan evaporimeter, which was located in one of the study plots. Four months daily mean pan evaporation values were used to calculate daily ETo. ETo was calculated using the pan evaporation method. Then, the crop water requirement was calculated using an equation suggested by FAO (1977), as follows:

$$ETc = kc\ (ETo) \qquad (11)$$

Where:

ETc = crop evapotranspiration

kc = crop coefficient

ETo = reference crop evapotranspiration

In order to be able to use the crop coefficient curve for selection of *kc* values, FAO (1977) suggested that crop-growing season be divided into four stages:

(i)	Initial stage (20 days)	germination and early growth when the soil surface is not or is hardly covered by the crop (ground cover <10%)
(ii)	Crop development stage (45 days)	from end of initial stage to attainment of effective full ground cover (ground cover 70 – 80%)
(iii)	Mid-season stage (20 days)	from attainment of effective full groundcover to time of start of maturity as indicated by discolouring of leaves.
(iv)	Late season stage (10 days)	from end of mid-season stage until full maturity or harvest.

3.2.4 Determination of equity of irrigation water supply

The equity of irrigation water was evaluated in terms of RWS calculated over the crop growth period. The mean RWS values were used to indicate the degree of inequity between watercourses within a block and inequity between sample blocks.

3.2.5 Assessment of overall irrigation system efficiency (E_i)

In order to evaluate the overall efficiency of an indigenous irrigation system conveyance, E_c, application, E_a, and root zone storage efficiency, E_r were determined. The overall system efficiency (E_i) was then obtained by multiplying the individual efficiencies. Equation (1) was used to obtain the overall system efficiency.

3.2.5.1 Conveyance efficiency (E_c)

Water conveyance efficiency was determined as a ratio, in percent, of the amount of water turned into an unlined canal (inflow rate, L/min) to the amount of water dclivered to the conveyance system (outflow rate, L/min). As suggested by James (1988), a big hole (enough for a 20-L bucket to fit) was dug in the canal and used to measure canal discharge rates (L/min) both at the entrance and at outlet using a calibrated 20-L bucket, and a stopwatch. Time taken to fill a 20-L water bucket was recorded, and the discharge rate was obtained by dividing the volume of the container by the time required to fill it (L/min, or m^3/s). The total volume of flow in a canal was determined by use of equation (4), while the velocity of flow was determined using equation (3).

3.2.5.2 Application efficiency (E_a)

Water application efficiency for an irrigated area (E_a) was taken as a ratio, expressed in percent, of the volume of water beneficially used by the crop to the volume of water delivered to the area. Equation (5) was used to estimate E_a. The volume of water beneficially used by the crop(s) in an area was obtained by multiplying the size of area irrigated (m^2) by the Readily Available Water (*RAW*, in m). *RAW* was obtained from the average soil retention parameters (field capacity, *fc*, and permanent wilting point, *pwp*), root zone depth (D_{rz}, in m) and the Maximum Allowable Deficiency (*MAD*). The D_{rz} was found by uprooting plants (about two hours after irrigation) and measuring root lengths using a ruler. This process was done

throughout the growth stage of the plants. The Maximum Allowable Deficiency (*MAD*) for most vegetables including leeks, is 0.5 (Raes, 1996). The total gross volume of water applied in an area was obtained by multiplying the discharge rate (m^3/s) by the duration of an irrigation event (s).

3.2.5.3 Root zone storage efficiency (E_r)

The root zone storage efficiency (E_r), was used as an index to adequacy of irrigation as suggested by James (1988). E_r was obtained as a ratio, expressed in percent, of the amount of water stored in the root zone during the irrigation event (W_s) to the amount of water required to fill the root zone to the field capacity (W_n).

3.2.6 Determination of gross soil erosion due to sprinkler irrigation

Nylon sheets were used to collect splashed-off soil. Before irrigation, the sheets were laid in the ridge furrows (between cropped-ridges). This method is well described by Grosh and Jarrett (1994). After each irrigation event, the sheets were carefully removed and all soil particles were kept in one container. The bulk soil was weighed, and 1 kg of soil was taken to the laboratory and oven-dried at 105 °C, for 24 hours. By oven drying the amount of water present in 1 kg of soil was known, the soil was re-weighed and the final amount of eroded soil was obtained by using ratios.

The starting time and finishing time for each irrigation event was recorded and irrigation time determined. The size of the area irrigated at each irrigation event was

calculated from radius of the wetted area covered after a particular event. Each swath was circular due to rotation of the sprinkler.

Sprinkler discharge was obtained by filling a 20-L calibrated container, and then, divided by the time spent to fill it (L/s). Equation (8) was then used to determine the application (precipitation) rate (mm/h). The calculated application rate was cross-checked with measurements obtained from two rain gauges that were located within the swath during irrigation events. Sprinkler spray was expressed by an index based on the kinetic energy of the spray.

3.2.6.1 Determination of net soil loss (Splashed off soil)

In order to determine the net soil loss from the plots, nylon sheets were laid all round the boundaries of each plot, extending 1.5-m wide beyond the boundaries. Again this methodology is fully described by Grosh and Jarrett (1994). These sheets were attached to the upper end (upslope) of each field in order to determine the amount of soil loss on the upper side of the each field referred to as *upslope splash*. Similar sheets were attached to the downslope in order to determine the splashed off soil through the downslope boundaries (*downslope splash*), and along the opposing sides in order to determine loss of soil across the side boundaries referred to as *across-slope splash* erosion.

3.2.6.2 Determination of sedimentation rate

Sedimentation rate in the irrigation canals was determined using the method described by Lundekvam and Skøien (1998). To find the quantity of sediment content in water, samples of water were collected from several sections along a canal by using a 10-l bucket. The mixture of water and sludge (which had been collected in the buckets) was stirred until the mixture was uniform; then put into individual bottle samplers and sent to the laboratory for sediment determination. In the laboratory, a chemical was added to the mixture and left to stand for 24 hours so that all sediments could settle. The excess water was siphoned off. The residue was dried in the oven at 105 °C for 24 hours and weighed. In order to get the total amount of sediment carried in a canal, the percentage of sediment carried in one sampler volume was multiplied by total canal flow. Equation (4) was used to determine the total volume of flow in an irrigation canal.

3.2.6.3 Measurement of physiographic features

Slope steepness was measured by using a clinometer; altitudes by an altimeter and the slope directions were measured by using a prismatic compass. Slope length was measured by using a 50-m tape measure.

3.2.7 Socio-economic study

A structured questionnaire shown in Appendix 1, was used to get farmers' opinions on various aspects of indigenous irrigation activities. Indeed, the use of a questionnaire as the main instrument in data collection has been blamed of some

weaknesses associated with it. Blablock and Blablock jr. (1982) pointed out one such weakness:

> "We do not know whether the respondents will tell us how they really feel and think. They may decide to tell us what they think we want to hear or what they consider to be a socially approved answer".

To minimise the magnitude of this limitation, the researcher employed a non-participant-as-observer technique, unstructured interviews, and informal discussions with different irrigators in the village. The information was then noted in the researcher's diary.

Following a small number of irrigators at Towero, all 22 farmers were interviewed. In this case, there was no sampling of irrigators.

3.3 Data processing and analysis

The overall objective of data analysis was to evaluate the performance of an indigenous irrigation system at Towero village by quantifying erosion rates, observing land-cover changes and determining land-use practices that lead to soil erosion.

Two forms of soil erosion were identified: sediment load resulting from canal scour and soil loss due to splash erosion, caused by erosive forces of *drag hose* sprinkler spray. For the case of soil loss due to sediment load transport, extent was judged in terms of kg of soil lost daily after irrigating the fields. The magnitude of soil loss due

to splash erosion was interpreted based on the amount of soil in kg splashed off the field (net downslope soil loss) after every single day's irrigation.

A statistical version of MSTAT package was used to analyse data. Duncan's New Multiple Range Test was used to distinguish data by separation of means. Complete analysed data were judged in terms of statistical significance at 95% confidence level (ANOVA; P=0.05).

Anthropological data were analysed according to the General Linear Models (GLM) procedure of the statistical analysis system (SAS 608). Data were coded and means, standard deviations, frequencies and percentages calculated.

Summarised and condensed data on technical and socio-economic studies are presented in the next chapter. Averages, standard deviations (s.d), coefficient of variation (cv), summations, percentages, graphs and maps were obtained to facilitate interpretation and analysis of the data.

4 RESULTS AND DISCUSSION

4.1 Extent of the area under indigenous irrigation systems

Results from this study have revealed that between 1964 and 1999 the area under indigenous irrigation systems has increased from 2.53 ha to 30.90 ha (Table 4.1). This is equivalent to an increase of 0.81 ha/year.

Nyingi and Bhatia (1996) concluded that the mountains as well as the forest resources in Towero village have been terribly mismanaged in pursuit of more agricultural lands. The result of such mismanagement is soil erosion, which has started to take place at an alarming rate. In this study land use practices and socio-economic factors were used to address the cause of expansion of indigenous irrigation activities and their consequent effects on soil erosion at Towero.

4.1.1 Socio-economic factors

4.1.1.1 Population explosion

Population increase has resulted in intensification of human agricultural activities at Towero. One such intensified activity is vegetable cultivation, which is done under indigenous irrigation methods. In line with population growth, this study has revealed that the size of settlement areas at Towero is also increasing. As illustrated in Table 4.1, between 1964 and 1999, the settlement area has increased by 0.83 ha/year. This is equivalent to an increase of 81%. Kilasara and Rutatora (1993) reported population increases at Towero. They pointed out two factors namely,

natural population growth and immigration to be responsible for the population growth.

The size of the settlement area has almost doubled between 1964 and 1999 (Table 4.1). As suggested by Lyamuya *et al.* (1994), increase in population has resulted in the decrease in size of plots for cultivation. Earlier studies, which were conducted by Senkondo (1992) in some villages within the Uluguru Mountains, show the diminishing available agricultural land per household. Senkondo (1992) estimated that, the average acreage per family in Mgeta and Mkuyuni areas in the Uluguru Mountains range between 2.02 to 2.28 acres.

Table 4.1 Towero land-use changes between July, 1964 and April, 1999

No.	Title	July, 1964 Area (ha)	July, 1992 Area (ha)	April, 1999 Area (ha)
1	Riverine vegetation	100.50	46.10	39.30
2	Settlement area	36.00	64.70	65.00
3	Cultivated:			
	a) Rainfed: Cereal crops (maize, sorghum, millet, rice, etc.)	44.30	184.51	184.70
	b) Rainfed: Bushy crops (fruits, bananas, cassava etc.)	29.37	79.40	75.10
	c) Under indigenous irrigation systems (vegetables)	2.53	21.91	30.90
4	Fallow land	0.00	42.70	44.32
5	Forest	226.62	0.00	0.00
6	Total	439.32	439.32	439.32

In order to combat shortage of food crops and vegetables, farmers have been forced to cultivate marginal areas, and have left no room for shifting cultivation. From Fig.

4.1, it can be seen that about 95% of total irrigated area is located on slopes steeper than 50%. Cultivation on steep parts has probably accelerated splash erosion and sedimentation problems.

Table 4.2 Population profiles in selected villages of the Uluguru Mountains

Year	Towero	Kibwaya	Tandai	Bigwa	Kibwe	Tangeni	Mlali
1978	1882	1406	2827	1065	1644	3707	2196
1988	2235	2013	3386	1757	n.a	3826	2256
Growth (%)	19	43	20	65	-	3.2	2.7

n.a = not available Source: Kilasara and Rutatora (1993)

Scarcity of land has forced farmers to resort to irrigated agriculture because they can plant crops even during the dry season. In pursuit of land for irrigated agriculture, such environmental problems as excessive cutting of trees, setting of fires and soil erosion have resulted (Lyamuya *et al.*, 1994). Besides clearing land for cultivation, more people have been reported to cut trees for fuelwood and timber (Nyingi and Bhatia, 1996). Finally, land has been left bare and hence, prone to soil erosion hazards.

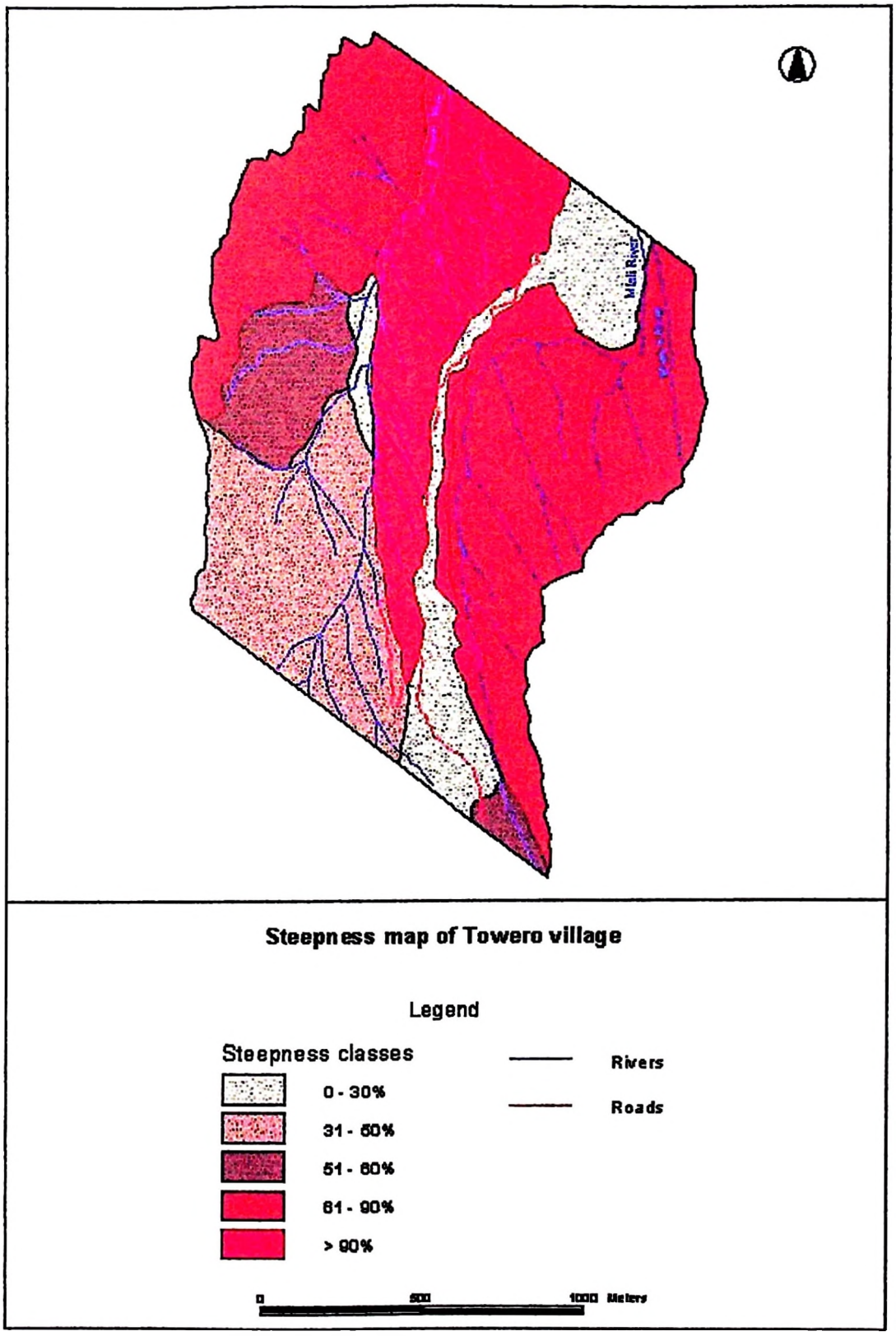

Fig. 4.1 Steepness map of Towero village

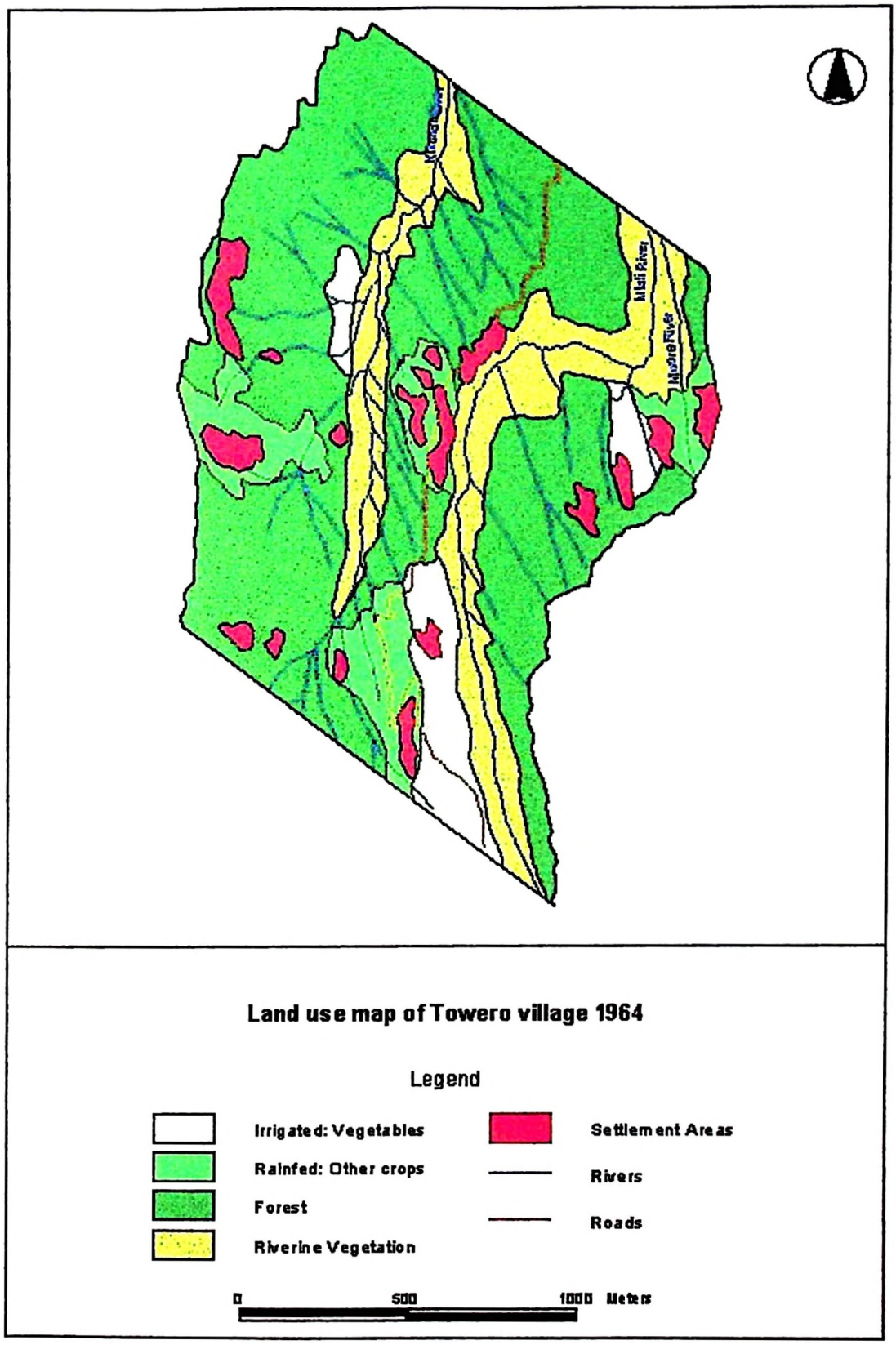

Fig. 4.2 Land use map of Towero village 1964

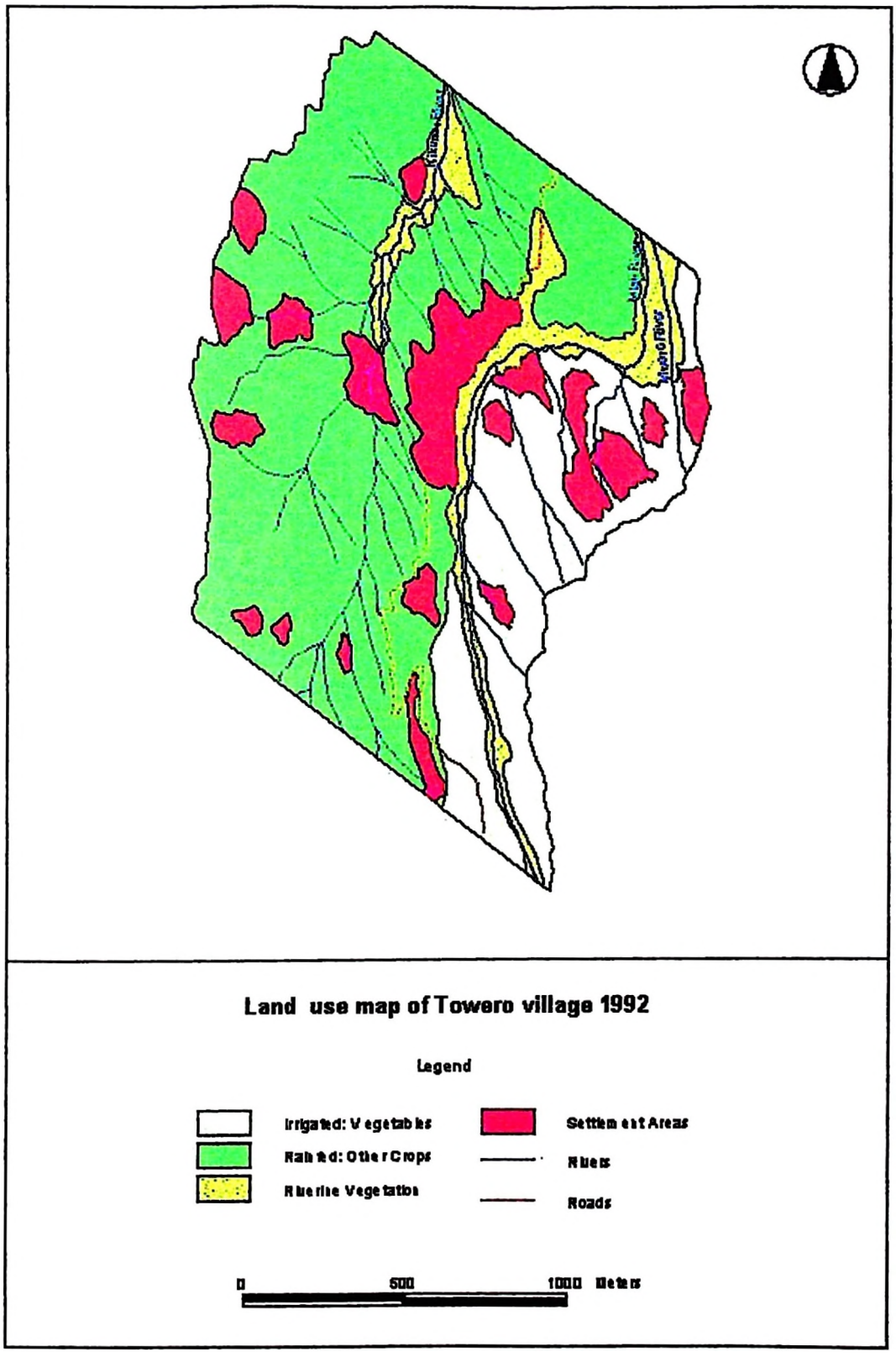

Fig. 4.3 Land use map of 1992

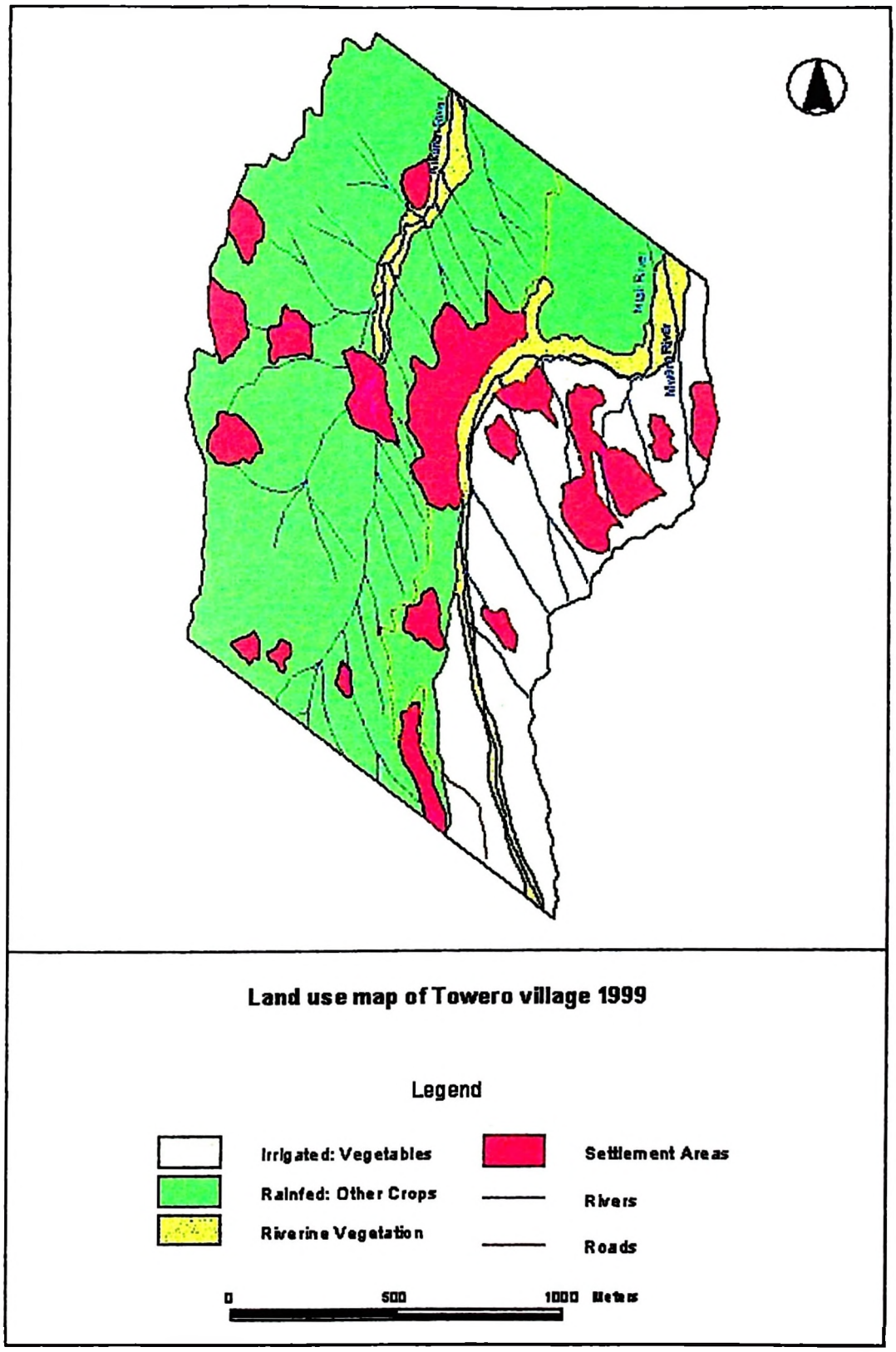

Fig. 4.4 Land use map of Towero village 1999

4.1.1.2 The village economy and occupation

Another factor leading to expansion of indigenous irrigation agriculture at Towero, is the nature of economic and occupational activities. This study found that the major activities for Towero villagers are crop and livestock farming. Similarly, according to Kilasara and Rutatora (1993), about 89% of the population in Towero village rely primarily on agriculture, and especially production of cereals and vegetables. The extent of increase of the agricultural land at Towero has been presented in Figs. 4.2, 4.3 and 4.4 showing land-uses for the years 1964, 1992 and 1999, respectively. Table 4.3 shows the population distribution on the basis of economic activities in selected villages on the Uluguru Mountains.

Table 4.3 Population distribution on the basis of economic activities in selected villages on the Uluguru Mountains

Village	Percentage of people involved in			
	Agriculture	Livestock	Commerce	Public sector
Towero	89	0	0	11
Tandai A	98	0	2	0
Tandai B	92	0	0	8
Bigwa	91	0	0	9
Kibwe	90	0	0	10
Tangeni A	90	0	0	10
Tangeni B	100	0	0	0
Mlali	94	0	1	5
Kibwaya	100	0	0	0

Source: Kilasara and Rutatora (1993)

Cultivation of vegetables in Towero village is a reliable economic activity because the commodities are always marketable and are in high demand in the neighbouring urban areas of Morogoro, Dodoma and the City of Dar es Salaam. As shown in Table

4.4, results of this study indicate that vegetables are more profitable in terms of cash than cereals. Out of the 22 irrigators who were interviewed during this study, 95.5% cultivate vegetables because vegetables are a good cash earner. Due to this fact, farmers have directed more efforts in vegetable cultivation.

Vegetable cultivation at Towero takes place during the dry season. Most farmers embark on vegetable production after the rain season, usually between March and June. In order to meet the plant water requirements, indigenous irrigation methods are used, mostly *drag hose* sprinklers.

A descriptive analysis of the anthropological study is presented in Table 4.4. The mean age of irrigators at Towero is 27.2 years, the minimum is 17.0 and the maximum is 44 years. According to the General Linear Models (GLM) procedure of statistical analysis system (SAS 608), the age standard deviation is $\pm$ 6.4 years. All 22 irrigators are men, out of whom 77.3% are married and 22.7% not married. Of all the irrigators, 86.4% acquired primary education while 13.6% have not attended any formal school. The main economic activities done by farmers who practice irrigation are crop farming and some livestock farming. A sample questionnaire for the anthropological study is shown in Appendix A and statistical analysis summarised in Appendix H.

Table 4.4 A summary of an anthropological study indicating responses of farmers when practising indigenous irrigation at Towero

Questions	Responses		
(a) The beginning of the use of *drag hose* sprinklers for irrigation at Towero	From time immemorial	After the colonial rule	Just recently
	0%	9.1%	90.9%
(b) Reasons for preferring using *drag hose* sprinklers to other methods of irrigation available	Less expensive (in terms of buying costs)	Does not cause soil erosion	Easier to manage and operate
	4.5%	86.4%	9.1%
(c) Means of acquiring a piece of land for irrigation agriculture	By renting	By clearing forests	Through inheritance
	18.1%	36.4%	45.5%
(d) Reasons for abandoning an irrigation canal	The canal gets eroded	Water intake points dry up	Fields are fallow
	81.8%	18.2%	0%
(e) Reasons for preferring cultivating vegetables to other crops (e.g. cereals), under irrigation	They are more profitable	They protect soil against erosion	None of the above
	95.5%	4.5%	0%
(f) Frequency of fertiliser application in irrigated vegetable fields	Not at all	Once	More than once
	86.4%	9.1%	4.5%
(g) Location of fields that are more expensive	Downslope fields	Middle fields	Upslope fields
	0%	0%	100%
(h) Reasons for upslope fields to be more expensive than middle and downslope fields	More fertile	Water availability is assured	No fear for vermin
	18.2%	81.8%	0%

Data analysed according to General Linear Models (GLM) procedure of the statistical analysis system (SAS 608)

(SAS 608).

The use of *drag hose* sprinklers at Towero started in the 1980s. This was revealed during this study whereby 90.9% of farmers acknowledged that the use of *drag hose* sprinklers started in the 1980s (Table 4.4).

Many researchers have found that the practice of cultivating on steep slopes aggravates soil erosion problems. It has been observed in this study that, cultivation and the use of *drag hose* sprinklers on steep slopes accelerates soil erosion at Towero (Figure 4.7). However, responses of the reasons for preferring *drag hose* sprinklers to other methods of irrigation indicated that 86.4% of the farmers acknowledge that sprinklers cause less erosion than other irrigation methods, 9.1% consider sprinklers easier to manage and operate while 4.5% consider sprinklers as less expensive to buy.

Two forms of soil erosion are caused by indigenous irrigation methods at Towero. Splash erosion occurred as a result of sprinkler sprays while sediment load occurred due to water velocities in erodible canals. Similar to findings by other researchers such as Bryan (1979) and Lundekvam and Skøien (1998), it has been found in this study that the rates of these forms of soil erosion are influenced by antecedent soil conditions, land form, vegetation cover, *drag hose* sprinkler characteristics and land management.

Appendices G 1 and G 2 illustrate the problem of sediment load transport in irrigation canals. Due to high rates of sediment load transport, some canals have turned into small gullies and hence abandoned. Responses to the reasons for abandoning irrigation canals showed that 81.8% of the irrigators abandon canals due to canal erosion whereby canals turn into gullies, 18.2% due to drying-up of intake points.

4.1.2 Land-use factors

4.1.2.1 Forest encroachment and setting of fires

There is a progressive slow deforestation of the forest reserve on the periphery of the Towero village with an intention of increasing the acreage of agricultural lands. Apart from increasing the acreage of agricultural land, farmers clear forests so that they can get more fertile land for vegetable cultivation. Different means of acquiring pieces of land for irrigated gardens found in this study, have been presented in Table 4.4. These results show that, about 45.5% of the farmers of Towero get land through inheritance, 36.4% by clearing forests and 18.1% by renting.

As shown in Table 4.1, between 1964 and 1999 the size of cultivated land in Towero has increased from 76.2 ha to 290.7 ha. This increase is equivalent to 6.13 ha/year, including land under indigenous irrigation systems. To some extent, the rate of increase of agricultural land, reflects the rate of deforestation - which is 6.47 ha/year. The difference, 0.35 ha/year, reflects the rate of fallow land.

Development of indigenous irrigation methods has affected the forests of Towero. Forest clearance has accelerated the rate of soil erosion in the catchment. For example, in 1964 the area occupied by forests was 226.62 ha, while in 1999 the area occupied by forests has been reduced to zero, as indicated in Table 4.1. In Table 4.1 and Figs. 4.2, 4.3 and 4.4, the whole area of Towero village has either been cultivated or partly left under fallow. The forest, which is presently visible on top of the Uluguru Mountains is not part of Towero's forest, this is a national forest reserve. Looking at the extent of irrigated area from land cover maps of 1964, 1992 and 1999 shown in Figs. 4.2, 4.3 and 4.4, it can be concluded that, the development of indigenous irrigation affects soil erosion because the process of establishing land for irrigated agriculture involves removal of vegetation.

Another land use malpractice leading to soil erosion at Towero, as far as the effects of indigenous irrigation practices are concerned, is setting of fires. Responses presented in Table 4.5 indicate that people use fire during land preparation and, for controlling vermin and scaring wild animals. Fire removes vegetative cover and consequently subjects the soil to erosion. The bare land becomes prone to soil erosion under the action of water, wind and human activities (Hussein and Laflen, 1982). Sometimes, the fires extend into some parts of the natural forest causing ecological devastation.

Other factors which could have contributed to soil erosion were: the burning of crop residues or trash which leaves the land bare and poor land preparation practices such

as scraping of the land surface with a hoe particularly where the burning is not effective.

Table 4.5 Percentage distribution of respondents according to reasons for setting fires in selected villages on the Uluguru Mountains

Village	Land preparation	Vermin control	Scare wild animals	Others
Towero	75	0	3	22
Tandai A	80	0	0	20
Tandai B	80	0	0	20
Kibwaya	73	21	0	6
Kibwe	69	0	31	0
Bigwa	88	0	0	12
Tangeni B	81	13	6	0
Tangeni A	62	5	0	33
Mlali	0	0	0	100

Source: Kilasara and Rutatora (1993)

4.1.2.2 Lack of interest in land and forest conservation

People in Towero village share common habits partly due to historical, social and political developments and partly due to a package of constraints such as land shortage, the low technological level of their agriculture and terrain characteristics of the land. These conditions have contributed to poor economic development and lack of planned and sustainable management of both the land and forest resources. Consequently, the Towero catchment is facing a serious level of degradation, which appears to advance as the population increases.

Table 4.6 Farmers' perception on soil erosion and conservation in selected villages on the Uluguru Mountains

Village	% of farmers who are aware of soil erosion problems	% of farmers who acknowledge soil erosion problems on their land	% of farmers who are knowledgeable of soil conservation measures	% of farmers who practice soil conservation
Towero	100	78	100	7
Tandai A	100	98	72	9
Tandai B	100	71	61	0
Kibwaya	86	71	85	0
Kibwe	100	100	95	0
Bigwa	90	64	41	38
Tangeni B	88	70	73	15
Tangeni A	83	95	83	0
Mlali	100	84	100	0

Source: Kilasara and Rutatora (1993)

Interviews conducted by Lyamuya *et al.* (1994) revealed that the peasants in Towero village are aware of the degradation of their land and forest resources, and are even ready to undertake measures to reverse the situation as shown in Table 4.6. However, by 1993 only 7% of the farmers were practicing conservation measures such as planting trees in the fields, mulching and terracing. The most probable reasons for the lack of action towards protection and conservation of the environment may be:

a) To most of them conservation of the environment is equivalent to terrace making, which is expensive in terms of labour and tools required. Even if the tools were cheap this activity contradicts their normal land preparation which is based on minimum work done on the land, and the use of fire to accomplish the exercise. It might also be true that the conflict which surfaced between the government and the villagers during the Uluguru Land Usage Scheme (ULUS), and which centred itself on the terracing issue, is not yet forgotten. To-date farmers still associate terracing with ancient memories, which were accomplished with severe

punishments, some of which led to deaths of their ancestors, who refused to adopted the land conservation measure. This was discovered when a team of researchers based at SUA under the Uluguru Mountain Integrated Soil Conservation Project (UMISCP) visited farmers of Towero and Magadu villages in October, 1993. Thus, future land and forest conservation measures need to be planned while taking into account these facts.

b) The high population pressure and the limited land for agriculture to individual households have forced the villagers to depend heavily on the neighbouring forest for timber and fuelwood. Population pressure has forced people to cultivate on marginal lands such as cultivation on very steep slopes, riverbanks and on the bottoms of steep slope valleys. Unfortunately, these rural people do not realise that marginal lands are fragile, needing a lot of care.

c) The lineage powers over the ownership of the land have a negative impact on land conservation and afforestation of the village land (Bhatia and Ringia, 1996). Trees are an individual property, virtually unrelated to the land on which they stand. This, together with the common practice of lending out land for cultivation of annual crops have limited the process of adopting afforestation or agroforestry activities. Systems of land ownership and business arrangements, which do not provide security to the farmer, are a major obstacle to conservation. Among the most pernicious of these are short-term land leases which fail to provide an incentive to a farmer to invest in long-term improvements. In general, the less secure the tenure, the greater the encouragement to exploit the land without conserving it.

4.2 Performance of indigenous irrigation systems in Towero village

4.2.1 Effects of soil properties on the performance of *drag hose* sprinkler irrigation at Towero

Soil texture has an agronomic importance. Agriculturally, loams are the most important soils as they are ideal for the majority of agronomic crops. Sandy soils are open, loose and friable, and possess good drainage and aeration. Sandy soils are also easy to handle in tillage operations.

Soil texture has an important bearing on soil erosion. As found by Ghadiri and Payne (1988), a fine-textured soil is more vulnerable to erosion than a coarse-textured one.

In Table 4.7, a 'soil-wise' and a 'texture-wise' description of the textural classes of some fields in Towero is shown. Results of particle-size analysis have been described as percentages of the whole sample. Generally, soils of Towero range between sandy clay and clay loam.

Slight soil compaction takes place in sprinkler irrigated fields probably due to impact of sprinkler drops. In order to loosen the soil farmers till their land prior to planting and continue to do so repeatedly in due course of the plant growth. As reported by Ben-Hur *et al.* (1992) tillage helps to pulverise the soil and makes it conducive for plant root growth by increasing infiltration rate and soil aeration.

Table 4.7 Particle-size distribution of some soils of Towero

Block	% sand	% coarse silt	% fine silt	% clay	Textural term (Soil-wise)	Alternative term (texture-wise)	Textural classification
A	45	6	10	39	Heavy	Fine	Sandy clay
B	53	4	11	32	Heavy	Fine	Sandy clay
C	41	8	13	38	Moderately heavy	Moderately fine	Clay loam
D	40	11	19	30	Moderately heavy	Moderately fine	Clay loam
E	37	10	15	38	Moderately heavy	Moderately fine	Clay loam
F	45	6	10	39	Heavy	Fine	Sandy clay

In Fig. 4.5, the basic infiltration capacity of cultivated sandy clay and clay loam soils in Towero was 48 mm/h. This infiltration rate is similar to those suggested by Maynard (1977) in vegetable cultivated sandy clay and clay loam soils as 46.72 mm/h and 49.00 mm/h, respectively. However, it has been found in this study that infiltration rates are the same for both sandy clay and clay loam soils. This rate is far higher than precipitation rates of the *drag hose* sprinklers which range between 3.8 – 5.0 mm/h. Based on this fact, no surface runoff was observed in all study plots throughout the growing season.

High infiltration rates and the use of ladder terraces contributed to the non-occurrence of surface runoff throughout the irrigation season. The non-occurrence of runoff was also due to the fact that the application ends before all surface depressions are filled with water. Figure 4.6 illustrates these concepts.

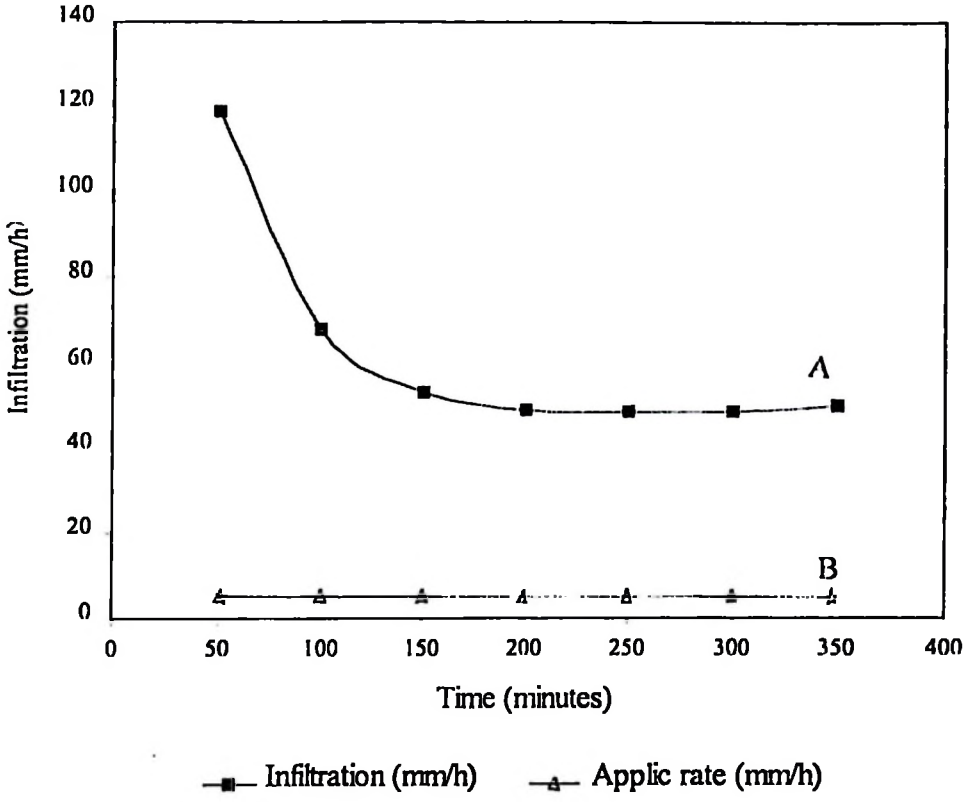

Fig. 4.5 Infiltration capacity curve of Towero soils

Line B in Fig 4.5 shows a constant application rate throughout the crop-growing season. The application rate did not exceed the infiltration capacity of the soil. All sprinkled water infiltrated into the soil. There was no possibility of runoff in such kind of an irrigation system. Apart from sediment load transport, splash was probably the only form of erosion caused by *drag hose* sprinkling at the field level in Towero.

Despite the non-availability of runoff, slight ponding occurred whereby ladder terraces and depressions in the soil surface were filled with water. Depressions in fields are caused by various tillage operations. The amount of water that accumulates in depressions and on the soil surface depends on the amount of vegetation and/or

residue. It also depends on the depth and extent of surface depressions as well as the slope of the soil surface. The presence of vegetation and/or residue, and tillage operations that leave rough surface tend to delay runoff by increasing the amount of water that can be stored. Stored water infiltrates slowly into the soil hence moistening the root zone and, if in excess, the subsoil.

There was strong evidence of soil moisture increase with soil depth during this study. An analysis of variance (ANOVA) indicated a significant increase of soil moisture with depth at 95% confidence level, as shown in Table 4.8. Separation of means using Duncan's New Multiple Range Test (DNMRT) revealed significant differences of soil moisture with sampling depth. The increase in soil moisture in the subsoil was contributed by over-irrigation and higher clay content. Over-irrigation resulted into deep percolation and subsurface flow. Soil moisture data has been presented in Appendices B 1 – B 24 and statistical analyses presented in Appendices H 13 - H 14.

Subsurface flow was evidenced by the presence of saturated soils below 0.8 m deep. Saturated clay loam and sandy clay soils were reported by Raes (1996) to be 44 and 46% (by volume), respectively. Subsurface flow supplements water to the root zone by capillary rise.

Table 4.8 Moisture variations with depth

Sampling depth[&] (m)	Mean moisture content[#] (% vol.)
0.0 – 0.2	20.90
0.2 – 0.4	25.02
0.4 – 0.6	29.78
0.6 – 0.8	36.25
0.8 – 1.0	40.38
1.0 – 1.2	42.08

Note: [&] Mean moisture content values in every sampling depth are significantly different according to Duncan's New Multiple Range Test (DNMRT).
[#] Standard error of the mean for 12 observations was 0.2869, coefficient of variation was 3.07%.

Since study plots were located on sloping areas, the fact that moisture content increase with depth is attributable to subsurface flow, that is, underground water movement from upslope to downslope parts. According to Lal (1990), subsurface flow may be of two types: the low and diffuse matrix flow, also called interflow; or quick, pipe or tunnel flow. Pipe flow may be initiated by cracks, rills, or animal burrows on the upslope side, hence providing a macropore network for quick transmission of throughflow to the downslope side.

The finer the soil texture the greater is its fertility (Urio *et al.*, 1979; Tengberg *et al.*, 1997). Application of commercial fertilisers is not a common practice at Towero. The observation is that 86.4% of Towero farmers do not apply fertiliser in their irrigated vegetable fields, 9.1% apply only once and 4.5% apply fertilisers more than once as shown in Table 4.4. This observation suggests that, soils of Towero are fertile enough to support crops. Probably this is due to clayey nature of the soils, which have minimal leaching effect.

4.2.2 Performance of indigenous irrigation systems in Towero village

The performance of the *drag hose* sprinkler irrigation system was evaluated in six sites at Towero using five performance indicators: (a) Crop yield (b) adequacy of irrigation water supply (c) equity of irrigation water supplies (d) regularity and, (e) sustainability of irrigation canals.

4.2.2.1 Crop yield

The mean crop and specific yield are presented in Table 4.9. The mean specific yields for leeks at Towero were ranging between 0.65 - 1.09 kg/m^3 while the mean crop yields ranged from 9.65 - 13.53 tonne/ha (Table 4.9).

Compared to international standard yields of irrigated leeks on farmers' fields (Table 4.10), yields from blocks A, B, C D and F were in agreement with international standard values, while the yield from block E was below standard.

Table 4.9 Seasonal crop yield

Block	Mean specific yield (kg/m^3)	Mean crop yield Tonne/ha
A	1.07	13.53
B	1.09	12.44
C	1.06	12.45
D	1.09	10.85
E	1.01	09.65
F	0.65	11.50

Table 4.10 International standard crop and specific yields for leeks

	Commercial yield (tonnes/ha)	Average farmer yield (tonnes/ha)	Water utilisation efficiency (kg/m^3)
Rainfed	14 – 20	5 – 10	
Irrigated	35 – 45	10 – 20	8 – 10

Source: FAO (1986) and Sys *et al.* (1993)

There was improper water management since mean specific yields for all blocks were below standard. This implies that much water was used to produce a small quantity of leeks. The low mean specific yields reflected poor water utilisation efficiency in all sampled blocks. Blocks B and D recorded the highest specific yields while block F recorded the lowest specific yield. The crop yields were high in almost all blocks. The specific yield obtained in block F was probably caused by water scarcity or erratic deliveries. High yields could also be due to crop management factors, low yielding varieties, inadequate weeding, diseases and so on. Any change in water management or water control practices plays a significant role in instigating improvement in yields.

4.2.2.2 Adequacy of irrigation water supply

Ability of the soil to store an adequate amount of water after irrigation plays a significant role in improving yields or produce. The concept directs attention to how completely the needed water has been stored in the root zone during irrigation.

The ANOVA did not indicate any significant difference in root zone storage efficiency between slopes and plant age at the 95% level of confidence. This implies that, all farmers had similar habits in irrigating their fields at various locations of their fields, that is, over-irrigation. With the exception of block E (15% slope), all the remaining blocks were irrigated beyond storage capacity. Over-irrigation causes water losses through deep percolation. Deep percolation is finally likely to cause leaching of nutrients and underground piping, which results into landslides. Table 4.12 shows seasonal RWS during the crop growth period. According to Gates *et al.* (1991) RWS values less than 1 may be due to water scarcity or inefficient management practices. RWS greater than 1 implies that, those fields were over-irrigated. Crop-water-requirement data have been presented in Appendix C.

Table 4.11 A summary of root zone storage efficiency (E_r)

Block	E_r value for the period between 0 – 20 days (%)	E_r value for the period between 20 – 65 days (%)	E_r value for the period between 65 – 85 days (%)	E_r value for the period between 85 – 95 days (%)	Average E_r (%)
A	100.0	100.0	100.0	100.0	100.0
B	100.0	100.0	100.0	100.0	100.0
C	100.0	100.0	100.0	100.0	100.0
D	100.0	100.0	100.0	100.0	100.0
E	100.0	94.7	100.0	98.0	98.2
F	100.0	100.0	100.0	100.0	100.0
		Average E_r (%)			99.69

Mean E_r values between plant age and slope are not significantly different according to ANOVA, P=0.05

Table 4.12 indicates that all RWS values are greater than 1. Relative Water Supply values varied between 1.0 and 3.4. According to Sakthivadiel *et al.* (1992) RWS values greater than 1 may be due to low water costs - hence over–irrigation and inefficient water management practices. Generally this range indicates that farmers at Towero irrigate their fields between 1.0 to 3.4 times in excess of the design crop water requirements. There is need to alleviate this poor water management practices at Towero.

Table 4.12 Relative Water Supply (RWS) and Coefficients of Spatial Water Distribution (CSWD) in leeks fields

Block	Sprinkler precipitation rate (mm/h)	Duration of irrigation (h)	IW (mm)	Water losses through deep percolation (mm)	Total ET_c prior to next irrigation (mm)	RWS[&] (dimensionless)	CSWD[#] (dimensionless)
			Between 0 – 20 days old				
A	4.8	7.1	34.08	13.96	7.30	1.6	1.6
B	4.5	7.7	34.65	10.12		2.0	2.0
C	4.2	7.1	29.82	3.84		2.7	2.7
D	4.5	5.8	26.10	17.92		1.0	1.0
E	3.9	6.4	24.96	0.00		3.4	3.4
F	4.1	5.7	23.37	5.04		1.9	1.9
			Between 20 – 65 days old				
A	4.8	7.6	36.48	6.40	20.90	1.3	1.3
B	4.4	7.1	31.24	4.84		1.2	1.2
C	4.2	7.2	30.24	7.28		1.1	1.1
D	4.2	7.8	32.76	4.64		1.3	1.3
E	3.8	8.4	31.92	0.00		1.5	1.5
F	3.8	8.2	31.16	0.00		1.5	1.5
			Between 65 – 85 days old				
A	4.9	7.2	35.28	14.60	16.11	1.1	1.1
B	4.1	7.8	31.98	3.92		1.6	1.6
C	4.9	7.1	34.79	5.32		1.6	1.6
D	4.1	7.9	32.39	6.72		1.4	1.4
E	4.6	7.2	33.12	0.00		2.0	2.0
F	4.0	7.9	31.60	8.72		1.3	1.3
			Between 85 – 95 days old				
A	5.0	6.8	34.00	9.88	16.56	1.3	1.3
B	4.8	7.1	34.08	0.00		2.1	2.1
C	4.3	7.0	30.10	0.60		1.8	1.8
D	4.4	7.4	32.56	7.80		1.3	1.3
E	4.0	7.6	30.40	0.00		1.8	1.8
F	3.9	7.9	30.81	1.80		1.7	1.7

Note: [&] RWS calculated using equation 10.

[#] Coefficient of spatial water distribution (CSWD) obtained by dividing the smallest RWS value by other RWS values.

The mean RWS values for the growing season indicate that all blocks received adequate irrigation water supply (Table 4.12). During the 20-days initial stage, blocks B, C and E, which are located upstream had higher values compared to the downstream fields A, D and F blocks. This shows the habit of upstream farmers in applying too much water in their fields. In the remaining growth stages, no definite RWS pattern was shown regarding upstream and downstream farmers.

Since there was no runoff throughout the irrigation season, salient water losses were undoubtedly due to deep percolation. The possible effects of deep percolation are leaching of plant nutrients and triggering of landslides. Likewise, excessive water in the soil could weaken soil shear strength and be responsible for occurrence of landslides at Towero.

4.2.2.3 Equity of irrigation water supply

According to Gates *et al.* (1991), at the farm levels the concept of RWS gives adequate representation of the spatial water distribution – or inequity situation. In this study, the unequal irrigation water supply in leek fields between the blocks is shown in Table 4.12. The non-uniform irrigation water supply between fields is indicated by the distribution of the coefficient of spatial water distribution values.

From Table 4.12, a high level of inequity as indicated by the coefficient of spatial water distribution (CSWD) values was experienced from upstream to downstream

blocks at the initial stage of the crop growth. At the initial growth stage the lowest CSWD was 1 while the highest was 3.4. Differences in CSWD indicate inequity. This means that block E received 3.4 times more water than block D during the first 20 days of plant growth. Although the inequity problem persisted in the remaining stages of growth, there was no definite pattern between upstream and downstream fields.

Questionnaire responses indicated presence of inequitable water distribution at Towero. It was learned that land at the top-end of the system had higher renting prices than in tail-end areas. Inequity is due to farmers' habit of diverting water in excess of the requirement into their fields. This habit causes losses during conveyance. Water losses caused by upstream farmers during conveyance results into irregularity of water distribution to downstream farmers. Presence of the inequity situation was confirmed by the fact that 100% of respondents reported land at the top-end of the system being more expensive than land at the tail-end areas as shown in Table 4.4.

The application efficiency (E_a) at each site was estimated using equation 5. The average E_a of 83.3% was obtained as shown in Table 4.13. This value is within acceptable range for sprinkler systems in mountainous areas, commonly quoted as 75% to 100% (Oad and King, 1991).

Table 4.13 Water application efficiency (E_a) at different plant growth stages

Block	E_a value for the period between 0 – 20 days (%)	E_a value for the period between 20 – 65 days (%)	E_a value for the period between 65 – 85 days (%)	E_a value for the period between 85 – 95 days (%)	Average E_a (%)
A	39.3	73.8	92.2	99.7	76.3
B	35.0	88.3	98.4	100.0	80.4
C	52.6	89.6	99.4	100.0	85.4
D	32.3	84.9	82.4	101.9	75.4
E	44.1	114.4	131.2	143.5	108.3
F	28.7	75.1	99.8	93.4	74.2
Average E_a (%)	38.7	87.7	100.6	106.4	83.3

Mean E_a values between plant age are statistically significant according to ANOVA, P=0.05.

A strong evidence of differences in application efficiency with various stages of plant growth was confirmed. The ANOVA performed to compare application efficiency for different plant growth stages at the 95% level of confidence revealed that, application efficiency was increasing significantly with plant growth (except for block F). Figure. 4.6 illustrates clearly this pattern. As plants grew the crop water requirement increased while the amount of water irrigated remained constant.

The average application efficiency when leeks were between 0 – 20 days old was 38.7% versus 87.7%, 100.6% and 106.4% when crops were 20 – 65, 65 – 85 and 85 - 95 days old, respectively. Low values of E_a at the time when plants were young (0 – 20 days old) shows that farmers were applying too much water as compared to crop water requirements at that particular growth stage. Excess water was wasted through deep percolation. Values of E_a for 65 days plants were higher than those of young

plants. Since water was constantly applied throughout the growth period, with increase in crop water requirements due to plant age, losses due deep percolation decreased.

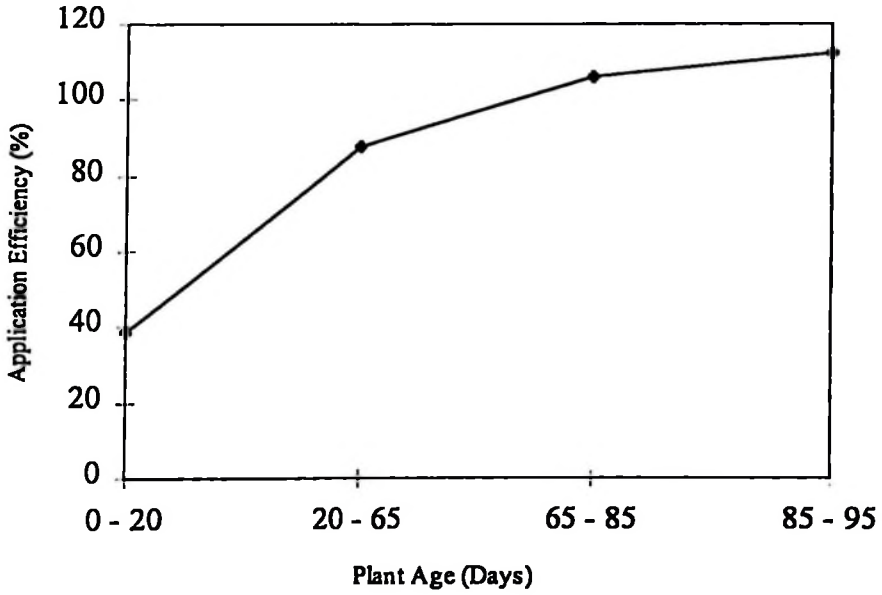

Fig. 4.6 Relationship between application efficiency and plant age

Farmers acknowledged that the use of *drag hose* sprinkler for irrigation was due to the fact that this is a better method than other methods available at Towero. The reason behind their choice was based on the fact that *drag hose* sprinklers apply water more efficiently than other indigenous irrigation systems available at Towero (Table 4.4). Another reason of choosing sprinkler irrigation was its ability to apply water efficiently, hence less erosive.

4.2.2.4 Irrigation water regularity and reliability

Water conveyance efficiency (E_c) was computed as a ratio, in percent, of the amount of water delivered by an irrigation canal to the amount of water diverted from the source. As shown in Table E 4 of Appendix E, the overall average E_c of 85.22% was obtained. When considered individually, block C had the highest average conveyance efficiency followed by B, D, A, F and E, respectively. Blocks C and B had highest conveyance efficiencies because they were located closer to water intakes than were D, F and E. Blocks E and F experienced the lowest conveyance efficiency because they are located farthest from the intakes.

Along with regularity, other aspects of the time-distribution of water flows were considered, especially reliability. It was observed that farmers' behaviour and attitudes towards water delivery were influenced by its reliability. If they felt that deliveries would occur according to some schedule, they planned their agricultural activities accordingly. But when experience taught them that the arrival of water was unreliable, they displayed one of the following two reactions: (a) the farmer who was

well placed (either possessing an upstream field, or having influence with the system's leaders) took more water than he needed, or, (b) farmers felt obliged to use drought-resistant varieties.

4.2.2.5 Sustainability of irrigation canals at Towero

Facilities for irrigation at Towero are communally shared and hence, benefit many farmers. Due to continual maintenance efforts, these facilities may last for several seasons before they erode and hence, abandoned. Traditionally, the general principle followed in maintenance of the irrigation canals is an annual contribution from all farmers served, in the form of labour or produce. The principle continues to be applied, although nowadays a farmer may also contribute cash instead of labour or produce. Farmers have always striven to control erosion of irrigation canals by letting grass grow on the canal beds and along the banks. They have also been desilting canals communally. Due to frequent canal maintenance programmes, irrigation canals at Towero can last for several irrigation seasons before they are abandoned. During this study it was observed that it is important to service irrigation canals at Towero because one of the major causes of their abandonment is soil erosion.

Irrigators at Towero have formed an organisation, which takes care of their day to day activities. Such activities are: harvesting and transporting crops to the markets, repair of irrigation facilities, seeking loans for organisation's members and many others. For example, during the irrigation season farmers patrol the common portion of the channel in turn to adjust and clear debris from the channel intake, plug leaks,

repair small breaches, and monitor water supply conditions. All these activities are organised by the leaders.

Similar maintenance measures have been reported in China, Indonesia and Pakistan, where spring is the time for general annual maintenance (Yanhua *et al.*, 1992). All the farmers may also participate in a one or two day mid-season desilting operation (Vander Velde, 1992). Maintenance of lateral or field canals not common to the system is the responsibility of individual farmers. It is important to devise measures that will counteract the soil erosion problem in irrigation canals.

4.3 Determination of the rate of soil erosion due to indigenous irrigation at Towero

4.3.1 Aggregate stability and erodibility

Organic matter is part of a complex interaction of physical, chemical and biological reactions that create and maintain a well-aggregated soil (Tisdall and Oades, 1982). The water stable aggregate (WSA) experiments were conducted on the premise that planting vegetables every season might decrease erodibility on the fields by increasing organic matter in the soil. Ziegler and Giambelluca (1998) described Loss on Ignition (LOI) values higher than 7.0% to be high. High amounts of organic material within cropped sites inferred from LOI data in Table 4.14 suggest that these areas may be creating greater aggregate stability by producing organic cements and/or enmeshing aggregates through root growth.

Table 4.14 Descriptive statistics of soil physical properties at Towero

Block	Slope (%)	ρ_b (g/cm^3)	Strength (kgf/cm^2)	GMAD (mm)	% aggregates ≥ 1.0 mm	% aggregates < 0.063 mm	LOI (%)
A	84	1.09^b	0.8^d	0.80^b	45.4^a	6.4^a	13.4^a
B	70	0.94^c	1.0^d	0.89^a	46.2^a	5.6^b	15.2^a
C	65	1.17^a	3.8^a	0.88^a	33.4^b	7.6^a	12.9^b
D	24	1.14^a	1.5^c	0.81^b	33.7^b	7.1^a	7.1^c
E	15	1.19^a	2.7^b	0.71^c	32.1^b	7.3^a	7.3^c
F	6	0.97^c	0.6^{dc}	0.78^b	46.7^a	6.2^a	6.2^c

Mean values within the same column with the same letter are not significantly different according to Duncan's New Multiple Range Test ($P < 0.05$).

The WSA data, combined with other data of soil physical properties are shown in Table 4.14. According to Ziegler and Giambelluca (1998), soil strengths greater than 1.5 kgf/cm^2 are high, suggesting that the soil is not highly erodible by typical forces that cause aggregate failure. High values of this index indicate that shear stress must also be high for sediment detachment to occur. As shown in Table 4.15, in the WSA experiments nearly 78% of the material remaining after shaking in water and sifting was greater than 0.25 mm.

Table 4.15 A summary of mean values of WSA indices

Class	Value
GMAD (mm)	0.81
WSA fraction > 0.25 mm (%)	77.6
WSA fraction 2.0-4.0 mm (%)	38.6
WSA fraction < 0.063 mm (%)	10.3

According to specifications set forth by Ziegler and Giambelluca (1998), WSA indices calculated for all fields shown in Table 4.15 are high. Generally, data obtained in this study indicate that Towero soils are dominated by clay material, which makes them resistant to detachment by sprinkler spray impact and low velocity overland flow.

4.3.2 Total canal sediment load transport

Appendix G 2 shows rates of sediment load transport in three irrigation canals in Towero village. Sediment load transport rates were found to be 0.211, 0.793 and 0.347 g/L in canals A, B and C, respectively. When computed on daily basis, the daily sedimentation rate in canals A, B and C is equivalent to 22.2, 187.6 kg and 54.7 kg per irrigation event. This loss of soil amounts to a total of 264.5 kg per day.

According to Lal (1990) suspended load, which consists primarily of clays and colloids, is normally distributed throughout the cross-section of the stream flow. It was observed in this study that suspended materials were responsible for frequent sprinkler clogging during irrigation. Suspended soil particles consequently stopped the sprinkling exercise for a while in the course of irrigation.

As shown in Appendix G 2, canal B had the highest sediment load transport because it was the longest of all three canals. The fact that canal B is on the steepest slope may also have contributed to its high sediment load transport. Farmers reported that during the rainy season sedimentation rate was higher than what was observed in this

study. High sedimentation rate during the rainy season is probably due to low ground cover soon after ploughing and crop establishment, and probably due to high intensity rains.

4.3.3 Soil loss due to splash erosion

Splash data were recorded as splash rates in kg per irrigation event. An irrigation event refers to a wetted field of an average area of 420 m^2, irrigated by one *drag hose* sprinkler in an average duration of 7.3 hours.

The Analysis of Variance for the slope effect on downslope, upslope, across-slope and gross splash erosion indicated significant differences at 95% confidence level. This implies that splash rate increased significantly with slope increase. This phenomenon is shown in Table 4.16 and plotted in Figure 4.7. Statistical analyses for splash erosion are shown in Appendices H 1 – H 11.

Table 4.16 Splash rates for six slopes in Towero village

	Splashed-off soil# (kg/m^2)						
Variable& / Slope	6%	15%	24%	65%	70%	84%	s.e.$
Downslope splash	0.310^{e}	0.460^{e}	0.610^{d}	0.801^{c}	0.959^{b}	1.318^{a}	0.0215
Upslope splash	0.464^{a}	0.417^{a}	0.357^{b}	0.298^{c}	0.159^{d}	0.104^{d}	0.0182
Across-slope splash	0.250^{e}	0.280^{de}	0.313^{d}	0.368^{c}	0.436^{b}	0.503^{a}	0.0109
Net downslope splash	-0.154	0.043	0.253	0.503	0.800	1.214	

Note: # Values are per an average of 7.3 h of irrigation (or one irrigation event).
& Mean values in each ROW with the same letter are statistically insignificant according to Duncan's New Multiple Range Test (DNMRT).
$ Mean of 8 observations.

At the 6% slope, the downslope splash was 0.310 kg, less than the upslope splash of 0.464 kg per irrigation event. This may have been caused by the slight ponding at the downstream end of the slope. At the 15% slope, there was more downslope splash than upslope, indicating that slope steepness had more effect on downslope splash transport for this gradient. Downslope splash was almost twice upslope splash at the 24% slope (0.610 versus 0.357 kg per irrigation event), and as slope gradient increased beyond 24% downslope splash increased at a higher rate while upslope splash decreased approaching zero at 70% slope and beyond. Across-slope splash increased slightly as slope increased, showing a clear progression as in downslope and upslope splash.

The increasing importance of downslope splash as slope steepness increases is seen in Figure 4.7. This is the net downslope transport due to splash, and it increased from -0.154 kg per irrigation event at 6% slope to 1.214 kg per irrigation event at 84% slope, as shown in Table 4.16. A negative net downslope splash value implies that more soil was splashed upslope than on the downslope side of the plot.

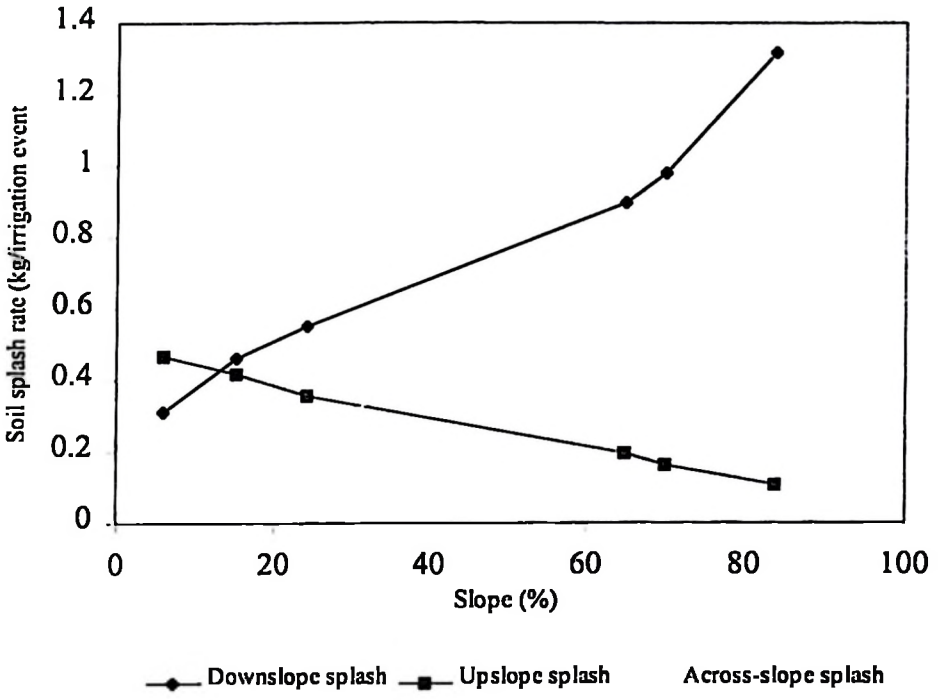

Figure 4.7. Splash rates for six slopes at Towero

Since the across slope splash remained almost constant as a function of slope, it would be expected that net downslope splash would approach zero as slope approached zero. In this study, net downslope splash was negative at 6% slope and was consistently negative for all plots averaging -0.10 kg per irrigation event. Again, this may have been caused by the slight ponding at the downstream end of the slope as suggested by Grosh and Jarrett (1994).

Plant age indicated a significant effect on downslope, upslope, across-slope and gross splash rate at 95% confidence level. This is probably due to the fact that leeks develops a good canopy cover at maturity. Table 4.17, indicates that the rates of splash erosion were decreasing with increase in plant age – hence, canopy cover.

Splash rate reduction is probably due to dissipation of sprinkler drop impact by vegetative cover. Many researchers have reported similar effects of canopy cover on sprinkler-spray erosivity and splash erosion. Ghadiri and Payne (1977, 1979, 1988) found that vegetative cover alters the volume, drop size distribution, impact velocity and kinetic energy of drops reaching the ground.

Table 4.17 Splash rates according to plant age per irrigation event

Plant age[&]	Gross splash erosion (kg)	Downslope splash erosion (kg)	Upslope splash erosion (kg)	Across-slope splash erosion (kg)	Net downslope splash erosion (kg)
0 - 20 days	13.566[a]	1.153[a]	0.445[a]	0.629[a]	0.708
20 – 65 days	10.393[b]	0.826[b]	0.302[b]	0.637[a]	0.524
65 – 85 days	6.391[c]	0.492[c]	0.219[c]	0.083[b]	0.273
85 – 95 days	5.938[c]	0.502[c]	0.232[c]	0.084[b]	0.270
s.e.[#]	0.3143	0.0176	0.0149	0.0089	

Note: [&] Splash values in each column with the same letter are statistically insignificant according to Duncan's New Multiple Range Test (ANOVA; P= 0.05).
[#] Mean for 12 observations

Since sprinklers weaken soil strength by detaching individual particles, when a storm comes all the fertile topsoil may be washed away by surface runoff. As indicated in Table 4.4, some farmers at Towero were already complaining of crops not doing well if no fertiliser was applied. If farmers cannot manage to buy fertilisers to replenish the lost fertility, yields will continue to decline. Some farmers may not be willing to tolerate such a situation and, as a result, clearing of natural forests will continue in the course of searching for more fertile land, and more marginal lands will be cultivated. This will accelerate the degradation of the Towero catchment. Due to this

fact, there is high need to control splash erosion currently occurring at Towero using indigenous soil conservation methods. Indigenous soil conservation methods that are available at Towero include: the use of manure (cover crops and green manure), mulch tillage, minimum tillage, contour farming, terrace systems, and the use of diversions and waterways to drain away surface runoff. These conservation methods protect the soil both from splash erosion and through safe runoff transport.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Soils of Towero range between sandy clay and clay loam. The basic infiltration capacity for both soils was 48 mm/h, while the sprinkler precipitation rate ranged between 3.8 – 5.0 mm/h. The infiltration rate was far higher than the precipitation rate. The *drag hose* sprinkler precipitation rate is slightly smaller than that of most commercial sprinklers which range between 5.0 – 10.0 mm/h. Under such circumstances, there is little possibility for runoff occurrences.

Between 1964 and 1999 the area under indigenous irrigation systems at Towero increased from 2.53 to 30.90 ha. The expansion of indigenous irrigation accelerated deforestation rate by 6.48 ha/year, between 1964 and 1999. Such a deforestation rate is threatening the sustainability of indigenous irrigation systems at Towero.

Many farmers in Towero prefer *drag hose* sprinkler irrigation to other irrigation methods because the former is less erosive than the later. The performance of *drag hose* irrigation at Towero was rated good. However, there was improper water management whereby all fields were over-irrigated. Over-irrigation caused water loss through deep percolation. Subsurface flow was another source of water in the subsoil. It flowed from upslope to downslope parts.

Sediment load transport and soil splash were two forms of erosion that were caused by indigenous irrigation at Towero. These forms of erosion are likely to cause land degradation if not hampered.

5.2 Recommendations

Since the *drag hose* irrigation method show the potential to expand in future, the use of sprinklers should be encouraged because sprinklers are less erosive as compared to other methods of irrigation available at Towero.

Further research is required in order to improve *drag hose* irrigation to suit in mountainous areas. In order to avoid locating canals on steep gradients, contours should be followed. These canals should be planted with grass. This recommendation is expected to reduce water velocities, and hence, reduce soil losses through sediment load transport. Improved methods should take into consideration the question of soil conservation and general sustainability of the scheme.

The use of farmyard manure, crop covers, mulch and minimum tillage should be encouraged so as to reduce splash rates.

6 REFERENCES

Abernethy, C. L. (1986). Performance Measurement in Canal Water Management.*ODI - IIMI Publication* no. 86/2d, London. Pp. 25.

Anderson, J. R., Hardy, E. E., Roach, J. T. and Witmer, R. E. (1976). A Land-Use and Land-Cover Classification System. *Professional Paper* 964, 137.

Badrashi, B., Jannett, A.R., and Hoover, J. R. (1981). The Role of Escaped Soil Air on Erosion in Sand, *ASAE paper.* Pp. 38.

Ben-Hur, M., Stern, R., Van der Merwe, A. J. and Shainberg, I. (1992). Slope and Gypsum Effects on Infiltration and Erodibility of Dispersive and Non-dispersive soils. *Soil Science Society of America Journal*, 56, 1571-1576.

Bhatia, Z and Ringia, O (1996). *Socio-economic survey of selected villages in the Uluguru Mountains, Tanzania.* Uluguru Slopes Planning Project Report, Morogoro. Pp. 80.

Bhutta, M. N. and Vander Velde, E. J. (1992). Equity of Water Distribution Along Secondary Canals in Punjab, Pakistan. *Journal of Irrigation and Drainage Systems*, 6, 161-177.

Blablock, A. B and Blablock, M. H Jr. (1982). *Introduction to Social Research.* Prentice Hall Inc. Englwood Cliffs, New Jersey. Pp. 153.

Blake, G. R. and Hartge, K. H. (1986). *Bulk Density.* In: *A. Klute (ed.). Methods of Soil Analysis, Part I. Physical and Mineralogical Methods.* Agronomy Monograph no. 9. Madison, USA. Pp. 363-375.

Boardman, J. (1991). Land Use, Rainfall and Erosion Risk on the South Downs. *Journal of Soil Use and Management*, 7, 34-38.

Bolline, A. (1978). Study of the Importance of Splash and Wash on Cultivated Loamy Soils of Hesbaye (Belgium). *Earth Surface Processes*, 3,71-84.

Bruce-Okine, E., and Lal, R. (1975). Soil Erodibility as Determined by Raindrop technique. *Soil Science Society of America*, 119, 149-159.

Bryan, R. B. (1974). 'A Simulated Rainfall Test for the Prediction of Soil Erodibility'. *Advances in Agronomy*, 18, 107-160.

Bryan, R. B. (1977). Assessment of Soil Erodibility. In. *Erosion, Research Techniques, Erodibility and Sediment Yield (Edited by Toy, T. J)*, Geo Book, Norwich. Pp. 165-178.

Bryan, R. B. (1979). The influence of Slope Angle on Soil Entrainment by Sheetwash and Rainsplash. *Earth Surface Processes* 4, 43-58.

De Plocy, J. (1971). Liquefaction and Rain-wash erosion. *Z. Geomorph.* 15, 491-496.

Djorovic, M. (1977). Use of Runoff Plots to Evaluate Soil Loss. in: *Watershed Management (Edited by Kunkle, S. H and Thames, T. L)*, FAO Publication, Rome, Italy. Pp. 143-146.

Duchhart, I. and Povel, S. (1991). Landscape Analysis: A Tool for Sustainable Irrigation Development. *Journal of Irrigation and Drainage Systems*, 5, 191-212.

El-Swaify, S. A. and Dangler, E. W. (1977). Erodibilities of Selected Tropical Soils in Relation to structural and hydrologic Parameters. *Soil Conservation Society Journal* , 21, 105-114.

Elwell, H. A. (1981). A soil loss estimation technique for southern Africa. In: *Morgan, R. P. C (Ed,) Soil conservation: Problems and prospects.* John Wiley and Sons, England. pp. 281-292.

Eweg, H. P. A., Van Lammeren, R., Deurloo, H. and Waldu, Z. (1998). Analysing Degradation and Rehabilitation for Sustainable Land Management in the

Highlands of Ethiopia. *Journ. Of Land Degradation and Development*, 9, 529-542.

Ezaki, T. (1985). Basic Research on Soil Erosion and Conservation of Slope. *Erosion Control Engineering Society Journal*, 3,45-50.

FAO (1977). Crop Water Requirements. *FAO publication*, 24, 144.

FAO (1985). Participating Experience in Irrigation Water Management. *Proceedings of Expert Consultation on Irrigation Water Management*, held in 1985, Yog Yakart and Bali, Indonesia. Pp. 200.

FAO (1986) Yield Response to Water. FAO *Irrigation and Drainage Paper*, 33, 193

FAO (1988). Irrigation Practices and Water Management. *FAO irrigation and Drainage paper*, 1,63.

FAO (1989). Guidelines for Designing and Evaluating Surface Irrigation Systems. *Irrigation and Drainage paper*, 45, 137.

Farmer, E. E. (1973). Relative Detachability of Soil Particles by Simulated Rainfall. *Soil Science Society of America Proceeding*, 37, 629-633.

Field, W. P. (1990). World Irrigation. *Journal of Irrigation and Drainage Systems*, 4, 91-107

Fisher, R. J. (1989). *Indigenous System of Common Property Management in Nepal.* East West Centre pub., Honolulu, Hawaii, USA. pp. 322.

Forster, G. R. and Meyer, L. D. (1975). *Mathematical Simulation of Upland Erosion by Fundamental Erosion Mechanics*. USDA Publishers, Washington. Pp.190

Foster, R. L., and Martin, G.L. (1979). Effects of Unit Weight and Slope on Erosion. *Proceeding of America Society of Civil Engineers*, 95, 551-561.

Foster, G. R. (1982). Modelling the erosion process. *Journal of the ASAE*, 5, 297-380.

Gardner, W. (1986). Water Content. In: *A. Klute (ed.). Methods of Soil Analysis, Part I. Physical and Mineralogical Methods*. Agronomy Monograph, 9, 493-541.

Gates, T. K, Heyder, W. E, Fontane, D. F and Salas, D. J (1991). Multi-criterion Strategic Planning for Improved Irrigation Delivery: Approach. *Journal of Irrigation and Drainage Engineering*, 117 (6):430-555

Gee, G. W. and Bauder, J. W. (1986). *Particle-Size Analysis. In: A. Klute (ed.). Methods of Soil Analysis, Part I. Physical and Mineralogical Methods.* Agronomy Monograph 9: 383-409.

Ghadiri, H. and Payne, D. (1977). Raindrop Impact Stress and the Breakdown of Soil Crumbs. *Journal of Soil Science.* 28, 247-258.

Ghadiri, H. and Payne, D. (1979). Raindrop Impact and Soil Splash. In: *(Lal, R. and Greenland, D. J (eds.)) Soil Physical Properties and Crop Production in the Tropics*, Wiley, England. Pp. 95-103.

Ghadiri, H. and Payne, D. (1988). The Formation and Characteristics of Splash Following Raindrop Impact on Soil. *Journal of Soil Science*, 39(4):563-575.

Grosh, J. L and Jarrett, A. R (1994). Interrill Erosion and Runoff on Very Steep Slopes. *Transactions of the ASAE*, Vol. 37(4): 1127-1133.

Gupta, A. K. and Ura, K. (1992). Indigenous Farming Technologies and Environment: Experiences in Bhutan. In: *Proceedings of the International Symposium for Strategies on Sustainable Mountain Agriculture (ISSSMA)* workshop (edited by Jodha, N.S., Banskota, M. and Partap, T), Kathmandu, India, 10-14 September, 1990. Pp. 539-568.

Hansen, B., Sibbesen, E., Shϕnning, P., Thomsen, A. and Hashott, B. (1996). *Surface Runoff, Erosion and Loss of Sediment and Phosphorus - Danish Plot Studies.* Proceedings of the International Workshop, 9-12 October, 1995, Silkeborg, Denmark. Pp. 123.

Hudson, N.W (1981). *Soil Conservation. 2ed.* ELBS Publishers, Great Britain. Pp. 324.

Hudson, N. W. (1995). *Land Husbandry.* Iowa State University Press, Washington. Pp. 389.

Hussein, M. H. and Laflen, J. M. (1982). Effects of crop canopy and residue on rill and interrill soil erosion. *Transactions of the ASAE,* 25, 1310-1315.

IFAD (1992). *Soil and Water Conservation in Sub-Saharan Africa: Towards sustainable production by the rural poor.* Free University Press, Amsterdam. Pp. 37.

Indrabudi, H., De Gier, A., and Fresco, L. O. (1998). Deforestation and its Driving Forces: A Case Study of Riam Kanan Watershed, Indonesia. *Journal of Land Degradation and Development,* 9, 311-322.

James, G. L. (1988). *Principles of Farm Irrigation Design*. John Wiley and Sons Ltd., New York. Pp. 543.

Jensen, M. E. (1983). Design and Operation of Farm Irrigation Systems. *American Society of Agricultural Engineers Journal*. Pp. 829.

Kaufmann, R. K (1995). The economic multiplier of environmental life support: can capital substitute for a degraded environment? *Ecological Economics Journal*, 12,67-79.

Kemper, W. D and Rosenau, R. C. (1986). Aggregate Stability and Size Distribution. In: *A. Klute (ed.). Methods of Soil Analysis, Part I. Physical and Mineralogical Methods*. Agronomy Monograph, 9, 425-441.

Khushalani, M. E. (1990). *Irrigation Practice and Design: Diversion and Distribution*. Mohan Primlani Pub., New Delhi, India. Pp. 570

Kilasara, M and Rutatora, D. .F (1993). *The Socio-economic and Land-Use Factors Affecting the Land Degradation of the Uluguru Catchment in Morogoro, Tanzania*. Proceeding of a national workshop held in Dodoma, Tanzania, November 22-24, 1993. Pp. 45-51.

Klute, A. (1986). *Water Retention: Laboratory Methods. Methods of Soil Analysis, Part I. Physical and Mineralogical Methods.* Agronomy Monograph, 9:635-660.

Laflen, J. M. and Colvin, T. S. (1981). Effect of crop residue on soil loss from continuos cropping. *Transactions of the ASAE* , 24, 695-709.

Lal, R. (1990). *Soil Erosion in the Tropics.* Department of Agronomy, Ohio State University, McGraw-Hill Press, USA.Pp. 580.

Lal, R., Lawson, T. L. and Anastase, A. H. (1980). Erosivity of tropical soils. In: *Assessment of erosion (M. De Boodt and D. Gabriels, eds.).* Wiley, England, pp. 143-151.

Lang, R. D. and McCaffrey, L. A. H. (1984). Ground cover, its effect on soil loss from grazed runoff plots, Gunnedah. *Journal of Soil Conservation,* 40, 56-61.

Liebenow, A. M., Elliot, W. J., Laflen, J. M. and Kohl, K. D. (1990). Interrill Erodibility: Collection and Analysis of Data from Cropland Soils. *Transactions of the ASAE,* 33(6):1882-1888.

Linsley, R. K., Kohler, M. A. and Paulhus, J. L. H. (1988). *Hydrology for Engineers.* Pub. McGraw-Hill Book Company, London, U. K. pp. 492.

Luk, S. H. (1979). Effect of Soil Properties on Erosion by Wash and Splash. *Earth Surface Processes and Landforms*, 4, 241-255.

Lundekvam, H. and Skøien, S. (1998). Soil Erosion in Norway. An overview of measurements from soil loss plots. *An International Journal of British Society of Soil Science*, (2)14:122.

Lyamuya, V. E, Noah, L.G, Kilasara, M, Kirenga, E. J and Burgess, N. D (1994). *Socio-economic and land use factors affecting the degradation of the Uluguru Mountains Catchment in Morogoro Region, Tanzania.* An unpublished PRA report of the Regional Natural Resources Office of Morogoro Region, Tanzania. Pp. 37.

Lyles, L., Dickerson, J. D., and Schmeidler, N. F. (1974). Soil detachment from clods by rainfall: Effects of wind, Mulch cover, and initial soil moisture. *Transactions of the ASAE*, 33, 302-306.

Maene, L. M. and Chong, S. P. (1979). *Drop size distribution and erosivity of tropical rainstorms under the oil palm canopy.* Proceedings of the Lapuran Penyelidikan Jabatan Sains Tanah, held in 1977-78, Universiti Pertanian Malaysia, Serdang, pp. 81-93.

Malongo, G. W. S. (1997). *Effects of Mswiswi Watershed Degradation on Stream Flow in Usangu Village Irrigation Project.* M.Sc. dissertation, Sokoine University of Agriculture. pp. 117.

Maynard, B. N. (1977). Knott's *Handbook for Vegetable Growers*, 4th edition. John Widely & Sons, inc., New York. pp. 582.

McGregor, K. C. and Mutchler, C. K. (1978). *The effect of crop canopy on raindrop size Distribution and Energy.* US Sedimentation Laboratory, Oxford, Missouri. Pp. 205.

Michael, A. M. (1978). *Irrigation: theory and practices.* Pub. By Vikas House, New Delhi, India. Pp. 801.

Miller, R. W. (1995). *Soils in Our Environment.* Iowa State University Press, USA. Pp. 649.

Morgan, R. P. C. (1982). Splash Detachment Under Plant Covers: Results and Implications of a Field Study. *Transactions of the ASAE*, 25, 987-991.

Morgan, R. P. C. (1978). Field Studies of Rainsplash Erosion. *Earth Surface Processes Journal*, 3, 295-299.

Mulk, M. (1992). Diversity of Farming Systems and Farmers' Strategies in Mountain Valley of Chitral, Pakistan. In: *Proceedings of the International Symposium for Strategies on Sustainable Mountain Agriculture (ISSSMA)* workshop (edited by Jodha, N.S., Banskota, M. and Partap, T), Kathmandu, India, 10-14 September, 1990. Pp. 446-496.

Nihal, F (1992). Monitoring Irrigation Water Delivery Performance: Concept of Cumulative Water Supply. In: *Advances in Planning, Design and Management of Irrigation System as Related to Sustainable Land Use (edited by Feyen, J. and Moussa, B)*. Vol. 2. Leuven, Belgium. 14-17 September, 1992.

Nijman, C. M. (1992). Performance Evaluation and Control in Water Delivery Decision-Making Process: Who Cares? *Journal of Irrigation and Drainage*, 6, 85-112

Nyingi, J. and Bhatia, Z. (1996). *A socio-economic survey in the Uluguru Mountains, Tanzania*. Uluguru Slopes Planning Project PRA Report, Morogoro, Tanzania. Pp. 89.

Omar, S. A. S., Madouh, T., El-Bagouri, I, Al-Musalem, Z., and Al-Telaihi, H. (1998). Land Degradation Factors in Arid Irrigated Areas: The Case of Wafra in Kuwait. *Journal of Land Degradation and Development*, 9, 283-294.

Oad, R. and King, P. (1991). Irrigation System Design for Management in Mountainous Areas. *Journal of Irrigation and Drainage Systems*. Pp. 123-136.

Palmer, R. S. (1973). The Influence of a Thin Water Layer on Water Drop Impact Forces. *IAH Publication*, 65, 141-148.

Park, S. W., Mitchell, J. K. and Bubenzer, G. D. (1980). An Analysis of Splash Erosion Mechanics. *Transactions of the ASAE*, 17, 80-250.

Park, S. W., Mitchell, J. K. and Bubenzer, G. D. (1982). Splash Erosion Modelling: Physical Analyses. *Transactions of the ASAE*, 25, 357-361.

Poesen, J. (1984). The Influence of Slope Angle on Infiltration Rate and Hortonian Overland Flow. *Transactions of the ASAE*, 49, 117-131.

Poesen, J. (1985). An Improved Splash Transport Model. *Z. F. Geomorph. Journal*, 29(2):193-211.

Quansah, C. (1981). The Effect of Soil Type, Slope, Rain Intensity and their Interactions of Splash Detachment and Transport. *Journal of Soil Science*, 32, 215-224.

Raes, D. (1996). *Irrigation Agronomy.* Unpublished lecture notes for the Inter-University Programme in Water Resources Engineering. KUL, Belgium. Pp. 145.

Rapp, A. (1977). Methods of Soil Erosion Monitoring for Improved Watershed Management in Tanzania. in: *Watershed Management (Edited by Kunkle, S. H and Thames, T. L)*, FAO Publication, Rome, Italy. Pp. 85-97.

Romwell, D.L. (1994). *Soil Science (Methods and Applications).* British Library Cataloguing, Essex, UK. Pp. 350.

Sakthivadiel, R., Merrey, D. and Nihal, F. (1993). Cumulative Relative Water Supply: A methodology for Assessing Irrigation Performance. *Journal of Irrigation and Drainage System*, 7:43-67.

Schottman, W. R. (1978). *Estimation of the penetration of high energy raindrops through a plant canopy.* Cornell University, Ithaca. pp. 56.

Senkondo, E. M. M (1992). *Farming Systems Analysis of Alternative Agroforestry Systems in Tanzania: The Case of Uluguru Area, Morogoro.* An unpublished M. Sc Thesis, Agricultural University of Norway. Pp. 142.

Sharma, K. S. (1992). The Small Farmer's Development Programme in Nepal: Institutional Initiative in Poverty Alleviation. In: *Proceedings of the International Symposium for Strategies on Sustainable Mountain Agriculture (ISSSMA)* workshop (edited by Jodha, N.S., Banskota, M. and Partap, T), Kathmandu, India, 10-14 September, 1990. Pp. 651-670.

Shrestha, S and Katwal, B. (1992). Farmer's Strategies in Middle Hills of Nepal. In: *Proceedings of the International Symposium for Strategies on Sustainable Mountain Agriculture (ISSSMA)* workshop (edited by Jodha, N.S., Banskota, M. and Partap, T), Kathmandu, India, 10-14 September, 1990. Pp. 447-476.

Svendsen, J. O and Hansen, L. A (ed.) (1993). *The Uluguru Biodiversity Survey.* Tanzania Forestry Research Institute, Morogoro. pp. 87.

Sys, C., Van Ranst, E., Debaveye, J. and Beernaert, F. (1993). Land Evaluation, part III: Crop Requirements. *Agricultural Publications*, 7, 99 – 102.

Tengberg, A., Stocking, M. and Falcidechen, S. C. (1997). The Impact of Erosion on Soil Productivity - An Experimental Design Applied in So Paulo State, Brazil. *Geografiska Annaler*, 79A:95-107.

Tisdall, J. M. and Oades, J. M. (1982). Organic Matter and Water-Stable Aggregates in Soil. *Journal of Soil Science Society of America*, 33, 141-163

Truman, C. C., Bradford, J. M. and Ferris, J. E. (1990). Antecedent Water Content and Rainfall Energy Influence on Soil Aggregate Breakdown. *Journal of Soil Science Society of America*, 54, 1385-1392.

Urio, A. P., Mongi, H. O., Chowdhury, M. S., Singh, B. R., and Semoka, J. M. R. (1979). *Introductory Soil Science.* Tanzania Pub. House, Dar es Salaam. pp. 232.

Van Asch, Th. W. J. (1980). Water erosion on slopes and landsliding in Mediterranean landscape. *Utrechtse Geograf. Stud.*, pp.20.

Vander Velde, E. J. (1992). Farmer-Managed Irrigation Systems in the Mountains of Pakistan. In: *Proceedings of the International Symposium for Strategies on Sustainable Mountain Agriculture (ISSSMA)* workshop (edited by Jodha, N.S., Banskota, M. and Partap, T), Kathmandu, India, 10-14 September, 1990. Pp. 569-590.

Verma, L. R. and Partap, T. (1992). The Experiences of an Area-based Development Strategy in Himachal Pradesh, India. In: *Proceedings of the International Symposium for Strategies on Sustainable Mountain Agriculture (ISSSMA)* workshop (edited by Jodha, N.S., Banskota, M. and Partap, T), Kathmandu, India, 10-14 September, 1990. Pp. 609-636.

Wischmeier, W. H. (1975). Estimating the soil loss equation's cover and management factor for undisturbed areas. In: *Present and prospective technology for Predicting Sediment yields and Sources*. ARS 40, USDA, Washington, pp. 118-124.

Wischmeier, W. H. and Smith, D. D. (1978). *Predicting Rainfall Erosion Losses - A Guide to Conservation Planning*. USDA, Agric. Hand book no. 537. U. S. Gov. Print. Office, Washington, DC. Pp. 234-345.

Walker, P. H., Kinnell, P. I.A., and Green, P. (1978). Transport of non-cohesive sandy mixture in rainfall and runoff experiments. *Soil Science Society of America Journal*, 42, 793-801.

Yanhua, L., Fei, W. and Dafu, Y. (1992). Farmer's Strategies in Mountain Areas of West Sichuan: China. In: *Proceedings of the International Symposium for Strategies on Sustainable Mountain Agriculture (ISSSMA)* workshop (edited by Jodha, N.S., Banskota, M. and Partap, T), Kathmandu, India, 10-14 September, 1990. Pp. 423-446.

Yoder, R. and Martin, E. (1985). *Identification and Utilisation of Farmer Resources in Irrigation Development: A Guide for Rapid Appraisal.* ODI Irrigation Management Network Paper 12C. London, UK. Pp. 107.

Young, R. A. (1984). A method of measuring aggregate stability under water drop impact. *Transactions of the ASAE,* 27, 1351-1354.

Young, R. A., and Wiersma, J.L. (1973). The role of raindrop impact in soil detachment and transport. *Water Resources Reserve Journal,* 9, 1629-1639.

Ziegler, A. D and Giambelluca, T. W. (1998). Influence of Re-vegetation Efforts on Hydrologic Response and Erosion, Kaho' ollawe Island, Hawai'i. *Journal of Land Degradation and Development*, vol. 9(3): 189-282.

7 APPENDICES

APPENDIX A: Questionnaire

GENERAL

1. Name.....Age..... Village.....

   Ward.....Division.....District.....

   Region.....Country.....

2. Marital status (check against appropriate answer):-

   Newly married.....

   Married.....

   Not married.....

   Separated.....

   Divorced.....

   Widowed.....

3. Level of education (check against appropriate answer):-

   Not attended any school.....

   Adult education.....

   Primary education.....

   Secondary education.....

   University education.....

4. Major activities (check against appropriate answer):-

Crop farming with irrigation agriculture during the dry season.....

Livestock farming.....

Mixed farming..... .....

Off-farm activities ....

All of the above.....

5. If crop farming with irrigation agriculture, proceed to questions 5.1 to 5.8.

5.1 Why do you prefer *drag hose* sprinkler irrigation to other methods of irrigation in your field?

a) it is less expensive

b) it does not cause soil erosion in the field [ ]

c) it is easier to manage and operate

5.2 When did *drag hose* sprinkler irrigation start to be used at Towero?

a) from time immemorial (hence indigenous)

b) after independence [ ]

c) just recently (1980s)

5.3 During the dry season, why do you prefer cultivating vegetables under irrigation to cereals?

a) vegetables are more profitable

b) they protect the soil against erosion better [ ]

c) None of the above

5.4. How do you get a plot for irrigation agriculture?

a) by renting

b) by clearing forests [ ]

c) through inheritance

5.5. How frequent do you apply fertilisers in your vegetable fields within a growing season?

a) not at all

b) once [ ]

c) more than once

5.6 Why do you have to abandon an irrigation canal?

a) the canal gets eroded

b) water intakes dry up [ ]

c) fields are fallow

5.7 Which fields are more expensive to rent?

a) downslope fields

b) middle fields [ ]

c) upslope fields

5.8 Why are they more expensive?

a) they are more fertile [ ]

b) water availability is assured

c) both answers are correct

APPENDIX B SOIL MOISTURE

B 1: Variations in moisture content (% vol.) in block A when leeks plants were 20 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.01	45.57	24.56	245.6	0.12	(29.5)49.1
0.2 – 0.4	25.17	44.67	19.50	195.0		39.0
0.4 – 0.6	30.06	45.06	15.00	150.0		30.0
0.6 – 0.8	37.88	45.29	7.41	74.1		15.0
0.8 – 1.0	41.38	45.33	3.95	39.5		8.0
1.0 – 1.2	41.95	46.14	4.19	41.9		8.4

B 2: Variations in moisture content (% vol.) in block A when leeks plants were 65 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.81	42.68	21.87	218.7	0.29	(43.7)43.7
0.2 – 0.4	24.93	44.71	19.78	197.8		(17.8)39.6
0.4 – 0.6	29.96	44.93	14.97	149.7		29.9
0.6 – 0.8	36.58	45.01	8.43	84.3		16.9
0.8 – 1.0	40.62	45.66	5.04	50.4		10.1
1.0 – 1.2	41.85	45.95	4.10	41.0		8.2

B 3: Variations in moisture content (% vol.) in block A when leeks plants were 85 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.13	44.73	23.60	236.0	0.34	(47.2)47.2
0.2 – 0.4	25.69	44.77	19.08	190.8		(26.7)38.2
0.4 – 0.6	30.78	45.11	14.33	143.3		28.7
0.6 – 0.8	38.46	45.34	6.88	68.8		13.8
0.8 – 1.0	42.13	45.63	3.50	35.0		7.0
1.0 – 1.2	42.45	46.04	3.59	35.9		7.2

B 4: Variations in moisture content (% vol.) in block A when leeks plants were 95 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.68	44.55	23.87	238.7	0.34	(47.7)47.7
0.2 – 0.4	23.72	44.18	20.46	204.6		(28.6)40.9
0.4 – 0.6	32.05	44.22	12.17	121.7		24.3
0.6 – 0.8	37.19	44.46	7.27	72.7		14.5
0.8 – 1.0	40.84	44.48	3.64	36.4		7.3
1.0 – 1.2	44.71	45.03	0.32	3.2		0.6

B 5: Variations in moisture content (% vol.) in block B when leeks were 20 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.39	43.21	22.82	228.2	0.11	(25.1)45.6
0.2 – 0.4	24.40	43.68	19.28	192.8		38.6
0.4 – 0.6	29.70	43.68	13.98	139.8		28.0
0.6 – 0.8	38.18	43.73	5.55	55.5		11.1
0.8 – 1.0	41.54	43.78	2.24	22.4		4.5
1.0 – 1.2	43.08	44.11	1.03	10.3		2.1

B 6: Variations in moisture content (% vol.) in block B when leeks plants were 65 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.24	43.63	23.39	233.9	0.29	(46.8)
0.2 – 0.4	25.19	43.97	18.78	187.8		(16.9)37.6
0.4 – 0.6	31.75	44.21	12.46	124.6		25.0
0.6 – 0.8	37.46	44.89	7.43	74.3		14.9
0.8 – 1.0	40.88	45.05	4.17	41.7		8.3
1.0 – 1.2	43.96	45.16	1.20	12.0		2.4

B 7 Variations in moisture content (% vol.) in block B when leeks plants were 85 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.06	40.66	19.60	196.0	0.36	(39.2)
0.2 – 0.4	25.65	43.00	17.35	173.5		(27.8)34.7
0.4 – 0.6	30.27	43.11	12.84	128.4		25.7
0.6 – 0.8	39.44	43.79	4.35	43.5		8.7
0.8 – 1.0	41.51	44.02	2.51	25.1		5.0
1.0 – 1.2	43.83	44.28	0.45	4.5		0.9

B 8: Variations in moisture content (% vol.) in block B when leeks plants were 95 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	18.93	39.16	20.23	202.3	0.36	(40.5)
0.2 – 0.4	24.39	39.28	14.89	148.9		(23.8)29.8
0.4 – 0.6	30.86	41.52	10.66	106.6		21.3
0.6 – 0.8	36.11	42.63	6.52	65.2		13.0
0.8 – 1.0	39.79	43.08	3.29	32.9		6.6
1.0 – 1.2	43.80	44.01	0.21	2.1		0.4

B 9 Variations in moisture content (% vol.) in block C when leeks plants were 20 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.77	38.91	18.14	181.4	0.12	(21.8)36.8
0.2 – 0.4	24.73	42.58	17.85	178.5		35.7
0.4 – 0.6	28.49	43.71	15.22	152.2		30.4
0.6 – 0.8	35.28	44.58	9.30	93.0		18.6
0.8 – 1.0	41.65	44.58	2.93	29.3		5.9
1.0 – 1.2	43.56	44.61	1.05	10.5		2.1

B 10: Variations in moisture content (% vol.) in block C when leeks plants were 65 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	(θ_a - θ_p) (% vol.)	Equivalent depth = 10 (θ_a - θ_p) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.13	39.77	18.64	186.4	0.30	(37.28)
0.2 – 0.4	24.78	40.93	16.15	161.5		(16.15)32.3
0.4 – 0.6	30.18	41.81	11.63	116.3		23.3
0.6 – 0.8	35.67	42.62	6.95	69.5		13.9
0.8 – 1.0	40.07	43.74	3.95	36.7		7.3
1.0 – 1.2	43.66	43.97	0.30	3.0		0.6

B 11: Variations in moisture content (% vol.) in block C when leeks plants were 85 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	(θ_a - θ_p) (% vol.)	Equivalent depth = 10 (θ_a - θ_p) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.00	40.28	19.28	192.8	0.37	(38.6)
0.2 – 0.4	25.16	41.26	16.10	161.0		(27.4)34.2
0.4 – 0.6	29.88	43.71	13.83	138.3		27.7
0.6 – 0.8	34.90	44.03	9.13	91.3		18.3
0.8 – 1.0	39.12	44.31	5.19	51.9		10.4
1.0 – 1.2	41.57	44.49	2.92	29.2		5.8

B 12: Variations in moisture content (% vol.) in block C when leeks plants were 95 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	(θ_a - θ_p) (% vol.)	Equivalent depth = 10 (θ_a - θ_p) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	22.05	40.60	18.55	185.5	0.37	(37.1)
0.2 – 0.4	26.14	42.55	16.41	164.1		(27.9)32.8
0.4 – 0.6	30.64	43.09	12.45	124.5		24.9
0.6 – 0.8	37.49	43.73	6.24	62.4		12.5
0.8 – 1.0	41.00	44.16	3.16	31.6		6.3
1.0 – 1.2	43.68	44.50	0.82	8.2		1.6

B 13: Variations in moisture content (% vol.) in block D when leeks plants were 20 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	(θ_a - θ_p) (% vol.)	Equivalent depth = 10 (θ_a - θ_p) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.07	40.13	19.06	190.6	0.13	(24.8)38.1
0.2 – 0.4	26.11	40.75	14.64	146.4		29.3
0.4 – 0.6	31.86	41.63	9.77	97.7		19.5
0.6 – 0.8	36.04	42.06	6.02	60.2		12.0
0.8 – 1.0	40.90	42.48	1.58	15.8		3.2
1.0 – 1.2	42.37	43.91	1.54	15.4		3.1

B 14: Variations in moisture content (% vol.) in block D when leeks plants were 65 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	(θ_a - θ_p) (% vol.)	Equivalent depth = 10 (θ_a - θ_p) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.60	38.81	17.21	172.1	0.31	(34.4)
0.2 – 0.4	23.74	40.00	16.26	162.6		(17.9)32.5
0.4 – 0.6	28.50	40.60	12.10	121.0		24.2
0.6 – 0.8	33.61	41.08	7.47	74.7		14.9
0.8 – 1.0	38.18	41.66	3.48	34.8		6.96
1.0 – 1.2	40.83	42.04	1.21	12.1		2.40

B 15 Variations in moisture content (% vol.) in block D when leeks plants were 85 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	(θ_a - θ_p) (% vol.)	Equivalent depth = 10 (θ_a - θ_p) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.98	39.33	17.35	173.5	0.36	(34.7)
0.2 – 0.4	25.00	39.94	14.94	149.4		(23.9)29.9
0.4 – 0.6	30.00	41.20	11.20	112.0		22.4
0.6 – 0.8	39.44	41.72	2.28	22.8		4.6
0.8 – 1.0	43.06	43.90	0.84	8.4		1.7
1.0 – 1.2	43.53	43.87	0.34	3.4		0.7

B 16: Variations in moisture content (% vol.) in block D when leeks plants were 95 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.82	37.60	16.78	167.8	0.36	(33.6)
0.2 – 0.4	27.33	40.18	12.85	128.5		(20.6)25.7
0.4 – 0.6	31.61	41.64	10.03	100.3		20.0
0.6 – 0.8	38.88	42.06	3.18	31.8		6.4
0.8 – 1.0	40.90	42.75	1.85	18.5		3.7
1.0 – 1.2	41.63	43.14	1.51	15.1		3.0

B 17: Variations in moisture content (% vol.) in block E when leeks plants were 20 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.33	40.18	19.85	198.5	0.12	(23.82)39.7
0.2 – 0.4	23.70	41.03	17.33	173.3		34.7
0.4 – 0.6	29.10	41.46	12.36	123.6		24.7
0.6 – 0.8	36.14	42.00	5.86	58.6		11.7
0.8 – 1.0	39.57	42.17	2.60	26.0		5.2
1.0 – 1.2	40.79	42.60	1.80	18.0		3.6

B 18: Variations in moisture content (% vol.) in block E when leeks plants were 65 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.55	37.58	16.03	160.3	0.32	(32.1)
0.2 – 0.4	25.40	38.46	13.06	130.6		(15.7)26.1
0.4 – 0.6	29.17	40.37	11.20	112.0		22.4
0.6 – 0.8	38.00	41.68	3.68	36.8		7.4
0.8 – 1.0	40.83	42.05	1.22	12.2		2.4
1.0 – 1.2	41.29	42.39	1.10	11.0		2.2

B 19: Variations in moisture content (% vol.) in block E when leeks plants were 85 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.57	37.00	16.43	164.3	0.37	(32.9)
0.2 – 0.4	24.81	40.11	15.30	153.0		(26.0)30.6
0.4 – 0.6	30.00	40.59	10.59	105.9		21.2
0.6 – 0.8	37.99	41.66	3.67	36.7		7.3
0.8 – 1.0	40.00	42.84	2.84	28.4		5.7
1.0 – 1.2	40.88	43.06	2.18	21.8		4.4

B 20: Variations in moisture content (% vol.) in block E when leeks plants were 95 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.85	38.44	16.59	165.9	0.37	(33.2)
0.2 – 0.4	26.55	39.05	12.50	125.0		(21.3)25.0
0.4 – 0.6	30.19	41.60	11.41	114.1		22.8
0.6 – 0.8	35.73	41.83	6.10	61.0		12.2
0.8 – 1.0	40.03	42.68	2.65	26.5		5.3
1.0 – 1.2	40.59	42.97	2.38	23.8		4.8

B 21: Variations in moisture content (% vol.) in block F when leeks plants were 20 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.31	40.01	18.70	187.0	0.10	(18.7)37.4
0.2 – 0.4	24.60	40.11	15.51	155.1		31.0
0.4 – 0.6	29.13	40.82	11.69	116.9		23.4
0.6 – 0.8	35.90	41.16	5.26	52.6		10.4
0.8 – 1.0	39.93	42.06	2.13	21.3		4.3
1.0 – 1.2	41.04	42.50	1.46	14.6		3.0

B 22 Variations in moisture content (% vol.) in block F when leeks plants were 65 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.62	36.00	15.38	153.8	0.26	(30.8)
0.2 – 0.4	27.51	39.71	12.20	122.0		(7.3)24.4
0.4 – 0.6	29.48	41.04	11.56	115.6		23.1
0.6 – 0.8	34.27	41.55	7.28	72.8		14.6
0.8 – 1.0	39.00	42.13	3.13	31.3		6.3
1.0 – 1.2	40.63	42.64	2.01	20.1		4.0

B 23: Variations in moisture content (% vol.) in block F when leeks plants were 85 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	21.14	39.63	18.49	184.9	0.34	(37.0)
0.2 – 0.4	26.80	40.75	13.95	139.5		(19.5)27.9
0.4 – 0.6	30.77	40.90	10.13	101.3		20.3
0.6 – 0.8	38.15	41.16	3.01	30.1		6.0
0.8 – 1.0	40.00	41.88	1.88	18.8		3.8
1.0 – 1.2	41.00	42.58	1.58	15.8		3.2

B 24: Variations in moisture content (% vol.) in block F when leeks plants were 95 days

Sampling depth (m)	Pre-irrigation moisture content (θ_p) (% vol.)	Moisture content after irrigation (θ_a) (% vol.)	($\theta_a - \theta_p$) (% vol.)	Equivalent depth = 10 ($\theta_a - \theta_p$) (mm/m)	Average root zone depth (D_{rz}) (m)	Water retained in the root zone depth (in brackets) (mm)
0.0 – 0.2	20.54	37.90	17.36	173.6	0.35	(34.7)
0.2 – 0.4	25.97	40.13	14.16	141.6		(21.2)28.3
0.4 – 0.6	29.40	40.48	11.08	110.8		22.2
0.6 – 0.8	33.74	40.76	7.02	70.2		14.0
0.8 – 1.0	37.96	41.00	3.04	30.4		6.1
1.0 – 1.2	40.00	41.37	1.37	13.7		2.1

APPENDIX C PLANT-WATER-REQUIREMENT

C 1: Irrigation water requirement for leeks plants during the initial stage of growth (20 days)

E_{pan} (mm/day)	K_{pan} (dimensionless)	ET_o (mm/day)	K_c (dimensionless)	ET_c (mm/day)
8.3		6.6		2.3
9.6		7.7		2.7
7.7		6.2		2.2
9.0		7.2		2.5
7.1		5.7		2.0
8.6		6.9		2.4
8.9		7.1		2.5
9.3		7.4		2.6
9.6		7.7		2.7
9.4	0.80	7.5	0.35	2.6
10.3		8.2		2.9
10.0		8.0		2.8
8.7		7.0		2.5
8.2		6.6		2.3
8.6		6.9		2.4
7.0		5.6		2.0
7.4		5.9		2.1
7.4		5.9		2.1
8.0		6.4		2.2
10.5		8.4		2.9

C 2: Irrigation water requirement for leeks plants during the crop development stage of growth (45 days)

E_{pan} (mm/day)	K_{pan} (dimensionless)	ET_o (mm/day)	K_c (dimensionless)	ET_c (mm/day)
10.7		8.6		9.8
10.9		8.7		9.9
9.1		7.3		8.3
9.3		7.4		8.4
11.8		9.4		10.7
8.0		6.4		7.3
9.5		7.6		8.7
8.9		7.1		8.1
6.0		4.8		5.5
7.5		6.0		6.8
8.3		6.6		7.5
8.4		6.7		7.6
8.9		7.1		8.1
10.0		8.0		9.1
10.6		8.5		9.7
8.4		6.7		7.6
10.1		8.1		9.2
8.8		7.0		8.0
4.0		3.2		3.6
6.8		5.4		6.2
7.4		5.9		6.7
6.7	0.8	5.4	1.14	6.2
7.5		6.0		6.8
6.5		5.2		5.9
5.0		4.0		4.6
5.3		4.2		4.8
5.4		4.3		4.9
5.1		4.1		4.7
6.1		4.9		5.6
6.6		5.3		6.0
4.4		3.5		4.0
5.5		4.4		5.0
5.7		4.6		5.2
4.2		3.4		3.9
4.2		3.4		3.9
5.9		4.7		5.4
8.5		6.8		7.8
8.5		6.8		7.8
8.4		6.7		7.6
8.5		6.8		7.8
8.4		6.7		7.6
9.4		7.5		8.6
7.8		6.2		7.1
8.4		6.7		7.6
8.7		7.0		8.0

C 3: Irrigation water requirement for leeks plants during the maturity Stage (20 days)

E_{pan} (mm/day)	K_{pan} (dimensionless)	ET_o (mm/day)	K_c (dimensionless)	ET_c (mm/day)
9.8		7.8		7.5
8.6		6.9		6.5
8.8		7.0		6.7
7.2		5.8		5.5
4.4		3.5		3.3
4.9		3.9		3.7
9.1		7.3		6.9
9.3		7.4		7.1
7.4		5.9		5.6
6.5	0.80	5.2	0.95	4.9
8.7		7.0		6.6
8.1		6.5		6.2
8.6		6.9		6.5
8.1		6.5		6.2
2.8		2.2		2.1
6.4		5.1		4.9
6.1		4.9		4.6
6.0		4.8		4.6
4.0		3.2		3.0
6.6		5.3		5.0

C 4: Irrigation water requirement for leeks plants during the late season Stage (10 days)

E_{pan} (mm/day)	K_{pan} (dimensionless)	ET_o (mm/day)	K_c (dimensionless)	ET_c (mm/day)
7.7		6.2		5.9
6.5		5.2		4.9
8.1		6.5		6.2
8.8		7.0		6.7
7.6	0.8	6.1	0.95	5.8
9.5		7.6		7.2
4.3		3.4		3.3
7.3		5.8		5.6
5.5		4.4		4.2
7.1		5.7		5.4

APPENDIX D SOIL MOISTURE CONSTANTS

D 1 Variations in field capacity (*FC* % vol.), permanent wilting point (*pwp* % vol.) and available water (*AW* cm)

Location		Depth of sample (m) 0 – 0.2	0.2 - 0.4	0.4 - 0.6	0.6 – 0.8	0.8 - 1.0	1.0 - 1.2	Total
Field 'A'	FC (%)	41.08	41.19	46.29	37.46	37.98	37.98	
	PWP (%)	21.07	20.17	19.16	20.99	19.65	19.96	
	AW (cm)	4.0	4.2	5.4	3.3	3.7	3.6	24.2
Field 'B'	FC (%)	39.68	39.82	34.22	33.12	32.24	27.94	
	PWP (%)	20.56	19.29	19.47	21.54	19.69	19.62	
	AW (cm)	3.8	4.1	3.0	2.3	2.5	1.7	17.4
Field 'C'	FC (%)	37.95	32.80	37.23	33.63	32.38	27.37	
	PWP (%)	17.94	20.26	20.37	18.33	20.51	18.74	
	AW (cm)	4.0	2.5	3.4	3.1	2.4	1.7	17.1
Field 'D'	FC (%)	35.65	39.41	36.57	34.43	32.46	28.82	
	PWP (%)	20.03	19.60	19.98	20.82	20.58	20.06	
	AW (cm)	3.2	4.0	3.3	2.7	2.4	1.8	17.4
Field 'E'	FC (%)	40.26	36.10	35.22	39.00	32.79	28.81	
	PWP (%)	18.59	17.82	18.94	21.18	19.05	18.86	
	AW (cm)	4.4	3.7	3.3	3.6	2.8	2.0	19.8
Field 'F'	FC (%)	37.45	33.93	38.30	33.30	41.58	27.52	
		21.10	20.92	18.76	21.04	21.69	19.91	
		3.3	2.6	3.9	2.5	4.0	1.5	16.3
Bulk density (Mg/M^3)			1.24	1.29	1.27	1.31	1.33	

APPENDIX E IRRIGATION EFFICIENCIES

E 1: Storage efficiency in leeks fields

Block	Moisture content at field capacity (fc) (% vol.)	Pre-irrigation moisture content (θ) (% vol.)	Fc - θ (% vol.)	Average root zone depth (D_{rz}) (cm)	Water stored in the root zone (W_s) (cm)	Water required to fill the root zone to field capacity (W_n) (cm)	E_r (%)
			Between 0 – 20 days old				
A	41.08	26.01	15.07	12	2.95	1.81	100.0
B	39.68	24.39	15.29	11	2.51	1.68	100.0
C	37.95	25.77	12.18	12	2.18	1.46	100.0
D	35.65	23.07	12.58	13	2.48	1.64	100.0
E	40.26	24.33	15.93	12	2.38	1.91	100.0
F	37.45	26.01	11.44	10	1.87	1.14	100.0
			Between 20 – 65 days old				
A	41.08	24.87	16.21	29	6.15	4.70	100.0
B	39.68	24.60	15.08	29	6.37	4.37	100.0
C	37.95	24.96	12.99	30	5.34	3.90	100.0
D	35.65	27.67	7.98	31	5.23	2.47	100.0
E	40.26	24.48	15.78	32	4.78	5.05	94.7
F	37.45	28.31	9.14	26	3.81	2.38	100.0
			Between 65 – 85 days old				
A	41.08	23.41	17.67	34	7.39	6.01	100.0
B	39.68	26.36	13.32	36	6.70	4.80	100.0
C	37.95	25.58	12.37	37	6.60	4.58	100.0
D	35.65	25.49	10.16	36	5.86	3.66	100.0
E	40.26	26.69	13.57	37	5.89	5.02	100.0
F	37.45	25.97	11.48	34	5.60	3.90	100.0
			Between 85 – 95 days old				
A	41.08	27.70	13.38	34	7.63	4.55	100.0
B	39.68	27.70	11.98	36	6.43	4.31	100.0
C	37.95	24.10	13.85	37	6.50	5.12	100.0
D	35.65	24.10	11.55	36	5.42	4.16	100.0
E	40.26	25.20	15.06	37	5.45	5.57	98.8
F	37.45	24.26	13.19	35	5.59	4.62	100.0

E 2: Irrigation water application efficiency for leeks fields (MAD = 0.5)

Block	Average wetted area per single plot (m^2)	Sprinkler discharge rate (m^3/s)	Duration of irrigation (h)	Readily Available Water (RAW) (cm)	Root zone depth (D_{rz}) (cm)	Fc–pwp (% vol.)	Volume of water applied (W_s) (m^3)	Volume of water beneficially used by crops (W_f) (m^3)	Application efficiency (%)
Between 0 – 20 days old									
A	444.70	0.00058	6.5	1.2	12	20.01	13.57	5.34	39.3
B	502.57	0.00061	7.2	1.1	11	19.12	15.81	5.53	35.0
C	483.11	0.00068	6.0	1.2	12	20.01	11.02	5.80	52.6
D	432.73	0.00054	6.9	1.0	13	15.62	13.41	4.33	32.3
E	392.24	0.00044	7.3	1.3	12	21.67	11.56	5.10	44.1
F	391.23	0.00041	7.4	0.8	10	16.35	10.92	3.13	28.7
Between 20 – 65 days old									
A	486.50	0.00069	7.7	2.9	29	20.01	19.13	14.11	73.8
B	398.99	0.00044	7.7	2.7	29	19.12	12.20	10.77	88.3
C	392.84	0.00044	8.3	3.0	30	20.01	13.15	11.78	89.6
D	380.96	0.00041	7.3	2.4	31	15.62	10.77	9.14	84.9
E	400.49	0.00046	7.4	3.5	32	21.67	12.25	14.02	114.4
F	389.48	0.00042	7.2	2.1	26	16.35	10.89	8.18	75.1
Between 65 – 85 days old									
A	473.65	0.00063	7.7	3.4	34	20.01	17.46	16.10	92.2
B	441.17	0.00055	7.7	3.4	36	19.12	15.25	15.10	98.4
C	409.88	0.00048	6.7	3.7	37	20.01	11.58	15.17	131.0
D	416.21	0.00051	7.7	2.8	36	15.62	14.14	11.65	82.4
E	379.81	0.00048	6.7	4.0	37	21.67	11.58	15.19	131.2
F	386.48	0.00041	7.3	2.8	34	16.35	10.77	10.82	100.5
Between 85 – 95									
A	436.64	0.00053	7.4	3.4	34	20.01	14.12	14.85	105.2
B	413.97	0.00051	7.4	3.4	36	19.12	13.59	14.07	103.5
C	393.14	0.00043	7.4	3.7	37	20.01	11.46	14.55	127.0
D	417.03	0.00052	6.1	2.8	36	15.62	11.46	11.68	101.9
E	400.00	0.00043	7.2	4.0	37	21.67	11.15	16.00	143.5
F	419.54	0.00051	7.1	2.9	35	16.35	13.03	12.17	93.4

E 3: Conveyance efficiency (E_c) for leeks fields

Block	Plot	Canal discharge rate at the intake point (m^3/s)	Canal discharge rate at the field taping point (m^3/s)	Hose pipe discharge rate at the intake point (m^3/s)	Sprinkler discharge rate (m^3/s)	Duration of irrigation (h)	E_c (%)
A	1	0.0045	0.0040	0.00059	0.00059	7.2	89.03
	2	0.0054	0.0040	0.00060	0.00059	7.4	74.63
	3	0.0041	0.0039	0.00057	0.00056	7.3	96.00
B	1	0.0053	0.0050	0.00057	0.00057	7.6	94.61
	2	0.0059	0.0048	0.00064	0.00063	7.1	81.38
	3	0.0062	0.0060	0.00065	0.00064	7.5	97.14
	4	0.0047	0.0041	0.00056	0.00056	7.2	86.97
	5	0.0051	0.0043	0.00056	0.00055	7.3	83.92
C	1	0.0104	0.0094	0.00054	0.00054	7.3	90.07
	2	0.0093	0.0088	0.00052	0.00052	6.9	94.35
	3	0.0100	0.0092	0.00052	0.00051	7.7	91.13
	4	0.0103	0.0090	0.00054	0.00054	6.8	86.98
	5	0.0113	0.0094	0.00054	0.00054	7.5	83.00
	6	0.0098	0.0089	0.00054	0.00054	7.1	90.65
D	1	0.0099	0.0086	0.00057	0.00057	7.4	86.09
	2	0.0095	0.0084	0.00053	0.00052	7.3	88.88
E	1	0.0117	0.0083	0.00058	0.00058	6.9	71.06
	2	0.0116	0.0081	0.00059	0.00058	6.8	69.94
F	1	0.0104	0.0078	0.00064	0.00063	7.2	74.93
	2	0.0101	0.0080	0.00063	0.00063	7.2	79.15
	3	0.0096	0.0081	0.00064	0.00063	7.3	84.54
	4	0.0097	0.0078	0.00057	0.00056	7.1	80.36

E 4 A summary of conveyance efficiency (E_c) for various leeks fields

Block	Mean E_c	s.d	c.v (%)
A	86.55	10.90	12.59
B	88.68	6.68	7.53
C	89.36	3.91	4.37
D	87.49	1.97	2.25
E	70.50	0.79	1.12
F	79.75	3.95	4.95

APPENDIX F CROP AND SPECIFIC YIELD

F 1: Average yields for leeks crops

Block	Plot	Name of Canal supplying irrigation water	Specific yield (kg/m^3)	Yield per irrigated area (ton/ha)
A	1	A	1.17	14.8
	2	A	0.98	12.0
	3	A	1.07	13.8
B	1	A	1.15	14.3
	2	A	1.13	11.0
	3	A	1.16	11.5
	4	B	1.11	13.6
	5	B	0.92	11.8
C	1	B	1.14	10.6
	2	B	1.21	14.1
	3	B	1.32	11.3
	4	B	1.01	13.0
	5	B	0.68	13.3
	6	B	0.99	12.4
D	1	B	1.17	11.0
	2	B	1.01	10.7
E	1	B	0.95	9.3
	2	B	1.06	10.0
F	1	B	1.18	9.8
	2	C	0.41	10.7
	3	C	0.34	11.9
	4	C	0.67	13.6

APPENDIX G SEDIMENT LOAD AND SPLASH EROSION

G1: Daily sediment yield in three main irrigation canals

Year	Month		Date of the day when irrigation was done	Mean sediment yield (g/l)	
			Canal 'A'	Canal 'B'	Canal 'C'
1998	November	05	0.190	0.793	0.361
	November	07	0.221	0.791	0.357
	November	10	0.200	0.796	0.377
	November	11	0.400	0.793	0.311
	November	14	0.119	0.814	0.314
	November	17	0.210	0.821	0.301
	November	20	0.227	0.711	0.341
	November	24	0.630	0.768	0.359
	November	26	0.470	0.861	0.333
	November	29	0.390	0.747	0.365
	December	02	0.140	0.781	0.322
	December	05	0.360	0.707	0.337
	December	07	0.311	0.956	0.344
	December	08	0.212	0.928	0.343
	December	09	0.101	0.776	0.348
	December	14	0.100	0.861	0.320
	December	17	0.093	0.800	0.319
	December	20	0.081	0.931	0.327
	December	22	0.077	0.730	0.318
	December	27	0.065	0.400	0.338
	December	28	0.161	0.701	0.349
	December	29	0.231	0.729	0.366
1999	January	03	0.613	0.796	0.391
	January	05	0.227	0.675	0.384
	January	07	0.200	0.869	0.376
	January	11	0.101	0.810	0.370
	January	14	0.107	0.691	0.552
	January	16	0.003	0.806	0.301
	January	19	0.010	0.824	0.300
	January	21	0.111	0.879	0.319
	January	24	0.378	0.741	0.314

G 2 Various variables for irrigation canals

Canal name	Slope (%)	Average discharge rate (m^3/s)	Average velocity (m/s)	Average cross-sectional area (m^2)	Average wetted perimeter (m)	Average hydraulic radius (m)	Canal lengt h (m)	Average sediment load (g/l)
A	0.27	0.004	0.40	0.035	1.49	0.10	297	0.211
B	7.40	0.009	0.90	0.068	2.56	0.19	688	0.793
C	0.94	0.006	0.70	0.049	1.95	0.14	309	0.347

G 3: Average rates of splash erosion in leeks fieldss

Block	Antecedent soil moisture content (0-20 cm depth) (% vol.)	Sprinkler precipitation rate (mm/h)	Duration of irrigation (h)	Wetted area (m^2)	Gross splash erosion (kg)	Downslope splash erosion (kg)	Upslope splash erosion (kg)	Across-slope splash erosion (kg)	Net downslope splash erosion (kg)
Between 0 – 20 days old									
A	26.01	4.8	7.1	444.70	20.11	2.16	0.19	0.91	1.97
B	24.39	4.5	7.7	502.57	22.73	1.57	0.25	0.74	1.32
C	25.77	4.2	7.1	483.11	21.18	1.42	0.45	0.67	0.97
D	23.08	4.5	5.8	432.73	12.43	1.10	0.50	0.60	0.60
E	24.33	3.9	6.4	392.24	9.03	0.88	0.57	0.51	0.31
F	26.01	4.1	5.7	391.23	5.55	0.69	0.66	0.46	0.03
Between 20 – 65 days old									
A	24.87	4.8	7.6	486.50	12.44	1.49	0.11	0.78	1.38
B	24.60	4.4	7.1	398.99	11.62	1.13	0.19	0.73	0.94
C	24.96	4.2	7.2	392.84	11.94	0.99	0.38	0.73	0.61
D	27.67	4.2	7.8	380.96	11.79	0.89	0.38	0.60	0.51
E	24.48	3.8	8.4	400.49	9.87	0.55	0.44	0.56	0.11
F	28.31	3.8	8.2	389.48	9.84	0.35	0.44	0.50	-0.15
Between 65 – 85 days old									
A	23.41	4.9	7.2	473.65	9.97	0.94	0.09	0.18	0.87
B	26.36	4.1	7.8	441.17	7.59	0.77	0.13	0.18	0.64
C	25.58	4.9	7.1	409.88	5.55	0.75	0.23	0.11	0.52
D	25.49	4.1	7.9	416.21	4.37	0.27	0.24	0.03	0.01
E	26.69	4.6	7.2	379.81	7.19	0.23	0.21	0.03	0.02
F	25.97	4.0	7.9	386.48	6.66	0.16	0.29	0.03	-0.13
Between 85 – 95 days old									
A	27.70	5.0	6.8	436.64	8.55	0.81	0.09	0.22	0.72
B	27.70	4.8	7.1	413.97	6.02	0.73	0.10	0.13	0.63
C	24.10	4.3	7.0	393.14	5.00	0.71	0.22	0.08	0.49
D	24.10	4.4	7.4	417.03	5.07	0.33	0.33	0.05	0.00
E	25.20	4.0	7.6	400.00	6.14	0.19	0.41	0.02	-0.22
F	24.26	3.9	7.9	419.54	3.97	0.18	0.39	0.02	-0.21

APPENDIX H STATISTICAL ANALYSES

H 1: ANOVA for effects of slope and plant age on downslope splash erosion

Factor A:slope: Factor B:Plant age
Variable: Downslope
Grand Mean = 0.743 Grand Sum = 35.660 Total Count = 48

T A B L E O F M E A N S

1	2	3	4	Total
1	*	*	0.761	18.270
2	*	*	0.725	17.390
*	1	*	1.318	10.540
*	2	*	0.959	7.670
*	3	*	0.801	6.410
*	4	*	0.610	4.880
*	5	*	0.460	3.680
*	6	*	0.310	2.480
*	*	1	1.153	13.830
*	*	2	0.826	9.910
*	*	3	0.492	5.900
*	*	4	0.502	6.020

A N A L Y S I S O F V A R I A N C E T A B L E

K Value	Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
1	Replication	1	0.016	0.016	4.3569	0.0481
2	Factor A	5	5.322	1.064	287.4541	0.0000
4	Factor B	3	3.552	1.184	319.7083	0.0000
6	AB	15	0.516	0.034	9.2915	0.0000
-7	Error	23	0.085	0.004		
	Total	47	9.491			

Coefficient of Variation: 8.19%

s_ for means group 1: 0.0124 Number of Observations: 24
y
s_ for means group 2: 0.0215 Number of Observations: 8
y
s_ for means group 4: 0.0176 Number of Observations: 12
y
s_ for means group 6: 0.0430 Number of Observations: 2
y

H 2: ANOVA for effects of slope and plant age on upslope splash erosion

Variable 5: Upslope
Grand Mean = 0.300 Grand Sum = 14.390 Total Count = 48

T A B L E O F M E A N S

1	2	3	5	Total
1	*	*	0.307	7.380
2	*	*	0.292	7.010
*	1	*	0.104	0.830
*	2	*	0.159	1.270
*	3	*	0.298	2.380
*	4	*	0.357	2.860
*	5	*	0.417	3.340
*	6	*	0.464	3.710
*	*	1	0.445	5.340
*	*	2	0.302	3.630
*	*	3	0.219	2.630
*	*	4	0.232	2.790

A N A L Y S I S O F V A R I A N C E T A B L E

K Value	Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
1	Replication	1	0.003	0.003	1.0754	0.3105
2	Factor A	5	0.819	0.164	61.7767	0.0000
4	Factor B	3	0.385	0.128	48.4470	0.0000
6	AB	15	0.114	0.008	2.8558	0.0116
-7	Error	23	0.061	0.003		
	Total	47	1.382			

Coefficient of Variation: 17.18%

s_y for means group 1: 0.0105 Number of Observations: 24
s_y for means group 2: 0.0182 Number of Observations: 8
s_y for means group 4: 0.0149 Number of Observations: 12
s_y for means group 6: 0.0364 Number of Observations: 2

H.3: ANOVA for effects of slope and plant age on across-slope splash erosion

Grand Mean = 0.358 Grand Sum = 17.190 Total Count = 48

T A B L E O F M E A N S

1	2	3	6	Total
1	*	*	0.357	8.570
2	*	*	0.359	8.620
*	1	*	0.503	4.020
*	2	*	0.436	3.490
*	3	*	0.368	2.940
*	4	*	0.313	2.500
*	5	*	0.280	2.240
*	6	*	0.250	2.000
*	*	1	0.629	7.550
*	*	2	0.637	7.640
*	*	3	0.083	0.990
*	*	4	0.084	1.010

A N A L Y S I S O F V A R I A N C E T A B L E

K Value	Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
1	Replication	1	0.000	0.000	0.0545	
2	Factor A	5	0.375	0.075	78.4779	0.0000
4	Factor B	3	3.625	1.208	1263.3269	0.0000
6	AB	15	0.099	0.007	6.8680	0.0000
-7	Error	23	0.022	0.001		
	Total	47	4.121			

Coefficient of Variation: 8.64%

s_ for means group 1: 0.0063 Number of Observations: 24
 y
s_ for means group 2: 0.0109 Number of Observations: 8
 y
s_ for means group 4: 0.0089 Number of Observations: 12
 y
s_ for means group 6: 0.0219 Number of Observations: 2
 y

H 4: ANOVA for effects of slope and plant age on gross-splash erosion

Grand Mean = 9.072 Grand Sum = 435.450 Total Count = 48

T A B L E O F M E A N S

1	2	3	7	Total
1	*	*	9.134	219.220
2	*	*	9.010	216.230
*	1	*	11.954	95.630
*	2	*	10.466	83.730
*	3	*	10.066	80.530
*	4	*	7.854	62.830
*	5	*	8.066	64.530
*	6	*	6.025	48.200
*	*	1	13.566	162.790
*	*	2	10.393	124.710
*	*	3	6.391	76.690
*	*	4	5.938	71.260

A N A L Y S I S O F V A R I A N C E T A B L E

K Value	Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
1	Replication	1	0.186	0.186	0.1571	
2	Factor A	5	184.135	36.827	31.0616	0.0000
4	Factor B	3	467.361	155.787	131.3984	0.0000
6	AB	15	197.572	13.171	11.1095	0.0000
-7	Error	23	27.269	1.186		
	Total	47	876.524			

Coefficient of Variation: 12.00%

s_ for means group 1: 0.2223 Number of Observations: 24
 y
s_ for means group 2: 0.3850 Number of Observations: 8
 y
s_ for means group 4: 0.3143 Number of Observations: 12
 y
s_ for means group 6: 0.7699 Number of Observations: 2
 y

H 5: Duncan's New Multiple Range Test for effect of plant age on downslope splash

Error Mean Square = 0.004000
Error Degrees of Freedom = 23
No. of observations to calculate a mean = 12

Duncan's New Multiple Range Test
LSD value = 0.05341
s_ = 0.01826 at alpha = 0.050
x

Original Order			Ranked Order		
Mean 1 =	1.153	A	Mean 1 =	1.153	A
Mean 2 =	0.8258	B	Mean 2 =	0.8258	B
Mean 3 =	0.4917	C	Mean 4 =	0.5017	C
Mean 4 =	0.5017	C	Mean 3 =	0.4917	C

H 6: Duncan's New Multiple Range Test for effect of plant age on upslope splash

Error Mean Square = 0.003000
Error Degrees of Freedom = 23
No. of observations to calculate a mean = 12

Duncan's New Multiple Range Test
LSD value = 0.04626
s_ = 0.01581 at alpha = 0.050
x

Original Order			Ranked Order		
Mean 1 =	0.4450	A	Mean 1 =	0.4450	A
Mean 2 =	0.3025	B	Mean 2 =	0.3025	B
Mean 3 =	0.2192	C	Mean 4 =	0.2325	C
Mean 4 =	0.2325	C	Mean 3 =	0.2192	C

H 7: Duncan's New Multiple Range Test for effect of plant age on gross splash

Error Mean Square = 0.001000
Error Degrees of Freedom = 23
No. of observations to calculate a mean = 12

Duncan's New Multiple Range Test
LSD value = 0.02671
s_ = 0.009129 at alpha = 0.050
x

Original Order		Ranked Order	
Mean 1 =	0.6292 A	Mean 2 =	0.6367 A
Mean 2 =	0.6367 A	Mean 1 =	0.6292 A
Mean 3 =	0.08250 B	Mean 4 =	0.08417 B
Mean 4 =	0.08417 B	Mean 3 =	0.08250 B

H 8: Duncan's New Multiple Range Test for effect of slope on downslope splash

Variable 4 : Downslope

Error Mean Square = 0.004000
Error Degrees of Freedom = 23
No. of observations to calculate a mean = 8

Duncan's New Multiple Range Test
LSD value = 0.06542
s_ = 0.02236 at alpha = 0.050
x

Original Order			Ranked Order		
Mean 1 =	1.317	A	Mean 1 =	1.317	A
Mean 2 =	0.9588	B	Mean 2 =	0.9588	B
Mean 3 =	0.8012	C	Mean 3 =	0.8012	C
Mean 4 =	0.6100	D	Mean 4 =	0.6100	D
Mean 5 =	0.4600	E	Mean 5 =	0.4600	E
Mean 6 =	0.3100	F	Mean 6 =	0.3100	F

H 9: Duncan's New Multiple Range Test for effect of slope on upslope splash

Variable 5 : Upslope

Error Mean Square = 0.003000
Error Degrees of Freedom = 23
No. of observations to calculate a mean = 8

Duncan's New Multiple Range Test
LSD value = 0.05665
s_ = 0.01936 at alpha = 0.050
x

Original Order			Ranked Order		
Mean 1 =	0.1037	D	Mean 6 =	0.4638	A
Mean 2 =	0.1587	D	Mean 5 =	0.4175	A
Mean 3 =	0.2975	C	Mean 4 =	0.3575	B
Mean 4 =	0.3575	B	Mean 3 =	0.2975	C
Mean 5 =	0.4175	A	Mean 2 =	0.1587	D
Mean 6 =	0.4638	A	Mean 1 =	0.1037	D

H 10: Duncan's New Multiple Range Test for effect of slope on across-slope erosion

Variable 6 : Acrosslope

Error Mean Square = 0.001000
Error Degrees of Freedom = 23
No. of observations to calculate a mean = 8

Duncan's New Multiple Range Test
LSD value = 0.03271
s_ = 0.01118 at alpha = 0.050
x

Original Order				Ranked Order			
Mean	1 =	0.5025	A	Mean	1 =	0.5025	A
Mean	2 =	0.4363	B	Mean	2 =	0.4363	B
Mean	3 =	0.3675	C	Mean	3 =	0.3675	C
Mean	4 =	0.3125	D	Mean	4 =	0.3125	D
Mean	5 =	0.2800	DE	Mean	5 =	0.2800	DE
Mean	6 =	0.2500	E	Mean	6 =	0.2500	E

H 11: Duncan's New Multiple Range Test for effect of slope on gross splash erosion

Variable 7 : Gross-splash

Error Mean Square = 1.186
Error Degrees of Freedom = 23
No. of observations to calculate a mean = 8

Duncan's New Multiple Range Test
LSD value = 1.126
s_ = 0.3850 at alpha = 0.050
x

Original Order				Ranked Order			
Mean	1 =	11.95	A	Mean	1 =	11.95	A
Mean	2 =	10.47	B	Mean	2 =	10.47	B
Mean	3 =	10.07	B	Mean	3 =	10.07	B
Mean	4 =	7.854	C	Mean	5 =	8.066	C
Mean	5 =	8.066	C	Mean	4 =	7.854	C
Mean	6 =	6.025	D	Mean	6 =	6.025	D

H 12: SAS for the anthropological study

Variable	N	Mean	Std Dev	Minimum	Maximum
AGE	22	27.22	6.413717.0000	44.00000	

The SAS System

AGE	Frequency	Percent	Cumulative Frequency	Cumulative Percent
17	1	4.5	1	4.5
19	1	4.5	2	9.1
20	1	4.5	3	13.6
21	2	9.1	5	22.7
22	1	4.5	6	27.3
23	1	4.5	7	31.8
24	1	4.5	8	36.4
25	1	4.5	9	40.9
27	1	4.5	10	45.5
28	2	9.1	12	54.5
29	4	18.2	16	72.7
30	2	9.1	18	81.8
31	1	4.5	19	86.4
35	1	4.5	20	90.9
38	1	4.5	21	95.5
44	1	4.5	22	100.0

SEX	Frequency	Percent	Cumulative Frequency	Cumulative Percent
M	22	100.0	22	100.0

The SAS System

MARSTAT	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	4	18.2	4	18.2
2	13	59.1	17	77.3
3	5	22.7	22	100.0

EDULEV	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	3	13.6	3	13.6
3	19	86.4	22	100.0

MAJACT	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	7	31.8	7	31.8
2	1	4.5	8	36.4
3	8	36.4	16	72.7
5	6	27.3	22	100.0

WHY51	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	1	4.5	1	4.5
2	19	86.4	20	90.9
3	2	9.1	22	100.0

WHEN52	Frequency	Percent	Cumulative Frequency	Cumulative Percent
2	2	9.1	2	9.1
3	20	90.9	22	100.0

WHY53	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	21	95.5	21	95.5
2	1	4.5	22	100.0

HOW54	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	4	18.1	4	18.2
2	8	36.4	12	54.5
3	10	45.5	22	100.0

HOW55	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	19	86.4	19	86.4
2	2	9.1	21	95.5
3	1	4.5	22	100.0

WHY56	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	18	81.8	18	81.8
2	4	18.2	22	100.0

WHICH57	Frequency	Percent	Cumulative Frequency	Cumulative Percent
3	22	100.0	22	100.0

WHY58	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	4	18.2	4	18.2
2	18	81.8	22	100.0

H 13: ANOVA for effect of change of soil depth on moisture content

MOISTURE

Title: depth

Two Factor Randomized Complete Block Design

Factorial ANOVA for the factors:

Replication (Var 1: plot) with values from 1 to 2
Factor A (Var 2: block) with values from 1 to 6
Factor B (Var 3: depth) with values from 1 to 6

Variable 4: moisture

Grand Mean = 32.403 Grand Sum = 2333.040 Total Count = 72

T A B L E O F M E A N S

1	2	3	4	Total
1	*	*	32.475	1169.110
2	*	*	32.331	1163.930
*	1	*	32.683	392.200
*	2	*	33.064	396.770
*	3	*	32.497	389.970
*	4	*	32.068	384.810
*	5	*	32.156	385.870
*	6	*	31.952	383.420
*	*	1	20.902	250.830
*	*	2	25.022	300.260
*	*	3	29.782	357.380
*	*	4	36.251	435.010
*	*	5	40.379	484.550
*	*	6	42.084	505.010

A N A L Y S I S O F V A R I A N C E T A B L E

K Value	Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
1	Replication	1	0.373	0.373	0.3772	
2	Factor A	5	10.824	2.165	2.1910	0.0774
4	Factor B	5	4389.204	877.841	888.4584	0.0000
6	AB	25	33.540	1.342	1.3578	0.1990
7	Error	35	34.582	0.988		
	Total	71	4468.523			

Coefficient of Variation: 3.07%

s_ for means group 1: 0.1657 Number of Observations: 36
 y
s_ for means group 2: 0.2869 Number of Observations: 12
 y
s_ for means group 4: 0.2869 Number of Observations: 12
 y
s_ for means group 6: 0.7029 Number of Observations: 2
 y

H 14: Duncan's New Multiple Range Test for effect of change of soil depth in moisture content

```
MOISTURE
Title :  depth

Variable 4 : moisture

Error Mean Square = 0.9880
Error Degrees of Freedom = 5
No. of observations to calculate a mean = 12

Duncan's New Multiple Range Test
LSD value = 1.043
s_ = 0.2869     at alpha = 0.050
 x
```

Original Order				Ranked Order			
Mean	1 =	20.90	F	Mean	6 =	42.08	A
Mean	2 =	25.02	E	Mean	5 =	40.38	B
Mean	3 =	29.78	D	Mean	4 =	36.25	C
Mean	4 =	36.25	C	Mean	3 =	29.78	D
Mean	5 =	40.38	B	Mean	2 =	25.02	E
Mean	6 =	42.08	A	Mean	1 =	20.90	F