INTEGRATED WATERSHED DEVELOPMENT FOR FOOD SECURITY AND SUSTAINABLE IMPROVEMENT OF LIVELIHOOD IN BARANI, PAKISTAN

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ICARDA International Center for Agricultural Research in the Dry Areas

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Contents

Executive Summary

Water scarcity is a major concern in Pakistan, as in many countries worldwide. Both availability (quantity) and quality of water are declining, due to agricultural expansion, population growth, urbanization and industrialization. Per capita water availability in Pakistan has fallen from 5600 m^3 in 1947 to about 1000 m^3 currently. Out of 80 million hectares (Mha) of land, around 41 Mha are arid, and populated mostly by poor communities whose livelihoods are at subsistence levels. Agricultural productivity in these areas is very low as a result of low and erratic rainfall, mismanagement of runoff, soil erosion, small and fragmented landholdings, and low level of inputs.

This report summarizes results from a large multi-partner project, *Integrated watershed development for food security and sustainable improvement of livelihood in Barani, Pakistan*. The project (2007 to 2010) aimed to develop, demonstrate, and evaluate cost-effective technologies for monitoring and use of water and land resources at watershed scale. It used an integrated approach combining applied research, capacity building, and watershed improvement/rehabilitation through community action plans. All key parameters — water quantity and quality, wastewater, soil erosion, livelihood improvement — were taken into account.

The project was implemented in the Dhrabi watershed, Chakwal, jointly by ICARDA; the University of Natural Resources and Applied Life Sciences (BOKU), Vienna, Austria; and several Pakistani organizations: Barani Agriculture Research Institute, Soil and Water Conservation Research Institute, University of Arid Agriculture, and the National Rural Support Program.

Socio-economic conditions and natural resources in the watershed were characterized. Twenty two communities were organized to form a watershed association. Soil erosion and low agricultural productivity were the communities' main concerns. Rainfall events of greater than 21 mm caused erosion, with sediment yields ranging from 4 to 12 t/ha/yr. Low-cost structures were installed at sub-watershed level and proved to be very effective in reducing erosion and conserving soil moisture. Gully farming was introduced to control soil erosion. Millet and sorghum, when grown in gullies using improved practices, yielded 44 and 49 t/ha of fodder, respectively. Clearly there is great potential to expand cultivation in gullied areas.

Water quality is a key issue, and should be fully considered during watershed planning and management. There was a strong interaction between water and crop management (improved variety, seed rate, sowing date, fertilizers etc.). Both factors must be well managed to achieve high yield and water productivity. With improved practices, crops yields were almost double those from traditional farmer practice.

Capacity building was an integral component of the project. About 600 farmers and 100 professional staff were trained. In addition, ten students from various disciplines completed their Master and PhD degrees with project support.

Project Overview

T. Oweis and M. Ashraf

Of the 22% of the world's land suitable for agricultural production, between 5 Mha and 7 Mha are being lost annually through land degradation, thus seriously threatening food security (Lal and Stewart, 1982; Buring, 1989). Successful conservation of diminishing water and land resources and better livelihood strategies are needed to feed an ever-increasing population. In Pakistan, dryland farming is practiced on 12 Mha. The area faces abject poverty and serious land degradation problems. At altitudes between 300 m and 700 m above sea level, the area consists of gullies (wasteland), terraced fields along hillsides, and irrigated fields. The annual rainfall varies from 300 mm to 800 mm. Poverty, severe erosion, and diminishing vegetation cover are the root causes of the land degradation.

Gullied areas, also called wasteland, are used as natural forests or rangelands. Intensive rainstorms in the monsoon season generate sharp peak runoffs which, combined with steep topography and low vegetation, cause gully expansion. This deepening and expansion of the gullies is one of the root causes of the ever-decreasing arable land in the area. Terraced fields are used for rainfed agriculture.

Depending on the rainfall, the farmers raise one to two crops a year. Rainwater harvesting and its conservation as soil-water are one way to meet crop-water requirements, but the high runoff rate during the monsoon overflows the ridges and damages them. This damage contributes to a heavy sediment influx and, in the worst case scenario, the breaching of the terraced fields may result in the development of new gullies and an expansion of the wasteland. This type of damage is difficult to rehabilitate. Other damage may include a washing away of part of the ridges, which carries away fertile soil, and farmers, given their crop and capacity constraints, may take one to two seasons to rehabilitate it. Rainwater harvesting as a mechanism for the safe disposal of surplus runoff across the terraces is key to the sustainable production of the terrace field system. Irrigated agriculture depends on water stored in small reservoirs created by 50 small dams and more than 900 mini-dams, and in groundwater wells. The construction of the dams has positively affected the groundwater. At some locations, the groundwater table has risen and the old wells that were once dry have become functional, allowing the farmers to extract water using simple animal traction (Ashraf *et al.,* 2007). However, erosion in the upper catchments and the transport of eroded soil downstream has rapidly reduced the water storage capacity of these small reservoirs, threatening the sustainability of the agricultural systems dependent on them (Ashraf *et al.,* 2002).

Crop production and livestock are the main sources of income. Landholdings are small, and a majority of the farmers lives at subsistence level, with insufficient resources to cope with crop failures resulting from either the effects of climatic variability or damage to terraced fields. Most of the time, recovering the damaged terraces is beyond the capacity of poor farmers.

Low crop yields are a result of poor land management, mismanagement of runoff, and low levels of inputs. The ever-increasing gully expansion engulfs the fertile land and threatens the existing infrastructure (settlements, roads, and water storage and communication facilities). Soil erosion and siltation also reduce water storage capacity and cause water quality problems in the existing reservoirs. It was estimated that upstream erosion and sediment deposition in the reservoirs downstream reduced their capacity by more than 50% during the first five years of their operation.

The depletion of natural resources is making it increasingly difficult for the local population to derive their livelihoods through farming activities. The results of this resource depletion and resource deficiencies are manifold and are mainly seen in the form of poor soil and water conservation measures, pressure on available resources, and poor social coherence in communities. These in turn cause low productivity and deterioration of the social infrastructure.

ICARDA, in collaboration with national and international institutions, undertook a project in the Dhrabi watershed, Chakwal, from 2007 to 2010. The project was implemented by adopting an integrated watershed development (IWD) approach, which considers a watershed as a consolidated biophysical and socio-economic unit for development planning. It integrates the key elements of the watershed in a fashion that permits sustainable development for both human and natural ecosystems. The approach is holistic, multi-disciplinary, community-based, and participatory. It combines natural resource development and conservation with agricultural production and social development in a balanced framework. The major accomplishments of the project are detailed below.

1. Watershed selection and characterization

Of 30 potential sites, the Dhrabi watershed, with an area of 196 km^2, was selected following a detailed survey and screening process. A watershed association was organized from 22 community organizations. A baseline survey of the area was conducted. The watershed and its communities were characterized and a community action plan was developed and implemented.

The watershed was characterized in terms of the socio-economic conditions and natural resources in the upstream, middle, and downstream reaches. The total human population of the watershed is 27,438, with a greater population in the downstream villages than in either the upstream or midstream ones. The population density was 139 per km^2; this compares to an average 166 people/km^2 for Pakistan as a whole. The average age of the respondents was 54 years, and the average family size was seven persons with a joint family system. In the upstream area, 87% were illiterate.

The rainfed upstream area had more small holdings – 76% of a size between 0 ha and 2.5 ha – than the downstream one, where 52% of the holdings were of this size. In the downstream area, 23% of the holdings were of a size between 5 ha and 10 ha. About 90% of the land downstream was eroded, compared to 70% upstream. About 75% of the uncultivated rainfed land upstream was wasteland. Over all, about 90% of the cultivated land was allocated to wheat in the Rabi (October-March) season and 10% to fodder during the *Kharif* (April-September) season.

Water is a limiting factor for sustainable agriculture, with rainfall being the only source and having very high spatial and temporal variation. Therefore, conservation and management of this resource is vital for agriculture development and socio-economic improvements in the area. In the irrigated upstream area, 70% of the farmers were located at the head reach of the Nikka dam and 20% were on the tail reach. About 10% of farmers had access to tubewell water.

Vegetation assessment, both in the upper- and under-stories, was carried out in the area and data for three seasons (winter, 2008, and spring and summer 2009) were collected. Stratification of the watershed area was done on the basis of altitude and resulted in three zones – upper, middle, and lower. In each zone, four sites were randomly selected and in each site four transects were taken on the basis of the soil physiography. These transects were from flat (F), gentle slope (GL, slope $< 15°$), steep slope (SL, slope $> 15°$), and gully bed (GB) areas. The average annual understory ground cover (herbaceous) was 62%, whereas the average vegetation cover provided by trees and shrubs was 19%. The average annual vegetation density (herbaceous) was 44 plants/m^2 and the vegetation density in terms of trees and shrubs was 158 trees or shrubs/ha. *Acacia modesta* (phulai) was the main contributing species among the trees, with a composition of 70%, frequency of 52%, and importance value of 177.52.

2. Community action/development plans – watershed improvement/ rehabilitation

Watershed improvement/rehabilitation is an integrated and concentrated effort by all stakeholders, with communities in a stewardship role. Twenty two community organizations (COs) and watershed associations (WAs) were organized. Based on the resource status of the micro-watersheds, ecosystems, or small catchments, a community action plan (CAP) was developed. The CAP was evaluated for on- and off-site impacts, and those with overall positive outcomes on livelihoods and the environment were approved and implemented by the communities.

3. Water and soil loss monitoring and management

Soil erosion is one of the most important land degradation issues in the watershed. A survey was conducted to determine the extent of the erosion in the watershed. Permanent gullies and bank gullies were the main types of gullies in the watershed. Permanent gullies were deep and wide, and under cultivation in most places. Badlands were most prevalent in the lower watershed. The gully lengths were shorter in the middle watershed and eastern parts of the lower watershed. In the upper watershed, permanent gullies were longer and many gullies had not yet been converted to badlands. Bank gullies were more common in the upper and lower parts of the watershed.

To estimate the extent of the soil erosion under different land-use practices linked with rainfall-runoff, five sub-catchments of sizes between 1.5 ha and 350 ha were selected for measurement of runoff and sediment yield. Runoff was measured by constructing stilling basins at the outlets of these catchments. Both bed and suspended loads were recorded. Bed load was measured at stilling basins upstream of the weirs, while suspended load was measured through depth-integrated sampling tubes on an event basis. Micronutrients were also determined from the sediment samples collected. One automatic weather station, three recording rain gauges, and nine automatic water-level recorders were installed at different locations to cover the spatial variability in rainfall and runoff. Innovative and cost-effective techniques were also introduced to reduce soil erosion.

The rainfall data, collected during the period 1977–2010 at the Soil and Water Conservation Research Institute (SAWCRI), Chakwal, showed an average annual rainfall of 630 mm; however, 62% of it occurred between June and September. During 2009, only 545 mm of rainfall was received. All runoff events were in summer, especially during the monsoon season, whereas winter rainfall was less intense. In 2009, the intensity of rainfall events had a range of between 50 mm/hour and 100 mm/hour. In 2010, rainfall intensity was generally between 38 mm/hour and 84 mm/hour for the main rainfall events that caused most soil erosion. During 2009, between eight and 11 rainfall events produced runoff in these sub-catchments.

However, during 2010 there were 17 or 18 runoff events. The sediment yield for two small gully catchments had a range of between 4.79 t/ha/year and 8.34 t/ha/year in 2009, a relatively dry year (annual rainfall 545 mm). However, during 2010 the sediment yield of the same catchments was between 8.15 t/ha/year and 12.31 t/ha/year, indicating an increase of up to 70% during the high rainfall year (annual rainfall 710 mm). The increase in sediment yield was the result of an increased number of runoff-producing events, which during 2010 was almost that of 2009. Terraced catchments with arable crops produced 4.10 t/ha/year of sediment compared to the 12.31 t/ha/year in adjacent gullies, showing the potential of terraces to reduce soil erosion.

Runoff was computed from the water levels recorded in the streams. The Hydrologic Modeling System HEC-HMS was used for event-based modeling of the watershed. The model was calibrated and validated for data of rainfall events and runoff recorded at Chak Khushi sub-catchment. The model provided good agreement between the measured and the computed rainfall and runoff.

About 140 low-cost structures were constructed to conserve soil and moisture and to safely dispose of excess runoff. These structures helped control the degradation of the cultivable land and also trapped sediment coming from the catchments. The performance of these structures improved with time as they settled and grasses grew within the structure. These structures also helped conserve soil moisture by reducing runoff.

4. Crop yield improvement through crop intensification and diversification

Rainfall in these areas is low to medium, with high spatial and temporal variation. Over 60% of the rainfall occurs between June and September, and, therefore, most rainfall is not available for cultivation. Moreover, following conventional farming systems, the land and water productivity are very low. Therefore, there is a need to conserve as much rainwater as possible in the soil profile for subsequent use by crops or store it on the surface in the form of ponds, mini-dams, and small dams to be used for supplemental irrigation (SI). There is also a need to change the conventional farming systems through crop intensification and diversification to improve crop yields, water productivity, and farmers' net incomes. The following trials were conducted in farmers' fields to demonstrate how yield, water productivity, and net income could be improved:

- Rainfed wheat yield improvement with improved practices
- Evaluation of efficient irrigation techniques, such as raised-bed sowing and small-plot sowing with SI
- Groundnut yield improvement under rainfed and SI conditions
- Summer and winter fodder improvement with improved practices and irrigation

- Cultivation of crops in gullies,
- cultivation of high value crops
- Application of gypsum for moisture conservation and yield improvement.

A brief summary of the results is given below:

- With improved practices, the yield of rainfed wheat was, on average, 31% higher compared to the farmers' practices. Net income under the improved practices was PKR 70,000/ha (PKR – Pakistan rupee, US$1 = PKR 72 in 2008–2009), almost double that under the farmers' practices, showing that improved practices can give significantly higher returns in terms of land and water productivity compared to existing practices.Efficient irrigation techniques with SI can help improve wheat yield and water productivity. The highest wheat yield of 5102 kg/ha was obtained in small-plot sowing and was 28% higher than that obtained following the farmers' practices. This was followed by raised-bed sowing which was 24% (4776 kg/ha) higher. Water productivity in small-plot and raised-bed sowing was almost the same and about 23% higher than for the farmers' practices. The highest net income of PKR 97,701/ha was for small-plot sowing, and was 35% higher than for the farmer's practices. Under raised-bed sowing, net income was 30% higher than that achieved following the farmers' practices. Therefore, with only a 13% extra cost of water used for SI under small-plot sowing and with improved practices, there was a 47% higher wheat yield and a 55% higher net income as compared to the farmers' practices. Similarly, with about a 12% additional cost for SI at the critical growth stages of groundnut, yields and net incomes were increased from four to seven times.
- Summer fodder under improved practices gave a 27% higher yield and 30% higher net income. Similarly, increases for winter fodder were 34% and 31% respectively. Mixed sowing of oats (*Avena sativa*) and berseem (*Trifolium alexandrium*) gave 43% and 35% higher green fodder yields than single crops of oats or berseem, while the net income from mixed oats and berseem was 42% to 52% higher. Since berseem requires huge amounts of water, its cultivation in rainfed areas seems to be uneconomical; the same amount of water can be used for SI of wheat or other crops that can give higher returns.
- Growing high value crops, where water is available, gives higher returns. Off-season coriander (*Coriandrum sativum*) and chilies (*Capsicum annum*) gave net returns of about PKR 100,000/ha, whereas growing flowers gave a tremendous net return of more than PKR 700,000/ha. However, the production costs of high-value crops are relatively high. Therefore, only those farmers who can afford the high investment can grow these crops.
- Growing millet and sorghum (*Sorghum bicolor*) in gullies with improved practices gave green fodder yields of 44,167 kg/ha and 48,611 kg/ha, respectively; the corresponding net incomes being PKR 37,449/ha and PKR 41,004/ha. Therefore, cultivation in gullies not only conserves soil from further deterioration, but also generates some income for farmers.
- Applying gypsum helped store moisture in the soil profile and increased crop yield. The treatment with gypsum (plus loose-stone structures) conserved 40% more moisture than the control; wheat grain yield (4501 kg/ha) and water productivity (1.5 kg/m^3) were 62% higher than the control. The net return was greater than PKR 100,000/ha. The highest groundnut pod yield of 1502 kg/ha was obtained using gypsum (plus stone structures), and was 50% higher than the control.

5. Surface and groundwater monitoring

Water quality monitoring is an important component in maintaining a healthy watershed. The surface water quality of the watershed was monitored for its suitability for irrigation at 16 locations at regular intervals during 2007–2010. Similarly, the groundwater quality was monitored at 10 locations for drinking and irrigation purposes.

There was high spatial and temporal variability in surface water quality. The surface water quality at certain locations was poor and exceeded the permissible limits for irrigation purposes. Even in the Dhrabi reservoir, the surface water quality was inferior to that found in most of the reservoirs of the area The electrical conductivity (EC) and residual sodium carbonate (RSC) either exceeded or fluctuated around permissible limits throughout the monitoring period at most locations. The use of such water for irrigation, therefore, needs special care as its prolonged use may pose soil salinity and sodicity problems.

Soil samples were collected from the catchment areas of the major polluting streams and from the beds of the Kallar Kahar Lake and the Dhrabi reservoir. The soil samples from the catchments showed high salinity and sodicity, which may be the cause of the high salinity and sodicity in the streams. The highest EC (43 dS/m), sodium adsorption ratio (SAR) (56), and exchangeable sodium percentage (ESP) (45) were found in the bed samples from the Kallar Kahar Lake. The high EC, SAR, and ESP in the bed resulted from the saline water brought into the lake with the runoff, and the evaporation from the lake increases the salinity in the water. The salts ultimately settle at the bottom thereby increasing salinity and sodicity. The EC at the bed of the Dhrabi reservoir was also high (up to 5.1 dS/m) with an ESP of 4.3. The Dhrabi reservoir became operational during 2007, and the salinity and sodicity level in the reservoir indicate that the salinity and sodicity of the reservoir bed will likely increase with time. Small dams, mini-dams, and ponds are the main sources of groundwater recharge in the area. Since sodic soils considerably reduce soil permeability, the recharge to the groundwater will be substantially reduced. It is necessary to conduct a systemic study on the effect of saline–sodic water on groundwater recharge.

6. Runoff and sediment yield modeling

Long-term annual runoff and soil loss, as well as the sediment yield leaving the area, were calculated using the Revised Universal Soil Loss Equation (RUSLE) and Water Erosion Prediction Project (WEPP) simulation models. The necessary climate input data were obtained from a nearby weather station as well as from long-term observations in Islamabad. The digital elevation model and the land-use/land-cover map were derived from the Advanced Spaceborne Thermal Emission and Reflection (ASTER) satellite images taken in June 2006 and December 2007. For land cover and soil data, additional field measurements and laboratory analyses were carried out.

Simulation runs were performed for two time scenarios:

- For a period of 100 years generated from observations in Islamabad
- Using the measured climate data of Chakwal SAWCRI station from 2009.

Runoff and sediment yield measurements performed in 2009 and 2010 in a 2 ha watershed were used to verify the WEPP simulations. The comparison between observations and simulations showed satisfactory agreement. For the 100-year simulation, the current land use without soil conservation measures was used. For the 2009 scenario, the presence of soil protection structures in the agricultural areas were also simulated – these structures consisted of stones which divert excess rainfall in a non-erosive way. It was assumed that rainstorms of 100 mm with an intensity of about 15 mm/hour will not cause overflow. For a 100-year simulation period, an average surface runoff of 66 mm from the whole watershed without soil conservation structures was calculated. Using climate data from 2009, an annual surface runoff of 25 mm was predicted. When applying protection structures to the areas used for agriculture, the annual runoff could be reduced to 18 mm (i.e. 28% reduction). Retention of rainwater in the watershed leads to increased available water and will increase crop yields.

Soil erosion processes occurred on 75% of the watershed, with a mean rate of 82 t/ha/year, which corresponds to an average loss of 5 mm to 6 mm annually. On 25% of the area, eroded soil was deposited at 97 t/ha/year. This dislocation of soil results in a high variability of soil fertility and productivity within the area and it affects the storage and filtering function of the soil. Dense forests, perennial trees, and grassland are the best land-use systems for protecting soil against erosion. Agricultural fields with low biomass production, bare fields, and low vegetative cover were major sediment sources in the investigated watershed; and soils with high runoff potential showed the highest erosion rates. Considering the climatic conditions of 2009, the average soil loss could be reduced by 21% – from 48 t/ha/year to 38 t/ha/year – by implementing soil conservation structures on all areas used for agriculture. Not all of the eroded sediment was deposited within the area.

The 100-year simulation period produced a mean sediment yield of 25 t/ha/year. This amount of sediment creates problems by silting up the reservoir and impairs the water quality of the rivers and surface water bodies. Under the 2009 scenario, a mean sediment yield of 13 t/ha/year was calculated; however, a reduction of 8 t/ha/year (38%) could be achieved by applying soil conservation measures. The simulation results showed that implementing the suggested soil conservation measures reduced surface runoff and soil loss. The decreased sediment yield will improve water quality and reduce off-site damage caused by erosion.

Nevertheless, land-use systems with annual erosion rates of more than 40 t/ha in the major parts of the watershed, and high deposition within the area, are not sustainable. Additional soil protection measures and, in some parts of the watershed, land-use changes need to be considered to achieve the ultimate goal of sustainable land management.

7. Training and capacity building

The capacity building of the farmers and the local institutions was an integral component of the project. Capacity building of the communities included improving their knowledge in the sustainable use of resources and protection of the resource base, building their capacity in communal decision-making and uses of common resources, and improving their interactions with the other stakeholders who directly or indirectly affect the watershed health and services.

Improving capacity building of the institutions in watershed planning, management, and development was achieved through formal training and field visits. Three on-the-job training experiences were arranged, covering rainwater harvesting, water management, rainfall-runoff and sediment monitoring, and tree planting and management. Two field visits, one to Turkey and another to Mangla watershed, were arranged. Additionally, ten students completed their Masters and PhD degree studies supported by the project.

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Chapter 1: Characteristics of Dhrabi watershed Barani, Pakistan

A. Khaliq, T. Oweis, A. Mahmood, S. Nizami, M. Ashraf, A. Majid, and A. Ali

1.1 Summary

The watershed was characterized in terms of socio-economic conditions and natural resources along the upstream and downstream reaches. The total human population of the watershed was 27,438 people. The populations of the downstream villages were greater than those of the upstream ones. The land to man ratio at upstream was 1.05 ha/person and the population density was 139 per km^2 as compared to 166 per km^2 for Pakistan as a whole. The average age of the respondents was 54 years and the average family size was seven persons with a joint family system. In the upstream area, 87% of the people were illiterate.

The rainfed upstream area had more small holdings – 76% of a size between 0 ha and 2.5 ha – than the downstream one, where 52% of the holdings were of this size. About 90% of the lands in the downstream area were eroded as compared to 70% in the upstream one. About 75% of the uncultivated rainfed land upstream was wasteland. About 90% of the cultivated land was allocated to wheat in the Rabi (October-March) season in the rainfed areas and about 10% was allocated to fodder during the *Kharif* (April-September) season. Upstream farmers were drawing more benefits from the available water and were better off than downstream farmers.

Rainfall is the major source of water. In Kallar Kahar village, only a few hectares were irrigated with water from the Nikka dam. In the midstream villages, a few farmers were lifting water from streams. On average, about one hectare of land was being minimally irrigated from tube wells.

A vegetation assessment, both in the upper storey and the under storey, was carried out in the area and data for three seasons (winter 2008 and spring and summer 2009) were collected. Stratification of the watershed area was done on the basis of altitude and three zones – upper, middle, and lower – were established. From each zone, four sites were randomly selected and from each site four transects were taken on the basis of soil physiography. These transects were from flat (F), gentle slope (GL) (slope <15 degree), steep slope (SL) (slope >15 degree) and gully bed (GB) areas. The average annual under story ground cover (herbaceous) was 62% whereas the average vegetation cover provided by trees and shrubs was 19%. The average annual vegetation density (herbaceous) was assessed at 44 plants/m^2 and the vegetation density in terms of trees and shrubs was 158 trees-shrubs/ha. *Acacia modesta* (Phulai) was the main contributing species among trees and was found with a composition of 70%, a frequency of 52%, and an importance value of 177.52.

Among grasses, the area was dominated by *Heteropogon contortus* (Sariala) – composition of 24%, frequency of 32%, and importance value 77.97 – and *Desmostachya bipinnata* (Dab grass) – composition of 21%, frequency of 45%, and importance value 61.94. The average height of the woody vegetation was 3.9 m, its diameter 9.7 cm, and crown area 18.6 m^2. The overall carrying capacity of the watershed area was recorded as 10.2 ha/AU/year, which indicates that the rangeland is from fair to good for grazing. The upper zone of the watershed was in a relatively good condition as compared to the middle and lower zones in term of vegetation health, most probably a result of the higher

rainfall and lower number of livestock. Steep slope areas and gully beds were richer in vegetation as compared to the gently sloped and flat areas.

The planting of Mott grass (*Pennisetum purporium*) was found to be successful in moist areas, but less successful in shady areas. It sprouted well in gullied areas, but could not survive because of the long, dry spells and scarcity of water. Moreover, the farmers were not interested in growing forest trees; they were more interested in growing fruit trees.

1.2 Background

Dhrabi watershed is located in Chakwal, a district of northern Punjab, Pakistan (Figure 1.1). The total area of Chakwal District is 6687 km^2. The total population of the district is 1.08 million people, of which 88% are living in rural areas, making Chakwal the most populous rural district of Punjab. Ecologically, the area is fragile and lies in the semi arid and drought prone region of Pothwar. The urban and rural areas of the watershed can be clearly differentiated on the basis of development. This is also reflected in terms of the poverty profile of the area. The natural resources are rapidly deteriorating and it is becoming increasing difficult for the local population to gain their livelihood through farming activities. This leads to the migration of the rural community to the urban areas, resulting in a shortage of labor in the rural areas. The consequences of this resource depletion and resource deficiency are manifold and can be seen in the form of poor soil and water conservation measures, inappropriate land use, low agricultural productivity, and poor social coherence within the village communities.

To improve the livelihood of these resource poor communities, the International Center for Agricultural Research in the Dry Areas (ICARDA), in collaboration with local research institutions, started a project for

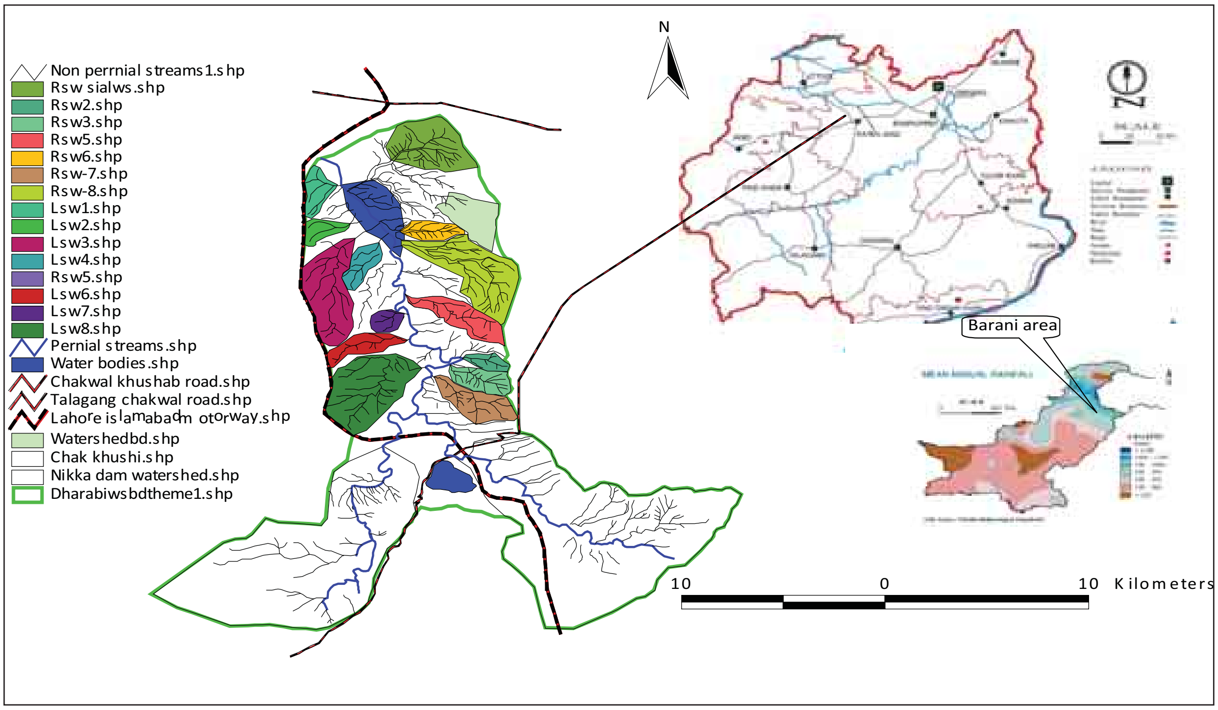

Figure 1.1. Location map of the Dhrabi watershed

improving socio-economic conditions of these communities in the watershed through the efficient use of land and water resources. To monitor the long-term effects of the interventions, it was essential to conduct a baseline survey and characterize the watershed. After consultation with all the stakeholders, a survey with the following objectives was conducted in the watershed:

- To identify the major resources available in the watershed
- To assess the different assets available in the area
- To identify the use of the various resources in the watershed
- To provide a baseline for the impact assessment of the project.

1.3 Watershed selection

Dhrabi watershed was selected from 30 potential watersheds identified in the Barani region through a process of screening and ranking following the watershed selection criteria. Village profiles were established through focus group discussions. Using these village profiles, three villages were selected in each of the upstream and downstream areas.

The watershed is located between latitudes 32° 42′ 36″ N and 32° 55′ 48″ N and longitudes 72° 35′ 24″ E and 72° 48′ 36″ E. It covers a drainage area of 196 km^2. Twenty villages and Kallar Kahar town are located within the watershed. It also has one lake, two small dams, 12 mini-dams and a reserve forest area.

Low to medium hills with elevations between 466 m and 800 m above sea level largely represent the topography. Slope steepness varies from 2% in the areas of the plain to more than 30% along the hillsides. A gullied area constitutes more than 50% of the total area. The minimum temperature varies from -0.5 °C in January to 16 °C in July and August. The maximum temperatures were 24 °C in January and 48 °C in June. The average annual rainfall is about 630 mm. The main land categories are wasteland/badlands (40%), rough grazed land (20%), dry farming (12%), and wetlands (8%). Built in and irrigated areas constitute less than 5%.

1.4 Watershed characterization

1.4.1 Methodology

A questionnaire was designed to collect information on socio-economic characteristics including the village profile, demographic conditions, availability of basic facilities, land and land-use patterns, agricultural production, farm machinery, soil, water, rangeland utilization, marketing, and labor, etc. The questionnaire was pre-tested in the field and any necessary changes were made to it before conducting the survey itself.

Secondary data were collected from government and non-governmental organizations working in the area. Primary information for the upstream and downstream reaches was obtained from the selected farmers through personal interviews using a structured questionnaire. In the upstream region, some areas were being irrigated with water from the Nikka dam and some from other mini-dams. Therefore, the upstream irrigated area was also included in the survey. The sampling frame consisted of 465 farmers, from which a sample of 124 farmers were interviewed (Table 1.1).

Table 1.1 Respondents in the selected villages

Location	Interviewed	%
Irrigated upstream	60	48
Rainfed upstream	33	26.6
Rainfed downstream	31	25.4

Population density (in agriculture standing stock and standing crop) is a measurement of population per unit area. The population density was calculated by dividing the population by the area.

1.4.2 Scope of the study

Most of the information collected was based on the reports of the farmers interviewed. Farmers might want to conceal some facts for certain reasons, thus, it was necessary to gain their confidence from the outset. Before the start of the interview, every farmer was told that the personal information provided by them would be kept strictly confidential and never be used for other purposes. Lack of proper record also turned out to be a serious difficulty in collecting accurate data. The researchers, therefore, had to partially depend upon the farmers' memories.

1.5 Area distribution and demography

1.5.1 Area and population

The Dhrabi watershed comprises about 19,803 ha as reported by the Municipal Committee office of Kallar Kahar. These figures were verified from the Small Dam Organization (SDO).

The area of the watershed is widely distributed among different villages. Kallar Kahar is the major town in the upstream area of the watershed with 16% of the total area. This town has recently been upgraded by the local government to the tehsil headquarters of the Chakwal District because of its historic importance and geographic location. In the past, Kallar Kahar also served as a central hub between the southern districts of Khushab and Sargodha and the northern districts of Rawalpindi and Chakwal. Recent industrialization in the area has greatly affected its socio-economic conditions. Four major cement production and processing plants were installed in the area, which created employment opportunities for the surrounding communities. Kallar Kahar Lake also attracts a great number of tourists throughout the year.

The total human population of the watershed was 27,438 people (Table 1.2). The population of the downstream villages is greater than that of the upstream ones. On the basis of population, Kallar Kahar is the major town in the upstream area, comprising about 11% of the total watershed and 58% of the upstream population. The land to man ratio in the upstream area (Kallar Kahar) was 1.05. Its population was increasing rapidly as a result of it being upgraded to the *tehsil*

A view of Kallar Kahar city and lake

Table 1.2. Area and population in the watershed

Village name	Area (ha)	% of total	Population	% of total	Population density (people/ha)
Chak Khushi	861	4.3	800	2.9	0.93
Dhok Chumbi	778	3.9	1,376	5.0	1.77
Kallar Kahar	3,179	16.1	3,000	10.9	0.94
Chakora	193	1.0	313	1.1	1.62
Ratta Sharif	787	4.0	1,400	5.1	1.78
Rahna Sadat	1,916	9.7	2,000	7.3	1.04
Dhok Zawar	162	0.8	250	0.9	1.54
Bhagwal	1,417	7.2	5,000	18.2	3.53
Chawli	2,024	10.2	6,000	21.9	2.96
Karsal	6,073	30.7	5,000	18.2	0.82
Bhoukani	244	1.2	195	0.7	0.80
Warhal	859	4.3	44	0.2	0.05
Miani	160	0.8	1,283	4.7	8.00
Pahar Khan	1,151	5.8	777	2.8	0.67
Total	19,803		27,438		1.39

headquarters and its geographic location. Another reason for the population increase was the mobility of labor from areas of low wages to one of high wage resulting from the recent industrialization and tourism development.

The population density of the watershed was 1.39 people per ha or 139 per km^2 as compared to 166 per km^2 in Pakistan as a whole (GoP, 2009). Therefore, the distribution of the population in the watershed was relatively thin as compared to the national average.

Age is an important factor which affects the potential employment and mobility status of communities. The respondents were mostly adults who were actively involved in farming and mostly retired from the army (Table 1.3). Mainly the over-50 year age group represents the decision-making portion of the community in farming and family matters.

Family structure is an important social indicator of the communities and directly represents the social, economic, and political importance of the family. It is also an indicator of labor availability and, ultimately,

Table 1.3. Age of the head of the household in the communities (years)

Location	Average	Maximum	Minimum
Rainfed upstream	54.58	85	30
Irrigated upstream	54.39	70	28
Rainfed downstream	56.47	85	32

professional capabilities. The average family size in the rainfed upstream area was found to be seven persons (Table 1.4) as against the average household size of 7.2 for rural Punjab. This indicates that more labor is available in upstream areas than in the downstream ones. The main reason for this large family size was the joint family structure in the upstream watershed communities. However, the adult labor force which takes part in agriculture farming was very low (2.7 head) in the rainfed upstream region as compared to the downstream one (4.7 head). Furthermore, the adult labor force (between 16 and 60 years) was normally involved in off-farm activities. Persons more than 60 years old and children under 16 years, together with the female members of the family, were the main agriculture labor force in the watershed.

The demography of any area depicts its population, their occupations, the number of households, the number of farming families and their tenancy status, the number of tenants, and the income groups of the respondents. The irrigated agriculture communities had more than four times the population of the downstream ones (Table 1.5). Skilled and unskilled labor is available in the watershed. The labor involved in agriculture was unskilled with conventional knowledge. This was the main reason for the low agricultural productivity in the area. Tenancy farming was highest (33%) in the rainfed upstream zone. The main reason for this high tenancy rate was the unconsolidated land holdings. The minimum proportion of tenancy farming (2%) was found in the rainfed downstream region, mainly because of the consolidated land holdings.

The rainfed communities are mainly characterized as poor communities as compared to the irrigated ones, indicating the importance of water availability in the area.

Table 1.4. Family composition and size in the watershed

Location	%		Average size (person)	Adults > 16 years	Children < 16 years
	Single	Joint			
Rainfed upstream	0.00	100	7.0	2.7	4.3
Irrigated upstream	0.81	99	7.3	4.7	2.6
Rainfed downstream	0.00	100	7.5	4.6	2.9

Table 1.5. General description of the watershed communities

Location	Population	Main occupation	No of households	No of tenants	% tenants	Income class
Rainfed upstream	800	Labor	300	100	33	Poor
Irrigated upstream	3,000	Farming	2,000	400	20	Poor, middle
Rainfed downstream	1,400	Labor	280	40	2	Poor

1.5.2 Economic empowerment and social status

Most of the people in the villages belong to the lower middle and poor classes. They were either unskilled laborers or conventional farmers. Their social status was poor because they could not afford to purchase inputs, such as fertilizer, improved seed varieties, etc. to increase their crop production. Therefore, given this lower profitability, the majority of them left agriculture and switched over to laboring. The individuals were asked to rank themselves according to their economic conditions. Mostly people ranked themselves as poor. The communities of the irrigated upstream zone were better off with 70% characterizing itself as poor and 30% characterizing itself as being moderately well off. In the rainfed upstream and downstream areas, 90% characterized itself as poor and only 10% characterized itself as moderately well off (Table 1.6). The main reasons for the better living standard of the farmers living in the irrigated upstream region were the irrigation system, tourism, and the spillover effects of industrialization and urbanization.

Education and communities

Education plays an important role in the overall growth and development of a country. The literacy rate in the irrigated upstream zone was better than that in the other communities (Table 1.6). One middle school, one cadet college, one private college, and one government college were available in the irrigated upstream areas. One person in the rainfed upstream area claimed to hold a Master of Arts degree and two people in Ratta village claimed to have had high school educations. An intriguing figure of 87% of the sample of respondents in the rainfed upstream areas identified themselves as illiterate. Lack of educational institutions, poor economic conditions, and a lack of access to the institutions were found to be the major reasons for the low literacy rate in the area.

Employment opportunities

In the past, agriculture was the sector which was most important for the provision of employment to the local communities. The major reason was the low population pressure on the soil resulting from the small population density. With an increase in population, conventional agriculture was unable to provide jobs for the inhabitants. The local communities were normally illiterate and were able to work only as unskilled laborers in the industrial sector as the earnings of unskilled industrial laborers are more than those of skilled agriculture laborers.

1.5.3 Farming experience

The average farming experience of the respondents in the rainfed and irrigated upstream areas was 19 years while in the rainfed downstream region it was 25 years. The farmers of the rainfed upstream and irrigated upstream areas have other sources of income besides farming, such as keeping poultry, shop keeping, and other sorts of off-farm jobs. However, in the rainfed downstream areas people were forced into

Table 1.6. Community prosperity ranking and education (%)

Location	Prosperity ranking		Education status	
	Moderate	**Poor**	**Educated**	**Uneducated**
Irrigated upstream	30	70	36	64
Rainfed upstream	10	90	13	87
Rainfed downstream	10	90	33	67

farming; they could not leave this occupation for social reasons even if they were not making a profit. The economic motives for farming were mainly.

- Infrastructure – like land available for farming
- Training on conventional agriculture starts from childhood at the age of 5-6 years
- It provides a complete solution to the daily kitchen requirements.

Off-farm activities

It is important to study the nature and location of off-farm work, because it indicates the type and level of employment available in the area. In rainfed areas, land holdings were generally small and agriculture was on a subsistence basis. In all the villages, the farmers try to find off-farm jobs as the income from farming is very small. In the rainfed upstream areas, the dominant off-farm work includes shop keeping, driving, the defense service, and a few government jobs.

Capital and social assets

Physical and social assets were major barriers to the poor. The communities which have physical assets can enjoy government programs and loans. The socially strong families were also supporting each other.

Availability of farm motive power

Agricultural machinery was used as a means to achieve higher levels of output as well as to save time. All the farmers were using a tractor to cultivate their lands and no one was using the traditional method of cultivation – using a bullock. Only two persons in all the villages owned a tractor, the rest of the farmers hired their tractors. Other farm implements, like levelers, harvesters, and threshers also have a great potential to increase production, but, unfortunately, none of the farmers in any of the three villages owned any of these implements.

Harvesting methods and labor shortages

In the past, the harvesting of wheat was the major farming activity which generated many social assets for the communities. The harvesting of wheat was a collective activity for all the villagers and every one would participate in this activity. However, the laborers now prefer to work away from the fields because they receive daily wages. This results in a shortage of labor at harvest time. Sometimes, the farmers have to delay their harvesting because of a shortage of labor and this increases harvesting and threshing losses.

Means of transportation

The means of transportation in an area reflects its connectivity to high income areas and determines both labor and product mobility. Small pickup trucks were the means of transportation from one place to another in the watershed for the majority of people, but a few had their own transportation, such as a motor car or motor cycle. Small trucks are used by about 98% farmers of the areas.

Land ownership

In the past, land ownership was considered as a matter of prestige in the area. Now this has become simply a physical asset. Communities used the land for crop production and livestock rearing in the past. The potential use was increased with the development of urban sectors, like housing schemes, commercial enterprises, etc.

Availability of land resources

The total area of the villages selected in the watershed was 5168 ha, of which 36% was cultivated and 64% was uncultivated. The total land resource owned by the watershed communities of the upstream rainfed village of Chak Khushi was 1250 ha – 32% being cultivated and 68% being left uncultivated. The rainfed downstream land resource was 777 ha, with 26% cultivated and 74% uncultivated (Table 1.7).

Table 1.7. Available land resources

Location	Total area (ha)	Cultivated (%)	Uncultivated (%)
Rainfed upstream	1,250	32	68
Irrigated upstream	3,140	40	60
Rainfed downstream	777	26	74
Total	5,168	36	64

Operational holding

Farm size is one of the major determinants of the financial status of the farmer, which in turn affects the farmer's ability to adopt improved farming practices and use proper inputs. The operational land holding plays a vital role in the family's labor employment as well as its income. The main problem with the Dhrabi watershed area is the small size of the land holdings. The major reason for this small size is the land fragmentation which directly affects crop production. The rainfed downstream area has no large farms. The irrigated upstream zone has the largest number of small farms with land holdings of less than 2.5 ha (Table 1.8).

Fragmented lands were mainly found in the rainfed upstream areas. The degree of fragmentation is moderate in the rainfed downstream areas and scarce in the irrigated upstream zone. According to the respondents, if action could be taken by the government to consolidate the land, it could bring positive changes in the production level and also in the income status of the communities.

Land types

The rainfed upstream and downstream areas had more eroded land than the irrigated upstream area (Table 1.9). The main reason for this is that when land starts to erode, no one pays any attention to it. After some time, it gets beyond the capacity of the individual farmer to control the erosion or to reclaim the land. No farmer reported salinity at his farm.

Uncultivated land use

In the rainfed upstream areas, all the uncultivated land was plain, but wasted because of a weed locally known as *Kundar*. It had deep roots so cannot be easily

Table 1.8. Size of operational land holdings of selected villages (%)

Location	0-2.5 ha	2.5-5 ha	5-10 ha	> 10 ha
Rainfed upstream	76	12	9	3
Irrigated upstream	67	12	17	5
Rainfed downstream	52	26	23	0

Table 1.9. Land types in the selected villages (%)

Location	Plain	Eroded	Saline
Rainfed upstream	20	80	0
Irrigated upstream	40	60	0
Rainfed downstream	10	90	0

eradicated. In the irrigated upstream villages and the downstream villages, the majority of the uncultivated land was used for grazing and fuel wood. The main reason for the lack of cultivation of this land was its mountainous nature and steep slopes.

Land allocation decisions for crops

In the agricultural sector, land allocation for various crops holds great importance in determining the profit of that particular entrepreneur. In modern agriculture, it is determined through different economic tools. However, these farmers have their own priorities for the allocation of land to crops. Most of the farmers grow wheat and fodder.

Crop diversification

Wheat, as a staple food, is cultivated by almost every farmer. In rainfed areas, farmers were practicing rainfed agriculture and were cultivating wheat and some fodder crops for their livestock. No crop rotation or agronomic practices were followed, and farmers plant local varieties using their own unimproved seeds. In irrigated areas, there was more diversification of crops and all farmers were practicing multi-cropping systems in their fields. Wheat was sown by most of the farmers and maize, millet, groundnut, and vegetables were also grown.

Tenancy farming

Tenant farming has been practiced historically in the study area. Large farmers rent out their lands to small or landless farmers. The terms of the tenancy were either a share of the main crops or their by-products. This system was also observed in all the villages of the watershed with the highest percent being in the rainfed upstream areas followed by the irrigated upstream areas (Table 1.6). The reason for the highest percent being in the rainfed upstream zones was the split or fragmented nature of the lands which, according to farmers, were difficult to look after.

Crop production

The crop yield in the irrigated area was almost double the production in the rainfed areas. Groundnut, which is a cash crop, was also cultivated to earn a reasonable profit. In the irrigated area, more inputs, like fertilizer, pesticide, and improved seeds, were used. By contrast, in the rainfed area, production was half that of the irrigated areas as all the outputs depended upon rainfall. Use of fertilizer in the rainfed zone does not ensure high production unless and until a timely and adequate amount of rainfall is received.

Soil condition

Chakwal district is well known for its stony soils. The soil condition in the selected villages was mostly sandy to clayey. Most of the peoples of the watershed were of the view that soil degradation was increasing with time. However, the extent of the erosion is different in different villages. In the rainfed upstream areas, soil erosion was low; its intensity increased towards the irrigated upstream and has resulted in the formation of gullies. Soil degradation and erosion are major factors in the deterioration of agricultural lands and in reducing productivity.

Land distribution

The watershed comprises 19,803 ha of land. This land was owned by more than 4000 farming families. The data collected in the household profile revealed that land distribution was very uneven among the farming families (Table 1.10). This ultimately gives rise to disparities which result in inefficiencies in the system. Small farmers with large families are unable to get their livelihood from a small rainfed piece of land and ultimately migrate to urban areas in search of jobs.

Table 1.10. Land distribution among farm households

Land holding (ha)	No. of households	% households	Total land (ha)	% of total land
0-2.5	176	45	3,740	9
2.5-5	103	26	7,852	18
5-10	68	17	9,764	23
10-15	19	5	4,556	11
15-20	8	2	2,819	7
20-25	2	1	890	2
25-30	6	2	3,170	7
> 30	11	3	10,232	24

1.6 Availability of water resources and irrigation sources

Water is a limiting factor for sustainable agriculture. Rainfall is the major source of water and its spatial and temporal variation is very high. Therefore, conservation and management of this resource is vital for agriculture development and the socio-economic uplifting of the area. In the rainfed upstream and downstream areas, no farmer has access to dam or tube well water. However, in the irrigated upstream zone, 70% of the farmers were located at the head reach of the Nikka dam and 20% were on the tail reach. About 10% farmers have access to tube well water (Table 1.11).

The main sources of water in this watershed are rainwater and tube wells. In Kallar Kahar village, a few hectares were being irrigated with water from the Nikka dam. About 2500 ha will be irrigated from Dhrabi reservoir. In mid-stream villages, a few farmers were also lifting water from streams.

On average, about one hectare of land was being minimally irrigated from a tube well.

1.7 Livestock, production and marketing

1.7.1 Livestock resources

Livestock is a physical capital for poor farmers and is considered as gold by the poor people in the *barani* farming system. Farmers rear livestock to supply their kitchens and to meet unforeseen expenditures (Table 1.12).

Table 1.11. Water resource availability

Location	Water resource availability				Irrigation source (%)		
	Water sources	No. of wells	Water table depth (m)	Water table variation	Rainfed	Dam	Tube well
Rainfed upstream	Rain	0	11	Yes	100	0	0
Irrigated upstream	Spring plus dam	2	5	Yes	20	70	10
Rainfed downstream	Rain	4	46	Yes	100	0	0

Table 1.12. Livestock resources

Location	Wet buffalo	Wet cow	Dry buffalo	Dry cow	Heifer	Sheep	Goat
Rainfed upstream	0.33±0.64	1.88±3.59	0.39±1.08	0.42±1.09	0.36±1.47	0.00±0.00	2.85±5.17
Irrigated upstream	0.62±1.08	0.59±1.16	0.49±1.34	0.44±1.02	0.49±1.02	0.00±0.00	2.0±3.88
Rainfed downstream	0.50±0.82	0.93±1.41	0.47±1.45	0.67±1.34	0.53±1.27	0.17±0.91	3.50±6.11

Buffalo is not common in the watershed; 85% of households have no dry buffalo and in the rainfed upstream area 76% have no wet buffalo. In the rainfed downstream area, people have more wet buffalo as compared to those upstream. Normally people rear only one buffalo. The main purpose for rearing buffalo is to get milk for home consumption and to cover kitchen expenditures by selling surplus milk (Table 1.13).

Cattle are native to this area. Previously, these were the only large ruminants. With the introduction of buffalo for milk purposes, the importance of cattle has been reduced. The normal trend was to raise milk animals. These were also a main source of livelihood for those farmers who were directly involved in the production of cattle (Table 1.14).

Table 1.13. Population pattern of wet and dry buffalo

Location	Buffalo wet			Buffalo dry		
	No buffalo	With one buffalo	With more than one buffalo	With no buffalo	With one buffalo	With more than one buffalo
Rainfed upstream	76	15	9	85	3	12
Irrigated upstream	64	23	13	84	5	11
Rainfed downstream	60	37	3	87	3	10

Table 1.14. Population pattern of wet and dry cow

Location	Cow wet			Cow dry		
	With no cow	With one cow	With more than one cow	With no cow	With one cow	With more than one cow
Rainfed upstream	55	3	39	81	6	12
Irrigated upstream	72	10	18	79	10	12
Rainfed downstream	57	17	27	77	3	20

1.7.2 Small ruminant production

Small ruminant production – raising sheep and goats – is the major livestock business of small farmers. It supports farmers in case of unforeseen expenditures. The average stocking rate of goat varies from five to six goats per family. The data indicate that more than 50% of the farming community was not involved in goat rearing and very few in sheep production (Table 1.15).

Table 1.15. Population pattern of goat and sheep

Location	Goat			Sheep		
	With no goat	With one goat	With more than one goat	With no sheep	With one sheep	With more than one sheep
Rainfed upstream	58		42	100		
Irrigated upstream	61	10	29	100		
Rainfed downstream	47	17	37	97		3

The livestock to man ratio is a major indicator of the concentration of livestock in the area and the behavior of the communities towards this asset accumulation. This also indicates the wealth of the communities.

1.8 Vegetation

The natural vegetation of the area mainly consists of scrub forest which is dominated by *Acacia modesta, Olea ferruginea, Capparis decidua, Dodonaea viscosa, Zizyphous nummularia, Heteropogon contortus, Desmostachya bipinnata, Cenchrus ciliaris, Cynodon dactylon, Saccharum bengalenses,* etc.

To have basic information regarding the vegetation of the area, an assessment of both the upper and under storey was carried out for three seasons (winter 2008 and spring and summer 2009). Stratification of the watershed area was done on the basis of altitude and three zones – upper, middle, and lower – were established. The representative sampling sites from each zone were selected randomly after visiting the target area. From each zone, four sites were randomly selected and from each site four transects were taken on the basis of soil physiography. These transects were from flat (F), gentle slope (GL) (slope < 15 degree), steep slope (SL) (slope > 15 degree), and gully bed (GB) areas. Line transects 50 m in size were used for the assessment of plant communities, vegetation cover, and carrying capacity. In addition 1 m^2 quadrates were laid at an interval of 10 m on alternate sides of the transect. The percent vegetation cover, its composition, plant density, frequency, index value, and range carrying capacity were determined using the following formula.

$$\text{Percent cover} = \frac{(\text{Sum of intercepts by a species on all the transects})}{(\text{Total length of all the transects})} \times 100 \quad (1)$$

$$\text{Percent composition} = \frac{(\text{Sum of intercepts by a species on all the transects})}{(\text{Sum of intercepts by different species on all the transects})} \times 100 \quad (2)$$

$$\text{Plant density (plant/m}^2\text{)} = \frac{\text{Number of individuals of the species in all quadrates}}{\text{Total area sampled}} \quad (3)$$

$$\text{Frequency (\%)} = \frac{\text{Number of quadrates in which a species occurred}}{\text{Total number of quadrates sampled}} \times 100 \quad (4)$$

$$\text{Index value (IV)} = \text{Relative cover} + \text{relative frequency} + \text{relative density} \quad (5)$$

$$\text{Carrying capacity (ha/AU/year)} = \frac{\text{Animal forage requirement (kg/year)}}{\text{Forage production (kg/ha)}} \quad (6)$$

1.8.1 Vegetation type

Using a walk through technique in each of the three seasons, 115 plant species were recorded from the entire watershed area. The count comprised 15 grasses, 30 shrubs, 42 herbs, 9 bushes, and 19 trees. However, in the 2008 winter season, a total of 38 plant species – comprising 8 grasses, 10 shrubs, 14 herbs and 6 trees – were present in 48 transects and 240 quadrates. Most of the grasses and herbs became dormant in the winter season and a lower number of species was recorded. In the spring season the count increased to 61 species – 12 grasses, 16 shrubs, 27 herbs, and 6 trees – with the emergence of 23 more. In the summer season (monsoon), the highest number of species was recorded in 48 transects when 14 more new species were present making a total of 75–15 grasses, 23 shrubs, 31 herbs, and 6 trees.

1.8.2 Vegetation cover

The average annual herbaceous ground cover of the three seasons was found to be 62%. In the upper zone, the average vegetation cover for three seasons was 69%, in the middle zone it was 61%, and in the lower zone, it was 54%. When the vegetation covers of three seasons for different soil physiographies were compared (Table 1.16), it was found that comparatively low vegetation cover was present in the flat area (51%); the highest was on the areas of steep slope (73%) followed by the gently sloping areas (63%), and the gully bed areas (60%). The main contributory grass species were *Heteropogon contortus* (Sariala), *Cenchrus ciliaris* (Dhaman), *Desmostachya bipinnata* (Dab grass), *Cynodon dactylon* (Khabbal), and *Chrysopogan aucheri*. The upper zone of the watershed area was comparatively cooler because of its greater elevation and it also received more precipitation than the middle and lower zones – hence the percent cover in the upper zone was higher than those of the middle and lower zones. Less vegetation cover on flat areas indicates that there is a higher grazing pressure while on the steep slopes the good cover indicates less grazing pressure because the animals face difficulties and require more energy to maintain their balance while walking. The better cover in the watershed area may be attributed to the protection provided by the motorway against

Table 1.16. Average annual herbaceous cover (%)

Zone	Flat area	G. Slope	S. Slope	Gully bed	Mean
Upper zone	59	72	80	66	69
Middle zone	52	62	69	61	61
Lower zone	41	54	69	53	54
Mean	51	63	73	60	62

free grazing, private land ownership, and decreasing livestock and farming activities. Amjad *et al.* (2004) conducted a study to determine the carrying capacity of an area which was 26% covered with grasses and 17% with shrubs. *Eleusine flagellifera* was found to be the key grass species.

Woody vegetation cover

Woody vegetation cover was determined for each tree encountered in a 100 m^2 (10 m x10 m) plot taken at the 30th meter of each line transect by measuring the diameter of the tree crown. The average cover provided by the tree and shrub components in the watershed area was 19%,which was highest in the gully bed areas (24%) followed by the flat areas (18%) and the steep slopes (17%); the lowest was on the gentle slopes (16%). The highest percent tree cover that occurs in gully beds may result from better moisture levels in these beds rather than on the flat or sloping areas. When zones were compared, the middle one was found to be healthy with a 27% cover. The lowest cover, at 8%, was recorded in the lower zone (Table 1.17). The main contributory tree species were Acacia modesta (Phulai), Acacia nilotica (Kikar), Zizyphus mauritiana (Ber), Dalbergia sissoo (Shisham), Olea ferruginea (Kaho), and Dodonia viscosa (Snatha). Arshad-ullah *et al.* (2007) conducted a study during 2005 to analyze the rangelands of the Pabbi Hills, Kharian, to determine range vegetation and the composition of the cover. Herbage species contributed more towards forage production than the browse ones. Grewia populifolia (Gangir) and Acacia modesta (Phulai) were the major contributors in the browse species. The total range vegetation cover was 32%. Tefera *et al.* (2007) assessed the condition of the semi-arid rangeland in southern Ethiopia by studying different land-use systems along a distance gradient (near, middle, and far) from water sources. Two methods were employed to evaluate the grass layer. The cover on the government farms was 22% greater than that on the traditional reserve and 26% greater than that on the communal land.

Seasonal vegetation cover

The average annual herbaceous ground cover was found to be 62%. The highest amount of cover (68%) occurred in summer, a consequence of the increased rainfall of the monsoon season. In winter the cover was good

Table 1.17. Average annual trees cover (%)

Zone	Flat area	G. Slope	S. Slope	Gully bed	Mean
Upper zone	20	30	19	20	22
Middle zone	27	9	27	46	27
Lower zone	7	10	7	7	8
Mean	18	16	17	24	19

because the severe climatic conditions limited grazing and the grasses were less palatable. In spring, comparatively less vegetation cover (53%) was present – the grasses were more palatable and there was a higher grazing pressure in the area (Figure 1.2).

In all three seasons, the cover was the highest on the areas of steep slope and the lowest on the flat areas followed by the gully beds, indicating that the animals prefer to graze on flat and gullied areas. When zones were compared in all three season, the highest cover was recorded in the upper zone. This region gets relatively more rainfall and there are less livestock per farmer (8 head). The lowest cover was recorded in the lower zone where there were 23 animals per farmer (Figure 1.3). Similarly, the site and zone cover provided by the tree and shrub components was 19%, and showed very minute changes between seasons. Although in spring, the tree/shrub cover provided by individual trees-shrubs was increased, the overall cover was reduced as a result of cutting. In summer, the cover again increased to 19% due to re-growth of the trees-shrubs (Figures 1.4 and 1.5).

1.8.3 Vegetation density

The average annual herbaceous vegetation density was 44 plants/m^2. In the upper

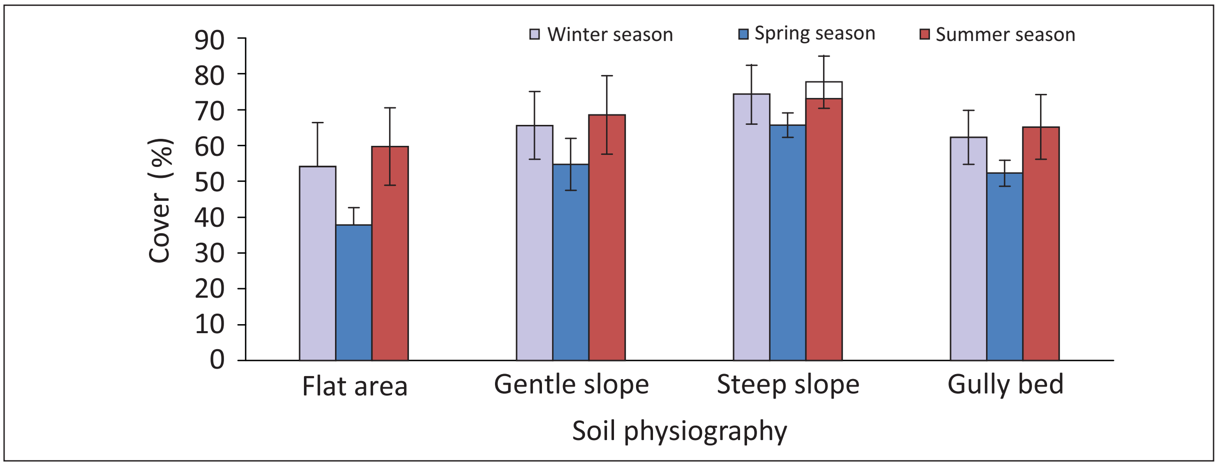

Figure 1.2. Seasonal comparison of herbaceous vegetation cover by site

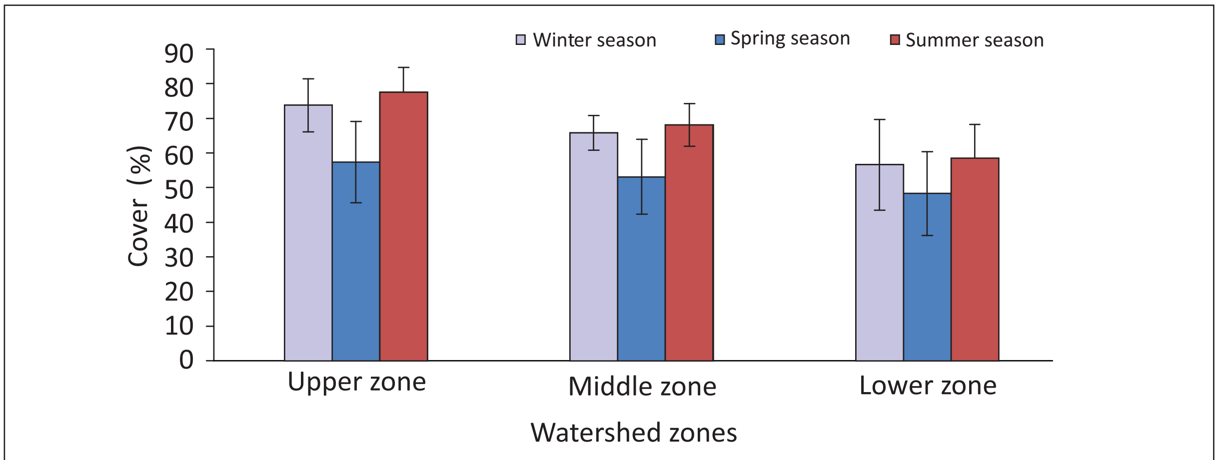

Figure 1.3. Seasonal comparison of herbaceous vegetation cover by zone

zone, more plants were present (52 per m^2) while the plant densities were 49 per m^2 in the middle zone and 30 per m^2 in the lower zone. When the average vegetation densities for the three seasons for the different soil physiography were compared, it was found that the flat areas showed the lowest density (36 plants/m^2) and gentle slopes the highest (50 plants/m^2). In steep slope areas, 47 plants/m^2 were recorded in comparison to gully beds where 41 plants/m^2 were counted (Table 1.18).

Woody vegetation density

Vegetation density in terms of the tree and shrub components in the watershed area was 158 per ha. The highest tree/shrub density was recorded on steep slopes where 192 plants/ha were present followed by the gully bed areas, with 183 trees-shrubs/ha. The lowest density was recorded on the flat areas where only 97 trees-shrubs/ha were present. Comparing the zones, the upper zone was the healthiest (200 trees-shrubs/ha) followed by the middle zone (181 trees-shrubs/ha). The lowest tree/shrub density was present in the lower zone – 92 trees-shrubs/ha (Table 1.18).

Seasonal vegetation density

The average annual herbaceous density was 44 plants/m^2 with the highest count occurring in summer (51 plants/m^2). In winter the density was 48 plants/m^2. The reason for this might be that there was less grazing pressure because of the severe climatic conditions; most of grasses become dormant and animals prefer not to graze them. In spring, comparatively less plants were present – a density of 32 plants/m^2. In winter and summer, the herbaceous density was the highest on gently sloped areas and was the lowest on the flat areas, while in spring, the highest density was on the steep slopes and the lowest was on flat areas. In all three seasons, the upper zone was highly populated while in the lower zone the herbaceous density was the lowest.

Similarly, the tree-shrub component density was the highest in winter with 163 trees-shrubs/ha. In spring, it was reduced to 156 trees-shrubs/ha through cutting. In summer the density was further decreased to 154 trees-shrubs/ha as a consequence of more trees being felled. In all three seasons, the

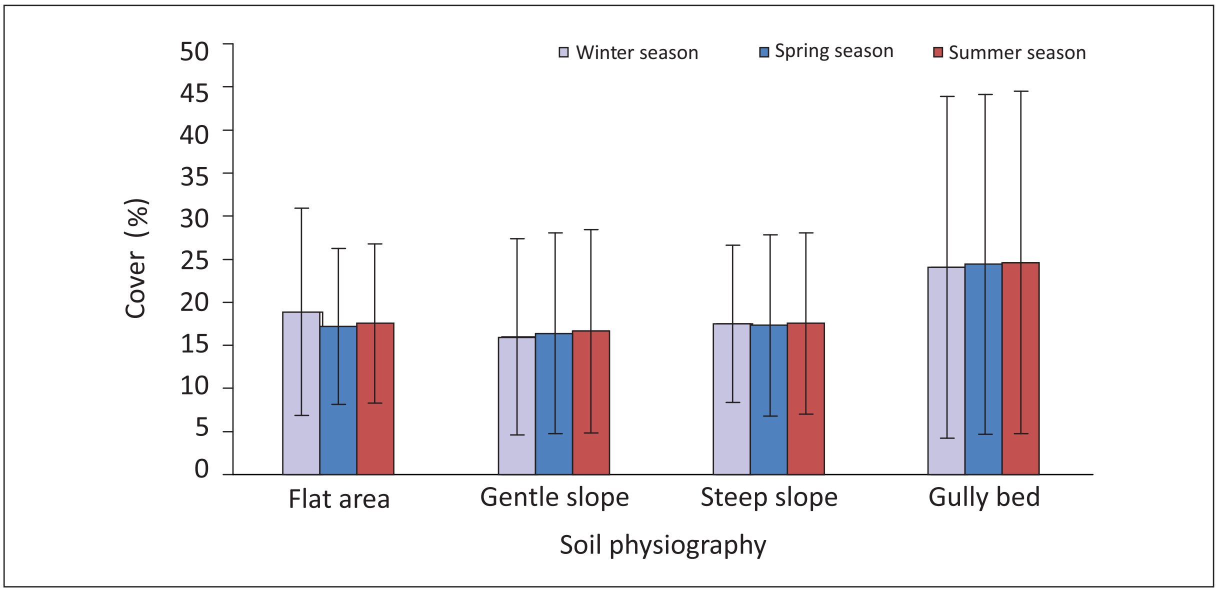

Figure 1.4. Seasonal comparison of woody vegetation cover by site

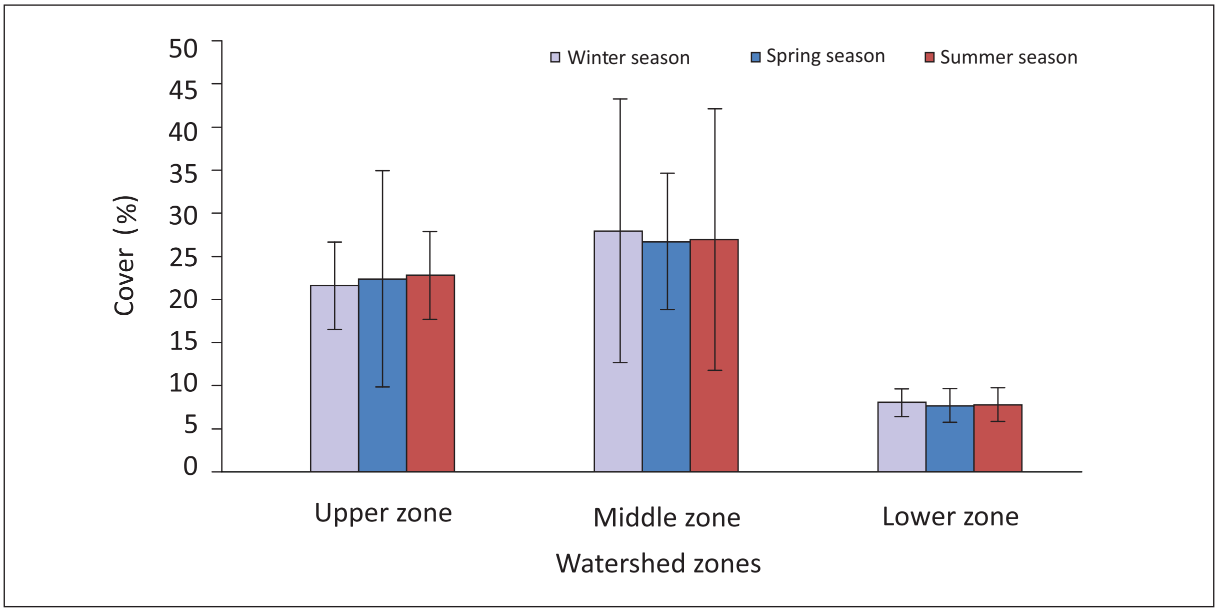

Figure 1.5. Seasonal comparison of woody vegetation cover by zone

Table 1.18. Average annual herbaceous density and tree density

	Herbaceous density (plants/m²)					Trees density (trees-shrubs/ha)				
Zone	**Flat area**	**Gentle Slope**	**Steep Slope**	**Gully bed**	**Mean**	**Flat area**	**Gentle Slope**	**Steep Slope**	**Gully bed**	**Mean**
Upper zone	39	57	59	51	52	200	200	275	125	200
Middle zone	39	59	52	46	49	33	150	200	342	181
Lower zone	29	34	31	26	30	58	125	100	83	92
Mean	36	50	47	41	44	97	158	192	183	158

highest density was recorded on the steep slopes and gully bed areas. Deforestation was recorded on the flat and gully bed areas which were more accessible and suitable for agriculture. The highest density was recorded in the upper zone and the lowest in the lower zone. Deforestation was recorded in the middle and lower zones where people depend on agriculture and livestock rearing while the upper zone is known as an economic activity area with it being close to Kallar Kahar city.

1.8.4 Vegetation composition and percent frequency

The *Acacia modesta* (Phulai) was the main contributing species among the trees and was found in all three zones and in each type of soil physiography. A total of 78 trees were found in all transects in winter, of which 75 were remaining in spring (3 trees were felled) and 74 in summer (1 tree felled). The highest contribution in species composition was from *Acacia modesta* (Phulai) with a composition of 70% and a frequency of 50%.

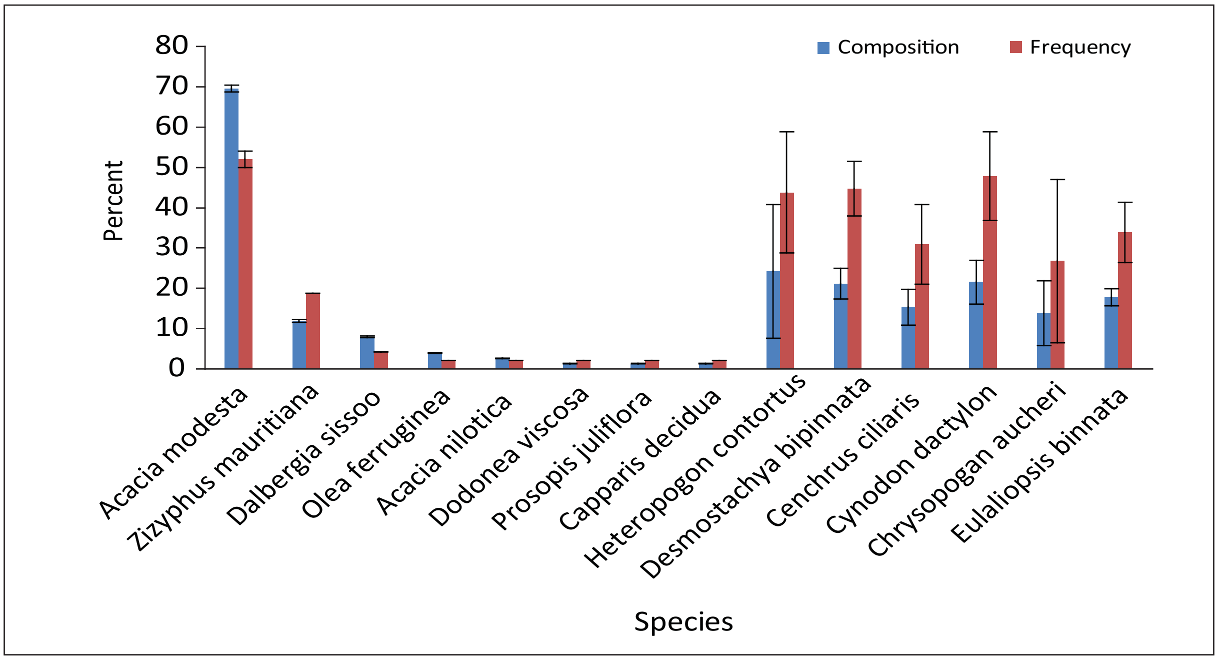

Figure 1.6. Vegetation composition and frequency by species

The second most abundant species was *Zizyphus mauritiana* (Ber) with a composition of 12% and frequency of 19% (Figure 1.6). More species diversity was found in the upper zone with 6 species of tree-shrub while in the middle and lower zones three species were found. The Acacia modesta and *Zizyphus* mauritiana were represented in all three zones, whereas *Dalbergia sissoo* (Shisham), *Olea ferruginea* (Kaho), *Acacia nilotica* (Kikar), and Dodonea viscosa (Snatha) were only found in the upper zone while *Prosopis juliflora* (Mesquite) was found in the *middle zone* and *Capparis decidua* (Karir) was found only in the lower zone.

The area was dominated by *Heteropogon contortus* (Sariala grass) with a composition of 24% and frequency of 44% (Figure 1.6). Zewdu and Oustalet (2007) conducted a study to characterize vegetation composition and to estimate the biomass production and the carrying capacity of the rangeland in eastern Ethiopia. There were good grazing lands in a hydromorphic depression in the Ordolla area, but the palatable grasses, trees, and shrubs were decreasing as a result of overgrazing, runoff, drought, and being replaced by an invader category of the plant community.

1.8.5 Importance value index

On the basis of relative density, relative frequency, and relative cover, the importance value index (IVI) of the species was calculated. This tells us about their richness (Table 1.19). On the basis of importance value, the sampled vegetation was divided into different plant communities. The community within each stand was named as the species having the highest importance value irrespective of its habit (Table 1.20).

In the grasses and herbs category, the vegetation was dominated by *Heteropogon contortus associated* with *Desmostachya bipinnata, Cynodon dactylon, Cenchrus ciliaris,* and *Eulaliopsis binnata.* From the point of view of the trees and shrubs, the vegetation was dominated by *Acacia modesta* associated

Table 1.19. Importance value index (IVI) for different grasses, trees, and shrubs

Grass	IVI Value	Tree/shrub	IVI
Heteropogon contortus	77.97	*Acacia modesta*	177.52
Desmostachya bipinnata	61.94	*Zizyphus mauritiana*	40.13
Cynodon dactylon	55.91	*Dalbergia sissoo*	19.12
Cenchrus ciliaris	36.80	*Olea ferruginea*	10.34
Eulaliopsis binnata	34.64	*Prosopis juliflora*	13.13

Table 1.20. Relative density, relative frequency, and relative cover of the main species

Species	Relative density	Relative frequency	Relative cover	Importance value index
Heteropogon contortus	30.67	20.58	26.72	77.97
Cenchrus ciliaris	14.01	8.04	14.75	36.80
Cynodon dactylon	21.81	17.64	16.46	55.91
Desmostachya bipinnata	20.53	16.52	24.89	61.94
Eulaliopsis binnata	10.65	13.49	10.50	34.64
Acacia modesta	66.57	42.89	68.06	177.52
Zizyphus mauritiana	12.16	18.75	9.22	40.13
Dalbergia sissoo	8.11	4.17	6.84	19.12
Olea ferruginea	2.70	2.08	5.56	10.34
Prosopis juliflora	2.70	2.08	8.35	13.13

with *Zizyphus mauritiana, Dalbergia sissoo, Prosopis juliflora, and Olea ferruginea.*

1.8.6 Productivity of woody vegetation

Tree height was measured in meters using a measuring rod. The average tree height in the watershed area was 3.9 m. In the flat areas, the trees were of a greater height (4.5 m) while in the gentle slope areas the trees were shorter with average height of 3.1 m. The diameter (in centimeters) was measured 1.37 meter above ground level using a measuring tape. The average diameter in the watershed area was 9.7 cm. Trees present on the flat areas had the highest diameter of 13.9 cm while for those in the gully bed areas, the average diameter was 7.3 cm. The average crown area in the watershed area was 18.6 m^2. In the flat areas, the crown area was 30.03 m^2, whereas in the steep slope areas, the tree crown area was 12.82 m^2 (Table 1.21). In the watershed area the growth increment recorded was 0.2 cm/6 month. Therefore, the average annual increment in the watershed area was around 0.4 cm, which is very low.

Seventy eight trees were sampled in the watershed area in the winter season and marked with waterproof paint for identification the next season. In summer, of those 78 trees, 4 had been felled leaving 74. The total volume of these 74 trees was calculated as 3.26 m^3 with an annual increment of 0.3 m^3/74 trees. The average volume of a tree was calculated to be 0.04 m^3. The total average tree volume, at the rate of 158 trees/ha, was calculated as 6.94 m^3/ha. The annual volume increment per tree was noted

Table 1.21. Tree/shrub growth in height, diameter, and crown area.

Growth parameter	Flat area	Gentle Slope	Steep Slope	Gully bed	Average
Height (m)	4.5	3.1	4.0	3.8	3.9
Diameter (cm)	13.9	8.3	9.0	7.3	9.7
Crown area (m^2)	30.03	13.84	12.82	17.67	18.6

as 0.004 m^3 and the average annual volume increment was calculated as 0.63 m^3/ha.

1.8.7 Range carrying capacity

Average annual carrying capacity

The overall carrying capacity (CC) of the watershed area was recorded as 10.2 ha/AU/ year, which indicates that the range is in poor to fair condition (Tables 1.22 and 1.23). On steep slopes, the carrying capacity was good (7.7 ha/AU/ year) as compared with other type of soil physiography. On the flat areas there was more grazing pressure and the carrying capacity remained very low (12.2 ha/ AU/ year). The gullied areas were the second most important for livestock grazing purposes with a carrying capacity of 10.8 ha/AU/ year. The upper zone was in good condition with a carrying capacity of 7.7 ha/AU/year. This might be due to more grass cover (69%) and the lower grazing pressure in this zone. In the lower zone, the carrying capacity was less (12.7 ha/AU/ year) as a result of the lower vegetation cover (54%) and the greater grazing pressure arising from the large number of livestock per farmer (23). The decreased carrying capacity in the lower zone might also be attributable to the greater agricultural farming activities in this area. The farmers do

Table 1.22. Average annual carrying capacity by site

Site	Total forage (kg/ha)	Available forage (kg/ha)	CC (ha/AU/ year)	Range condition
Flat area	532.5	266.3	12.2	Poor
Gentle slope	654.2	327.1	9.9	Fair
Steep slope	836.7	418.4	7.7	Fair to good
Gully area	597.5	298.8	10.8	Poor to fair
Overall average CC	655.2	327.6	10.2	Poor to fair

Table 1.23. Average annual carrying capacity of Dhrabi watershed by zone

Zone	Total forage (kg/ha)	Available forage (kg/ha)	CC (ha/AU/ year)	Range condition
Upper zone	835.8	417.9	7.7	Fair to good
Middle zone	621.5	310.8	10.4	Poor to fair
Lower zone	508.3	254.2	12.7	Poor
Overall average CC	655.2	327.6	10.2	Poor to fair

not allow free grazing on arable lands during cropping seasons; they force their livestock to graze on waste/uncultivated lands.

Winter season carrying capacity

In winter the carrying capacity was low (11.8 ha/AU/4 month) which indicates that the range was in poor to fair condition. On the flat areas, the carrying capacity was very low (13.8 ha/AU/4 month) indicating that the range was in poor condition. For the steep slope areas, the carrying capacity was 9.2 ha/AU/4 month (Table 1.24). It was found that in the upper zone, the range was in fair to good condition while in the lower zone, the range was in poor condition (Table 1.25).

Spring season carrying capacity

In spring the carrying capacity was very good (3.2 ha/AU/4 month) which indicates that the range was in very good condition. On the flat areas the carrying capacity was relatively lower at 3.7 ha/AU/4 month, while on the steep slope areas the carrying capacity was on the higher side at 2.5 ha/AU/4 month (Table 1.26). Similarly, in the upper zone the range condition was very good (2.3 ha/AU/4 month) while it was good in the lower zone.

Summer season carrying capacity

In summer, the carrying capacity was good (2.1 ha/AU/4 month) indicating that the range was in very good condition. On the flat areas, the carrying capacity was relatively low (2.5 ha/AU/4 month) while on the steep slopes, the carrying capacity was 1.5 ha/AU/4 month indicating that the range was in excellent condition (Table 1.27). The carrying capacity of summer for the different zones was found to be excellent in the upper zone (1.6 ha/AU/4 month). In the lower zone, the range was in very good condition (2.5 ha/AU/4 month). Sultan *et al.* (2000) determined the carrying capacity of sown pasture in the Pothwar Plateau of Pakistan. The highest forage yield, protein yield, and carrying capacity were recorded for elephant grass followed by Mott grass, blue panic grass, and sesbania.

Table 1.24. Winter season carrying capacity of watershed by site

Site	Total forage (kg/ha)	Available forage (kg/ha)	CC (ha/AU/4 month)	Range condition
Flat area	156.7	78.4	13.8	Poor
Gentle slope	186.7	93.4	11.6	Poor to fair
Steep slope	234.2	117.1	9.2	Fair
Gully area	170.8	85.4	12.6	Poor
Overall average CC	187.1	93.6	11.8	Poor to fair

Table 1.25. Winter season carrying capacity of watershed by zone

Zone	Total forage (kg/ha)	Available forage (kg/ha)	CC (ha/AU/4 month)	Range condition
Upper zone	227.5	113.8	9.4	Fair to good
Middle zone	188.1	94.1	11.4	Poor to fair
Lower zone	145.6	72.8	14.8	Poor
Overall average CC	187.1	93.6	11.8	Poor to fair

Table 1.26. Spring and summer carrying capacity of the watershed by site

Site	Spring season				Summer season			
	Total forage (kg/ha)	Available forage (kg/ha)	CC (ha/AU/4 month)	Range condition	Total forage (kg/ha)	Available forage (kg/ha)	CC (ha/AU/4 month)	Range condition
Flat area	579.2	289.6	3.7	Very good	861.7	430.9	2.5	Very good
Gentle slope	733.3	366.7	2.9	Very good	1042.5	521.3	2.1	Very good
Steep slope	862.5	431.3	2.5	Very good	1413.3	706.7	1.5	Excellent
Gully area	630.8	315.4	3.4	Very good	990.8	495.4	2.2	Very good
Overall average CC	701.5	350.8	3.2	Very good	1077.1	538.6	2.1	Very good

Table 1.27. Spring and summer carrying capacity of the watershed by zone

Parameter	Spring season				Summer season			
	Total forage (kg/ha)	Available forage (kg/ha)	CC (ha/AU/4 month)	Range condition	Total forage (kg/ha)	Available forage (kg/ha)	CC (ha/AU/4 month)	Range condition
Upper zone	922.5	461.3	2.3	Very good	1357.5	678.8	1.6	Excellent
Middle zone	656.9	328.5	3.2	Very good	1019.4	509.7	2.1	Very good
Lower zone	525.0	262.5	4.1	Good	854.4	427.2	2.5	Very good
Overall average CC	701.5	350.8	3.2	Very good	1077.1	538.6	2.1	Very good

It was indicated that the rangeland could be improved by reseeding with improved varieties of forage grasses and legumes. Yaxing and Quangong (2001) conducted a grassland survey to specify the biological and socio-economic characteristics of animal husbandry. The information from the survey was used to classify grassland resources and to evaluate grazing capacity. The assessment of grazing capacity indicated that the grasslands in the eastern countries of the temperate wet zone and some counties in the central and western parts are severely overgrazed, which has resulted in serious grassland deterioration. Amjad *et al.* (2004) conducted a study to determine the carrying capacity of rangelands. The carrying capacity was found to be 1.003 AU/ha/year and shrubs were considered as the major contributors of forage. This indicated the poor condition of the grasses. They recommended that a rotational grazing system should be adopted rather than repeated grazing year after year.

1.9 Rehabilitation of vegetation

Twice a year during the planting seasons, mobile nursery days were arranged in the watershed area, in collaboration with the Barani Agricultural Research Institute (BARI), Chakwal. Forest plants were distributed free of charge to the communities of the watershed. More than 6000 forest plants were distributed for wasteland/gullied area rehabilitation through these mobile nursery days during 2008 and 2009. The tree species included Lauqat (*Eriobotrya japonica*), Kachnar (*Bauhinia variegata*), Willow (S*alix spp.*), Iple Iple (*Leucaena leucocephala*), Arjan (*Terminilia arjuna*), Bakain (*Melia azedirach*), Jamun (*Syzygium cumunii*), Sukh Chain (*Pongamia glabra*), and Siris (*Albezia lebbek*). The survival rate of the forest plants was more than 50%. Farmers were of the view that plants require irrigation and protection from livestock. The farmers were willing to plant the trees, but would have preferred fruit plants like lokat, jamun, anar, apple, etc.

In order to stabilize the gully areas and to increase the vegetation cover, Mott grass (*Pennisetum purpureum*) was planted for soil conservation at two sites in Dhoke Mohri and Rahna Sadat villages, during the spring and summer of 2009. First time its cutting failed to sprout because of the dryness in the soil. However, the second time it succeeded in sprouting in shady places and depressions with better moisture in the soil, but latter on could not survive because of a long dry spell. As Mott grass is fast growing and highly palatable forage, farmers were interested in raising it on their farms for livestock.

1.10 Conclusions

The socio-economic conditions in the watershed were found to be poor because of the small and fragmented land holdings, illiteracy, tenancy farming, lack of access to advance agricultural machinery, soil erosion, and low and erratic rainfall. In the rainfed areas, about 90% of the cultivated lands were allocated to wheat in the Rabi (October-March) season and about 10% to fodder during the *Kharif* (April-September) season.

There was almost no trend toward the planting of new trees, shrubs, and grass. The existing vegetation was all natural and was declining. The area was rich in plant diversity as 115 plant species were recorded in the area. Tree cover was about 19% and the herbaceous cover was about 62%. The watershed was dominated by Acacia modesta (Phulai) trees (70%) and the grasses *Heteropogon contortus* (Sariala) (24%) and Desmostachya bipinnata (Dab grass) (21%). The average herbaceous vegetation density was 44 plants/m^2 and the vegetation density of trees-shrubs was 158 per ha. The overall carrying capacity of the watershed was 10.2 ha/AU/year indicating that the rangeland was in a fair to good condition for grazing. The upper zone of the watershed was in relatively good condition as compared to the middle and lower zones in term of vegetation health and grazing potential, most probably because these have more rainfall and carry less livestock. Steep slopes and gully beds were richer in vegetation as compared to gently sloping and flat areas. There is need to develop a comprehensive plan to control soil erosion, improve the land cover and socio-economic conditions of the local community.

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Chapter 2: Improving land and water productivities in the Dhrabi watershed

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2.1 Summary

In Pakistan, dryland farming is practiced on 12 Mha. Rainfall in these areas is low to medium, with high spatial and temporal variation. About 70% of the rainfall occurs during the monsoon months from June to August; thus, most of the rainfall is not available for cultivation. Moreover, given the conventional farming systems followed, land and water productivity is very low. Hence, there is a need to harvest as much rainwater as possible, either in the soil profile for its subsequent use by the crops, or on the surface (in ponds, mini- and small dams) to be used for supplemental irrigation. There is also a need to change the conventional farming systems to ones promoting crop intensification and diversification to improve crop yields, water productivity, and the net income of the farmers.

This study was conducted during the period 2007 to 2009 in Dhrabi watershed. The watershed covers 196 km^2 in the Chakwal district of Pakistan. The experiments included:

- Improving rainfed wheat yields using improved practices
- Evaluating efficient irrigation techniques, such as raised bed sowing and small plot sowing with supplemental irrigation (SI)
- Improving groundnut yields under rainfed and supplemental irrigation conditions
- Increasing summer and winter fodder through improved practices and irrigation
- Cultivating crops in gullies (vi) cultivating high value crops
- Applying gypsum for moisture conservation and yield improvement.

A brief summary of the results is given below.

- Using improved practices, the yield of rainfed wheat was increased 31%, on average, over that obtained following the farmers' usual practices. Net income following the improved practices (PKR 70,000/ha) was almost doubled, showing that the adoption of improved practices can give significantly higher returns in terms of land and water productivity as compared to the existing practices.
- Efficient irrigation techniques with supplemental irrigation can help improve wheat yields and water productivity. The highest wheat yield of 5102 kg/ha was obtained in a small plot sowing. This was 28% higher than that obtained following traditional practices. Raised bed sowing resulted in a yield of 4776 kg/ha, which was 24% higher than that achieved following the farmers' usual practices. Water productivity in small-plot sowing and raised bed sowing was almost the same and was about 23% higher than that obtained following the farmers' practices. The highest net income – PKR 97,701/ha – was obtained under small plot sowing. This was a 35% improvement over that achieved under the farmers' traditional practices. Under raised bed sowing, the net income was 30% higher. Thus, with just a 13% extra cost for the water used for SI under small plot sowing and with improved practices, a 47% higher wheat yield and a 55% higher net income were obtained. Similarly, with about a 12% additional cost for SI at the critical growth stages of groundnut, its yield and the resulting net income was increased between four and seven times.

- Using the improved practices, summer fodder yields were 27% higher and net income was 30% higher. Similarly, the yield of winter fodder was 34% higher and net income increased 31%. Mixed sowing of oats and berseem provided 43% and 35% higher green fodder yields than single crops of oats and berseem, respectively. Moreover, net income from the mixture of oats and berseem was between 42% and 52% higher than their single crops. Since berseem requires huge amounts of water, its cultivation in the rainfed areas seems to be uneconomical. The same amount of water can be used for the SI of wheat or other crops that can give returns much higher than those obtained from berseem.
- Growing high value crops where water is available, gives higher returns. Off-season coriander and chilies gave a net return of about PKR 100,000/ha whereas growing flowers gave a tremendous net return of over PKR 700,000/ha. However, the production costs of high-value crops are very high. Therefore, only those farmers who can afford the high investment should grow these crops.
- Growing millet and sorghum in gullies with improved practices gave green fodder yields of 44,167 kg/ha and 48,611 kg/ha. The corresponding net incomes were PKR 37,449/ha and PKR 41,004/ha. Thus, cultivation in gullies not only conserves soil from further deterioration, but also generates some income for the farmers.
- Applying gypsum helped store moisture in the soil profile and increased the crop yield. A treatment with gypsum plus a loose-stone structure conserved 40% more moisture than the control. Wheat grain yield (4501 kg/ha) and water productivity (1.5 kg/m^3) were 62% higher than the control (0.6 kg/m^3) with a net return of over PKR 100,000/ha The highest groundnut pod yield of 1502 kg/ha was obtained under gypsum plus a stone structure; this was 50% higher than the control.

2.2 Introduction

About 80% of the world's agricultural land is rainfed, and contributes at least two-thirds of global food production (Oweis and Hachum, 2006) while about 70% of the world's poor people live in these areas where livelihood options outside agriculture are limited. These areas, however, have a great potential for contributing to the livelihoods and food security of the poorest because (i) there is a wide gap between the current level of agricultural productivity and its potential, (ii) they largely belong to poor communities, and (iii) a large area is available for out-scaling any promising interventions. Therefore, these lands need to be exploited to meet the ever increasing demands for food and fiber. A better selection of crops, management of soil, rainwater, soil moisture, and supplemental irrigation are the key factors to improving the land and water productivity and livelihoods of these areas (Albeyi *et al.,* 2006; Passioura, 2006; Rockstorm *et al.,* 2007).

The geographic area of Pakistan is about 80 million hectares (Mha), of which 18 Mha is irrigated and dry land farming is practiced on 12 Mha. The *barani* (rainfed) areas of Punjab cover about 7 Mha and are home to over 19 million people. The average annual rainfall ranges from over 1000 mm in the northeast to less than 200 mm in the southwest. These areas, however, contribute less than 10% to total agricultural production and depend solely on the rainfall. This contribution is further reduced if the rainfall is insufficient or occurs at inappropriate times. For example, during *Rabi* cropping (October-March) 2000-2001, when the rainfall was very small (62 mm), the contribution of wheat from *barani* Punjab to the total production in the country was only 3% with an average yield of 505 kg/ha (MINFAL, 2009). It was a similar case with other crops.

Therefore, the average yields of major crops are far below what is achievable. The major constraints which contribute to low agricultural productivity are

- Low and erratic rainfall, causing stress at critical growth stages
- Soil erosion, resulting in the loss of fertile top soil and moisture
- Small and fragmented land holdings
- Low levels of agricultural inputs (Ashraf *et al.,* 2007).

There could be two possible approaches to increasing agricultural production; either bring more land under cultivation (horizontal expansion) or increase the yield per hectare (vertical expansion). There is also a vast scope for both horizontal and vertical expansions by increasing water productivity (Ashraf *et al.,* 1999). Water productivity can be enhanced by either improving the production per unit of water consumed, or maintaining the same production with reduced water use (Kijne *et al.,* 2003; Rijsberman, 2006). Water productivity can also be improved through crop intensification, by improving the yield of the existing crops, and through diversification, by introducing high value crops into the system (Passioura, 2006).

In dry land farming, various techniques, such as deep tillage and mulches, are used to conserve soil moisture in the root zone during the fallow season for use by the crops in the next growing season. Mulching is neither economical nor socially acceptable because the value of straw as an animal feed is the same as the grains produced from the wheat, sorghum, and maize crops (Ashraf, 1999).

Gypsum ($CaSO_4$ $2H_2O$) is generally used to reclaim sodic soils and waters. Application of gypsum improves the structure and hydrologic properties of clayey or sodic soils. It contains 23.28% calcium, 2.34% hydrogen, 18.62% sulfur, and 55.76% oxygen. The use of gypsum has also shown good results in conserving soil moisture under rainfed conditions and its use increases the infiltration rates (Chartres *et al.,* 1985; Farina *et al.,* 2000; Yu *et al.,* 2003; Hamza and Anderson, 2004). Rashid *et al.,* (2008) reported a wheat yield increase of 46% in fields where gypsum was applied at a rate of 2.5 t/ha during 2001-2002. Since the solubility of gypsum is very low, generally less than 1%, its benefits in conserving moisture can last for an extended period of time.

It has been estimated that about 11 million cubic meter (Mm^3) of water is lost as surface runoff annually from these regions, 70% of which occurs during the summer months from July to September. Therefore, much of the summer rain is not available for agriculture because of surface runoff. This is not only a loss of water, but it also results in the loss of fertile top soils. Moreover, given the uncertainty of the rainfall, farmers normally minimize inputs to reduce the risk of loss in the event of a drought and mainly depend on off-farm incomes for their sustenance. Agriculture in this area is just at the subsistence level, primarily as a result of an acute shortage of assured irrigation supplies (Ashraf *et al.,* 2007). It is necessary to harvest as much of this water as possible either on the surface or underground. The stored water can be used for SI which can act as a buffer against crop failure during dry periods.

Supplemental irrigation is an option with a high potential for increasing water productivity in rainfed areas. Scarce water used for full irrigation could be reallocated to supplement dry farming for improved water productivity (Oweis and Hachum, 2006; Passioura, 2006). Both the productivity of irrigation water and that of rainwater are improved when they are used conjunctively (Oweis *et al.,* 1999; 2000). Supplemental irrigation at the reproductive stages – the flowering and seed filling periods, for example – could be a very good management option if these critical periods coincide with favorable weather conditions (Wang *et al.,* 2001; Norwood and Dulmer, 2002; Faraji *et al.,* 2009). Optimization of SI in rainfed areas is based on the following three basic principles.

- Water is applied to a rainfed crop that would normally produce some yield without irrigation
- Since rainfall is the principal source of water for rainfed crops, SI is only applied when the rainfall fails to provide the essential moisture for improved and stable production
- The amount and timing of SI are scheduled not to provide moisture-stress-free conditions throughout the growing season, but to ensure a minimum amount of water available during the critical stages of crop growth that would permit optimal instead of maximum yield (Oweis, 1997).

However, to maximize the benefits of SI, other inputs such as improved germplasm, fertility, and cultural practices must also be optimized (Oweis and Hachum, 2006).

This study was conducted in the Dhrabi watershed of Pakistan with the objectives of improving agricultural productivity by:

- Conserving rainwater in the field with innovative techniques and improved practices
- Using supplemental irrigation
- Crop intensification and diversification
- Adopting high value crops.

2.3 Methodology

The study was conducted in the watershed area of Dhrabi reservoir (Figure 2.1). It is located between latitudes 32° 42′ 36″ N to 32° 55′ 48″ N and longitudes 72° 35′ 24″ E to 72° 48′ 36″ E in Chakwal District. The total area is 196 km^2 and it includes one lake, two small dams, and twelve mini-dams. Rainfall is the main source of freshwater in the watershed. Small springs originate from the hills. The topography varies from shallow to deep gullies, small to large terraces, and mounds to hillocks. The soil is predominantly of a sandy loam type and low in organic matter (less than 1%). The study was conducted from 2007 to 2009. Climatic data were collected at the Soil and Water Conservation Research Institute (SAWCRI), Chakwal, located at about 3 km from the sites. A description of the experiments conducted is given in Table 2.1.

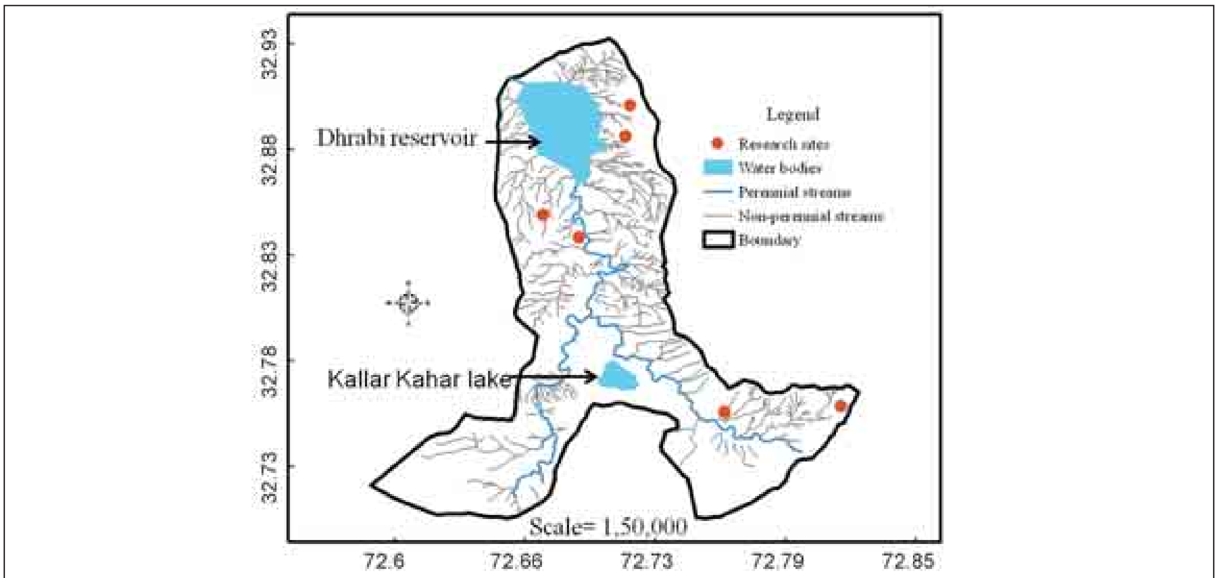

Figure 2.1. Location map of the study area

Table 2.1. Description of the studies conducted

Trials	Treatments	Description
Wheat yield improvement under rainfed conditions	Improved practices	Latest high yielding variety (Chakwal-50), recommended fertilizer (NPK at 90-60-30 kg/ha), seed rate (125 kg/ha) and cultivation practices (weedicides, hoeing, etc)
	Farmers' practices	Existing practices with old/local variety (C-591, Inqlab-91, or a mixture of different varieties), little or no fertilizer, low seed rate (75-100 kg/ha), no cultivation practices
Wheat yield improvement with efficient irrigation system and supplemental irrigation (SI)	Raised beds (45 cm beds with three rows of wheat)	Latest high yielding variety (Chakwal-50), recommended fertilizer (NPK at 90-60-30 kg/ha), recommended seed rate (125 kg/ha), and cultivation practices (weedicides/hoeing, etc.) and 2 SI at the appropriate times
	Small plots (2.25 m wide and 30 m long)	Latest high yielding variety (Chakwal-50), recommended fertilizer (NPK at 90-60-30 kg/ha), recommended seed rate (125 kg/ha), and cultivation practices (weedicides/hoeing, etc.) and 2 SI at the appropriate times
	Farmers' practices (5 m wide and 30 m long)	Old/local variety (C-591, Inqlab-91, or mixture of different varieties), little or no fertilizer, low seed rate (75-100 kg/ha), no cultivation practices, and irrigation as usual
Groundnut yield improvement under rainfed conditions and with SI	Improved practices with SI	Latest high yielding variety (Golden), recommended fertilizer (NPK at 30-80-30 kg/ha), gypsum application at flowering (500 kg/ha), recommended seed rate (100 kg kernel/ha), cultivation practices (hoeing, etc.), and one SI at the appropriate time
	Improved practices under rainfed conditions	Latest high yielding variety (Golden), recommended fertilizer (NPK at 30-80-30 kg/ha), gypsum application at flowering (500 kg/ha), recommended seed rate (100 kg kernel/ha), cultivation practices (hoeing, etc.)
	Farmers' practices	Existing practices with old/local variety (No. 334, mixture of different varieties), no fertilizer, no gypsum, low seed rate (30-40 kernels kg/ha), no cultivation practices
Summer fodder yield improvement with irrigation	Sorghum with improved practices	Latest high yielding variety (Chakwal Sorghum), recommended fertilizer (NPK at 110-60-0 kg/ha), recommended seed rate (75 kg), sown with broadcast method and two SI

Table 2.1. Continued

Trials	Treatments	Description
	Sorghum and maize with improved practices	Latest high yielding varieties (Chakwal Sorghum + Akber), recommended fertilizer (NPK at 110-60-0 kg/ha), recommended seed rate (sorghum 37 kg, maize 50 kg), and irrigations at the appropriate time
	Sorghum and maize with farmers' practices	Old/local variety, or mixture of varieties, little or no fertilizer, low seed rate (sorghum 20 kg/ha and maize 30 kg/ha), and irrigations as usual
Winter fodder improvement with crop diversification	Oats	Latest high yielding variety (Chakwal Selection), recommended fertilizer (NPK at 80-60-0 kg/ha), recommended seed rate (75 kg/ha), and irrigation during crop growth period
	Berseem	Latest high yielding varieties (Anmol), recommended fertilizer (NPK at 110-60-0 kg/ha), recommended seed rate (20 kg/ha), and irrigation during crop period
	Oats + berseem	Latest high yielding varieties (oats-Chakwal and berseem-Anmol), recommended fertilizer (NPK at 110-60-0 kg/ha), recommended seed rate (oats 37 kg/ha and berseem 10 kg/ha) and irrigations during crop period
Crop production in gullies	Millet with improved practices	Latest high yielding variety (Chakwal Selection), recommended fertilizer (NPK at 90-60-0 kg/ha), recommended seed rate (10 kg/ha)
	Millet with farmers' practices	Old/local variety, or mixture of varieties, no fertilizer, low seed rate (5 kg/ha)
	Sorghum with improved practices	Latest high yielding varieties (Chakwal Sorghum), recommended fertilizer (NPK at 90-60-0 kg/ha), recommended seed rate (75 kg/ha)
	Sorghum with farmers' practices	Old/local variety, or mixture of varieties, no fertilizer, low seed rate (40 kg/ha)
Production of high value crops with irrigation	Off-season coriander	Latest seed variety of coriander (Anmol Irani) with recommended fertilizer (NPK at 90-60-0 kg/ha), seed rates (100 kg/ha), and an assured water supply
	Chilies	Latest seed variety of chili (local) with recommended fertilizer (NPK at 90-60-0 kg/ha), and seed rates (5 kg/ha)
	Flowers	Improved varieties of flowers with recommended fertilizer (NPK at 45-115-60 kg/ha), and seed rates
Gypsum application	Wheat and groundnut fields	Installation of low cost soil erosion control structures and application of gypsum for moisture conservation
	Farmers' practice	Existing practices without soil control structures and gypsum application

Table 2.2. Wheat yield improvement trials under rainfed conditions

Farmer's name	Village	Area (ha)	Date of sowing	Date of harvesting
Ghulam Murtaza (Site 1)	Murid	0.4	29/10/07	22/4/08
Muhammad Hussain (Site 1)	Rehna Sadat	0.4	11/11/08	6/5/09
Ghulam Mustafa (Site 2)	Rehna Sadat	0.4	29/11/08	9/5/09
Muhammad Ayub (Site 3)	Rehna Sadat	0.4	28/11/08	9/5/09

2.3.1 Wheat yield improvement under rainfed conditions

The wheat yield improvements trials were conducted with improved practices (Table 2.2). At each site, a field of the same size was treated as a control (farmers' practices) which was sown and harvested on the same dates as that of the improved practices. Soil samples were collected to a depth of 105 cm at 15 cm interval before sowing and again at the heading stage and after harvesting. The moisture content of the samples was determined gravimetrically. Bulk densities at these depths were also determined and were used to convert the gravimetric moisture content into volumetric moisture content. Crop yield and the costs of all the inputs were recorded in the field for both the improved and the farmers' practices.

2.3.2 Wheat yield improvement with supplemental irrigation

Where irrigation water is available (for example, a small/mini-dam, ponds, dug well/turbine), the farmers use conventional methods of irrigation resulting into low land and water productivity. Trials were conducted in the farmers' fields with efficient irrigation systems and applying SI only at the critical growth stages. The techniques evaluated were: raised beds of 45 cm width and 30 m length (45 cm beds with three rows of wheat) and small plots (2.25 m wide and 30 m long). These were compared with the farmers' existing practices of basin irrigation (5 m wide and 30 m long) (Table 2.3). Raised beds were made with a tractor driven planter, while the small plots were made manually with a locally made *Jandra* (land leveler). Soil samples were collected to a depth of 105 cm at intervals of 15 cm before sowing, and again at heading and at harvesting to determine the moisture content. The discharge was measured with a water meter installed with the delivery pipe from the tubewell. The crop yield, amount of water applied, costs of water, and non-water inputs were recorded, the crop water productivity was determined and an economic analysis was done.

2.3.3 Groundnut yield improvement under rainfed conditions and with SI

Groundnut is a major cash crop of the region and mainly grown under rainfed conditions. In the Dhrabi watershed area, however, the groundnut is not commonly cultivated – only a few farmers grow it. They use neither an improved variety seed nor adopt recommended management practices, with the result that the yield is very low. Trials were conducted under both rainfed and SI conditions with improved practices (Table 2.1). Groundnut was sown with locally designed topa (3 pores mounted on a tractor cultivator) in 45 cm rows with one SI at the flowering stage. These were compared with the farmers' existing practices (Table 2.4). The fields where the farmers' practices were followed were sown and harvested on the

Table 2.3. Farm trials for wheat with supplemental irrigation (SI)

Farmer's name	Village	Area (ha)	Date of 1st irrigation	Date of 2nd irrigation	Date of sowing	Date of harvesting
Gul Haider Shah-1 (Site 1)	Rehna Sadat	0.2	27/11/07	9/3/08	1/11/07	22/4/08
Gul Haider Shah-2 (Site 2)	Rehna Sadat	0.2	28/11/07	10/3/08	2/11/07	22/4/08
Muhammad Hussain (Site 3)	Rehna Sadat	0.2	10/12/07	11/3/08	3/11/07	23/4/08
Ghulam Hasnain (Site 4)	Kot Chaudhrian	0.2	25/11/07	15/03/08	8/11/07	5/5/08
BARI, Chakwal (Site 5)	BARI	0.05	5/12/07	6/3/08	26/11/07	13/5/08
Ahmad Nawaz (Site 1)	Murid	0.4	20/11/08	3/3/09	5/11/08	5/5/09
Muhammad Nawaz (Site 2)	Murid	0.4	21/11/08	5/3/09	6/11/08	5/5/09
Gul Haider Shah (Site 3)	Rehna Sadat	0.4	29/11/08	9/3/09	12/11/08	6/5/09
Muhammad Arshad (Site 4)	Murid	0.4	2/12/08	7/3/09	21/11/08	9/5/09
Muhammad Hussain (Site 5)	Rehna Sadat	0.4	30/11/08	8/3/09	11/11/08	6/5/09

Table 2.4. Groundnut under irrigated and rainfed conditions

Farmer's name	Village	Area (ha)	No. of irrigations (SI)	Date of sowing	Date of harvesting
Ghulam Husnain (Site 1)	Kot Chaudhrian	0.2	1	17/5/08	25/10/08
Muhammad Hussain (Site 2)	Rehna Sadat	0.2	1	26/4/08	12/10/08
Ahmad Nawaz (Site 3)	Murid	0.2	1	20/5/08	3/11/08
Abdul Khaliq (Site 4)	Dhoke Mohri	0.2		17/5/08	22/10/08
Ahmad Nawaz (Site 1)	Murid	0.2		12/4/09	16/10/09
Muhammad Arshad (Site 2)	Murid	0.2	1	13/4/09	16/10/09
Muhammad Hussain (Site 3)	Rehna Sadat	0.2		20/4/09	22/10/09

same dates as those where the improved practices were used. Soil samples were collected to a depth of 105 cm at 15 cm intervals before sowing and after harvesting and the moisture contents were determined gravimetrically. The crop yields and the costs of all the inputs were recorded for all fields.

2.3.4 Summer and winter fodder yield improvement

Livestock rearing is a common practice in the watershed. The health and yield performance of livestock depends on a continuous supply of fodder throughout the year. However, during the periods October to December and March to June, the shortage of green fodder becomes severe. This study was conducted to explore the possibility of overcoming this green fodder shortage during these critical months (Table 2.5). The summer fodders included sorghum and sorghum and maize with improved practices, with two SI – one at the stem elongation stage and the other before flowering – sown on an area of 0.2 ha each. These were compared with sorghum and maize grown under the farmers' practices. The winter fodders included oats, berseem, and oats plus berseem (mixed) sown on an area of 0.2 ha each with irrigation. Soil samples were collected to a depth of 105 cm at 15 cm intervals before sowing and after harvesting, and the moisture contents were determined gravimetrically. The crop yield and the costs of all the inputs were recorded for all fields.

2.3.5 Crop production in gullies

About 70% of the annual rains occur during the monsoon period and the high intensity rain storms cause severe soil erosion. Gullies are common features of the area. The unattended gullies are soon converted into badlands due to soil erosion. One option to reduce the soil erosion is to keep vegetation cover, in the form of crops, on a regular basis and construct low cost loose stone structures for the safe disposal of excess rainwater. The continuous cropping can increase water productivity over a series of crops (Schillinger *et al.,* 1999). To make use of such marginal lands and to assess crop potential, trials were conducted in these gullies using improved practices and following the traditional farmers' practices (Table 2.6).

2.3.6 Production of high value crops

Wheat is a staple crop which is cultivated under both rainfed and irrigated conditions (where possible). Oil seed crops, mostly canola, are cultivated on small areas in the winter and groundnut or fodder (millet and sorghum) in the summer. The irrigation water is not being used properly to grow high value crops, such as vegetables, fruits, and green fodder. In this study, the possibility of cultivating high value crops, such as off-season coriander, chili, and flowers, was explored (Table 2.7).

In addition a weedicide, Pendimetholine, was applied at a rate of 2.5 L/ha to the coriander crop and farm yard manure was applied to the flower fields at a rate of 20 t/ha. Nitrogen was also applied at a rate of 115 kg/ha to flowers and the fields were irrigated.

Table 2.5. Summer and winter fodder under irrigated conditions

Farmer's name	Treatments and year	Village	Crop variety	No. of irrigations	Seed rate (kg/ha)	Date of sowing	Date of harvesting
Muhammad Akram	IP (sorghum, 2008)	Karsal	Chakwal	2	75	12/7/08	22/9/08
Ahmad Nawaz	IP (sorghum + maize, 2009)	Murid	Sorghum (Chakwal), maize (Akber)	4	Sorghum (37), maize (50)	10/4/09	15/6/09
Muhammad Hussain	IP (sorghum + maize, 2009)	Rehna Sadat	Sorghum (Chakwal), maize (Akber)	4	Sorghum (37), maize (50)	10/4/09	15/6/09
Ahmad Nawaz	IP (oats, berseem, oats + berseem)	Murid	Oats (Chakwal), Berseem (Anmol)	4-8	Oats (75), Berseem (20)	20/10/08	Dec-Apr 09

IP: improved practices

2.3.7 Gypsum applications

Keeping in mind moisture stress and low crop productivity, the demonstration trials for wheat and groundnut yield improvements were conducted in the farmers' fields, each on an area of 0.2 ha, under different conditions. These conditions included

- A control (without structures and without gypsum)
- Gypsum without structures
- Gypsum without structures, but with fertilizer application
- A structure without gypsum
- A structure with gypsum.

Generally, the farmers do not use mineral fertilizers to supplement the nutritional needs of the crop.

The gypsum was applied at the rate of 2.5 t/ha during the summer fallow period in 2008. At the time of sowing the wheat and groundnut, two sets of soil samples were collected, one from 0 cm to 30 cm deep, the other from 0cm to 120 cm deep, before the gypsum was applied. The former were taken in order to determine the chemical properties and the latter were taken for moisture content determination. The wheat variety Chakwal-50 was sown at a seed rate of 125 kg/ha during the first week of November 2008 and harvested during the third week of April 2009. Farmyard manure was applied at a rate of 2 t/ha. Where plots were receiving additional treatment nitrogen and phosphorous were applied each at a rate of 57 kg/ha. The local groundnut variety No. 334 was sown at a rate of 35 kg/ha (shelled) during the last week of April and harvested during the last week of September. It was sown using the traditional pore method (longitudinal tubes attached to a tractor driven cultivator). After one year, the infiltration rates of the fields were measured with a double ring infiltrometer.

Table 2.6. Summer fodder (millet and sorghum) in gullies

Farmer's name	Village	Area (ha)	Crop variety	Pre-sowing fertilizer (kg/ha)	Seed rate (kg/ha)	Date of sowing	Date of harvesting
Muhammad Manzoor (Site 1)	Khokhar Bala	0.2	Millet (Chakwal)	NPK at 90-60-0	10	2/8/09	15/10/09
Muhammad Manzoor (Site 1)	Khokhar Bala	0.2	Sorghum (Chakwal)	NPK at 90-60-0	75	2/8/09	15/10/09

Table 2.7. High value crops under irrigated conditions

Farmer's name	Crop	Area (ha)	Crop variety	Seed rate (kg/ha)	Date of sowing	Time of harvesting
Ahmad Nawaz (Site 1)	Coriander	0.4	Anmol Irani	100	10/7/08	Aug-Oct, 09
	Chilies	0.1	Local	5	10/4/08	Jun-Sep, 08
Ahmad Nawaz (Site 1)	Coriander	0.4	Anmol Irani	100	13/6/09	Jul-Aug, 09
Muhammad Nawaz (Site 2)	Coriander	0.4	Anmol Irani	100	18/6/09	Aug, 09
Muhammad Arshad (Site 3)	Coriander	0.4	Anmol Irani	100	19/6/09	Aug, 09
Ahmad Nawaz	Flower	0.05	Narcissus	110,000 bulbs	21/10/08	Jan-Feb, 09
Ahmad Nawaz	Flower	0.05	Dutch Iris	110,000 bulbs	21/10/08	Mar, 09

2.4 Results and discussion

2.4.1 Rainfall analysis

A rainfed crop's water supply comprises the available water in the soil at the time of sowing plus any rainfall during the growing season (Passioura, 2006). Rockstrom and Falkenmark (2000) reported that a decrease of one standard deviation from the mean annual rainfall often led to a complete loss of the crop. Therefore, for better planning of rainfed agriculture, an analysis of the long-term rainfall is very important. Rainfall data for the last 33 years (1977-2010), collected at SAWCRI Chakwal, show an average annual rainfall of 630 mm (Figure 2.2). More than half (62%) the annual rainfall occurred in the summer months from June to September. During 2007 and 2008, the rainfalls were 15% and 38% higher than the average. However, during 2009, the total rainfall (545 mm) was 13% less than normal and of this 49% (265 mm) occurred during the months of July and August. Therefore, any activity that conserves moisture in the high rainfall period (the monsoon) and retains it for a longer period of time will help improve agricultural productivity. Figure 2.2 also shows the average class A pan evaporation (Ep) data collected at SAWCRI from 2000 to 2010. The average Ep was 1510 mm/year, more than double the average rainfall.

Information on rainfall that can be expected for a specific period is helpful for the selection of a crop and the time of sowing and for planning for SI. The probability of exceeding the long-term data was calculated using the Weibull method and is given in Table 2.8. A rainfall of 601 mm is expected with a 50% probability, which can occur in alternate years, and a rainfall of about 300 mm can be expected every year with a probability of 95%. Since there is lot of variability in the annual rainfall, the probabilities of exceeding this were also calculated for *Rabi* (October to March) and *Kharif* (April to September) and are shown in Table 2.8. During the Rabi season, the maximum rainfall of about 400 mm can be expected with a probability of less than 5%, whereas a rainfall of 210 mm can be expected with a 50% probability with a return period of two years. Therefore, during the Rabi season, the expected rainfall is insufficient to meet the water requirements of the major crops grown in the area, thus necessitating supplemental irrigation. However, during *Kharif* season, a rainfall of about 380 mm can be expected with a 50% probability over a return period of two years. This shows that most of the common *Kharif* (summer) crops can be grown with the rainfall if moisture is properly managed/conserved.

Wheat, groundnut, fodder (sorghum, maize, millet, oats, berseem), vegetable (coriander, chili), and flowers were the main crops studied. The cropping period (shaded) and the corresponding rainfall during the study period along with the long-term average are shown in Table 2.9. It is interesting to note that, the total rainfall during the wheat period (sowing to harvesting) varied from 158 mm to 296 mm. However, the minimum water requirement for the wheat crop is about 325 mm (Table 2.10). Therefore, the remaining water requirement can be met either from the deeper soil horizon of the already conserved moisture or from supplemental irrigation. Where SI is not possible, conservation of the monsoon or post monsoon rainfall is crucial for successful crop establishment.

2.4.2 Wheat yield improvement under rainfed conditions

Wheat is a staple food and every farmer in the watershed tends to grow it to meet his family's needs. Most of the farmers grow it under rainfed conditions using local low yielding varieties, little or no fertilizer, a low rate of seed application, and no cultivation operations. The objectives of these experiments were to demonstrate the benefits linked with crop and water productivity enhancement achieved through proper inputs under the same rainfall conditions.

Moisture profile

Soil moisture is one of the most important parameter for successful crop production in rainfed agriculture; the moisture content at the time of sowing plays a particularly important role in seed germination and crop establishment. During both years, the soil moisture content was sufficient at the time of sowing under both the improved and the farmers' practices (Table 2.11). It increased with increasing soil depth. Wheat is a relatively deep-rooted crop and is capable of extracting moisture and nutrients from the deeper depths. There were rainfalls of about 158 mm and 296 mm during 2007-2008

Table 2.8. Probability of exceeding an estimated rainfall

Annual (January-December)			*Rabi* (October-March)		*Kharif* (April-September)	
Probability of exceedence (%)	**Return period (years)**	**Annual rainfall (mm)**	**Return period (years)**	***Rabi* rainfall (mm)**	**Return period (years)**	***Kharif* rainfall (mm)**
Px	**Tx**	**Xp = Px 140.44)/ (-0.151)**	**Tx**	**XR = -3.71 x Px + 396**	**Tx**	**XK = -4.74 x Px + 618**
5			20.0	377	20.0	594
10	10.0	867	10.0	358	10.0	570
15	6.7	833	6.7	340	6.7	547
20	5.0	800	5.0	321	5.0	523
25	4.0	767	4.0	303	4.0	499
30	3.3	734	3.3	284	3.3	475
35	2.9	701	2.9	266	2.9	452
40	2.5	667	2.5	247	2.5	428
45	2.2	634	2.2	229	2.2	404
50	2.0	601	2.0	210	2.0	381
55	1.8	568	1.8	191	1.8	357
60	1.7	534	1.7	173	1.7	333
65	1.5	501	1.5	154	1.5	310
70	1.4	468	1.4	136	1.4	286
75	1.3	435	1.3	117	1.3	262
80	1.3	402	1.3	99	1.3	239
85	1.2	368	1.2	80	1.2	215
90	1.1	335	1.1	62	1.1	191
95	1.1	302	1.1	43	1.1	168

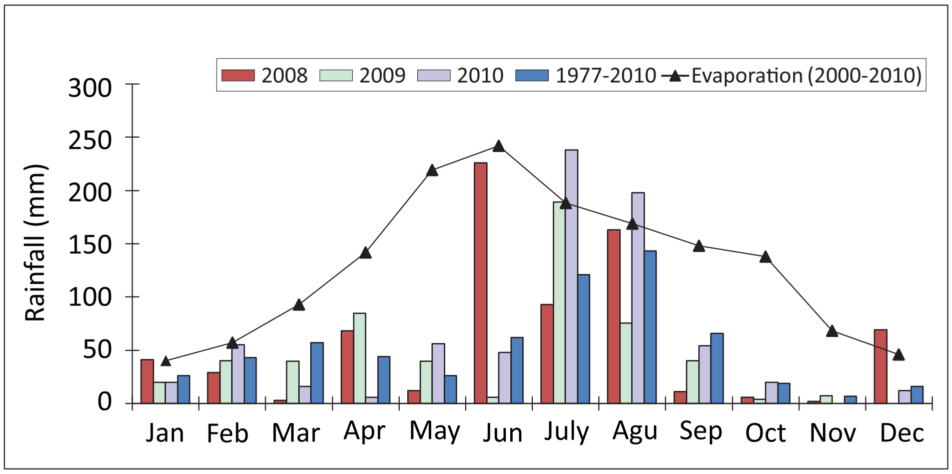

Figure 2.2. Long-term average rainfall and pan evaporation at SAWCRI, Chakwal

and 2008-2009. It is interesting to note that a reasonable amount of moisture was still available in the soil profile at harvesting under both the treatments.

Crop yield, water productivity and net return
Several factors, such as soil moisture, crop variety, seed quality and quantity, time and methods of sowing, and balanced applications of chemical fertilizers, affect crop yield. On average, a 31% higher yield was obtained under the improved practices as compared to the farmers' practices (Table 2.12). Over all, under the improved practices the wheat yield in 2008-2009 was 53 % higher than that obtained in 2007-2008. This might have resulted from the relatively higher rainfall during 2008-2009 (Figure 2.2, Table 2.9). Each millimeter of excess rainfall during 2008-2009 produced about 15 kg more wheat grain yield and about PKR446 more net income. Since the moisture profile was almost the same under both practices (Table 2.11), the higher yield under the improved practices may, therefore, be attributed to the cumulative effect of improved seed variety, higher seed rate, and appropriate applications of chemical fertilizers.

On average, the water productivity (WP) of the wheat was 33% higher under the improved practices (Table 2.12). As the rainfall was same under both practices, the higher WP under the improved practices was, therefore, a result of the higher yield obtained.

The farmer's net income is the most important indicator of the success of any crop or management practice. If both the yield and WP of a particular crop are high, but net income is low, then the farmers may not accept the practice. Particularly for small farmers, the input cost is very important. Table 2.19 shows that the cost of production was 30% higher in 2007-2008 under the improved practices and 19% higher in 2008-2009. However, they resulted in a 66% higher net income in 2007-2008 and a 38% higher net income in 2008-2009. Overall, net income under the improved practices was almost double that achieved following the farmers' traditional practices. This shows that adoption of improved practices can give significantly higher returns in terms of land and water productivity.

2.4.3 Wheat yield improvement with an efficient irrigation system and SI

Moisture profile
The amount of moisture available in the soil profile at the time of sowing was

Table 2.9. Crop period (shaded) and rainfall during the cropping period

Crops	Year/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Rainfall (mm)	Av. 1977-2009 (mm)
Wheat															
Rainfall (mm)	2007-2008	41	29	3	68							16	1	158	228
	2008-2009	20	40	40	85	40						2	69	296	
Winter fodder															
Rainfall (mm)	2008-2009	20	40	40	85	40								225	198
Flowers															
Rainfall (mm)	2008-2009	20	40	40	85	40								225	228
Groundnut															
Rainfall (mm)	2008				68	12	226	93	163	11	6	2		581	551
	2009				85	40	6	189	76	40	4	7		447	
Sorghum															
Rainfall (mm)	2008							93	163	11	6			273	342
Sorghum and millet															
Rainfall (mm)	2009							189	76	40	4			309	342
Sorghum and maize															
Rainfall (mm)	2009				85	40	6							131	132
Coriander															
Rainfall (mm)	2008							93	163	11	6			273	342
	2009							189	76	40	4			309	
Chilies															
Rainfall (mm)	2008			3	68	12	226	93	163					565	447
	2009			40	85	40	6	189	76					436	

Table 2.10. Salient features of the crops studied

Crop	Botanical name	Cropping period	Root zone depth (m)	Water req. (mm)	Sensitive stages
Wheat	*Triticum aestivum*	Nov-May	0.9-1.5	325-450	Tillering, anthesis, grain filling
Groundnut	*Arachis hypogea*	Mar-Nov	0.5-1.0	500-700	Peg formation, pod formation/filling stage
Maize (fodder)	*Zea mays*	Jul-Oct	0.9-1.5	300-350	Establishment stage, vegetative growth stage until 50% flowering
Sorghum (fodder)	*Sorghum bicolor*	Jul-Oct	0.9-1.5	450-650	Establishment stage, vegetative growth stage until 50% flowering
Oats (fodder)	*Avena sativa*	Oct-Dec	0.9-1.5	400-500	Establishment stage, vegetative growth stage until 50% flowering
Berseem	*Trifolium alexandrium*	Nov-Mar	0.5-1.0	800	Early establishment stage, vegetative growth stage
Coriander (off-season)	*Coriandrum sativum*	Jun-Oct	0.6	800-1100	Early establishment stage, vegetative growth stage
Chilies	*Capsicum annum*	Mar-Sep	0.7	400-500	Early establishment stage, flowering to fruit formation stage

Source: OFWM, 1997

Table 2.11. Average moisture contents in the soil profile (mm)

Depth (cm)	2007-2008				2008-2009			
	Improved practices		Farmers' practices		Improved practices		Farmers' practices	
	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting
0-15	14	44	13	45	27	32	26	27
15-30	23	40	20	40	30	39	29	37
30-45	37	29	31	31	33	43	31	42
45-60	36	28	35	28	35	44	35	43
60-75	44	30	46	34	43	45	44	44
75-90	58	31	52	35	48	46	49	45
90-105	61	33	58	38	51	46	50	46
Total	273	235	255	251	268	295	264	284

Table 2.12. Wheat yield and water productivity under rainfed conditions

Site	Treatments	Grain yield (kg/ha)	Rainwater ± ΔS (m^3/ha)	WP (kg/m^3)	Total cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
			2007-2008				
Site 1	IP	1,844	1,958	0.94	25,400	34,344	8,944
	FP	1,125	1,608	0.70	17,900	20,952	3,053
			2008-2009				
Site 1	IP	4,074	2,485	1.64	36,970	112,035	75,065
	FP	2,681	2,551	1.05	29,940	73,728	43,788
Site 2	IP	3,985	2,663	1.50	36,970	109,588	72,618
	FP	2,874	2,729	1.05	29,940	79,035	49,095
Site 3	IP	3,659	2,814	1.30	36,970	100,623	63,653
	FP	2,489	2,865	0.87	29,940	68,448	38,508
Average	IP	3,906	2,654	1.47	36,970	107,415	70,445
	FP	2,681	2,715	0.99	29,940	73,737	43,797

IP = Improved practices; FP = Farmers' practices; ΔS = soil moisture storage

about 300 mm in 2007-2008 and over 350 mm in 2008-2009 (Table 2.13). Particularly at shallow depths, the moisture content was sufficient to support seed germination and crop establishment. Two SI were applied to the crop, the first during November-December and the second during March (Table 2.3). At harvest time, almost the same amount of water was available in the root zone as there was at the time of sowing. The reason for this is that the farmers always try to over irrigate their fields to avoid the risk of crop failure.

Crop yield, water productivity and net return

During 2007-2008, the yields obtained from sowing in raised beds (RBS) and sowing in small-plot (SPS) were 16% and 23% higher than those obtained following the usual practices of the farmers (FP). The amount of water applied under RBS was 48% less than that supplied under the FP while the amount applied under SPS was 36% less (Table 2.14). Water productivity was almost the same under both the RBS and SPS treatments and was about 40% higher than for FP. The water cost component in the total cost of production was 13% for RBS, 17% for SPS, and 19% for FP. The net incomes from RBS and SPS were between 51% and 57% higher.

During 2008-2009, the highest wheat yield (5,102 kg/ha) was achieved in a small plot sowing; this was 28% higher than that achieved by the farmers' practices. Raised bed sowings gave a 24% higher yield (Table 2.15). The water productivities of the small plot sowings and the raised beds sowings were almost the same and about 23% higher than that of the farmers' practices. The highest net income of PKR 97,701/ha was obtained under small-plot sowing and this was 35% higher than that achieved with the farmers' practices. Under raised bed sowing, the net income was 30% higher.

The contribution of the cost of the SI to total production costs was 13% for raised bed sowing, 17% for small plot sowing, and 24% for the farmers' practices. Thus, with

Table 2.13. Average moisture content profile with efficient irrigation and SI

Depth (cm)	2007-2008						2008-2009					
	At sowing			At harvesting			At sowing			At harvesting		
	RBS	SPS	FP	RBS	SPS	FP	RBS	SPS	FP	RBS	SPS	FP
0-15	25	23	21	64	62	60	39	39	36	33	37	40
15-30	38	34	28	59	55	55	48	48	46	41	45	51
30-45	50	45	45	43	42	42	55	56	54	45	51	56
45-60	45	43	46	40	37	36	57	57	55	50	56	61
60-75	52	47	54	43	40	40	59	60	58	51	56	63
75-90	54	51	56	43	37	38	63	64	64	49	52	59
90-105	51	48	51	42	36	36	62	63	63	52	53	56
Total	315	291	301	335	309	307	383	388	376	321	350	386

just a 13% extra cost for the water used for SI under SPS and with improved practices, a 47% higher yield and a 55% higher net income was obtained. This indicates an opportunity to increase wheat production significantly with SI. Albeyi *et al.* (2006) showed that 50 mm of irrigation water at wheat sowing time increased grain yield by over 65% and added about 2000 kg/ha to the average rainfed yield of 4200 kg/ha in the Central Anatolian Plateau of Turkey. It has also been observed during this research that the raised bed sowing method can only be practiced on properly leveled fields. Therefore, small-plot sowing seems to be a reasonable option that can

increase crop yield, water productivity, and net return which can also be easily adopted by the farmers.

Wheat sown on small plots and raised beds

Table 2.14. Wheat yield and water productivity with different irrigation techniques and SI (2007-2008)

Site	Treatment	Grain yield (kg/ha)	SI (m^3/ha)	Rainwater ± ΔS (m^3/ha)	Total water (m^3/ha)	WP (kg/m^3)	Cost of non-water inputs (PKR/ha)	Cost of water inputs (PKR/ha)	Total cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
Site 1	RBS	3,278	900	1,037	1,937	1.69	31,130	4,550	35,680	61,052	25,372
	SPS	3,244	1,125	841	1,966	1.65	31,558	6,370	37,928	60,400	22,472
	FP	2,578	1,574	953	2,527	1.02	34,482	7,670	42,152	53,727	11,575
Site 2	RBS	3,122	851	1,074	1,925	1.62	30,554	4,640	35,194	58,147	22,953
	SPS	3,756	1,101	814	1,915	1.96	31,172	6,520	37,692	69,955	32,263
	FP	3,278	1,612	1,064	2,676	1.22	35,310	7,530	42,840	61,052	18,212
Site 3	RBS	3,178	978	2,019	2,997	1.06	30,348	4,710	35,058	59,190	24,132
	SPS	3,389	1,148	1,836	2,984	1.14	31,118	6,640	37,758	63,120	25,362
	FP	2,456	1,764	1,789	3,553	0.69	27,761	7,750	35,511	45,743	10,232
Site 4	RBS	3,511	673	1,164	1,837	1.91	28,952	4,460	33,412	65,392	31,980
	SPS	3,911	865	1,461	2,326	1.68	29,030	6,270	35,300	72,842	37,542
	FP	2,689	1,542	1,580	3,122	0.86	28,930	7,390	36,320	50,000	13,680
Site 5	RBS	2,767	767	1,577	2,344	1.18	29,964	4,380	34,344	51,535	17,191
	SPS	3,067	906	2,032	2,938	1.04	29,570	6,170	35,740	57,122	21,382
	FP	2,344	1,523	2,177	3,700	0.63	30,302	7,240	37,542	43,656	6,114
Average	RBS	3,171	834	1,374	2,208	1.44	30,190	4,548	34,738	59,063	24,326
	SPS	3,473	1,029	1,397	2,426	1.43	30,490	6,394	36,884	64,688	27,804
	FP	2,669	1,603	1,513	3,115	0.86	31,357	7,516	38,873	50,836	11,963

RBS = Raised bed sowing; SPS = Small plot sowing; FP = Farmers' practices (conventional sowing)

Table 2.15. Wheat yield and water productivity with different irrigation techniques and SI (2008-2009)

Site	Treatment	Grain yield (kg/ha)	SI (m^3/ha)	Rainwater ± ΔS (m^3/ha)	Total water (m^3/ha)	WP (kg/m^3)	Cost of non-water inputs (PKR/ha)	Cost of water inputs (PKR/ha)	Total cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
Site 1	RBS	5,007	859	4,341	5,200	0.96	35,510	5,190	40,700	137,693	96,993
	SPS	5,556	1,070	3,783	4,853	1.14	35,210	7,400	42,610	152,790	110,180
	FP	3,822	1,446	3,162	4,608	0.83	28,550	8,890	37,440	105,105	67,665
Site 2	RBS	4,963	892	3,990	4,882	1.02	35,510	5,190	40,700	136,483	95,783
	SPS	5,185	1,101	4,088	5,189	1.00	35,210	7,400	42,610	142,588	99,978
	FP	4,044	1,460	2,581	4,041	1.00	28,550	8,890	37,440	111,210	73,770
Site 3	RBS	4,622	969	3,078	4,047	1.14	35,510	5,190	40,700	127,105	86,405
	SPS	4,770	1,220	2,644	3,864	1.23	35,210	7,400	42,610	131,175	88,565
	FP	3,570	1,557	2,408	3,965	0.90	28,550	8,890	37,440	98,175	60,735
Site 4	RBS	4,385	858	3,010	3,868	1.13	35,510	5,190	40,700	120,588	79,888
	SPS	4,681	1,152	3,059	4,211	1.11	35,210	7,400	42,610	128,728	86,118
	FP	3,274	1,441	3,233	4,674	0.70	28,550	8,890	37,440	90,035	52,595
Site 5	RBS	4,904	1,075	3,299	4,374	1.12	35,510	5,190	40,700	134,860	94,160
	SPS	5,319	1,257	2,906	4,163	1.28	35,210	7,400	42,610	146,273	103,663
	FP	3,556	1,515	2,708	4,223	0.84	28,550	8,890	37,440	97,790	60,350
Average	RBS	4,776	931	3,544	4,474	1.07	35,510	5,190	40,700	131,346	90,646
	SPS	5,102	1,160	3,296	4,456	1.15	35,210	7,400	42,610	140,311	97,701
	FP	3,653	1,484	2,818	4,302	0.85	28,550	8,890	37,440	100,463	63,023

2.4.4 Groundnut yield improvement under rainfed conditions and with SI

Moisture content profile

Groundnut is sown in the period March to April and harvested in November. Before sowing, the land is mostly kept fallow. At sowing, the moisture contents in the soil profile were quite good (above 300 mm) and were sufficient for seed germination and crop establishment (Table 2.16). The groundnut growing period extends over the monsoon period during which the rainfall generally is sufficient to support the crop till maturity. However, at harvest the moisture contents were reduced throughout the soil profile during both years. Therefore, it seems difficult to grow wheat on the residual moisture immediately after harvesting groundnut. Supplemental irrigation becomes essential at the time of sowing if wheat is to be sown immediately after harvesting groundnut.

Crop yield, water productivity and net return

During 2008, the SI contribution to the total water used was 12% and the cost of the SI in the total cost of production was only 6% (Table 2.17). Pod yield under improved practices (IP) with SI (2126 kg/ha) was 68% higher than that achieved with the FP (rainfed) and 30% higher than that using the IP (rainfed). Pod yield under the IP (rainfed) was 53% higher than that following the FP (rainfed). Water productivity under the IP (irrigated) was 65% higher than with the FP (rainfed).

Net income under IP (irrigated) was PKR 57,221/ha which was 85% higher than that earned following the FP (rainfed). Net income under IP (rainfed) was 73% higher than that under FP (rainfed). During 2009, however, less rain occurred during the pod formation and filling period which badly affected the pod weight and resulted in a low yield in the case of IP (rainfed) and FP (rainfed). However, the effects of low rainfall were reduced by using SI in the case of IP (irrigated). The contribution of the SI to the total water used was increased to 17%. Pod yield (1635 kg/ha) under IP (irrigated) was 69% higher than under FP (rainfed). The average net income was highest (PKR 70,598/ha) for IP (irrigated), being 78%

Table 2.16. Moisture content in the soil profile at sowing and at harvesting

Depth (cm)	At sowing			At harvesting			At sowing			At harvesting		
	IP (irri)	IP (rainfed)	FP (rainfed)	IP (irri)	IP (rainfed)	FP (rainfed)	IP (irri)	IP (rainfed)	FP (rainfed)	IP (irri)	IP (Rfd)	FP (rainfed)
	2008						2009					
0-15	37	32	36	34	28	37	34	54	33	19	16	16
15-30	41	39	38	40	31	42	44	59	43	23	17	19
30-45	47	35	50	42	31	50	50	68	48	32	19	21
45-60	50	38	50	43	34	57	55	72	55	33	23	25
60-75	57	53	55	49	49	57	62	68	61	40	27	29
75-90	56	50	58	48	53	51	63	64	62	43	32	32
90-105	53	47	56	48	44	54	63	62	61	44	35	35
Total	340	294	342	304	270	349	372	447	364	234	169	178

higher than FP (rainfed) and 90% higher than IP (rainfed). Therefore, with an additional cost for SI at the critical growth stages of about 12%, the groundnut yield and net income increased from four to seven times.

2.4.5 Summer and winter fodder yield improvement

Summer fodder under IP gave a 27% higher yield and a 30% higher net income as compared to that achieve following FP (Table 2.18). Similarly, winter fodder gave a 34% higher yield and a 31% higher net income. This shows the high potential for improving the availability of fodder with proper management of the resources.

A mixed sowing of oat and berseem provided 43% and 35% higher green fodder yields than their single crop (Table 2.19). This resulted from the earlier growth of the oats and their better tolerance to the cold period (November and December). This early growth of the oats provided the added advantage of frost shelter to the berseem. Net income from a mix of berseem and oat was between 42% and 52% higher than for single crops of berseem and oat. From two to eight irrigations were applied and the cost of these reduced the net income. If we compare the net income of fodder crops with that obtained from wheat receiving two SI, it seems that growing berseem in the area may not be a better option. As livestock is an integral part of dryland agriculture, the farmers mostly use fodder to feed their livestock and are relatively less concerned with the net income obtained directly from the fodder. They get the income indirectly from their livestock.

2.4.6 Crop production in gullies

For millet, using IP, the fodder yield was 30% higher and the net income 22% higher than those obtained following FP (Table 2.20). However, for sorghum under IP, the fodder yield and net income were 38% and 33% higher. Thus, cultivation in gullies not only protects the gullies from further deterioration, but also provides a good return to the farmers.

2.4.7 Production of high value crops

Off-season coriander gave a net income of over PKR 95,000/ha and green chili gave a net return of over PKR 100,000/ha (Table 2.21). Thus, both the crops have a high potential for economic returns to the farmers. During 2008, the off-season coriander crop experienced comparatively moderate temperatures and good showers of rain (226 mm) in June, with the early onset of the monsoon. This weather trend prevailed for the whole growing season (July to Sept) and as a result the quality and quantity of the produce was very good. The coriander growers enjoyed a higher market price (PKR 42/kg) and a high economic return.

However, during 2009, in an attempt to capture the early market, the farmers planted coriander in June. The month was very hot and dry with a mean maximum temperature of 39.4^{o}C. This weather pattern increased the number of irrigations required and hampered the growth of the coriander. The result was a lower number of cuts and early bolting, seriously affecting the quality of the product. Consequently, the price for the coriander was relatively low (PKR 26/kg), which reduced the net return and water productivity.

Both varieties of flowers gave tremendous net returns (Table 2.22). However, the cost of production of bulbous flowers (PKR 1,287,240/ha for Narcissus and PKR 1,177,240/ha for Dutch Iris) is very high. Hence, only those farmers who can afford the huge initial investment can grow such crops. Moreover, there are issues related to the marketing of these crops given their

Table 2.17. Groundnut performance (yield and income) under rainfed and SI

Sites	Treatments	Pod yield (kg/ha)	SI (m^3/ha)	Rainwater ± ΔS (m^3/ha)	Total water (m^3/ha)	WP (kg/m^3)	Cost of non-water inputs (PKR/ha)	Cost of water inputs (PKR/ha)	Total cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
2008											
Site1	IP (irrigated)	2,359	822	5,647	6,469	0.36	47,844	2,730	50,574	117,950	67,376
Site2	IP (irrigated)	1,737	764	6,220	6,984	0.25	45,632	2,340	47,972	86,850	38,878
Site3	IP (irrigated)	2,282	791	6,653	7,444	0.31	46,190	2,470	48,660	114,100	65,440
	FP (rainfed)	690	_	5,745	5,745	0.12	26,200		26,200	34,500	8,300
Site4	IP (rainfed)	1,482	_	6,042	6,042	0.25	43,303		43,303	74,100	30,797
Average	IP (irrigated)	2,126	792	6,173	6,965	0.31	46,555	2,513	49,069	106,300	57,231
	IP (rainfed)	1,482	_	6,042	6,042	0.25	43,303		43,303	74,100	30,797
	FP (rainfed)	690	_	5,745	5,745	0.12	26,200		26,200	34,500	8,300
2009											
Site1	IP (irrigated)	1,574	1,011	6,263	7,274	0.22	53,013	3,750	56,763	123,050	66,287
	FP (rainfed)	441	_	6,606	6,606	0.07	25,364		25,364	36,075	10,711
Site2	IP (irrigated)	1,695	991	6,080	7,071	0.24	53,166	4,050	57,216	132,125	74,909
	FP (rainfed)	578	_	6,682	6,682	0.09	25,878		25,878	46,350	20,472
Site3	IP (rainfed)	685	_	7,375	7,375	0.09	49,429		49,429	56,375	6,946
Average	IP (irrigated)	685	1,001	6,172	7,173	0.23	53,090	3,900	56,990	127,588	70,598
	IP (rainfed)	510	_	7,375	7,375	0.09	49,429		49,429	56,375	6,946
	FP (rainfed)	685	_	6,302	6,302	0.08	25,621		25,621	41,213	15,592

Table 2.18. Production of summer fodder under irrigated conditions

Treatments	Green fodder yield (t/ha)	SI (m^3/ha)	Rainwater ± ΔS (m^3/ha)	Total water (m^3/ha)	WP (kg/m^3)	Cost of non-water inputs (PKR/ha)	Cost of water inputs (PKR/ha)	Total cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
Improved practices (sorghum 2008)	55.2	1,199	2,730	3,929	14.1	20,696	5,200	25,896	55,240	29,344
Improved practices (sorghum plus maize 2009)	63.7	2,587	1,300	3,887	16.4	17,280	12,750	30,030	79,625	49,595
Farmers' practices (sorghum plus maize 2009)	46.4	2,463	1,300	3,763	12.3	8,350	15,000	23,350	58,000	34,650
Improved Practices (sorghum plus maize 2009)	37.5	1,333	1,300	2,633	14.2	17,280	6,750	24,030	46,875	22,845
Farmers' practices (sorghum plus maize 2009)	24.4	1,294	1,300	2,594	9.4	8,350	7,500	15,850	30,500	14,650

Table 2.19. Production of winter fodder under irrigated conditions

Treatments	Green fodder yield (t/ha)	No. of irrigation	SI (m^3/ha)	Rainwater ± ΔS (m^3/ha)	Total water (m^3/ha)	WP (kg/m^3)	Cost of non-water inputs (PKR/ha)	Cost of water inputs (PKR/ha)	Total cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
Oats (irrigated)	43.0	4	2,262	2,560	4,822	8.9	16,960	10,500	27,460	64,425	36,965
Berseem (irrigated)	66.4	8	4,760	2,560	7,320	9.1	16,760	19,500	36,260	99,600	63,340
Berseem plus oats	74.82	8	5,491	2,560	8,051	9.3	15,985	19,500	35,485	112,200	76,715

Table 2.20. Summer fodder production (millet and sorghum) in gullies

Farmer name/ fodder crop	Treatments	Green fodder (kg/ha)	Rainwater ± ΔS (m^3/ha)	WP (kg /m^3)	Total cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
Muhammad Manzoor, Khokhar Bala (Millet)	Improved practice (rainfed)	44,167	3,090	17.9	17,760	55,209	37,449
	Farmer’s practice (rainfed)	30,778	3,090	12.5	9,150	38,473	29,323
Muhammad Manzoor, Khokhar Bala (Sorghum)	Improved practice (rainfed)	48,611	3,090	19.7	19,760	60,764	41,004
	Farmer’s practice (rainfed)	30,278	3,090	12.2	10,400	37,848	27,448

Green fodder priced at PKR 1.25/kg

A very good fodder crops stand in the field

Growing of high value flowers

perishability. Nevertheless, where irrigation water is available, there is a high potential for growing high value crops and improving the well being of farmers.

Off-season coriander and chili crops in the field

2.4.8 Effect of applying gypsum on crop production

Soil characteristics

Soil moisture stress is one of the most important factors for low crop yield in rainfed areas. Moreover, damage to terraces results in loss of soil, moisture, and nutrients. Any activity that conserves soil moisture results in improved crop yields. Tables 2.23 and 2.24 show that the soils are poor in fertility and are coarse textured in nature.

Tables 2.25 and 2.26 show the salinity and sodicity in the soil profile after one year of applying gypsum. After the gypsum application, the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) of the soil decreased whereas the ECe increased. This might be because the gypsum is a source of Ca which replaces the exchangeable Na complex, reducing the soil SAR and ESP. Applying gypsum, therefore, improved the permeability of the soil profile (Table 2.28) which helped improve the moisture content in

Table 2.21. High value crops (green coriander and green chilies) under irrigated conditions

Sites	Treatments	Green biomass (t/ha)	No. of irrigations	SI (m^3/ha)	Rain ± ΔS (m^3/ha)	Total water (m^3/ha)	WP (kg /m^3)	Cost of non-water inputs (PKR/ha)	Cost of water inputs (PKR/ha)	Total cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
						2008						
Site1	Coriander	16.1	18	10,791	2,730	13,521	50	232,090	36,400	268,490	674,359	405,869
	Chilies	13.3	15	8,993	2,730	11,723	27	103,975	29,900	133,875	311,222	177,347
						2009						
Site1	Coriander	11.3	18	9,837	2,710	12,547	29	126,802	42,000	168,802	360,032	191,230
	Chilies	5.6	15	8,056	2,710	10,766	18	47,393	35,250	82,643	196,350	113,707
Site2	Coriander	6.2	16	9,064	2,710	11,774	14	76,850	37,500	114,350	160,992	46,642
Site3	Coriander	6.3	16	8,795	2,710	11,505	14	76,943	37,500	114,443	162,864	48,421
Ave	Coriander	7.9	17	9,232	2,710	11,942	19	93,531	39,000	132,531	227,963	95,431
	Chilies	5.6	15	8,056	2,710	10,766	18	47,393	35,250	82,643	196,350	113,707

Table 2.22. High value flowers under irrigated conditions (2008-2009)

Flower	No. of irrigations	SI (m^3/ha)	Rain ± ΔS (m^3/ha)	Total water (m^3/ha)	WP (kg / m^3)	Cost of non-water inputs (PKR/ha)	Cost of water input (PKR/ha)	Total cost (PKR/ha)	Harvested bulb weight (kg/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
Narcissus	8	4,390	2,980	7,370	280	1,267,740	19,500	1,287,240	10,318	2,060,000	772,760
Dutch Iris	8	4,390	2,980	7,370	267	1,157,740	19,500	1,177,240	4,628	1,965,000	787,760

the soil profile. There was no effect from the gypsum on the infiltration rate of sandy loam and loamy sand soils. However, in a sandy-clay-loam soil, the infiltration rate increased by 26% after one year of applying gypsum.

Shanmuganathan and Oades (1983) reported that a small amount of gypsum (0.2% w/w) coagulated most of the clay by lowering the ESP and raising the electrolyte concentration. Chartres *et al.* (1985) found that in the presence of gypsum, crust formation was reduced because less clay was mobilized and redistributed in the surface soil layers. Yu *et al.* (2003) also reported that spreading gypsum at the soil surface improved the final water infiltration rate compared to that of a control.

Soil moisture profile

A rainfed crop's water supply comprises available water in the soil at the time of sowing plus rainfall during the growing season. Capturing the rainwater that may otherwise drain away can greatly boost the yield. For example, harvesting 30 mm of this water could translate to an increased yield of 1000 kg/ha, a very substantial increase in a water-limited environment in which the average yield may be less than 2000 kg/ha (Passioura, 2006).

The soil moisture in the profile is considered as one of the primary indicators showing the extent of soil water conserved in each treatment. Figure 2.3 shows that the maximum moisture was conserved in the gypsum plus structure treatment where the terraced fields were protected with a soil conservation structure and gypsum was also applied. The soil moisture in these fields was about 40% higher than in those under the farmers' practices i.e. the control field without structure and without an application of gypsum. The treatment in which only gypsum was applied to the terraced field, conserved around 190 mm in the soil profile, almost 30% higher than that achieved with traditional practices. The effect of the structure only was less visible. The soil moisture conserved by this treatment was just 11% higher than that resulting from the farmers' practices. It takes normally one or two monsoons seasons to stabilize the structure with the natural grasses acting as the cementing agent and retaining maximum runoff in the field. The long-term average rainfall (between 1977 and 2009) during the wheat growing season was 228 mm, while wheat requires between 325 mm and 450 mm for optimum production. During 2008-2009, 258 mm of rainfall was received in the wheat growing season. The remaining water requirement was met from the moisture conserved in the soil profile during the preceding months. Passioura (2006) reported that after the anthesis stage, when the products of the photosynthesis go almost entirely towards filling the grain, with little respiratory or other losses, the crops can extract moisture from the deep soil horizon. Unfortunately, for the groundnut trials the soil moisture profile was not available for 2008. Figure 2.4 shows the moisture conserved in the soil profile by various treatments during 2009. The maximum moisture (about 200 mm) was conserved in the treatment in which the terraced field was protected with the soil conservation structure and gypsum was also applied. It was 31% higher than the control (field without a structure and without a gypsum application). The treatments in which only gypsum was applied to the terraced field conserved about 13% more moisture than the control.

Yield, water productivity and net income

The maximum grain yield of 4501 kg/ha was obtained from a terraced field, where a structure was installed and gypsum was also applied (Table 2.28). It was 62% higher than the control and comparable to that of an irrigated wheat yield in Pakistan. During 2007-2008, the average irrigated wheat yield in Pakistan was 2664 kg/ha and a rainfed

Table 2.23. Initial soil status of wheat fields before applying gypsum

Treatment	pH	ECe (dS/m)	Organic matter (%)	Available P (mg/kg)	Extractable K (mg/kg)	Texture class
Gypsum	7.9	0.6	0.5	3.5	140	Sandy loam
Gypsum plus fertilizer	7.8	0.6	0.4	4.2	145	Sandy-clay-loam
Structure	7.8	0.8	0.4	4	135	Sandy loam
Structure plus gypsum	8	0.5	0.4	5	75	Sandy-clay-loam

ECe – electrical conductivity of a saturated soil paste extract .

Table 2.24. Initial soil status of groundnut fields before applying gypsum

Treatments	pH	ECe (dS/m)	Organic matter (%)	Available P (mg/kg)	Extractable K (mg/kg)	Texture class
Control	7.80	0.44	0.26	2.3	57	Loamy sand
Gypsum	7.78	0.41	0.42	3.2	50	Loamy sand
Structure	7.80	0.36	0.41	3.3	85	Loamy sand
Structure plus gypsum	7.85	0.5	0.44	2.8	57	Loamy sand

Table 2.25. Soil salinity status of the wheat fields after one year of applying gypsum

Treatments	EC (dS/m)		pH		SAR		ESP	
	Before	After	Before	After	Before	After	Before	After
Gypsum	0.59	1.14	7.92	7.82	0.48	0.41	1.97	1.88
Gypsum plus fertilizer	0.50	0.90	7.80	7.7	1.18	0.86	2.96	2.53
Structure	0.46	1.18	8.06	7.8	0.66	0.41	2.24	1.86
Structure plus gypsum	0.43	0.79	8.08	7.97	0.7	0.39	2.30	1.85

Table 2.26. Soil salinity status of the groundnut fields after one year of applying gypsum

Treatments	EC (dS/m)		pH		SAR		ESP	
	Before	After	Before	After	Before	After	Before	After
Gypsum	0.42	0.53	7.75	7.76	0.79	0.52	2.42	2.08
Structure plus gypsum	0.58	0.68	7.88	7.81	0.62	0.56	2.18	2.1

Table 2.27. Effect of applying gypsum for one year on soil infiltration rate

Sr. no	Soil Texture	Infiltration rate (mm/hour)	
		Without gypsum	With gypsum
1.	Sandy-clay loam	8.4	11.4
2.	Sandy loam	24.0	24.0
3.	Loamy sand	30.0	30.0

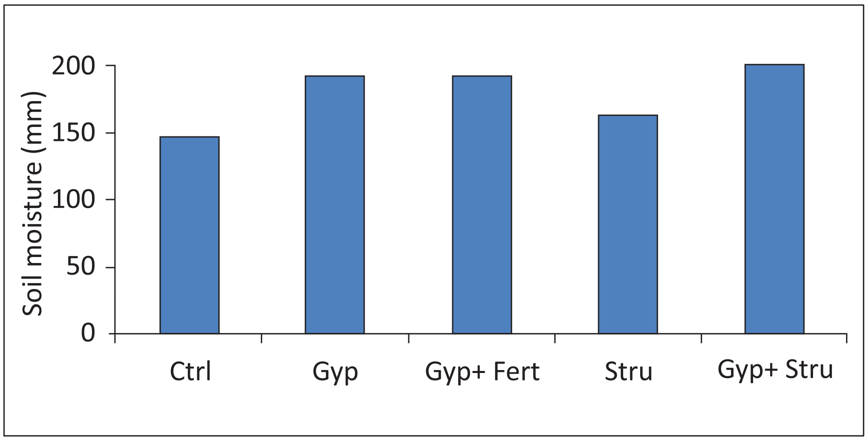

Figure 2.3. Moisture content in the soil profile (0-120 cm) before sowing wheat

one, 1123 kg/ha (MINFAL, 2009). Under the gypsum plus fertilizer, gypsum, and structure treatments the wheat yields were 60%, 53%, and 44% higher than the control, respectively. The marvelous increase in grain yield with gypsum plus structure resulted from the higher soil water content conserved by them. The higher initial soil moisture saved the crop from the usual early season stress. It is also important to note that gypsum alone is not very effective in increasing crop yield. This is because the structures help conserve the soil and moisture. In the absence of a structure, the gypsum together with the top soil layer may be removed with the runoff, reducing the effects of the gypsum application.

\Water productivity (WP) is an estimate of how much of the water (irrigation/rainfall) has been used for crop production. Any effort that tends to increase crop yield or reduce the amount of water needed, without reducing the crop yield, increases the water productivity. In the literature, water productivity is used interchangeably with water use efficiency (WUE). In the broadest sense, WP reflects the objectives of producing more food, income, livelihood, and ecological benefits at less social and environmental cost per unit of water consumed (Molden *et al.,* 2010). Water productivity is useful for looking at the potential increase in crop yield that may result from increased water availability (Singh *et al*., 2006). It may be expressed in terms of crop yield (kg/m^3). Alternatively, crop yield may be transformed into monetary units (i.e., \$/m^3). The latter will be particularly convenient when comparing different crops or different types of water use (Playan and Luciano, 2006). In this study however, WP has been calculated as kg of crop yield per cubic meter of water applied or rainfall received. The rainfall received was assumed to be

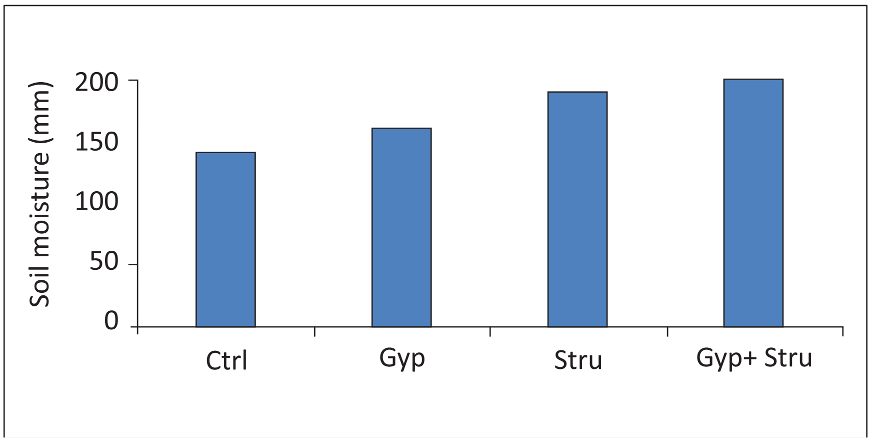

Figure 2.4. Moisture content in the soil profile (0-120 cm) before sowing groundnut

Table 2.28. Average wheat yield and net income from the interventions

Treatments	Yield (kg/ha)	WP (kg/m³)	Production cost (PKR/ha)	Gross income (PKR/ha)	Net income (PKR/ha)
Control	1,721	0.6	23,052	5,1630	28,578
Gypsum	3,655	1.2	26,753	109,650	82,897
Gypsum plus fertilizer	4,300	1.5	35,643	129,000	93,357
Structure	3,098	1.0	25,356	92,940	67,584
Structure plus gypsum	4,501	1.5	28,361	135,030	106,669

100% effective rainfall. Since the terraced fields were properly protected with bunds, no runoff occurred from these fields. The water productivities of wheat under the gypsum plus structure treatment and the gypsum plus fertilizer treatment were almost the same (1.5 kg/m^3) and were 62% higher than the control (Table 2.29). It was 31% and 19% higher than the structure alone and the gypsum alone treatments, respectively.

Table 2.28 also shows the net income for the various interventions. The production cost includes: cost of cultivation, seed, fertilizers, gypsum, harvesting, threshing, etc., while the gross income includes income from grain and straw. The average cost of gypsum was PKR 3500 per ha whereas the average cost of a structure was PKR 5000/ha. The average life of the structure was assumed to be 10 years and that of gypsum 3 years. The price for wheat grain was fixed by the government at PKR 23.75 per kg and the straw rates were assumed to be PKR 6.25 per kg, based on the prevailing market rates. The structure plus gypsum treatments gave a 73% higher return than the control. Application of gypsum alone gave a 65% higher return than the control. During 2008, the maximum groundnut pod yield of 1502 kg/ha was obtained under the structure plus gypsum treatment; this was 50% higher than the control. This was followed by the structure only treatment which was 38% higher than the control (Table 2.29). The increase in pod yield during 2008 may be attributed to the higher level of soil moisture retained under the different treatments as compared to the control. However, during 2009, the maximum pod yield of 754 kg/ha was recorded under the

Table 2.29. Groundnut yield and economic return under different treatments

Treatments	Pod yield (kg/ha)		Production cost (PKR/ha)		Gross income (PKR/ha)		Net income (PKR/ha)	
	2008	2009	2008	2009	2008	2009	2008	2009
Control	749	624	10,312	10,912	37,450	43,680	27,138	32,768
Gypsum	861	630	11,479	12,079	43,050	44,100	31,571	32,021
Structure	1,210	690	10,712	11,312	60,500	48,300	49,788	36,988
Structure plus gypsum	1,502	754	11,879	12,479	75,100	52,780	63,221	40,301

structure plus gypsum treatment. This was followed by the treatment where the terraced field was protected with a structure. The lowest pod yield was recorded in the control where no structure was constructed or gypsum applied. Low rainfall during the early growth period affected the crop yield badly. Table 2.29 also shows that the application of gypsum alone is less effective in increasing the pod yield for the reasons discussed earlier. The cost of production includes the cost of cultivation, seed, fertilizers, gypsum, harvesting, threshing, etc., while the gross income includes income from pods only. The rate used for the dry pod was PKR 70 per kg and was based on the prevailing market rates. The net income from the gypsum plus structure treatment was 57% higher than the control during 2008 and 19% higher in 2009. The fields protected with the structure gave a net income about 45% higher than the control during 2008 and 11% higher in 2009.

2.5 Conclusions and recommendations

2.5.1 Conclusions

Based on the three years of study, the following conclusions were drawn:

- An analysis of long-term rainfall data (1977-2010) shows that the average rainfall in the area is about 630 mm. However, 62% of it occurs during the monsoon months of July to September. Therefore, any activity that conserves soil moisture during high rainfall periods (monsoon) would help improve agricultural productivity during the subsequent months.
- Average rainfall during the wheat growing period (November to May) is 228 mm, while wheat requires 325-450 mm of water for optimum production, thus emphasizing the importance of supplemental irrigation.
- With the improved practices, the yield of rainfed wheat was almost double that obtained following the farmers' practices, showing that adoption of improved practices can give significantly higher returns in terms of land and water productivity.
- Efficient irrigation techniques with supplemental irrigation can help improve wheat yield and water productivity. The highest net income of PKR 97,701 per ha was obtained under small plot sowing; this was 35% higher than that following the farmers' practices. Under raise bed sowing, the net income was 30% higher than that of the farmers' practices. Therefore, with only a 13% extra cost for the water used for SI under SPS, and with improved practices, a 47% higher wheat yield and a 55% higher net income were obtained. Similarly, with about a 12% additional cost for SI at the critical growth stages, the groundnut yield and net income were increased between four and seven times.

- Under improved practices and irrigation, the yields of summer fodder (sorghum and maize) and winter fodder (oats, and berseem) were over 30% higher; likewise the net income. However, as berseem requires huge amounts of water its cultivation in the rainfed areas seems to be an uneconomical option. The same amount of water can be used as supplemental irrigation for wheat or other crops that can give much higher returns.
- Growing high value crops, where water is available, gives higher returns. Off-season coriander and chilies gave net return of about PKR 100,000/ha, while growing flowers gave tremendous net returns of over PKR 700,000/ha. However, the cost of production of high value crops is also very high. Therefore, only those farmers who can afford these can grow these crops.
- Gully farming has emerged as a very promising intervention. It not only saves the soils from further degradation, but helps generate considerable income from these abandoned lands.

2.5.2 Recommendations

- The application of gypsum has shown tremendous results in improving soil moisture and crop yields. However, its availability in the rainfed areas is still a problem. Therefore, arrangements should be made to make gypsum easily available.
- Soil erosion is a big issue in the area, resulting in low land and water productivity. Loose-stone structures are cost effective and help control soil erosion. However, small and poor farmers cannot afford to install these structures. Therefore, efforts should be made to conserve these soils through the lesson learnt from the present study.
- Where water is available, the farmers are using it to fully irrigate their crops. The farmers should be motivated to use it for supplemental irrigation at the critical growth stages. It will help expand the crop area while using the same amount of water and would also help increase net incomes. Agricultural extension can play a great role in changing the mindset of the farmers towards supplemental irrigation.
- Land leveling is very important when applying SI or for full irrigation in the case of small plot sowing or raise beds sowing. The On-Farm Water Management (OFWM) project is providing a laser leveling facility to farmers in the irrigated areas. This facility should also be extended to farmers in the rainfed areas.

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Chapter 3: Natural resources degradation: assessment and options for improvement

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3.1 Summary

Soil erosion is one of the most important land degradation issues in the rainfed areas. A study was conducted in the Dhrabi watershed of Pakistan to measure the sediment yield linked with the rainfall-runoff phenomenon under different land use practices. Five sub-catchments with sizes varying from 1.5 ha to 350 ha were selected for measurement of runoff and sediment yield. Runoff was measured by constructing sharp crested-weirs at the outlets of these catchments. Both bed and suspended loads were recorded. Bed load was measured at stilling basins upstream of the weirs while suspended load was measured with depth integrated sampling tubes on an event basis. One automatic weather station, four recording rain gauges, and nine automatic water-level recorders were installed at different locations to cover the spatial variability in rainfall and runoff. Innovative and cost effective techniques were also introduced to reduce the soil erosion.

The rainfall data collected from 1977 to 2010 at the Soil and Water Conservation Research Institute (SAWCRI) Chakwal show an average annual rainfall of 632 mm. However, 62% of it occurs between June and September. During 2009, against a long-term average of 630 mm, 547 mm of rainfall was received. All runoff events occurred in summer, especially during the monsoon season, while the rainfall events were less intense during winter. In 2009, the rainfall intensity of events ranged between 50 mm/hour and 100 mm/hour whereas during 2010, it ranged between 38 mm/hour and 84 mm/hour for the main rainfall events which caused most of the erosion. During 2009 between eight and 11 rainfall events produced runoff in these sub-catchments and during 2010, there were 17 or 18 such events. The sediment yields of two small gully catchments ranged from 4.79 t/ha/year to 8.34 t/ha/year in 2009, a relatively dry year. However, during 2010, the sediment yield of the same catchments was between 8.15 t/ha/year and 12.31 t/ha/year. Terraced catchments with arable crops produced 4.1 t/ha/year of sediment as compared to 12.31 t/ha/year in the adjacent gully catchment, showing the potential of terraces for reducing erosion. Runoff coefficients were also calculated for gully and terraced land-use systems. These varied from 0.02 to 0.51 for gully system and from 0.03 to 0.44 for the terrace land-use systems. The macro and micro nutrients present in the sediment indicate that the soil in the watershed is being depleted due to erosion. A survey of the watershed indicated that permanent and bank gullies were most dominant. On average, the permanent gullies were 9 m deep, 35 m wide and 192 m long – the permanent gullies were deep and wide.

Runoff was computed from the water level recorded in the streams. The hydrologic modeling system HEC-HMS was used for the event based modeling of the watershed. The model was calibrated and validated for rainfall events and runoff data recorded at Chak Khushi sub-catchment. There was good agreement between the measured and the model-computed rainfall and runoff.

The loose stone structures helped control the degradation of the cultivable lands and also trapped sediment coming from the catchments. The performance of these

structures improves with time as they settle down and grasses grow within the structure.

3.2 Introduction

Soil is one of the most important natural resources since it provides a base for crop and livestock production. However, this component is the one most affected by erosion. Deforestation, overgrazing, urbanization, low organic matter, improper tillage practices, leaving the land fallow, competing land uses, small and fragmented land holdings, the land tenure system, and overall poverty have accelerated soil erosion (Ashraf *et al.,* 2002).

Globally, water erosion affects 1094 million hectare (Mha) and wind erosion 549 Mha (Jie *et al.,* 2002; Lal, 2003). Soil erosion rates are highest in Asia, Africa, and South America, averaging between 30 t/ha/year and 40 t/ha/year; they are the lowest in the United States, Europe, and Australia, averaging between 5 t/ha/year and 20 t/ha/year (Pimentel *et al.,* 1995). Soil erosion is estimated to be severe in south Asia with water erosion as the most serious problem in the region. According to the global assessment of land degradation (GLASOD), of a total 680 Mha of land, almost 82 Mha are affected by water erosion and 59 Mha by wind erosion.

The top soil is being lost at least 16 times faster than it can be replaced; between almost 5 Mha/year and 7 Mha/year is lost globally and this rate is increasing annually. This continuous and rapid loss of nutrient rich top soil can eventually lead to desert-like situations by making conditions unsuitable for plant growth. Soil erosion causes not only on-site degradation of agricultural land, but also off-site problems such as the downstream deposition of sediment in fields, floodplains, and water bodies. Land degradation resulting from erosion is widespread and it is important to keep track of the quantitative data on the extent and actual soil erosion rate in order to assess the magnitude of the problem (IAEA, 2004).

Along with the various problems that arise from land degradation, it also causes a tremendous loss to the economy. Global estimates of productivity loss in dry lands range from US$13 billion to US$28 billion per year (Scherr and Yadav, 1996). A study conducted by the FAO, UNDP, and UNEP in South Asia revealed that the countries in this region are losing at least US$10 billion annually as a result of land degradation. This was equivalent to 2% of the region's gross domestic product, or 7% of the total agricultural output. However, this figure is still an underestimate, because it measures only the on-site effects leaving out off-site costs (Mythili, 2003).

Thirteen of the large rivers in the world carry annual sediment loads of over 5.8 billion tonne. Annual soil loss in the middle Yellow River basin of China amounts to 3700 t/km^2, the largest sediment carrying river in the world. The Indus River in Pakistan ranks third with an annual sediment load of 435 million tonne and an average sediment concentration of 2.49 kg/m^3. According to an estimate, the Indus River is adding 500,000 tonne of sediment to the Tarbela reservoir every day, as a result of which the dam has lost about 35% of its reservoir capacity in twenty four years. Similarly, the Warsak and Khushdil Khan reservoirs have almost silted up (Ashraf *et al.,* 2000).

In Pakistan, of a total geographical area of 80 Mha, almost 16 Mha (20% of the total) are affected by soil erosion. Of these, about 11 Mha are affected by water erosion. In Pothwar Plateau, the largest contiguous drylands, 1.21 Mha of 2.2 Mha are affected by gully erosion and only 0.61 Mha are cultivated.

High intensity rainfalls, steep slopes, and erodible soils without adequate protection have led to extensive soil erosion in the area and the consequences are devastating. They include loss of fertile soil, loss of vegetation, reservoir depletion by sedimentation, and eutrophication and contamination of surface and groundwater (Ashraf *et al.,* 2002).

Despite this huge soil loss and its consequences to agricultural lands and the terrestrial environment, very little work has been done in Pakistan to address this issue. Nasir *et al.* (2006) carried out a study using the Revised Universal Soil Loss Equation (RUSLE) and GIS at the small mountainous watershed of Rawal Lake near Islamabad. The predicted soil loss ranged from 0.1 t/ha/year to 28 t/ha/year. Similarly, Ahmad *et al.* (1990) reported soil loss rates of between 17 t/ha/year and 41 t/ha/year under fallow conditions and between 9 t/ha/year and 26 t/ha/year under vegetative cover in the Fateh Jang watershed, which has a slope of between 1% and 10%. More recently, Sarah (2010) estimated soil erosion risk using a Coordination of Information on the Environment (CORINE) model in the Rawal lake watershed. The soil loss ranged between 24 t/ha/year and 28 t/ha/year, with a high erosion risk (26%) in areas with steep slopes and sparse vegetative cover. These studies however, were confined to areas of relatively high rainfall (> 1000 mm). The objectives of the present study were to study

- The watershed degradation process
- Sediment yield estimation and behavior
- The rainfall-runoff relationship and its impact on sediment yield
- The effect of land-use changes on the sediment yield in the medium rainfall areas of Chakwal.

3.3 Material and methods

3.3.1 Site selection

The study was conducted in the watershed area of Dhrabi reservoir. It is located between latitudes 32° 42′ 36″ N and 32° 55′ 48″ N and longitudes 72° 35′ 24″ E and 72° 48′ 36″ E in Chakwal District. It comprised 196 km^2 having one lake, two small dams, and twelve mini-dams. The watershed drains through a perennial stream – Dhrab Kass – which is a tributary of the Soan River. The Soan River drains to the Indus River at Kalabagh. Rainfall is the main source of freshwater in the watershed. Some small springs originate from the hills. The topography varies from shallow to deep gullies, small to large terraces, and mounds to hillocks. The soil is predominantly of a sandy loam type and low in organic matter (less than 1%). The study was conducted from 2007 to 2010. The location map of the area is shown in Figure 3.1.

3.3.2 Characterization of small catchments

To determine the degree of soil erosion, sediment yield was measured from five sub-catchments in the watershed. These catchments consisted of gully and terraced land-use systems. The selection was based on the following criteria:

- Catchments had to have well defined boundaries
- Sites were representative of the area
- Access to the catchment and its outlet was relatively easy
- Installed equipment would be safe.

However, access to the outlets of the catchments was comparatively difficult for all the potential sites. The salient features of the catchments are given in Table 3.1 and topographic maps are provided in Figures 3.2 to 3.6. The soil texture and chemical analyses are given in Tables 3.2 and 3.3.

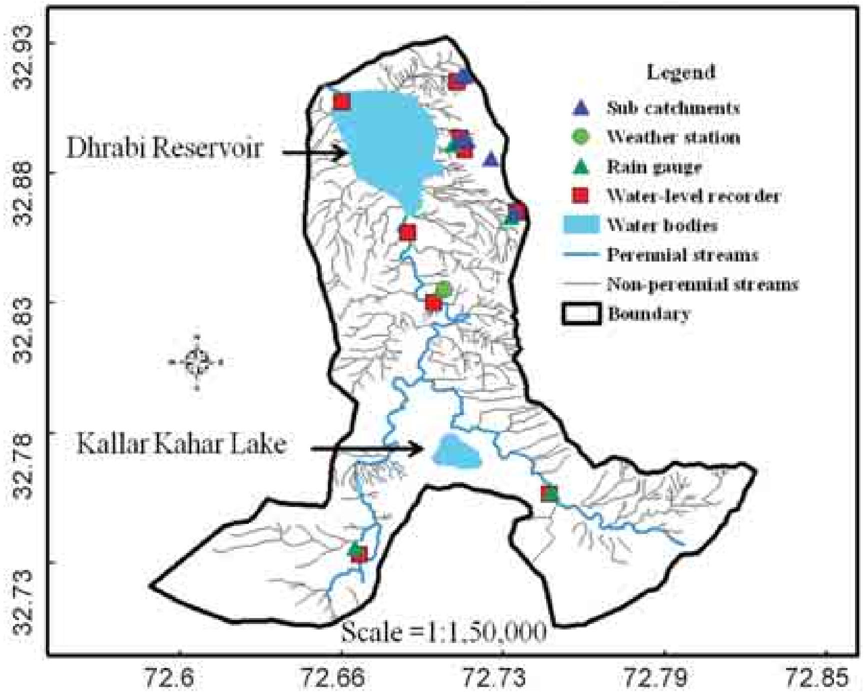

Figure 3.1. Map of the area with instrumentation

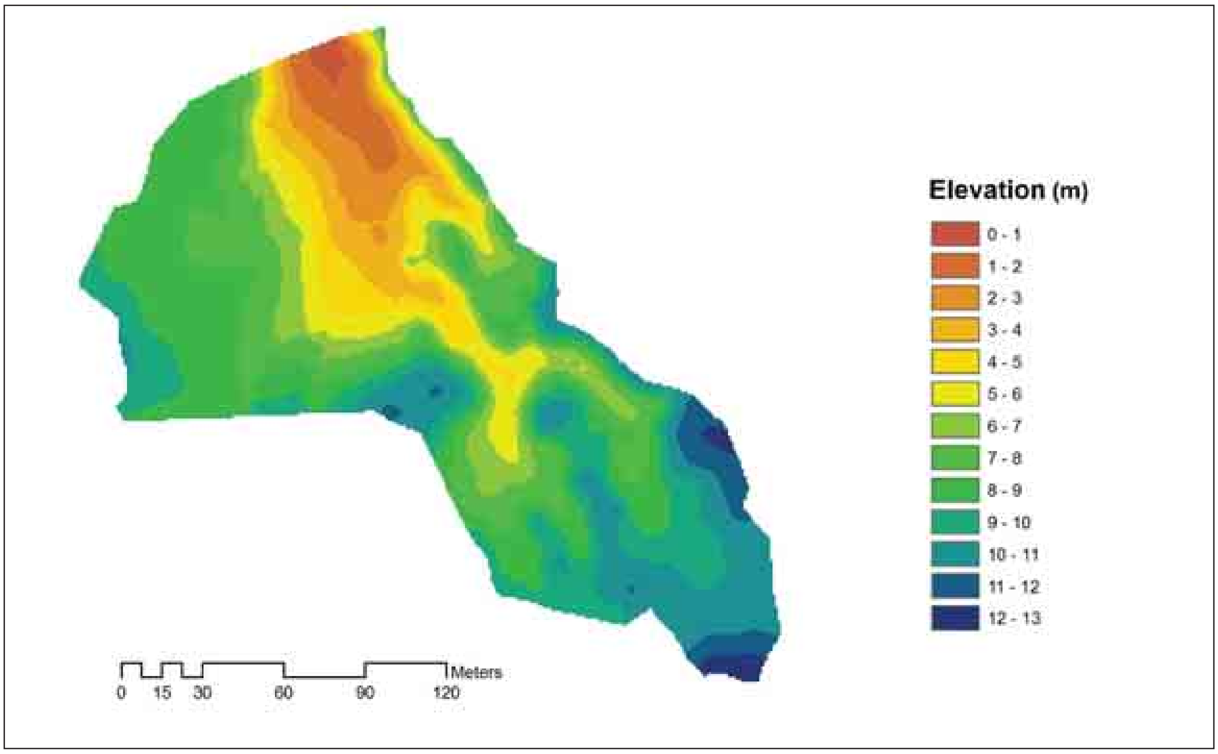

Figure 3.2. Topographic map of catchment 25

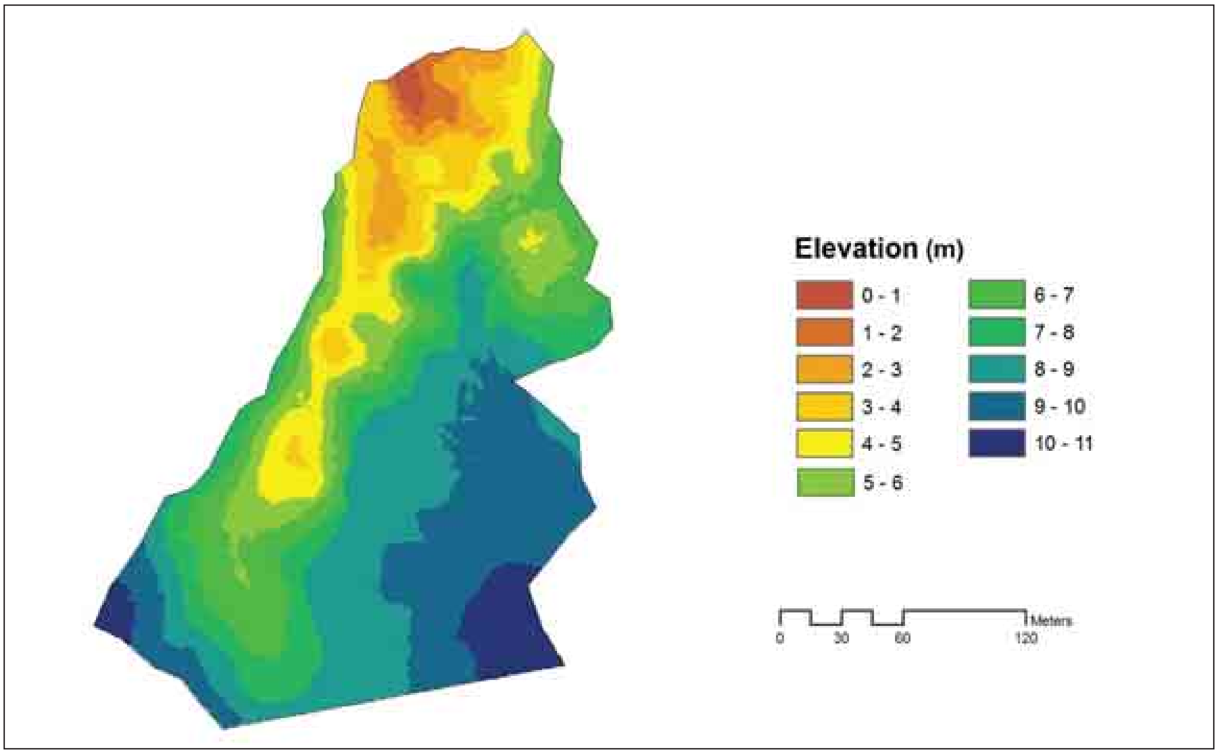

Figure 3.3. Topographic map of catchment 27

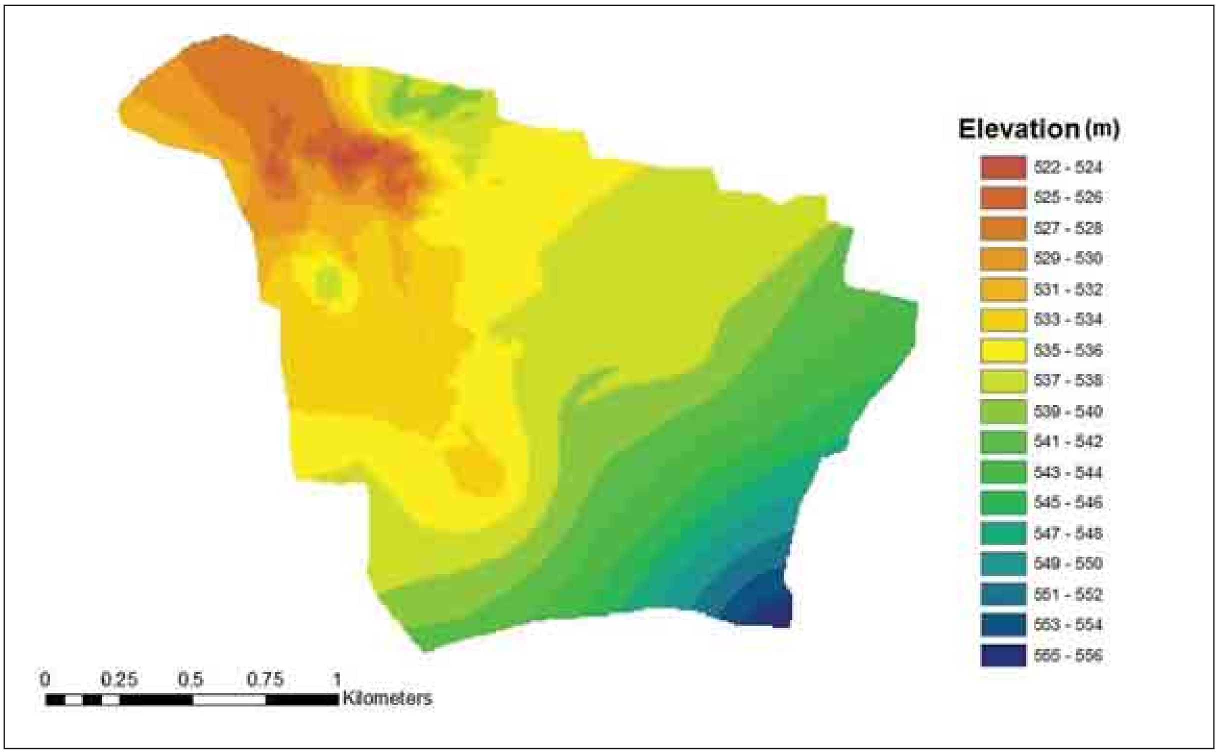

Figure 3.4. Topographic map of catchment 29

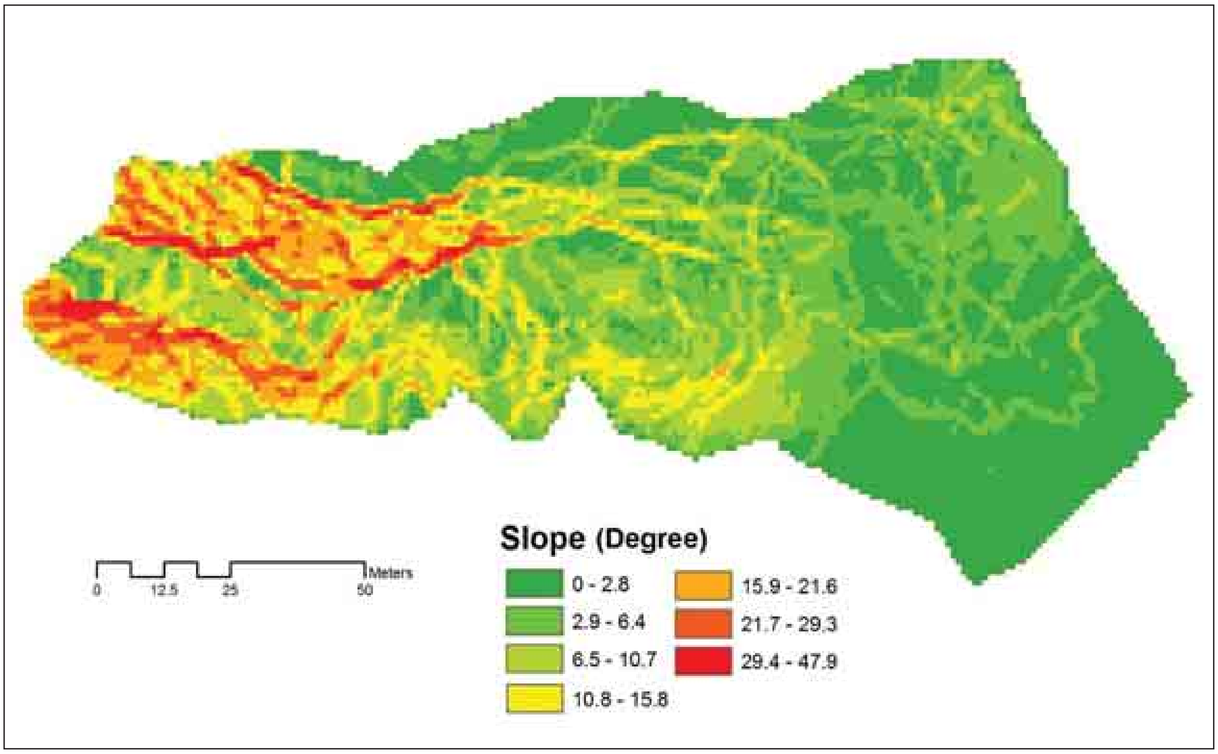

Figure 3.5. Topographic map of catchment 31

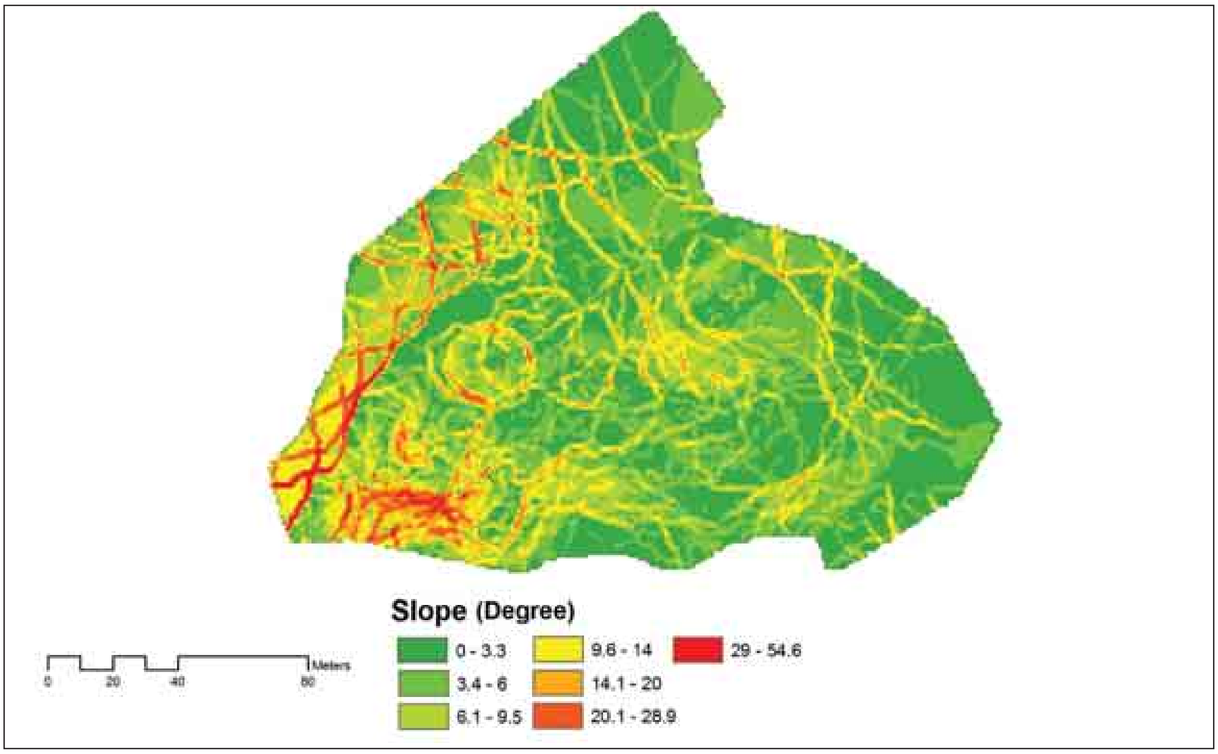

Figure 3.6. Topographic map of catchment 32

Table 3.1. Salient characteristics of selected catchments

ID	Soil type	Catchment type	Land use system	Vegetation/ crop detail	Area (ha)	Main channel slope (%)
25	Sandy loam	Generally deep gullies with wide gully beds	Scrub trees, bushes, and grasses on gully top and walls used for grazing in summer	Phulahi (*Acacia modesta*) trees, grasses, and the shrubs saroot (*Saccharum bengalensis*), dab (*Desmostachya bipinnata*), khavi, khabbal (*Cynodon dactylon*)	2.0	3.5
27	Sandy loam	Generally deep gullies with terraces in the gully beds; average vertical interval is 0.5 m	Scrub trees and bushes used for controlled grazing	Scrub trees phulahi, kikar (*Acacia nilotica*), sheesham (*Dalbergia sissoo*), arable crops and grasses on terraces in gully bed	3.0	3.0
29	Sandy loam	Gently sloping land, deep and wide gullies with terraces with strong bunds (dikes)	Cultivated fields with grass cover, terraces used for arable crops and controlled grazing	Wheat and brassica in winter; groundnut and sorghum/millet mixed fodder in summer, phulahi, kikar, bushes, and grasses	350	1.3
31	Sandy loam	Slightly deep gullies with vertical gully walls near catchment outlet	Grasses on gully slopes used for grazing	Dab, creen (*Capparis deciduas*), and khabbal grasses on gully beds and slopes, saroot in gully beds. Few scrub trees of phulahi	1.5	4.5
32	Sandy loam	Shallow gullies with beds modified to terraces	Terraces on gully beds; used for arable crops and controlled grazing	Sorghum and millet mixed fodder on terraces except for a few abandoned terraces, wheat crop during winter in gully top fields, usually single cropping system	3.3	3.7

Table 3.2. Soil texture analysis of the sub-catchments

Catchment	Textural class	Sand	Silt	Clay
			(%)	
25	Sandy loam	67	19	14
27	Sandy loam	72	15	13
29	Sandy loam	71	17	12
31	Sandy loam	68	22	10
32	Sandy loam	74	14	12

Table 3.3. Soil chemical analysis of the sub-catchments

Parameter	Catchment				
	25	**27**	**29**	**31**	**32**
ECe (dS/m)	0.44	0.89	0.63	0.49	0.39
pH	7.62	7.78	7.74	7.81	7.74
Av P (mg/kg)	4.7	3.5	4.8	3.9	3.5
Ex K (mg/kg)	96	135	105	90	121
OM (%)	0.80	0.21	0.53	0.63	0.44
$CaCO_3$ (%)	15.67	16.17	17.18	15.67	15.42
Zn (mg/kg)	1.50	1.84	1.53	1.61	2.15
Cu (mg/kg)	0.06	0.13	0.11	0.02	0.00
Fe (mg/kg)	4.72	3.04	2.15	1.70	2.33
Mn (mg/kg)	26.63	44.74	29.39	16.11	12.48

3.3.3 Weather and runoff

The automatic rain gauges and water-level recorders were installed to determine the rainfall and water level at different locations in the sub-watersheds. The details of the equipment installed are given below.

The Hobo weather station is a data logger designed for multi-channel climate monitoring installed on a 2 m tripod stand. The weather station uses a network of smart sensors for taking measurements. The following smart sensors and input adapters are used with the weather station: (i) temperature, relative humidity, rain, barometric pressure, soil moisture, wind speed, and direction, (ii) solar radiation, and (iii) phosynthetic active radiation (PAR).

The logger uses non-volatile memory which means it retains data indefinitely once power runs out. It contains 512 k bytes of memory. This weather station was installed at Ratta Sharif and the daily recording of the weather data was started on April 6, 2009.

A rain gauge (Global Water Model RG 600) was installed in the upper right-hand side of the watershed at Chak Khushi, one was installed in the upper left side at Miani, upstream of Nikka dam, and a third located at Rehna. The RG 600 rain gauge consists of a gold anodized aluminum collector

An automatic weather station installed at Ratta Sharif

funnel 20 cm in diameter that diverts the water to a tipping bucket mechanism. The precipitation was measured at two to five minute intervals.

Eight automatic water-level recorders (WL 16) were installed at the monitoring sites to record stage hydrographs. The installation of water-level recorders was a very difficult task because it involved many issues, such as

Water-level recorder installed at Chak Khushi

site selection, instrument security and safety, etc. The water levels were recorded at ten minute intervals in perennial streams while in small catchments runoff was recorded at two minute intervals.

Sharp-crested weirs were constructed at the catchment outlets and were used to determine the discharge (runoff) passing over the weir. The salient features of these weirs are given in Table 3.4. The stage hydrograph was converted to discharge using the formula $Q = C\ B\ H^{3/2}$, where Q is the discharge in m^3/sec, C is a constant, B is the width of the weir (m), and H is the height of water (m) passing over the weir. C was taken as 1.48 for SI units. The locations of the rain gauges and the water-level recorders installed in the watershed are given in Table 3.5 and Figure 3.1.

3.3.4 Measurement of sediments

Coarser sediments were trapped in the stilling basin during the runoff event. This was considered as the bed load. After the runoff event or the very next day, the standing water from the stilling basin was drained off through the drain pipe and the wet sediments were collected and weighed. A representative sample of wet bed load was collected after mixing five to six sub-samples from the stilling basin. A part of the sample was placed in an oven at 105 °C to determine its moisture content. The moisture content was determined as the difference between the wet weight and the dry weight of the sediment . To measure the bed load at the catchment 29 outlet, steel pins were installed in the stilling basin and their height was measured at the end of the season (Figure 3.7). For finer sediments passing over the weir, the data from the immediate upstream catchment 25 was used.

Finer sediments in the runoff water passing over the weir were sampled using vertical sampling

Weir with water level-recorder and vertical pipes for sediments sampling

Table 3.4. Salient features of the sharp-crested weirs

Catchment	Area (ha)	Width (m)	P (height from base to crest (m)	Wall height (m)
25	2.0	0.5	0.50	0.65
27	3.0	0.5	0.50	0.65
29	350	4.25	1.20	1.00
31	1.5	0.3	1.00	0.70
32	3.3	0.7	1.00	0.50

Table 3.5. Locations of rain gauges and water-level recorders installed in the watershed

Equipment	Location	Latitude (N)	Longitude (E)	Reach
Weather station	Ratta	32^{o} 50.258	72^{o} 42.142	Middle
Water-level recorder	Ratta stream	32^{o} 49.904	72^{o} 41.951	Middle
Rain gauge	Miani	32^{o} 44.40	72^{o} 40.2	Upper
Water-level recorder	Miani stream	32^{o} 44.40	72^{o} 40.2	Upper
Rain gauge	Chak Khushi	32^{o} 45.659	72^{o} 44.601	Upper
Water-level recorder	Chak Khushi stream	32^{o} 45.629	72^{o} 44.535	Upper
Water-level recorder	Rehna stream	32^{o} 51.562	72^{o} 41.358	Lower
Rain gauge	Rehna	32^{o} 53.51766	72^{o} 42.3843	Lower
Water-level recorder	Dhrabi reservoir	32^{o} 54.549	72^{o} 39.875	Lower
Water-level recorder	Rehna large catchment	32^{o} 32.5385’	72^{o} 42.3348’	Lower
Water-level recorder	Rehna catchment 25	32^{o} 53.6783’	72^{o} 42.5644’	Lower
Rain gauge	Thoa Bahadar			Lower
Water-level recorder	Thoa Bahadar	32^{o} 54.970’	72^{o} 42.502’	Lower

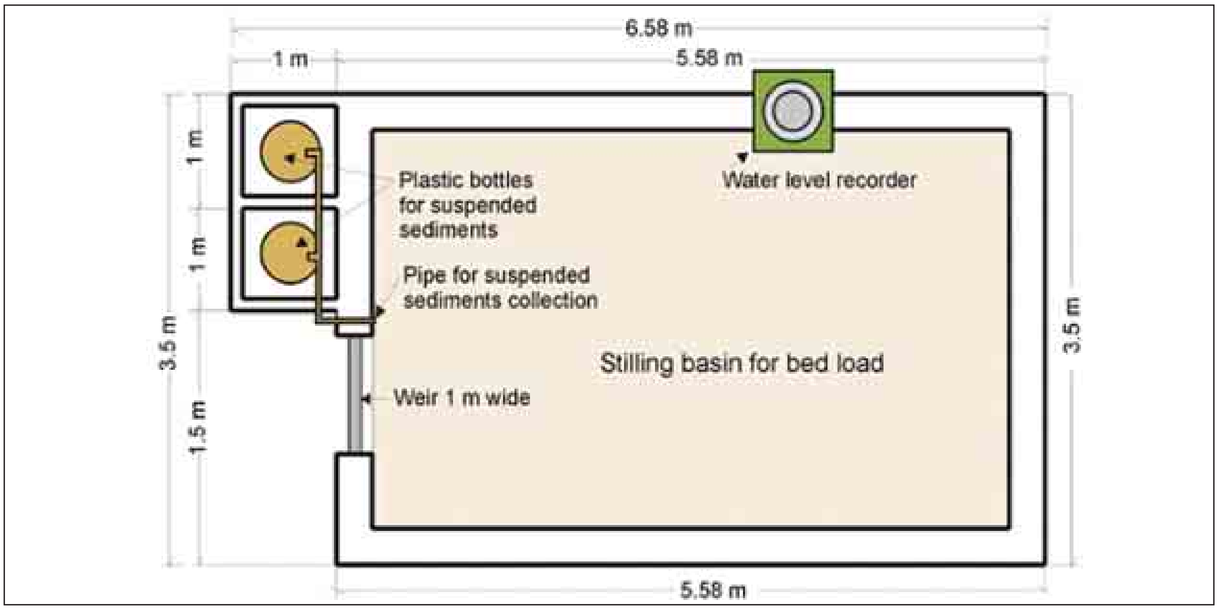

Figure 3.7. A schematic diagram showing the arrangement for collecting sediment samples

Stilling basin and water-level recorder for measurement of runoff and sediment

tubes with holes. After every runoff event, when the water had passed over the weir, the samples present in the container were collected and brought to the laboratory for analysis.

3.3.5 Measurements of nutrients in the sediment

The sediment collected was also analyzed to determine the nutrient content, such as available P, extractable K, organic matter (OM), Zn, Cu, Fe, and Mn.

3.3.6 Survey of the eroded gullies

A survey was conducted to assess the extent of degradation in the watershed. Twelve gullies were selected in the watershed in the upper, middle, and lower reaches. Two main types of gullies exist in the watershed – permanent gullies and bank gullies. Ephemeral gullies are usually less common because long slopes or fields are less common in the watershed – conditions which are necessary for the formation of ephemeral gullies. The permanent gullies were measured once while the bank gullies were measured in December 2009 and November 2010 after taking baseline data in December 2008.

3.3.7 Erosion control measures

To control the soil erosion, terraces were protected with loose-stone structures with grasses grown along their slopes. These structures were installed in clusters with the help of the communities in the upper, middle, and lower parts of the watershed (Figures 3.8, 3.9, 3.10). The sediment trapped behind these structures was measured by establishing

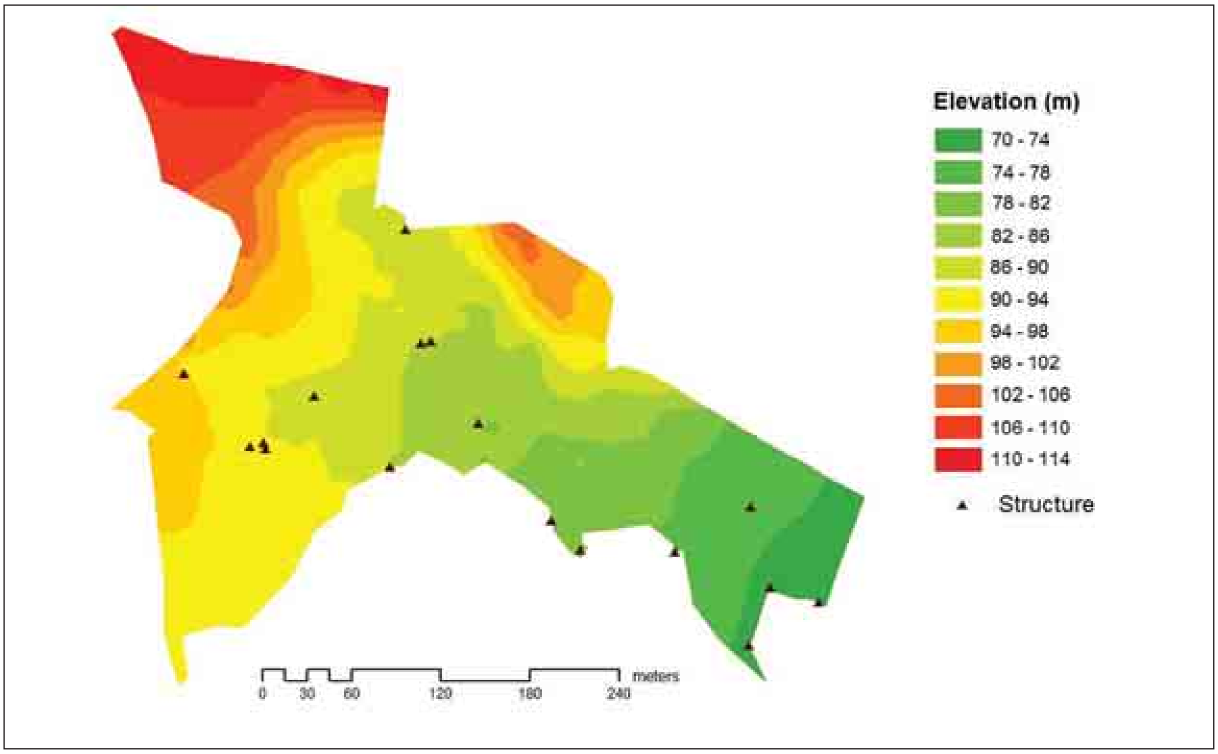

Figure 3.8. Locations of the soil conservation structures at Khandoa (upper catchment)

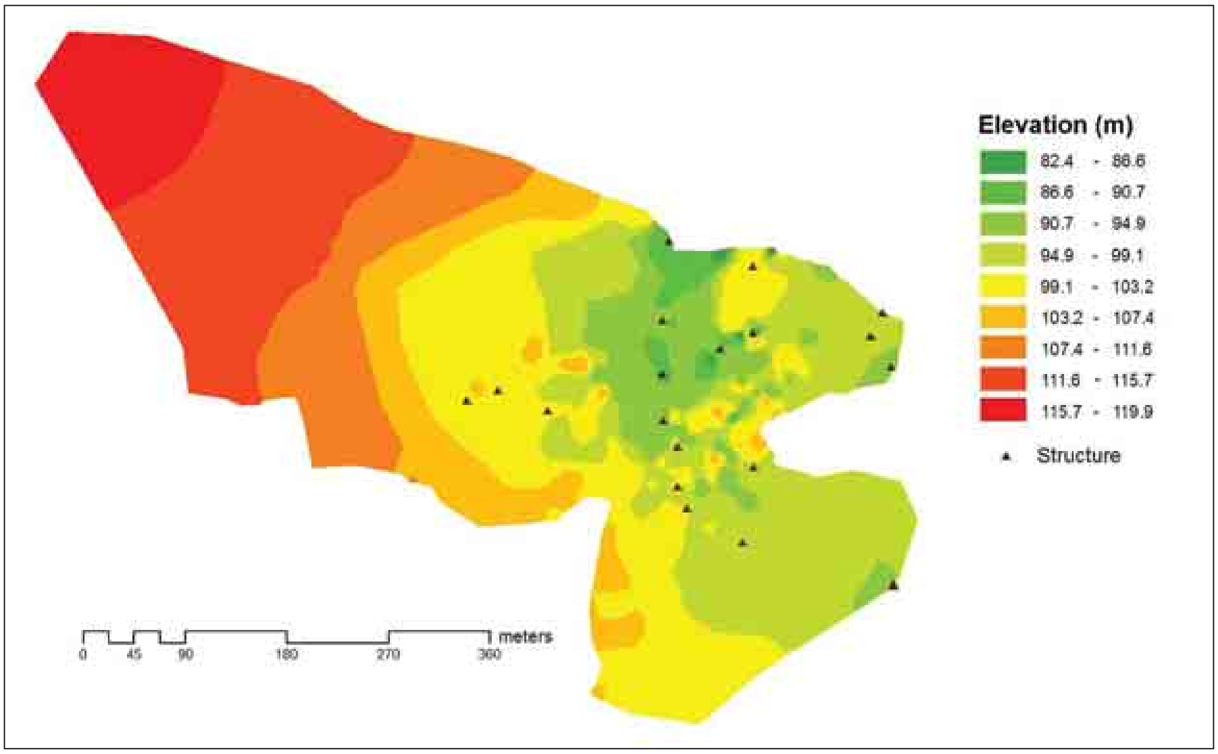

Figure 3.9. Locations of the soil conservation structures at Dhoke Muhri (middle catchment)

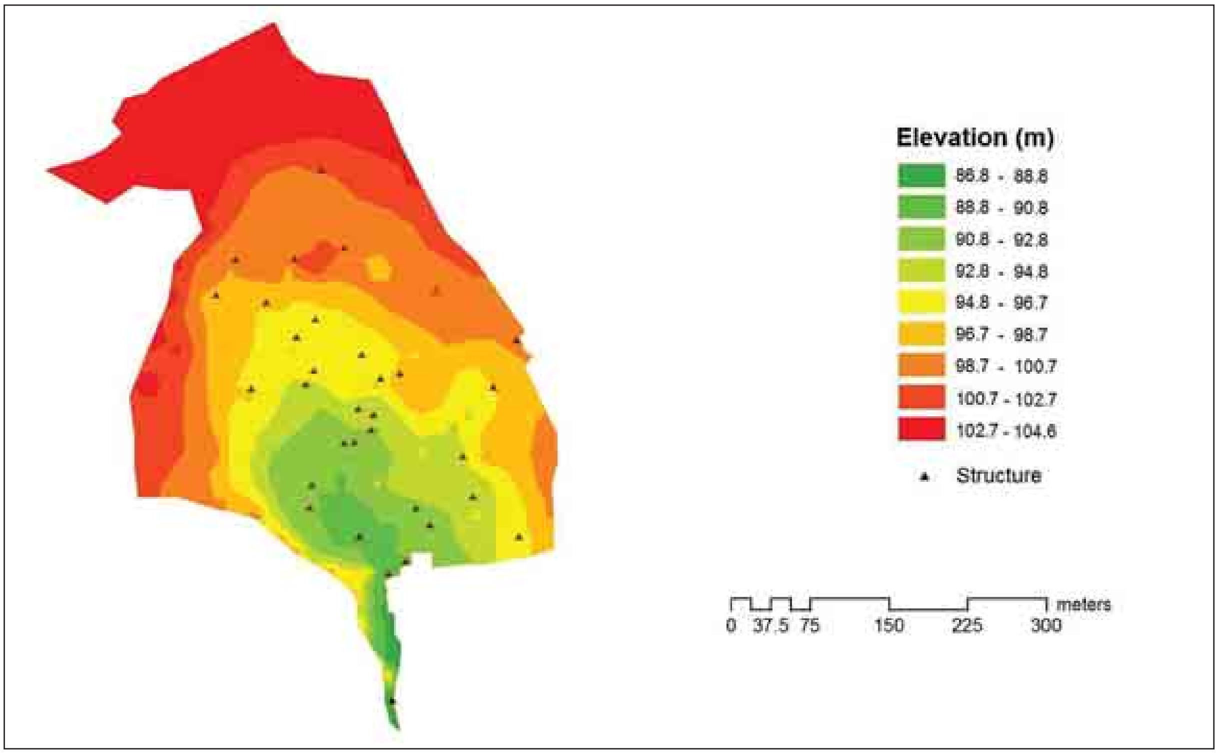

Figure 3.10. Locations of the soil conservation structures at Rehna (lower catchment)

Runoff harvesting and soil-conservation structures installed in gullies

benchmarks and measuring the field levels at the appropriate intervals.

3.4 Results and discussion

3.4.1 Rainfall characteristics

Rainfall intensity and duration have profound impacts on soil erosion. To control the erosion and to plan soil management practices, an analysis of the long-term rainfall is very important. Rainfall data for the last 33 years (1977-2010), collected at SAWCRI Chakwal, show an average annual rainfall of 630 mm (Figure 3.11). Sixty two percent of the annual rainfall occurs in the summer from June to September. During 2008 and 2010, the rainfalls were 14% higher than the average. However, during 2009, the total rainfall (545 mm) was 14% less than normal. Of this, 49% (265 mm) occurred during the months of July and August. Therefore, any activity that conserves moisture and reduces the runoff would help control soil erosion.

Information on the rainfall that can be expected for a specific period is helpful when selecting a crop, identifying the time for sowing, and planning soil management practices. The probability of exceeding the long-term data was calculated using the Weibull method and is given in Figure 3.12. A straight line best fitted the points. The outliers are kept to show the extreme events. A rainfall of 601 mm is expected with a 50% probability suggesting that it can occur in alternate year. A rainfall of about 300 mm can be expected every year with a 95% probability.

3.4.2 Dominant erosion processes in the watershed

Sheet erosion

A considerable portion of the lands of Chak Khushi, Khairpur, and Kallar Kahar in the upper watershed, and Dhoke Mori, Dhoke Awan, and Dhoke Sial have soils that are stony in nature or contain small and large stones at the upper surface. The high intensity rainfall events coupled with the low vegetative cover have resulted in a sheet of surface soil being removed from the landscape, leaving behind small stones and boulders. The stoniness of the soil means that conditions are less favorable for the formation of rills and deep gullies.

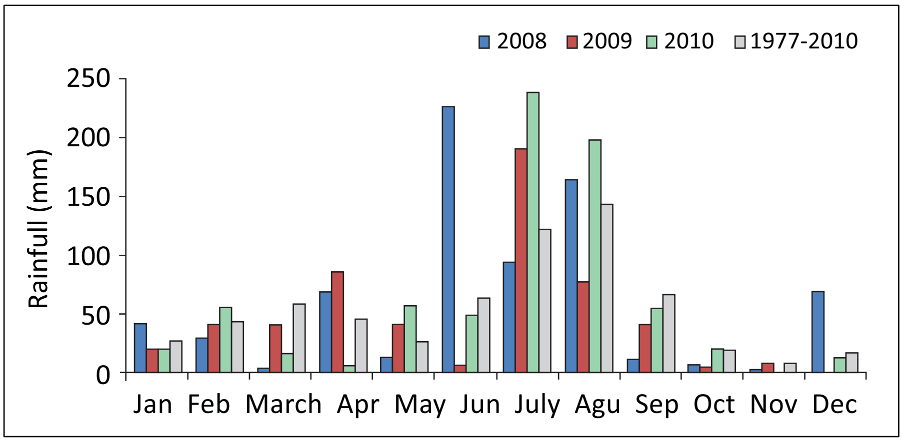

Figure 3.11. Rainfall at SAWCRI, Chakwal

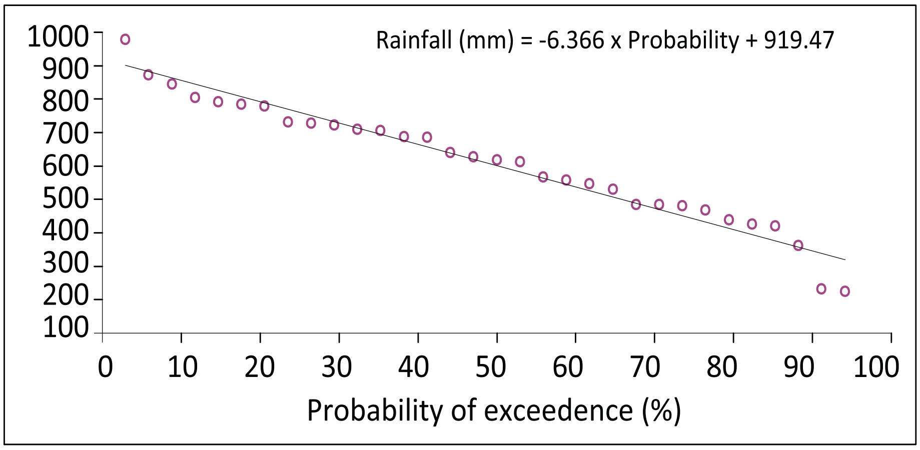

Figure 3.12. Estimated annual rainfall and the probability of exceeding this amount (1977-2010)

Top soil removed with sheet erosion at Dhoke Sial

Rill erosion

The rill erosion phenomenon occurs usually in cultivated fields. The severity of the problem is comparatively less in cultivated fields because of the presence of calcium carbonate nodules at the surface. This is also one of the erosion processes in the cultivated fields of the lower and middle reaches of the watershed i.e. at Rehna, Dhoke Mohri, Dhoke Sial, Murid, Dhoke Awan, and Dhoke Mori where farmers have prepared terraces. The severity of the problem is less in the upper watershed because of the stoniness of the soil. However, rill erosion with less severity exists in the soils of Chak Khushi and Khairpur.

Gully erosion

Gully erosion is major problem in the watershed. Permanent gullies and bank gullies are dominant erosion types in the lower watershed i.e. Rehna, Murid, Thoa Bahadar, and Dhoke Sial. Tunnel erosion is a dominant erosion process near the village of Thoa Bahadar and the adjoining lands on the eastern side. Agricultural farms are being converted to badlands through this process. A major area near Dhrabi reservoir has already been converted to badlands as a result of the high density of gullies. These badlands are mostly under natural vegetation and grazing is the dominant land use. However, at suitable places, the farmers have brought these lands under cultivation. The process of gully erosion has been accelerated by the removal of the natural vegetation. Ephemeral gullies are less frequent given the absence of long slopes.

Another area with major gully systems exists on the northern side of Khokhar Bala village and on the western side of Khokhar Bala hills. These gully systems need to be preserved and further expansion prevented. Re-vegetation of denuded lands has been found to be a viable option in various studies around the world.

Tunnel erosion and badlands near Thoa Bahadar

Gravity erosion

Gravity erosion is one of the main erosion processes in the middle and lower watersheds. Loess material is usually less stable than alluvial material. In the upper watershed, this type of erosion is less frequent because of the stoniness of the soil. In the middle watershed, near Dhoke Awan, Ratta, and Dhoke Mori, landslides along stream banks and in deep ravines are major sources of sediments. In the lower watershed, i.e. Rehna, Thoa Bahadar, and Murid area, the collapse of vertical gully walls also contributes to sediment production among other processes. Such type of erosion has left behind pedestals of soil in the badlands of the lower watershed.

Stream bank erosion

There are two main streams which originate in the upper watershed. These two streams join at Domale, situated about 3 km downstream from Kallar Kahar town. From here, a single stream carries water to Dhrabi reservoir. The stream bank erosion phenomenon is moderate to severe in parts of the middle and lower watersheds below Domale and at Ratta and Rehna. One reason for this is the widening of the stream bed and its decreasing stoniness. Another reason for the severe erosion at Ratta is the presence of highly erodible red soils.

Stream bank cutting and gravity erosion

Storm water erosion

A series of hills extends from Khokhar Bala to Kallar Kahar on the eastern boundary of Dhrabi watershed in the upper watershed. These mountains have comparatively low vegetative cover. During major rainfall events, the overland flow concentrates in the foothills of the mountains. The storm water causes a lot of erosion to the soils in the foothills of the mountain near the villages of Khokhar Bala and Chak Khushi. Top soils have been completely eroded in many places. This storm water is also a source of sediments to the Chak Khushi stream.

3.4.3 Assessment of current status of gully erosion

Permanent gullies

Data on twelve permanent gullies were collected in the summer of 2009. Table 3.6 indicates that gully length is shorter in the lower watershed than in the upper watershed (gully numbers 10, 11, 12). Given the high erodibility, the gully is soon converted into badlands as its length increases beyond few hundred meters. It was observed that the depth of the gully and its height at headcut continued to increase. In the middle reaches of the watershed i.e. Ratta, Dhoke Mori, and Dhoke Awan, the gullies have mostly stony beds and walls. Here, therefore, the depths of the gullies are relatively shallow as compared to those on the other reaches of the watershed. The lengths of the gullies are also short because the gullies soon end in deep ravines or badlands. In the upper reaches of the watershed, the lengths of the gullies are comparatively greater, because in most places only a small area has been converted into badlands. This area includes Chak Khushi, Khairpur, Khokhar Bala, and Kallar Kahar. The gullies with wider beds are being used for the cultivation of arable crops through the creation of terraces.

Table 3.6. Permanent gullies recorded in the Dhrabi watershed

Gully number	Location	Gully width (m)	Gully length (m)	Gully depth (m)	Gully bed width (m)	Gully bed slope (%)	Drainage area (ha)	Height of head cut (m)
1	Rehna Sadat	21.4	118	14.0	2.2	8.0	0.5	6.0
2	Rehna Sadat	30.8	198	13.2	3.8	7.0	0.2	7.0
3	Rehna Sadat	23.3	101	15.7	4.7	8.7	0.5	5.3
4	Rehna Sadat	27.0	300	7.3	17.6	3.5	0.7	0.5
5	Dhoke Mori	35.0	266	8.1	33.9	4.0	40.0	5.0
6	Dhoke Mori	26.8	55	10	3.7	10.0	40.0	2.0
7	Dhoke Awan	55.0	65	7	20.0	9.5	1.0	1.5
8	Dhoke Ratta	7.7	52	7.3	31.0	8.5	2.0	8.0
9	Tootan Wali	19.7	90	3.8	8.0	7.5	30.0	2.0
10	Khairpur	70.8	356	10.8	63.4	5.9	8.0	6.0
11	Khairpur	63.2	500	12.5	48.0	4.0	8.0	9.0
12	Khairpur	39.6	200	5.8	13.0	3.0	6.0	2.0

Bank gullies

Twelve bank gullies were selected in the upper, middle, and lower reaches of the watershed. The data for the gullies were collected in December 2008 (Table 3.7). These gullies were surveyed again in December 2009 and 2010 and the data for nine gullies were recorded. The other three gullies in the middle portion of the watershed were converted into terraces by the farmers (Table 3.8).

Over a period of two years, on average, the gully length of six small gullies was increased by 6.25 cm while the width was increased by 7.5 cm. The gully lengths of three comparatively larger gullies increased by 54.7 cm while their widths increased by 41.7 cm.

3.4.4 Rainfall-runoff relation

The simultaneous measurements of rainfall and runoff are required for the development of rainfall-runoff relationships. All the rainfall and runoff events were recorded at Chak Khushi sub-watershed. The rainfall and water levels were recorded also for Miani sub-watershed. However, the cross-section survey could not be done for this location for security reasons so discharge data were not available for this site. The Ratta sub-watershed is located downstream of Chak Khushi and Miani. The rainfall could not be measured from August 22 to December 16, 2009 at Ratta watershed. Moreover, the water-level recorder did not work properly throughout

Table 3.7. Data recorded for bank gullies in the watershed (December 2008)

Gully number	Site	Gully length (cm)	Max gully width (cm)	Height of head cut (cm)	Depth of gully (cm)
1	Thoa Bahadar	230	370	84	164
2	Khokhar Bala	120	225	163	192
3	Khokhar Bala	127	330	36	147
4	Khokhar Bala	268	350	104	188
5	Khokhar Bala	270	530	114	370
6	Thoa Bahadar	930	548	36	155
7	Thoa Bahadar	822	747	53	202
8	Thoa Bahadar	130	250	97	176
9	Ratta Sharif	420	195	27	102
10	Ratta Sharif	960	330	64	171
11	Ratta Sharif	100	100	10	60
12	Rehna Sadat	792	960	46	88

Table 3.8. Data recorded for bank gullies in the watershed (December 2010)

Gully number	Site	Gully length (cm)	Max gully width (cm)	Height of head cut (cm)	Depth of gully (cm)
1	Thoa Bahadar	250	385	80	150
2	Khokhar Bala	125	230	170	170
3	Khokhar Bala	145	370	34	165
4	Khokhar Bala	270	360	110	170
5	Khokhar Bala	280	530	90	350
6	Thoa Bahadar	1,020	625	52	172
7	Thoa Bahadar	893	780	68	202
8	Thoa Bahadar	150	270	73	130
9	Rehna Sadat	795	1,100	45	80

the year; hence discharge data were not available for this station.

The Rehna sub-watershed is located downstream of the Ratta sub-watershed. The rain gauge was not located within the watershed; therefore the data of the adjacent rain gauge was used. Moreover, with the silting up of the cross section, the water-level data were available only for five weeks (July 1, 2009 to July 2009). The monthly rainfall measured at different sub-watersheds is shown in Table 3.9, for 2009, and Table 3.10 for 2010.

3.4.5 Mass curves

For rainfall analysis, the mass curve is a plot of the cumulative depth of rain against time. The mass curve helps to find the total rainfall

Table 3.9. Rainfall (mm) recorded in the watershed during 2009

Month	Chak Khushi	Miani	Ratta	Rehna	SAWCRI
January	†	†	†	†	20
February	†	†	*	46	39
March	†	†	*	44	40
April	95	78	47	122	85
May	32	20	42	43	40
June	88	75	30	0	6
July	174	89	168	193	189
August	104	101	32	52	76
September	11	5	‡	31	40
October	5	7	‡	7	4
November	7	7	‡	14	7
December	0	0	0	0	0

† Instrumentation was not completed.
‡ Instrument was not working because of battery problems

Table 3.10. Rainfall (mm) recorded in the watershed during 2010

Month	Chak Khushi	Miani	Ratta	Rehna	SAWCRI
January	15	11	13	4	20
February	69	38	45	55	55
March	18	10	13	24	16
April	12	7	8	6	6
May	65	27	49	76	56
June	115	75	44	104	48
July	324	89	168	293	238
August	210	101	32	169	198
September	118	53	0	41	10

depth against time. Further, we can find the amount of rainfall that has occurred during a certain period of a year. The total rainfall and the dry periods can also be calculated from the mass curve. The straight portion of the mass curve shows no rainfall. From the mass curve, the total depth of rain and the intensity of the rainfall at any instant in time can be found. The amount of rainfall for any increment of time is the difference between the ordinates at the beginning and end of the time interval, and the intensity of rainfall at any time is the slope of the mass curve at that time. The mass curve for the design storm is generally obtained by maximizing the mass curves of the severe storms in the basin.

The mass curves of Miani, Ratta, Chak Khushi, and Rehna are shown in Figures 3.13 to 3.16. The mass curves of Miani shows that total rain

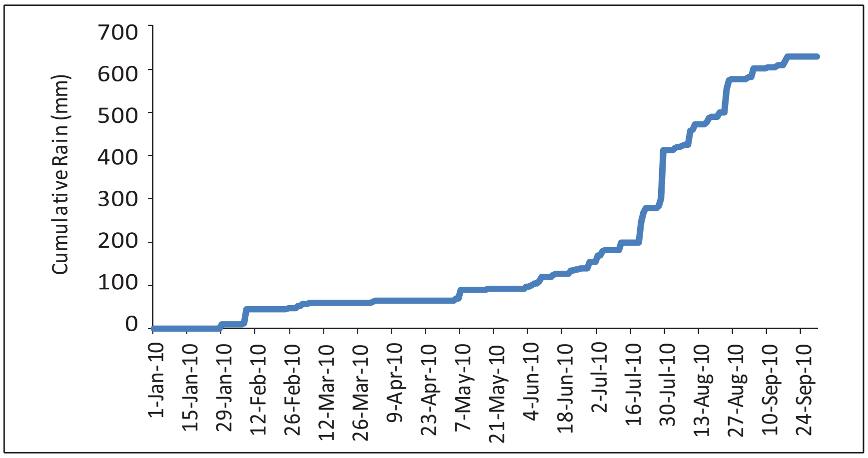

Figure 3.13. Mass curve of daily rain for Miani catchment (2010)

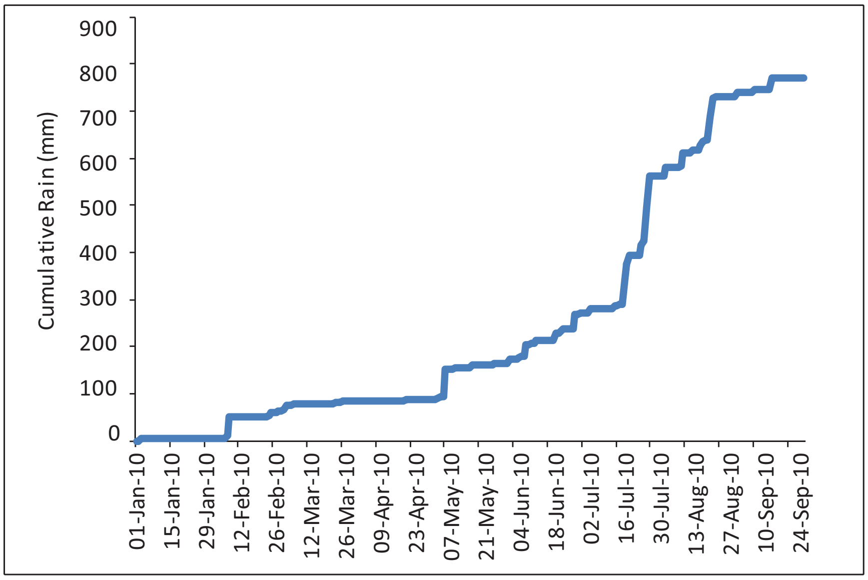

Figure 3.14. Mass curve of daily rain for Rehna catchment (2010)

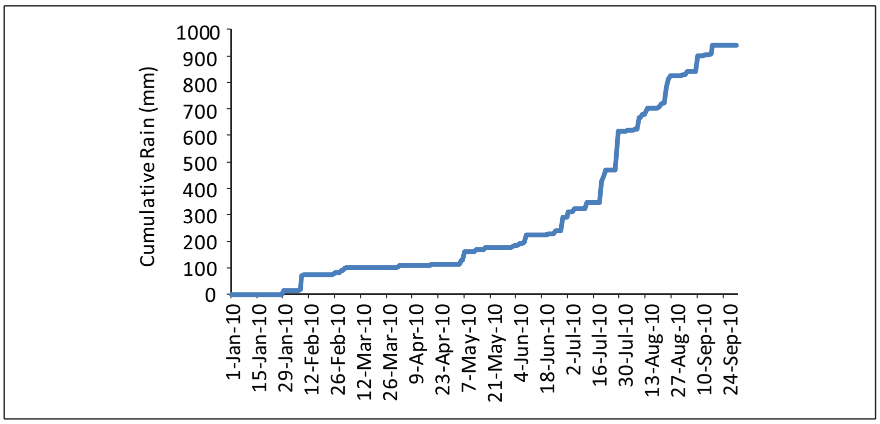

Figure 3.15. Mass curve of daily rain for Chak Khushi catchment (2010)

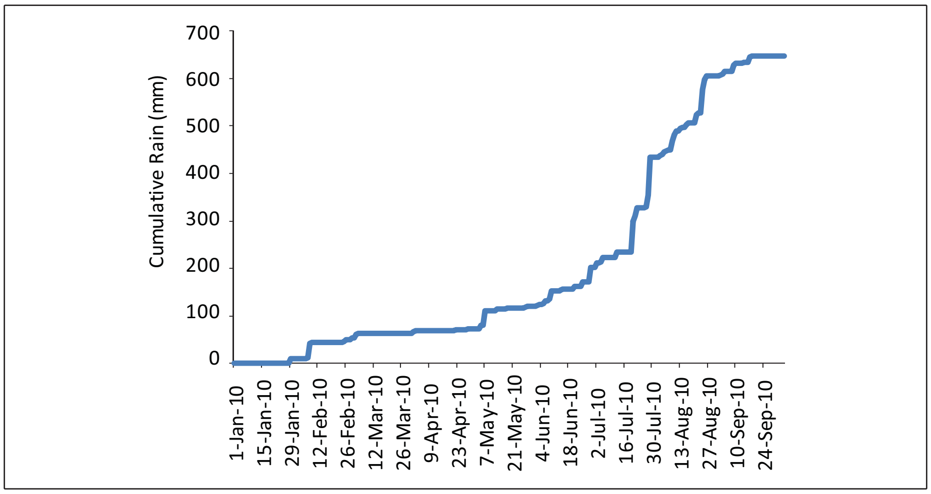

Figure 3.16. Mass curve of daily rain for Ratta catchment (2010)

recorded in 2010 was 630 mm while the total rainfall measured at Ratta was 771 mm, at Chak Khushi 939 mm, and at Rehna 648 mm. All mass curves show almost similar trends.

3.4.6 Discharge measurements

As discussed earlier, the water-level recorders were installed to estimate rainfall runoff. During 2010, most of the water-level recorders were working well except the one at Ratta which was damaged by the high flow. This water-level recorder was shifted nearer the inlet of the Dhrabi reservoir. The discharge measured at different stations is shown in Figures 3.17, 3.18, and 3.19.

3.4.7 Weighted average rainfall

Rainfall is normally measured at different points. The point data does not represent the average rainfall on the catchment within which the rainfall recorder is installed. The weighted average of Miani, Chak Khushi, Ratta, and Rehna sub-catchments were used to calculate the weighted average of the Dhrabi watershed. The weighted average rainfalls for 2009 and 2010 are shown in Figures 3.20 and 3.21.

3.4.8 Rainfall-runoff modeling

Hydrologic and hydraulic modeling is a basic requirement for watershed management and the optimal use of land and water resources. Hydrologic modeling simulates the hydrologic response (flow) of a basin to a given input of rainfall. The U.S. Army Corps of Engineers Hydrologic Modeling System (HEC HMS) model was used for rainfall-runoff modeling. It is an event-based model widely used for hydrologic modeling at different locations in the world. In this model, a number of assumptions are made that reduce the watershed to three separate processes – loss, transform, and base flow. The number of assumptions is controlled by the hydrologic methods selected by the user for the simulation. The HEC (2000) reports the specific assumptions for each method and the algorithm used in HEC-HMS. The following are the strengths of the model:

- Simplified methods of hydrologic simulation require a reduced number of parameters for model calibration
- Capable of modeling common types of hydraulic control structures with appropriate on and off features

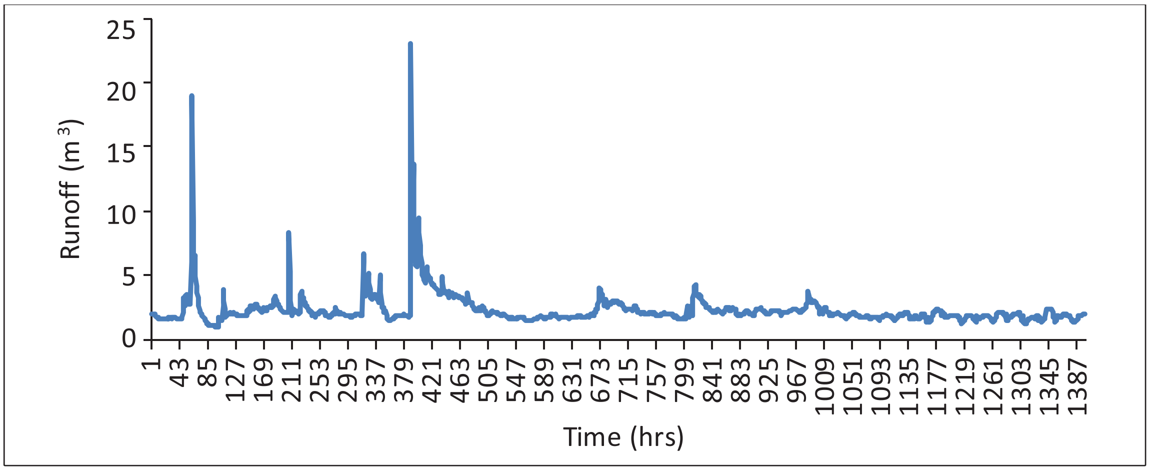

Figure 3.17. Runoff versus time at Chak Khushi

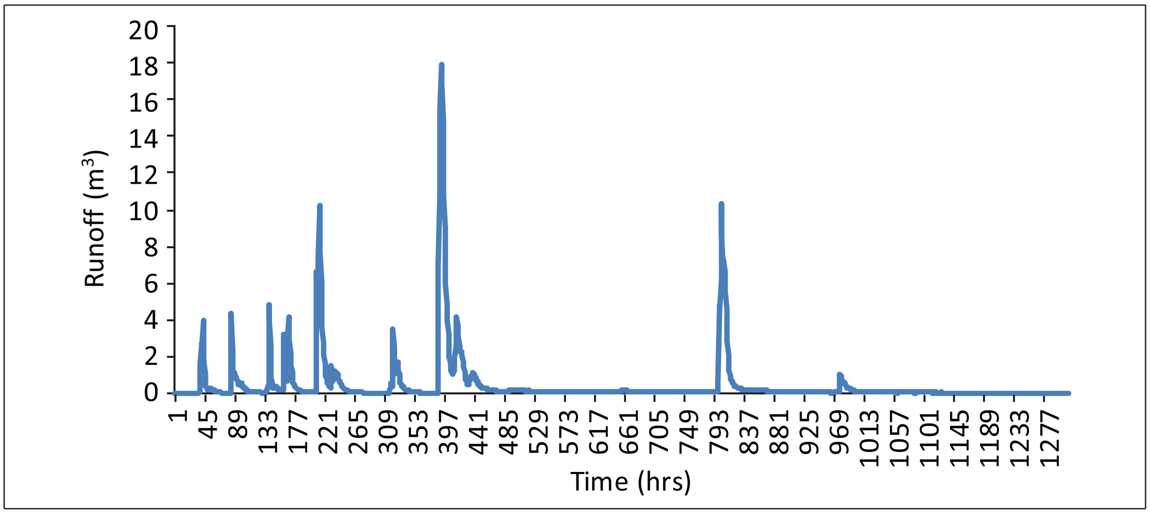

Figure 3.18. Runoff versus time at Ratta

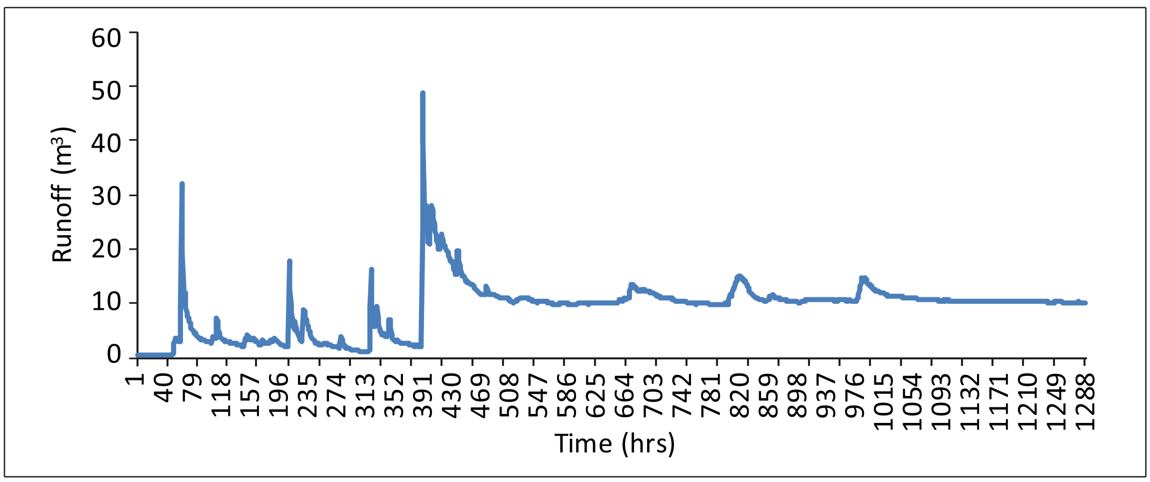

Figure 3.19. Runoff versus time at Rehna

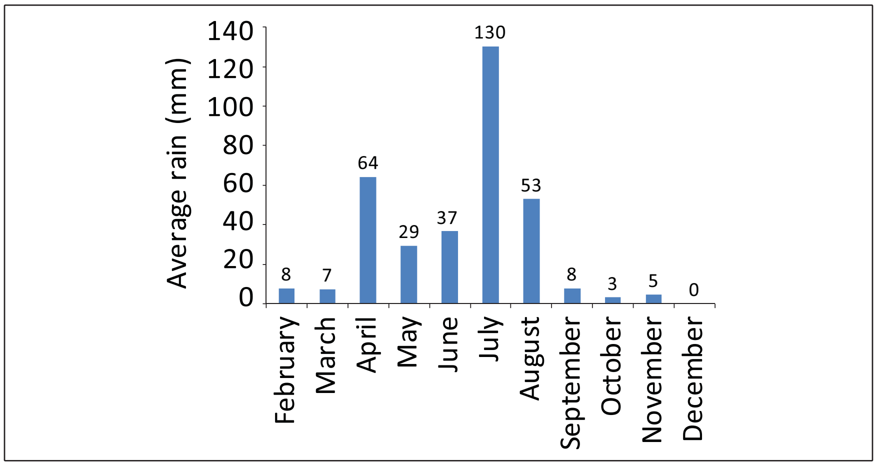

Figure 3.20. Monthly weighted average rainfall for 2009 in the watershed

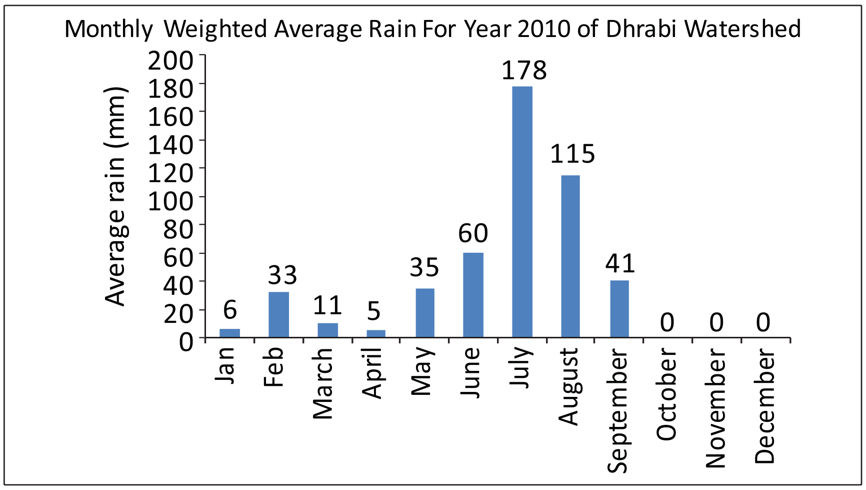

Figure 3.21. Monthly weighted average rainfall for 2010 in the watershed

- Includes a GUI with pre- and post-processing capabilities.

The following are the limitation of this model:

- Cannot simulate water quality processes
- Relatively difficult to use in conjunction with other water-quality models
- Cannot simulate groundwater levels.

The HEC-HMS calculates discharge hydrographs for a given rainfall event. The model is designed to simulate the surface runoff response of a river basin to precipitation by representing the basin as an interconnected system of hydrologic and hydraulic components. Representation of a component requires a set of parameters which specify the particular characteristics of the component and the mathematical relations which describe the physical processes.
The result of the modeling process is the computation of stream flow hydrographs at desired locations in the river basin. Thus for computer modeling purposes, HEC-HMS divides the watershed into sub-watersheds and reaches. Each sub-watershed and reach uses values averaged over the area or stream length for the mathematical coefficients for the hydrologic and hydraulic computations.

Setting up the model

The watershed was divided into different sub-watersheds and each sub-watershed was connected to the next by a channel reach. A junctions point was created for joining different reaches and sub-watersheds. The reservoir is located at the downstream end of the catchment. The arrangement of each hydrological element is shown in Figure 3.22. The flow direction is shown by the arrow heads.

The different hydrological elements of Figure 3.22 are described below.

Sub-basin: A sub-basin is an element that usually has no inflow and only one outflow. Outflow is computed from the meteorological data by subtracting losses, transforming excess precipitation, and adding the base flow. The sub-basin can be used to model a wide range of watershed catchment sizes.

Reach: A reach is an element with one or more inflows and only one outflow. Inflow comes from other elements in the basin. If there is more than one inflow, all inflows are added together before computing the outflow. Outflow is computed using one of the several available methods for simulating open channel flow. The reach can be used to model rivers and streams.

Junction: A junction is an element with one or more inflows and only one outflow. All inflows are added together to produce the outflow by assuming zero storage at the junction. It is usually used to represent the confluence of rivers or streams.

Diversion: A diversion is an element with two outflows, main and diverted, and one or more inflows. Inflow comes from other elements in the basin. If there is more than one inflow, all inflows are added together before computing the outflows. The amount of diverted outflow is computed from a user-specified monotonically increasing inflow-diversion relationship. Diverted outflow can be connected to an element that is computationally downstream. The diversion can be used to represent weirs that divert flow into canals, flumes, or off-stream storage.

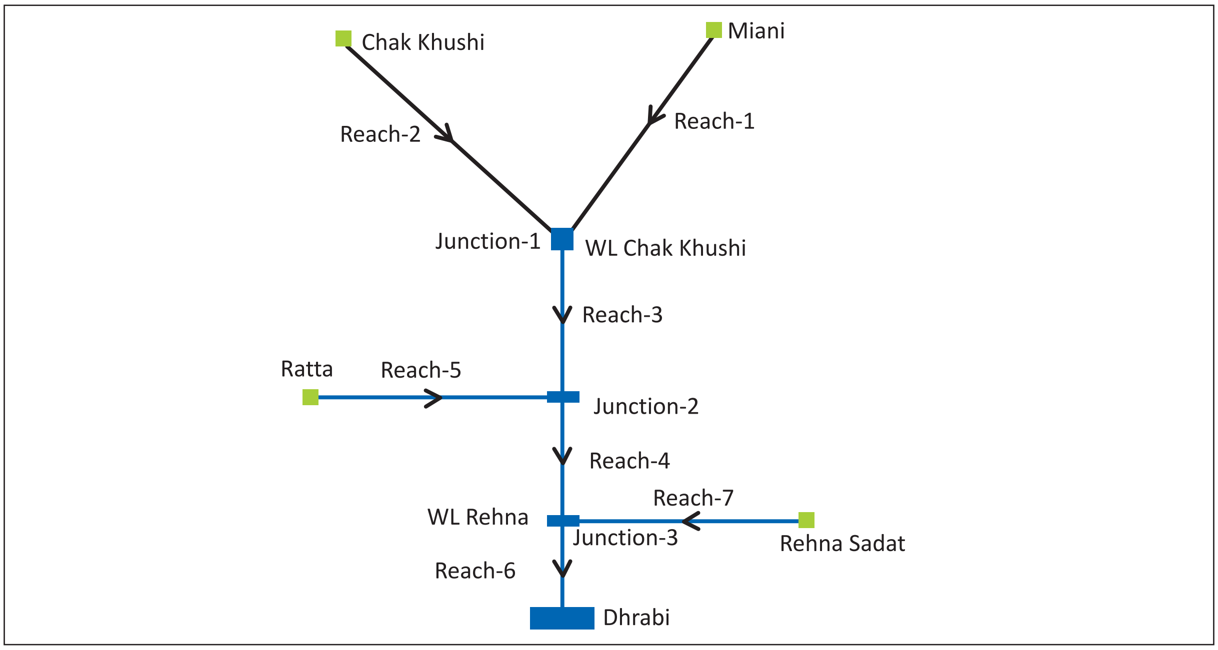

Figure 3.22. Different hydrological elements in the watershed

Source: A source is an element with no inflow, one outflow and is one of only two ways to produce flow in the basin model. The source can be used to represent boundary conditions to the basin model, such as the measured outflow from reservoirs or un-modeled headwater regions.

Reservoir: A reservoir is an element with one or more inflows and one computed outflow. Inflow comes from other elements in the basin model. If there is more than one inflow, all inflows are added together before computing the outflow. Assuming that the water surface is level, outflow is either computed using a user-specified monotonically increasing storage-outflow relationship or an outlet structure and an elevation-storage relationship. The element can be used to model reservoirs, lakes, and ponds.

In HEC HMS, a project was created which contained separate models – the Basin Model, the Precipitation Model, and the Control Model. Different data sets are required for each model and the hydrologic simulation is completed by using the data sets for these models. The Basin Model contains the basin and routing parameters of the model, as well as connectivity data for the basin. The Precipitation Model contains the historical or hypothetical rainfall data for the model. The Control Model contains all the timing information for the model, including model time steps and the start and stop dates and times of the simulation.

Data input

The input data included the areas of the different sub-catchments, topographic properties, slopes, imperviousness, time of concentration, and other parameters. The time series data included the precipitation measured at different locations in the catchments and the discharge measured at the outlet positions of the sub-catchments. The measured discharge for different events is used to calibrate and validate the model. In this study, only the rainfall events measured during June 2009 at Chak-Khushi sub-watershed were used for model calibration and validation, because complete rainfall and runoff data for different events were available for this location only.

Model calibration

The model calibration consists of a number of processes, such as collection of rainfall-runoff data for the selected catchments and simulation and comparison of observed and simulated flows. If the comparison is within the acceptable limits, then it will be satisfactory, otherwise the estimated flows will have to be recomputed by adjusting different calibration parameters until the results are within the acceptable limits.

The output was derived for the whole watershed using the topographic and hydrologic parameters. The input data comprise the area of the sub-watershed, measured rainfall and runoff, parameters for rainfall losses, and the routing method in the channel. The data used for the model input for different sub-watershed are shown in Table 3.11. The measured rainfall and discharge for Chak Khuski are shown in Figure 3.23, and the elevation-capacity curve of the reservoir in Figure 3.24.

The model was run for a rainfall-runoff event measured in June 2009. The model output was the discharge hydrograph measured at the outlet of the sub-watershed. The comparison between measured and observed flows for model calibration is shown in Figure 3.25. Dhrabi reservoir is the last point of the watershed and all the flow ultimately accumulates to the reservoir.

Table 3.11. Different input parameters for sub-watersheds

Parameter	Chak Khushi	Miani	Ratta Sharif	Rehna
Area (km^2)	31.5	9.9	68.2	94.4
Initial loss (mm)	7	4	12	5.9
Constant loss rate (mm/hour)	5.6	3.5	3.6	3.5
Impervious (%)	1.5	1.5	1.5	1.5

Model validation

After calibration, the model was validated for other rainfall event measured in August 2009 at Chak Khushi sub-watershed. The rainfall data was used as input and all the other parameters used for model calibration were kept constant. The output of the model was compared with the discharge hydrograph measured at the outlet of the sub-watershed. The comparison between the measured and observed discharge hydrographs is shown in Figure 3.26.

Model applications

Based on the same calibration parameters used for 2009, the model was applied for a rainfall-runoff simulation for 2010. The comparison between observed and simulated runoffs for two connective rainfall events is shown in Figure 3.27. The HEC-HMS model is event-based so it can only handle a single rainfall event at a time. The correlation coefficient between the observed and simulated discharge is 0.95 which is quite reasonable.

Estimation of water yield

The rainfall-runoff relationship is essential for estimating the potential available water from a certain amount of rainfall for a catchment. For this purposes, a rainfall-runoff relationship was developed for the different sub-catchments. The rainfall events were analyzed for the measured runoff for each event. Figure 3.28 shows the relationship between rainfall and water yield for Chak Khushi sub-catchment. The equation for the line of best fit is

$$Q = 58.49\ P \quad (R^2 = 0.78) \qquad (1)$$

where Q is the water yield (m^3), and P the rainfall intensity (mm/hr).

The generalized formula for the water yield of the Dhrabi watershed was derived as:

$$Q = 58.49\ P \qquad (2)$$

$$Q = 0.33\ P\ A \qquad (3)$$

where Q is the water yield volume in thousand cubic meters , P is rainfall in mm , and A is the catchment area in km^2.

The relationship developed was based on the data available for 2009 and 2010. The relationship can be refined if more data is made available. In the equation above , the surface run-off consists of the water left after the different water losses. In an arid area, light rainfall evaporates immediately after falling or infiltrates into the upper part of the soil profile from where it subsequently evaporates. Prolonged heavier rainfall will permit a proportion of the rain to infiltrate deeply into the ground to join the groundwater. Intense rainfall, where the rate of precipitation is greater than the combined rates of evaporation and infiltration, allows the surplus water to remain on the ground and eventually results in run-off. The steeper and more impervious the ground, the greater the proportion of any given storm that will result in run-off. Keeping this in mind, a detailed study should be undertaken to evaluate the different topographic and climatic factors of runoff. At present, the

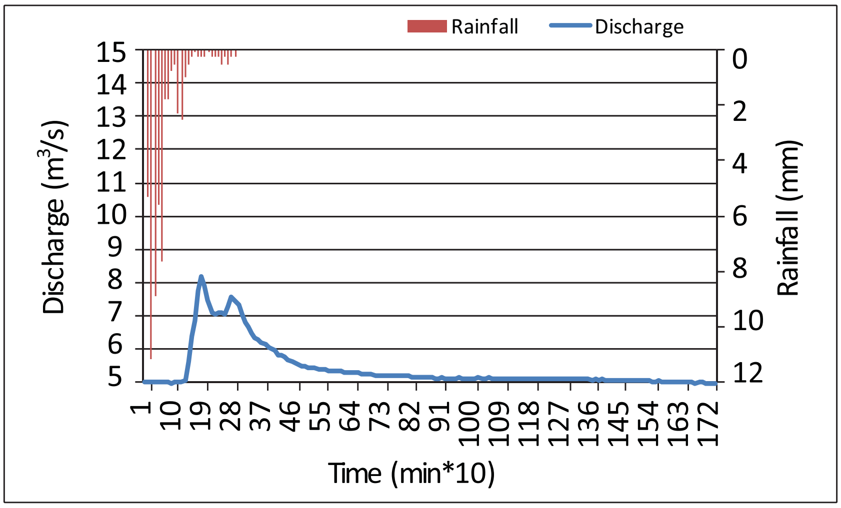

Figure 3.23. Precipitation and runoff measured at Chak Khushi for model input

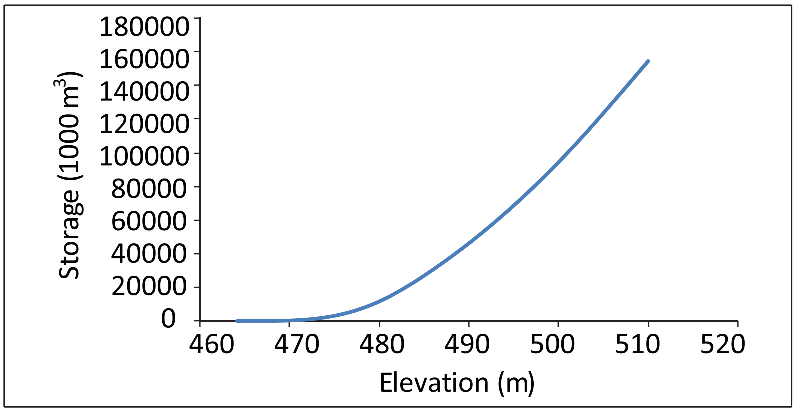

Figure 3.24. Elevation-storage curve of the Dhrabi reservoir

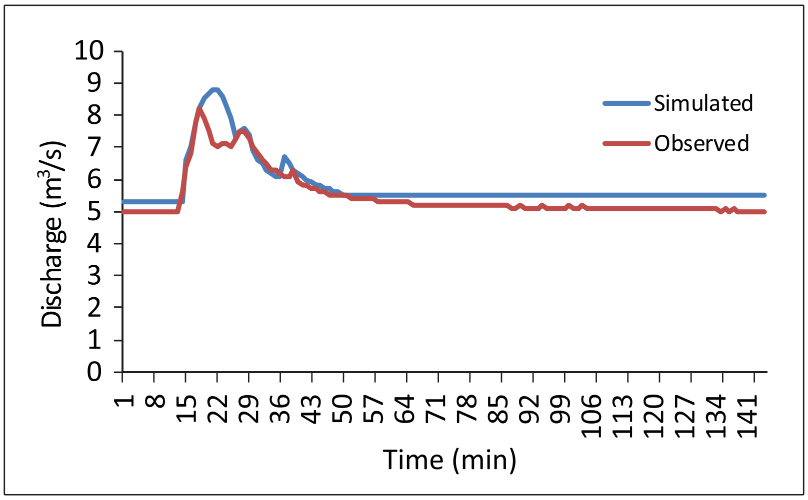

Figure 3.25. Comparison between observed and simulated discharge at Chak Khushi

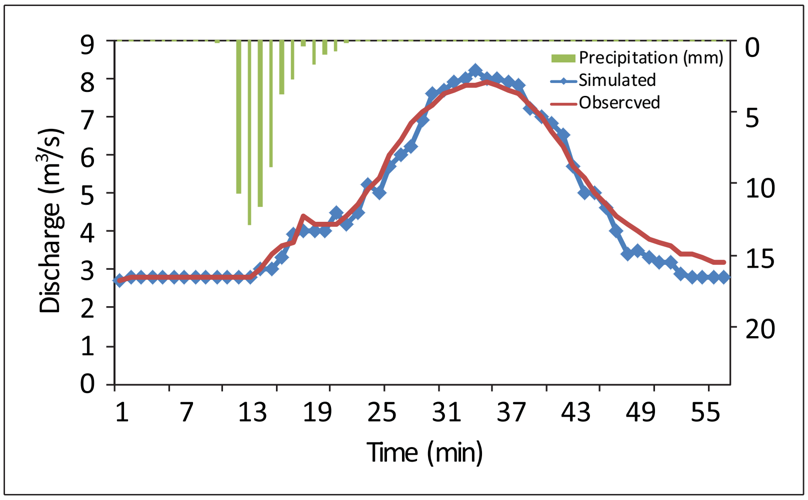

Figure 3.26. Comparison between measured and simulated discharge for model validation

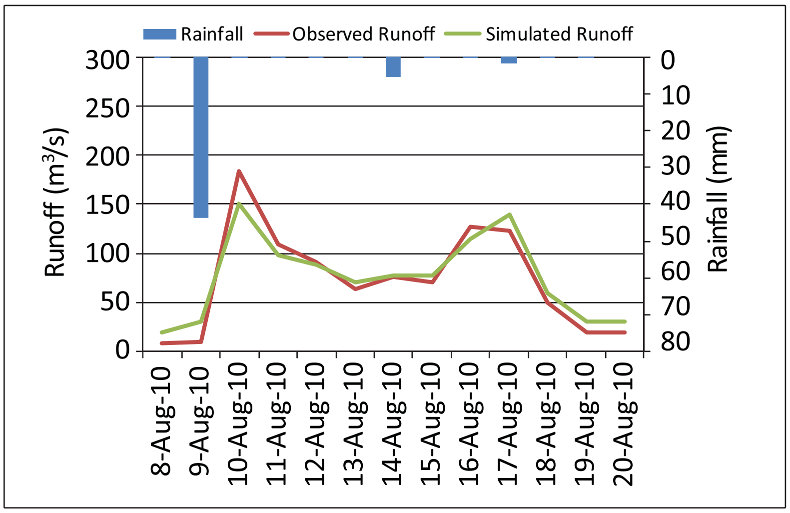

Figure 3.27. Observed and simulated runoff events August 8-20, 2010

relationship developed can be used to estimate surface runoff at various locations of the catchments.

3.4.9 Total sediment yield

The sediment yield data for small catchments for two years are presented in Table 3.12. Most of the runoff events were received during the summer season, between April and September. In 2009 rainfall was low as compared to 2010. In 2010, the sediment yields of gully catchments 25 and 31 were about 1.5 times more than in 2009. Terraced catchments 27 and 32 showed substantially lower sediment yields as compared to the gully catchments.

McCormack *et al.* (1982) defined the soil loss tolerance limit (SLTL) as the maximum rate of annual soil erosion that will permit a level of crop productivity to be obtained economically and indefinitely. According to the bio-physical approach, the SLTL is 11.2 t/ha/year since it approximates the maximum rate of a horizon development under optimum conditions. In

Table 3.12. Sediment yield (t/ha) of small catchments at Dhrabi watershed

	2009			2010		
Catchment	Coarser sediments	Finer sediments	Total sediment yield	Coarser sediments	Finer sediments	Total sediment yield
25	3.13	1.66	4.79	0.92	7.23	8.15
27	0.77			0.11	2.67	2.78
31	1.96	6.38	8.34	3.95	8.36	12.31
32	0.81			1.47	2.62	4.09

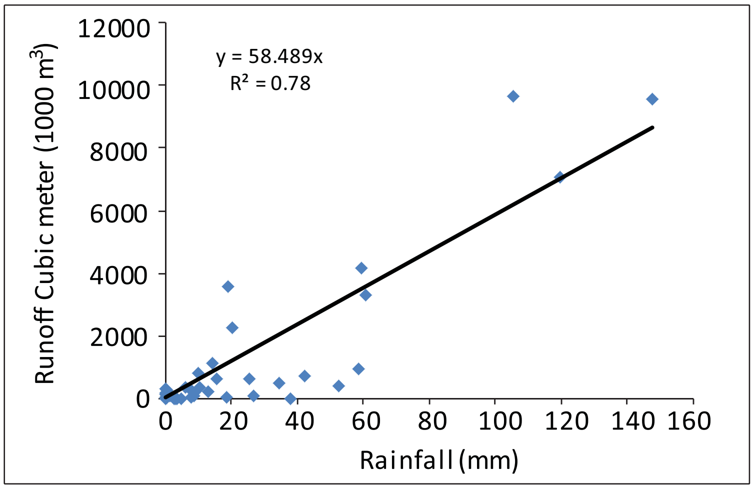

Figure 3.28. Rainfall-water yield relationship for Dhrabi reservoir

India, 11.2 t/ha/year is followed as the default SLTL value (Mandal *et al.,* 2006) assuming a soil formation rate of 2.5 cm in 30 years. The USDA-NRSC (1999) has proposed a range for the SLTL from 2.5 t/ha/year to 12.5 t/ha/year. Considering the SLTLs, it appears to be difficult to maintain long-term productivity of the gully system. So interventions are needed to reduce the soil loss. The terracing of catchment 32 and 27 has shown its potential to reduce the erosion.

For catchment 25, runoff events were received only during the summer season in 2009. No runoff occurred during the winter. A total of 28 rainfall events occurred during the study period. During 2009, two main runoff events, of 46 mm (June 4, 2009) and 43 mm (July 29, 2009) were received that caused most of the erosion. The rainfall intensity in 30 minute (I30) of these events was 81 mm/hour, producing a peak discharge of 0.38 $m/^3s$, for the former and 85 mm/hour, with a peak discharge of 0.41 m^3/s, for the latter. Similarly, during 2010, there were four runoff events which resulted in sediment yields of more than 0.7 t/ha (Table 3.13). Most of the erosion was caused by just a few high intensity rainfall events as has also been reported by Toy *et al.* (2002) and Ramos *et al.* (2007). Since the catchment was a natural gully system with no engineering or vegetative protection established by the farmers, there were no obstacles to the overland flow. As a result, nearly all the catchment contributed to the runoff during most of the storms. The critical rainfall intensity I30 for initiating runoff at the small catchment scale (size 2.0 ha) was

Table 3.13. Main runoff events with sediment yield at catchment 25

Date	Rainfall (mm)	Peak discharge (m^3/sec)	Coarser sediments trapped (kg)	Finer sediments passing over weir (kg)	Sediment yield (kg/ha)
June 4, 09	46	0.38	1,985	901	1,343
July 28/29, 09	23, 43†	0.41	3,724	1,832	2,778
July 5, 10	60	0.44	554	3,695	2,125
July 20, 10	60	0.44	304	7,017	3,661
July 27, 10	21	0.15	172	1,013	592
July 29, 10	42, 64	0.12, 0.16	226	1,197	711

† Rainfall occurred twice a day

Table 3.14. Main runoff events with sediment yield at catchment 27

Date	Rainfall (mm)	Peak discharge (m^3/sec)	Coarser sediments trapped (kg)	Finer sediments passing over weir (kg)	Sediment yield (kg/ha)
April 6, 09	26	0.15	16		
June 4, 09	46	0.14	216		
July 28/29, 09	23, 43†	0.16	449		150
July 20, 10	60	0.16	22	1,461	1,483
July 27, 10	21	0.03	13	150	163
July 29, 10 am	42	0.05		405	405
July 29, 10 pm	64	0.08	9	157	166
Aug 24, 10	50	0.06	4	179	183

† Rainfall occurred twice a day

29 mm/hour. Hudson (1965) reported that 25 mm/hour was the critical rainfall intensity for initiating erosion in the tropical climate of Zimbabwe at runoff plot scale. In temperate climates, erosion has been reported to start at a much lower intensity. Lower threshold values of 6 mm/hour and 10 mm/hour have been identified in Germany and Great Britain (Kirkby and Morgan, 1980). Most of the sediments were transported as finer sediments in all the catchments (Table 3.13).

Similar to the adjacent catchment 25, catchment 27 was a single gully that had been converted to terraces by the farmers. There was a strong bund in the middle of the catchment. The bund was strong enough and did not break even with a rainfall event of 60 mm during summer. One reason for the lower runoff from the catchment was the cultivation of sorghum and millet crops. No runoff event occurred during the winter seasons between December 2008 and March 2009 and October and December 2009 (Table 3.14). The receiving area for the runoff from all the runoff events was the lower part of the catchment. Similar to catchment 25, only two rainfall events produced major runoff and the peak discharge of these two events was less than that in catchment 25 as a result of the bunds and the smaller contributing area. A decrease in peak discharge resulting from terracing has also been reported by Huang *et al.* (2003). Similarly, the bed load of this catchment was also less than that of the gully catchment. The bunds helped decrease the runoff from the catchment by storing water in the soil profile. Since 2009 was a year of comparatively low rainfall, with no extraordinary rainfall events, most of the rainfall was retained in the terraces and most of the runoff occurred from the lower part of the catchment. In 2010, the same trend was observed and no bund breakage occurred in the catchment.

Catchment 29 was comparatively larger (350 ha) than the other catchments. It contains gullies and terraces. In catchment 29, measurement of the coarser sediment yield was made on an annual basis. To estimate the amount of finer sediments passing over the weir, data on the amount of finer sediments passing over the weir in the adjacent catchment 25 was used. This was multiplied by the runoff volume to obtain an event-wise weight of finer sediments leaving the catchment. The total sediment yield of the catchment was obtained by adding the coarser and finer sediment amounts. The sediment yield of this catchment during the two consecutive years was 123 kg/ha/year in 2009 and 416 kg/ha/year in 2010. This latter amount was a result of the ten runoff events during 2010 as compared to the five of 2009. The sediment yield of catchment 25, a gully catchment, was 1.7 times more in 2010 than in 2009. And the sediment yield of catchment 29 was 3.38 times more in 2010 than in 2009.

At catchment 31, there were ten runoff events during the two years. These ten events resulted in a soil loss of more than 18 t/ha. The sediment yield of these storms is presented in Table 3.15. The sediment yield was closely related to the peak discharge.

Table 3.15. Main runoff events with sediment yield at catchment 31

Date	Rainfall (mm)	Peak discharge (m^3/sec)	Coarser sediments trapped (kg)	Finer sediments passing over weir (kg)	Sediment yield (kg/ha)
July 22, 09	21	0.15	748	1,948	1,797
July 29, 09	56	0.27	1,370	4,322	3,795
Aug 18, 09	32	0.06	263	553	544
Sept 2, 09	25	0.14	362	2,448	1,873
July 5, 10	32	0.18	826	1,002	1,219
July 20, 10	55	0.29	1,148	4,357	3,670
July 21, 10	36	0.09	1,335	1,209	1,696
July 29, 10	39, 16, 38 †	0.08	801	2,602	2,268
Aug 24, 10	42	0.08	117	1,294	941
Sept 10, 10	44	0.15	260	913	782

† Rainfall occurred thrice a day

The higher sediment yield of this gully system catchment as compared to those of catchments 25 and 27 appears to be a result of less vegetative cover and more slope. The comparatively smaller catchment area may also be a reason for the higher sediment yield as the sediment delivery ratio of smaller catchments is higher. The terraces in catchment 32 were gently sloped and were without bunds. The peak discharges of the events were lower in this catchment. A maximum rainfall of 56 mm occurred on July 29, 2009 (Table 3.16). During 2009 and 2010 there were 6 runoff events in catchment 32; it was the three runoff events in 2010 which produced the 2.7 t/ha of sediments .

3.4.10 Nutrient analysis of sediments

Nutrients in the soil are very important for better crop growth and yield. Farmers in the rainfed areas do not use micro nutrients and the use of macro nutrients is also rare. The micro nutrients naturally available in the soil are depleted as a consequence of the soil erosion. Tables 3.17-3.21 show the nutrients analysis of the sediment collected at the outlets of the catchments. Generally, the organic matter (OM) is low in the cultivated lands of the areas (less than 1%). However, up to 2.17% OM was found in the sediment in a single rainfall event in catchment 27. This high OM in the sediment explains the reason for the low OM in the soils.

The sediments trapped in the stilling basins were within the safe limits for Zn, Cu, Fe, and Mn. The sediments were rich in available K. The OM contents of these sediments which were removed from the catchments were appreciable. Further research should be conducted to study the depletion of macro and micro nutrients from the soil and their impact on reservoir capacity and quality.

3.4.11 Runoff coefficients

An analysis of the runoff coefficients provides an essential insight into the catchment response, particularly if a range of catchments and a range of events are compared through a single indicator (Norbiato *et al.,* 2009). The runoff coefficient is the ratio of the rainfall to the runoff and is used to calculate the runoff from a given rainfall. It depends on the catchment characteristics and the rainfall intensity. Unfortunately, in Pakistan runoff coefficients have not been calculated and only book values are used to calculate the runoff from a given rainfall. This study provides an opportunity to present runoff coefficients for a range of small catchments.

The rational method is a commonly used method to estimate runoff from small watersheds. The rational method of predicting a design peak runoff rate is expressed by the equation (Schwab *et al.,* 1993)

$$Q = 0.0028\ CIA$$

where Q is the design peak runoff rate (m^3/s), C is the runoff coefficient, I is the rainfall intensity (mm/hour) for the design return period and for a duration equal to the time of concentration (Tc) of the watershed, and A is the watershed area (ha).

In the present study, the runoff coefficient, C, was calculated from the runoff data for small watersheds. On the basis of this measured data, the suggested values for the runoff coefficients are presented in Table 3.22.

The runoff coefficient depends on soil type, slope, vegetative cover, and land-use systems. The basic assumption for the application of the rational method is that rainfall occurs at a uniform intensity over the entire area of the

Table 3.16. Main runoff events with sediment yield at catchment 32

Date	Rainfall (mm)	Peak discharge (m^3/sec)	Coarser sediments trapped (kg)	Finer sediments passing over weir (kg)	Sediment yield (kg/ha)
July 29, 09	56	0.39	224	na	na
Aug 18, 09	32	0.06	194	na	na
Sept 2, 09	25	0.15	108	na	na
July 20, 10	55	0.31	1,426	4,334	1,745
July 21, 10	36	0.09	352	1,097	439
July 29, 10	39, 16, 38 †	0.10	462	1,337	545

na – not available or data could not be collected ; † Rainfall occurred thrice a day

Table 3.17. Nutrients present in the sediments of catchment 25

Date	Rainfall (mm)	Av P (ppm)	Ext K (ppm)	OM (%)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)
Apr 6, 09 pm	46	6.1	674	0.31	3.3	1.01	22.0	69.2
July 28/29, 09	23, 43 †	18.7	230	0.74	2.3	0.50		78.8
May 7, 10	60							
July 20, 10	60	0.17	155	0.22				
July 27, 10	21	0.03	149	0.64				
July 29, 10	42, 64 †	0.10	163					

na – not available or data could not be collected ; † Rainfall occurred twice a day.

Table 3.18. Nutrients present in the sediments of catchment 27

Dates	Rainfall (mm)	Av P (ppm)	Ext K (ppm)	OM (%)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)
Apr 6, 09	26	6.6	302	0.49	3.3	1.15	7.6	90.8
Apr 6, 09	46	9.5	631	0.49	2.1	0.53	2.1	54.8
July 28/29, 09	23, 43†	10.8	295	0.76	2.8	0.13	29.2	91.3
July 20, 10	60	0.15	215	1.39	na	na	na	na
July 27, 10	21	0.14	257	0.64	na	na	na	na
July 29, 10 am	42	na	na	na	na	na	na	na
July 29, 10 pm	64	0.24	221	2.17	na	na	na	na
Aug 24, 10	50	0.49	254	na	na	na	na	na

na – not available or data could not be collected ; † Rainfall occurred twice a day

Table 3.19. Nutrients present in the sediments of catchment 29

Year	Av P (ppm)	Ext K (ppm)	OM (%)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)
09	6.7	137	0.45	2.5	2.1	7.0	9.38
10	7.9	156	0.51	1.9	2.5	5.9	7.14

Table 3.20. Nutrients present in the sediments of catchment 31

Date	Rainfall (mm)	Av P (ppm)	Ext K (ppm)	OM (%)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)
July 27, 09	21	11.4	262	0.46	2.5	0.37	25.3	68.1
July 29, 09	56	8.0	154	0.99	1.8	0.55	21.6	65.5
Aug 18, 09	32	9.5	295	1.02	3.1	0.14	17.8	69.6
Sept 2, 09	25	9.7	na	0.65	1.9	0.30	7.00	65.2
May 7, 10	32	na	110	1.31	na	na	na	na
July 20, 10	55	0.00	99	1.62	na	na	na	na
July 21, 10	36	0.00	88	0.91	na	na	na	na
July 29, 10	93	0.00	69	0.10	na	na	na	na
Aug 24, 10	42	0.02	83	Na	na	na	na	na
Sept 10, 10	44	na	97	na	na	na	na	na

na – not available or data could not be collected.

Table 3.21. Nutrients present in the sediment of catchment 32

Date	Rainfall (mm)	Av P (ppm)	Ext K (ppm)	OM (%)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)
July 29, 09	56	6.6	153	0.87	1.4	0.42	14.6	66.2
Aug 18, 09	32	12.4	245	0.43	2.6	0.20	7.1	82.2
Sept 2, 09	25	10.7	na	0.31	1.8	0.10	5.8	37.6
July 20, 10	55	0.00	97	0.79	na	na	na	na
July 21, 10	36	0.00	110	1.01	na	na	na	na
July 29, 10	93	0.00	110	0.70	na	na	na	na

na – not available or data could not be collected.

Table 3.22. Calculated values of the runoff coefficients (C) in the Dhrabi watershed

Catchment	Area (ha)	C for rainfall intensity (mm/hour) equal to Tc		
		50	100	150
25	2.0	0.02-0.16	0.11-0.30	0.31-0.51
27	3.0	0.05-0.15	0.15-0.30	0.35-0.45
29	350	0.05-0.19	0.20-0.40	0.30-0.50
31	1.5	0.06-0.17	0.18-0.30	0.31-0.44
32	3.3	0.03-0.08	0.08-0.18	0.10-0.24

watershed (Schwab *et al.,* 1993). However, the monsoon rainfall events are known for their extreme, non-uniform intensity over a few hectares. These phenomena also affect the runoff coefficients.

3.4.12 Prediction of sediment delivery to Dhrabi reservoir

Eroded soil particles are ultimately carried by the streams to the reservoir in the form of suspended sediments and the larger solids move along the stream beds as bed loads. When sediment-laden water reaches a reservoir, the velocity and turbulence are greatly reduced. The large suspended particles and most of the bed load (having high specific weights) are deposited at the upstream end of the reservoir. However, the smaller particles remain in suspension and are deposited farther down the reservoir and may pass the dam through the sluice gate or over the spillway.

The sediment yield from the small catchments of a watershed may be used to determine the total sediment flowing into the reservoir. To transfer the sediment yield directly, the drainage areas should not be different in size by a factor greater than two. For drainage areas that differ by a factor greater than two, the United States Soil Conservation Service recommends that the following relationship for humid areas east of the Rocky Mountains be used to estimate transfer sediment yields (Kirkby and Morgan, 1980):

$$S_e = S_m [A_e/A_m]^{0.8}$$

where S_e is the sediment yield of the unmeasured watershed, S_m is the sediment yield of measured watershed, A_e is the drainage area of the unmeasured watershed, and A_m is the drainage area of the measured watershed.

The sediment yield of the 350 ha catchment (catchment 29) was 123 kg/ha for 2009. Using the above formula, the predicted sediment yield of Dhrabi watershed (19,100 ha) would be about 1056 t/year. Using the annual sediment yields of catchments 25 and 27, i.e. 4.7 t/year and 8.34 t/ha/year , the predicted sediment yield of Dhrabi watershed would be between 24,055 t/year and 14,359 t/year, respectively. Similarly, given the sediment yield of the 350 ha catchment (catchment 29) was 416 kg/ha during 2010, then the predicted sediment yield of Dhrabi watershed (19,100 ha) would be about 3570 t/year. Using the annual sediment yields of catchments 25 and 31, i.e. 8.15 t/year and 12.31 t/ha/year , the predicted sediment yield of Dhrabi watershed would be between 24,055 t/year and 35,514 t/year. There is large variation in these estimates because of the inaccuracies in quantifying the sediment delivery ratio and the problems of extensive extrapolation. The measurement of the sediment yields from plots or small catchments cannot be directly extrapolated to large catchments, since the effect of the sediment delivery ratio is not easily quantifiable (Dickinson and Collins, 1998).

3.4.13 Land-use activities affecting erosion processes

Cropping pattern

The cropping pattern affects the process of detachment and transportation of sediments through (i) the canopy effect, which depends on the crown density, height above ground, and degree of closure and (ii) the mulch effect of residues and low plants. This is the most important because it describes the effective interception of splash and slows down the overland flow. There is a residual effect which lingers for some years after the causal vegetation has gone. In Dhrabi watershed, only one crop is sown during a year because of the limited amount of moisture available. Fallow-wheat-fallow is the main winter cropping pattern and fallow-groundnut-fallow is the main summer cropping pattern. Other summer crops include millet, guar, and pulses. During winter, the main crops sown are wheat and canola (*brassica*). Canola is usually sown alone, but sometimes it is mixed with wheat mostly for fodder purpose.

Experiments carried out at SAWCRI have shown that in summer, groundnut is more effective in reducing soil loss from sloping fields than millet and mung. The groundnut is sown in March. By the time the monsoon season starts, it has provided a considerable cover to the soil. However, the farmers do not sow groundnut in areas where there is a danger of wild boar attacks. To conserve the soil moisture, farmers cultivate the land before the onset of the monsoon. This loosens the soil, allows absorption of the rainwater, and controls weeds. Tillage usually stops overland flow during low to medium rainfall events, but these operations lead to the detachment and transportation of sediments when a major rainfall event is received.

Terracing and leveling operations

The desire to bring more land under cultivation has led to the degradation of virgin lands, which results in the erosion of soil. The government provides bulldozers to farmers at subsidized rates for carrying out terracing and leveling operations. These bulldozers are used to develop terraces, mostly cutting the sloping lands, gully beds, and badlands. With the dominance of silt in the loess soils, it takes many years to re-stabilize the soil. When a high intensity rainstorm is received, particularly if it occurs soon after the leveling operation, bank gullies start developing in these terraces.

The conversion of slopes into terraces is common in the upper and middle reaches of the watershed i.e. in Chak Khushi, Ratta, Dhoke Awan, and Dhoke Mori. The conversion of gully beds into terraces is common in Khokhar Bala in the upper watershed and in Rehna, Murid, etc., in the lower watershed where the gully system already exists. The terrace embankments usually need maintenance after every two to three years. With the increasing cost of these operations, many farmers have abandoned these terraces. Once the bunds on these terraces are breached, erosion progresses. These abandoned terraces are a source of sediments, especially where the natural vegetative cover is less. These types of abandoned terraces are present throughout the watershed especially on the terraces in gully beds in Khokhar Bala, Ratta, Rehna, and the extreme western parts of lands belonging to Murid village, etc.

Stone mining

Shallow mining of stone is the main industry in the upper watershed especially in lands belonging to Khairpur and Chak Khushi villages. During the process of excavation of small stones, vegetation from the surface soil is removed; which weakens the protection against rainfall. These stones are being used for construction of houses, roads, and other structures. Many stone crushers are also present on Kallar Kahar-Choa Syden Shah road near Chak Khushi. Stones are sold while the fine particles are carried to the stream through runoff. A cement manufacturing industry is also attached to the Dhrabi watershed at its extreme south at the village of Khairpur. These activities have accelerated the production of sediments.

Stone excavation near Chak Khushi and Khairpur

Native vegetation removal

Vegetative cover protects the soil from the force of the raindrops. Phulahi, kikar, and Ziziphus *jujuba* are the main tree species present in gullies. Removal of these plants for timber and firewood has exacerbated the erosion process in many parts of the watershed. During the summer months, with the lack of fodder, uncontrolled grazing reduces or completely removes the vegetative cover in certain parts of the watershed. However, no study has been conducted to measure the impact of vegetation removal on soil erosion.

3.4.14 Impact of interventions on soil and water conservation

Any intervention that reduces runoff and conserves the soil moisture reduces soil erosion. Structures reduce the runoff, help conserve soil and moisture, and also help trap the sediments (Table 3.23). The sediment trapped behind a structure helps develop the land as the long-term deposition of soil helps reduce the difference in elevation between the head and tail of a field. These sediments are rich in micro nutrients (Tables 3.17-3.21) that help increase the crop yield. These structures indirectly help maintain the sustainability of the downstream water bodies by reducing the amount of sediment coming into them.

3.4.15 Conclusions and recommendations

The process of erosion in the selected gullies is rapid and it may be difficult to maintain long-term fertility of the soil. The production of more sediment will eventually decrease the life of the reservoir. The practice of terracing for arable crops inside a gully has shown the potential to reduce sediment delivery. Soil erosion is at its maximum during the monsoon (July-August) before considerable vegetative cover has been established.

Table 3.23. Sediment trapped behind the structures

Year	Village name	Structure	Cost per structure (PKR)	Cost of installation (PKR)	Cost of repair (PKR)	Average amount of sediment trapped (t/ha)
2008	Dhoke Mohri	22	3,995	87,890	15,900	na
	Rehna	8	3,625	29,000	na	na
	Chak Khushi	24	4,000	96,000	na	na
	Khokhar Bala	12	4,667	56,004	na	na
2009	Dhoke Mohri	22	na	na	na	2.2
	Rehna	31	5,761	132,515	na	1.1
	Chak Khushi	24	na	na	na	3.1
	Khandua	16	3,500	56004		
	Khokhar Bala	13	5,600	5600	1,000	2.3
2010	Dhoke Mohri	22	na	na	na	125.4
	Rehna	31	na	na	na	365.8
	Chak Khushi	24	na	na	na	231.8
	Khandua	16	na	na	na	204.8
	Khokhar Bala	13	na	na	na	184.6

na – not available or data could not be collected.

Therefore, permanent vegetation cover needs to be maintained in the watershed.

The facilities and infrastructure established for determining the rainfall and runoff for the watershed is capable of providing satisfactory measurements. The HEC-HMS model can be successfully applied for rainfall-runoff estimation. The relationship developed for estimating water yield can be applied for the design of soil and water conservation activities. The relationship developed should be improved by incorporating more data during subsequent periods.

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Chapter 4: Spatial and temporal analysis of water quality in Dhrabi watershed

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4.1 Summary

Water quality monitoring is one of the important components for maintaining a healthy watershed. In the Dhrabi watershed of Pakistan, from 2007 to 2010, surface water quality was monitored at 16 locations at regular intervals for its suitability for irrigation purposes. Similarly, the groundwater quality was monitored at 10 locations for its suitability for drinking and irrigation purposes. The status of wastewater disposal in the watershed was also studied.

There was high spatial and temporal variability in the surface water quality. The surface water quality at certain locations was poor and exceeded the permissible limits for irrigation purposes. Even in the Dhrabi reservoir, the surface water quality was inferior to that found in most of the other reservoirs. The electrical conductivity (EC) and residual sodium carbonate (RSC), at most of the locations, either exceeded or fluctuated around the permissible limits throughout the monitoring period. Therefore, the use of such water for irrigation purpose needs special care otherwise its prolonged use may pose soil salinity and sodicity problems. The trend in groundwater quality was very similar to that of the surface water and there was high spatial and temporal variability. Exchangeable Mg^{2+} exceeded the permissible limits for most of the surface and groundwater samples.

The following strategies may be useful in handling this issue:

- Reduce the entry of high RSC water into the reservoir. Since Kallar Kahar Lake and its catchment are the main contributors of high salinity, no water should be allowed to spill over from the lake. This may be done by raising the dikes of Kallar Kahar Lake and storing as much as water from the catchment
- Use chemical amendments, such as gypsum, in the field to reduce the negative impacts of the sodic water
- Adopt an appropriate cropping pattern.

Groundwater is also used for drinking purposes. Microbiologically, two out of eight points were found fit for drinking purposes during August 2009, one out of eight samples were found fit for drinking purposes during February 2010, and one out of 10 samples were found fit for drinking purposes during June 2010. Microbiological contamination of drinking water is responsible for directly or indirectly spreading major infections and parasitic diseases, such as cholera, typhoid, dysentery, hepatitis, giardiasis, cryptosporidiosis, and guinea-worm infections. Therefore, this water may be used only after proper treatment.

Soil samples were collected from the catchment areas of the major polluting streams and also from the beds of the Kallar Kahar Lake and the Dhrabi reservoir. The soil samples from the catchments show high salinity and sodicity that might be the cause of high salinity and sodicity in the streams. The highest EC, SAR, and exchangeable sodium percentage (ESP) in the bed samples from the Kallar Kahar Lake were about 43 dS/m, 56, and 45, respectively. The high EC, SAR, and ESP in the bed result from the saline water brought into the lake with the runoff. The evaporation from the lake increases the

salinity of the water. The salts ultimately settle to the lake bed increasing the salinity and sodicity. The EC at the bed of the Dhrabi reservoir was also high (up to 5.1 dS/m) with an ESP of 4.3. The Dhrabi reservoir became operational during 2007. Keeping in mind the salinity and sodicity levels of the reservoir, it is anticipated that the salinity and sodicity of the bed of the reservoir will also increase with time. The small dams, mini-dams, and ponds are the main source of groundwater recharge in the area. However, with such a high sodicity in the bed of the reservoir, the recharge to the groundwater will be reduced substantially. It is necessary to conduct a systematic study of the effect of saline-sodic water on groundwater recharge.

4.2 Introduction

With increased population, urbanization, and industrialization, water quality is becoming a serious issue all over the world and particularly in developing countries. Water quality is important for drinking, irrigation, and for the maintenance of the ecosystem. A large part of the 900 million people living in the rural areas, particularly the poorest of the poor, lacks access to safe drinking water. The lack of access to safe drinking water and sanitation, along with poor personal hygiene, result in massive health impacts, particularly through diarrheal diseases, which are estimated to the cost of lives of 2.18 million people, three-quarters of whom are children less than 5 years old (Pruss *et al.,* 2002).

Water quality defines the usefulness of water for an intended purpose and is equally important as quantity. Water is required for domestic, industrial, municipal, and agricultural uses where acceptable quality standards vary based on the intended use. With surface and groundwater being the major potential sources of water in Pakistan, their quality and management requirements are generally different.

The river waters in Pakistan, like other rivers in the world, contain soluble salts, the concentrations of which vary from river to river depending on the type of catchment area, the sources of the water, and the season. Generally, there is an increase in the salt content during low flows in winter and a decrease in concentration during the high flow period in summer. The quality of river waters is generally good in terms of salinity.

Groundwater is another source of water supply for agricultural, domestic, and industrial uses. However, its quality is far inferior to surface water. About 70% of the tubewells are pumping sodic water (Qureshi and Barrett-Lennard, 1998). The use of sodic water has, in turn, affected soil health and crop yields. This situation is being further aggravated with the reduced rainfall as a consequence of climate change.

The annual generation of wastewater in Pakistan is about 4.43 billion cubic meters (BCM), of which 3.06 BCM is municipal and 1.37 BCM is from industries. On the one hand, this huge volume of water is a resource that can be reused after proper treatment. On the other hand, it is a nuisance, as less than 1% of the wastewater is being treated and about 1.7 BCM is being disposed off directly into water bodies with serious consequences for the aquatic life and downstream users. Because of this improper disposal and the use of unlined drains, the wastewater percolates and ultimately recharges (contaminates) the groundwater – more than 90% of our drinking water comes from groundwater (Ashraf *et al.,* 2008). A study conducted by the Pakistan Council of Research in Water Resources (PCRWR) shows four major contaminants in the drinking water. These are bacterial (68%), arsenic (24%), nitrate (13%), and fluoride

(5%). Overall, of 357 drinking water samples, only 45 (13%) were found to be safe while the remaining 312 (87%) were found to be unsafe for drinking purposes (Kahlown *et al.,* 2008). These contaminants are responsible for most of the water-born and water-related diseases prevalent in the country.

A watershed is a land area which receives and transports the rainwater to an outlet, most frequently a reservoir. A part of the rainwater is stored either in the soil or percolates through the soil to recharge the groundwater and build a shallow aquifer. These shallow aquifers are mostly perched water which is the main source of drinking water for the inhabitants. The remaining water moves to the outlets in the form of runoff. During the runoff process, the water also receives some point and non-point pollution and transports this to the water body. During the transportation, some of these pollutants are leached down and contaminates the groundwater. The monitoring of surface and groundwater quality is very important for assessing the health of any watershed. The main objective of this study was to monitor the surface and groundwater quality of the Dhrabi watershed from irrigation, drinking, and environmental points of view.

4.3 Material and methods

4.3.1 Surface water quality monitoring

A number of perennial and non-perennial streams flow to the Dhrabi reservoir. The surface water quality of these streams and the reservoir was monitored regularly at 16 representative locations (Table 4.1 and Figure 4.1) and the water quality was assessed for irrigation purposes only.

4.3.2 Groundwater quality monitoring

Groundwater is a major source of drinking water and some farmers also use it for irrigation. The groundwater quality of 10 open wells/dug wells, hand pumps, and water turbine pumps was monitored for both irrigation and drinking purposes. The details of these monitoring points are given in Table 4.2 and Figure 4.1.

Table 4.1. Locations of surface water quality monitoring points

Location	Description	Location	Description
1	Nikka dam stream on Bhurpur road	9	Outflow from KK lake weir (exit)
2	Inflow to Kallar Kahar (KK) lake near Khushab Road	10	Outflow from KK city drain
3	Inflow to KK lake near police rest house	11	Outflow from KK lake plus city drain through box pipe
4	Inflow to KK lake, right side of tourist point	12	Outflow after the junction of four points 8, 9, 10, and 11
5	Inflow to KK lake, left side of tourist point (now choked)	13	Outflow near Baba Totanwali Tomb
6	Inflow to KK lake, behind KK motorway rest area	14	Outflow at Ratta Bridge
7	Outflow at Chak Khushi drain bridge	15	Near Dhoke Choi main inlet to Dhrabi dam
8	Outflow at KK Chakwal Road Bridge	16	Dhrabi reservoir exit

Table 4.2. Groundwater monitoring points

Point No	Description	Point No	Description
1	Chak Khushi hand pump	6	Dhoke Choi stream
2	Ghulam Haider Kallar Kahar hand pump	7	Rahna Sadat turbine
3	Ratta Sharif hand pump	8	Dera Shahid Abbasi Ratta tubewell
4	Dhoke Mori Rajwali dug well	9	Downstream of Kallar Kahar
5	Dhoke Zawar near Rehna Sadat dug well	10	Upstream of Kallar Kahar

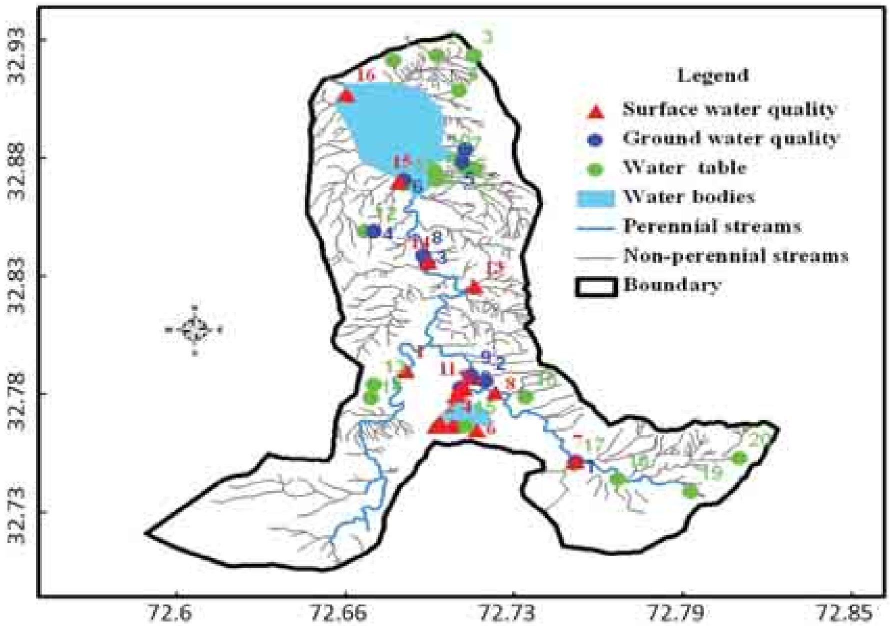

Figure 4.1. Map of the area showing the monitoring points

4.3.3 Water-table monitoring

The water-table depth is an important factor in the design, installation, and operation of a tubewell and it has a profound effect on the quality of the groundwater. The water-table depth was regularly monitored at 20 different locations and the water table was measured by a water-table indicator.

4.3.4 Wastewater monitoring

The wastewater is of major environmental concern and affects the surface and groundwater qualities and the ecosystem. The major source of wastewater is from the town of Kallar Kahar which joins the stream at point 11 (Table 4.1). Wastewater samples were collected from point 11 and 2 km downstream from it. These samples were analyzed for their biological oxygen demand (BOD) and chemical oxygen demand (COD). Wastewater generation in the villages was almost negligible except for Khandoa village where the wastewater was being stored outside the village and used for watering animals and the small-scale growing of vegetables.

The wastewater from this pond was also analyzed for its BOD, COD, and chemical parameters.

4.3.5 Soil samples

To have an idea about the parent material and its effects on surface and groundwater quality, soil samples were collected from depths up to 15 cm from different catchments and also from the beds of Kallar Kahar Lake and Dhrabi reservoir.

4.3.6 Parameter analysis

The electrical conductivity (EC) was measured using a conductivity meter. The EC is an index of the soluble salts collectively present in the water. Anions, like carbonate and bicarbonates, were determined by titration of the water against a standard sulfuric acid solution using phenolphthalein (for carbonates) and methyl orange (for bicarbonates) as the indicators. Chlorides were estimated by titration against a standard solution of silver nitrate with potassium chromate as the indicator. For cation estimation, the most common method for determining the level of calcium and magnesium in irrigation waters was followed – using a standard solution of ethylene diamine tetra acetic acid (EDTA) in the presence of eriochrome black T indicator under pH buffer conditions. Calcium was determined by titration against standard EDTA in the presence of ammonium purporate indicator while magnesium was determined as the difference between the calcium and calcium plus magnesium values. The sodium cation was determined as the difference between the total soluble salts and the calcium plus magnesium. Residual sodium carbonate (RSC) and the sodium adsorption ratio (SAR) were determined using the following formulas:

$$RSC = (CO_3 + HCO_3) - (Ca + Mg) \quad (1)$$

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \quad (2)$$

The concentrations are expressed in meq/L.

The drinking water samples were analyzed for Cl, Mg, SO_4, NO_3, NO_2, As, Mn, total coliforms, fecal coliforms, and E. coli. The analyses were undertaken in the laboratories of the Pakistan Council of Research in Water Resources (PCRWR) and the National University of Science and Technology (NUST), Islamabad.

4.3.7 Water quality standards

Water quality standards vary according to the uses to which it is to be put. There are no unified irrigation water quality standards in Pakistan and different agencies propose and use different standards (Table 4.3).

The World Wildlife Fund (WWF)-Pakistan has also proposed a further set of criteria for irrigation water quality based on the soil type (Table 4.4).

In India, water quality is further classified into different sub-classes (Table 4.5).

WAPDA irrigation water quality standards were followed in this report.

It has now been established that calcium and magnesium do not behave equally in soil systems and magnesium causes deterioration of the soil structure particularly when the water is sodium dominated and highly saline. High levels of Mg^{2+} usually promote a higher development of exchangeable Na^{+} in irrigated soil. Table 4.6 shows the standards of water quality based on the Ca^{2+} and Mg^{2+} analysis.

Similarly, there are no unified standards available for drinking water quality. National

Table 4.3. Irrigation water quality standards proposed and followed by various agencies

Quality	EC (dS/m)	SAR	RSC (meq/L)
Water and Power Development Authority (WAPDA)			
Fit	< 1.5	< 10	< 2.5
Marginally fit	1.5-2.7	10-18	2.5-5.0
Unfit	> 2.7	> 18	> 5.0
Punjab Agricultural Department (followed by SAWCRI)			
Fit	< 1.15	< 6	< 1.25
Marginally fit	1.15-1.45	6-10	1.25-2.25
Unfit	> 1.45	> 10	> 2.25
United State Salinity Laboratory Staff, USA (USDA, 1954)			
Fit		< 10	< 1.25
Marginally fit		10-18	1.25-2.5
Unfit		> 26	> 2.5

Table 4.4. Irrigation water quality standards proposed by WWF-Pakistan

Soil Type	EC (dS/m)	SAR	RSC (meq/L)
Coarse texture	3	10	2.5
Medium texture	2.3	8	2.3
Fine texture	1.5	8	1.25

Source: WWF, 2007

Table 4.5. Groundwater quality standards for irrigation in India

Water quality class		EC (dS/m)	SAR	RSC (meq/L)
Main	Sub-class			
Good		< 2	< 10	< 2.5
Saline	Marginally saline	2-4	< 10	< 2.5
	Saline	> 4	< 10	< 2.5
	High-SAR saline	> 4	> 10	< 2.5
Alkaline	Marginally alkaline	< 4	< 10	2.5-4.0
	Alkaline	< 4	< 10	> 4.0
	Highly alkaline	Variable	> 10	> 4.0

Source: Gupta et al., 1994.

Environment Quality Standards (NEQS) and World Health Organization (WHO) guidelines are mostly used to define drinking water quality. Table 4.7 shows the drinking water quality standards.

The Pakistan Standard Quality Control Authority (PSQA) has also proposed drinking water quality standards which are more complicated (Table 4.8).

4.4 Results and discussion

4.4.1 Surface water quality

In the beginning, a survey of 35 water sources was conducted to monitor the surface water quality (Annex I). Based on this monitoring, 16 points (contributing streams) to the Dhrabi reservoir were selected for regular monitoring of the surface water quality (Annexures 2-4).

Table 4.6. Irrigation water quality standards based on Ca^{2+} and Mg^{2+} analysis

Class	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Mg^{2+}/Ca^{2+}ratio
Safe	< 75	< 30	< 1.5
Moderate	75-200	30-150	1.5-3.0
Unsafe	> 200	> 150	> 3.0

Source: Tandon, 1993

Table 4.7. Drinking water quality standards (WHO, 1996)

Parameters	Units	Permissible limits	Parameters	Units	Permissible limits
pH		6.5-8.5	K^+	mg/L	12
EC	µS/cm	NGVS†	Na^+	mg/L	200
Turbidity	NTU	5	Ca^{2+}	mg/L	75
Color	TCU	15	Cu	µg/L	2,000
TDS	mg/L	1000	Cd	µg/L	3
Alkalinity	mmol	NGVS	Cr	µg/L	50
Coliforms	cfu/mL	0	As	µg/L	10
Hardness	mg/L	500	Pb	µg/L	10
SO_4	mg/L	250.0	Fe	µg/L	300
CO_3	mg/L	NGVS	Mn	µg/L	100
HCO	mg/L	NGVS	Ni	µg/L	20
Cl	mg/L	250	Zn	µg/L	3,000
Mg	mg/L	150	Hg	µg/L	1

† NGVS: No guidelines values set

Table 4.8. PSQA water quality standards

Parameters	Units	MAC†	MAC‡	Parameters	Units	MAC†	MAC‡
pH		7.0-8.5	≥6.5≤9.2	SO4	mg/L	200	400
Turbidity	NTU	5	25	NO3	mg/L		10
Color	TCU	5	50	Cl	mg/L	200	600
TDS	mg/L	1000	1500	Mg	mg/L	50	150
Coliforms	cfu/mL	0		As	μg/L	0.01	
Hardness ($CaCO_3$)	mg/L	20	500	Mn	μg/L		0.5

† Maximum acceptable concentration, ‡ Maximum allowable concentration

The water quality at some important locations is presented in Figures 4.2, 4.3, and 4.4. There was high spatial and temporal variation in the surface water quality. Figure 4.2 shows the high temporal variability of the EC at points 1 and 10. The EC was very high at point 10 (downstream of Kallar Kahar city) and was about four times higher than at the threshold. However, after entering the Dhrabi reservoir (Point 16), the quality of the water improved, most probably the result of the salts being leached out during their transit to and their dilution in the reservoir.

The SAR was also higher at Point 10 as compared to other locations and was more than 1.5 times higher than the permissible limits during November 2007, August 2008, and August 2009 (Figure 4.3). However, in the reservoir, the SAR remained below the threshold. The RSC at point 10 was the highest during November 2007 and June 2008 (> 20 meq/L) and fluctuated during the rest of the period (Figure 4.4). In the reservoir, most of the time, the RSC was either higher than or remained close to the threshold limit.

The water quality in the streams depends on the rainfall and the flow (perennial or non-perennial) at the time of sampling. From an irrigation point of view, the SAR and the RSC, along with the EC, are very important parameters to be considered. The management of high salinity is relatively easy because the salts can be leached out using mechanical methods. However, the management of sodic water (water with high SAR and RSC) is rather difficult to deal with. The continuous use of such water may cause deterioration of the soil structure and reduce the crop yield. Therefore, under such conditions, care should be taken to manage the root-zone salinity, maintaining it below the salt tolerance level of the crop. If low quality irrigation water has to be used, there is sufficient information available in the literature on the importance of changes in the land configuration, exchange phenomenon and salt leaching, the use of gypsum and the water requirement for its dissolution, irrigation scheduling, salinity/sodicity tolerance of the crop cultivars at various phonological stages, and the agro-techniques to be used, etc. However, physical, chemical, and biological methods alone may not be sufficient for the safe use of low quality water. A combination of methods and proper cultural practices could, nevertheless, help when using low quality water without incurring the risk of a salinity build-up in the root zone (Gupta and Abrol, 1990; Pratharpar, and Qureshi, 1999; Azhar *et al.,* 2001).

Table 4.8 shows the overall quality of the surface water samples over time. If we look at the number of marginally fit and unfit

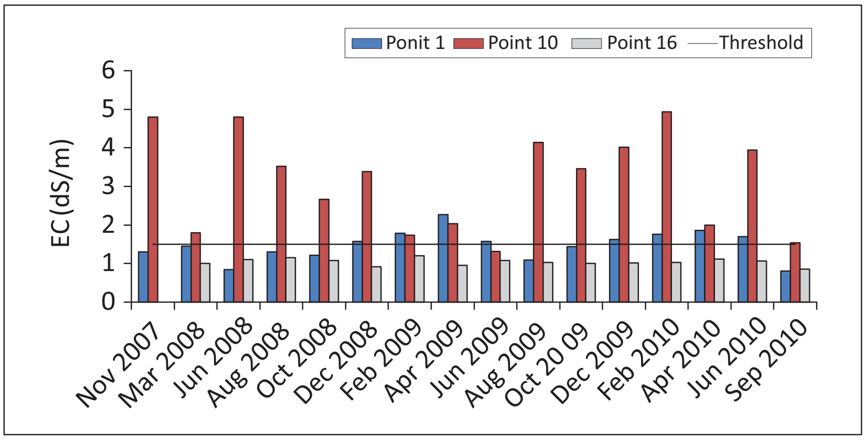

Figure 4.2. EC of the surface water at certain critical locations

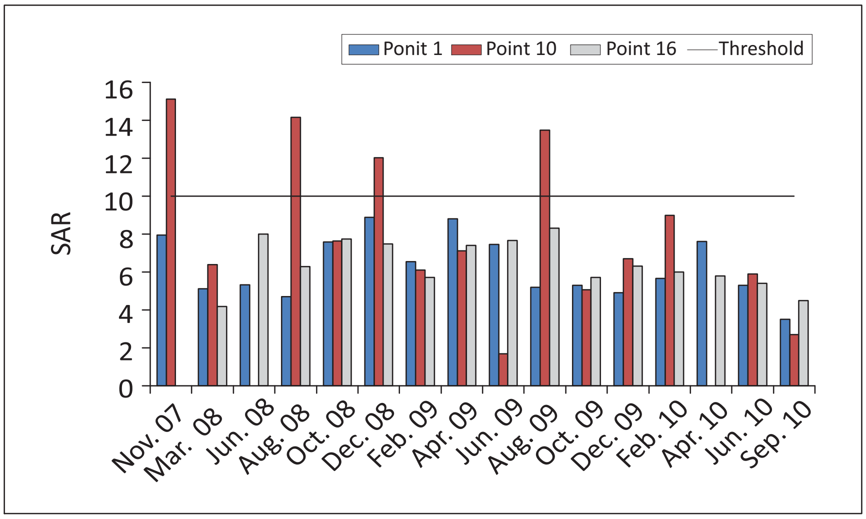

Figure 4.3. SAR of the surface water at certain critical locations

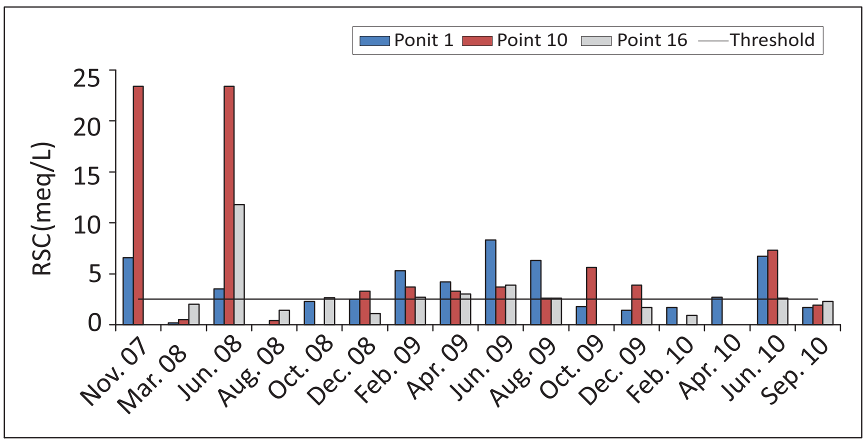

Figure 4.4. RSC of surface water at certain critical locations

samples, it is clear that most of the samples were unfit because of a high RSC value. As discussed earlier, the long-term use of water with a high RSC value may pose serious problems for the soil. The following strategies may be useful in handling this issue:

- Reduce the entry of high RSC water into the reservoir. Since Kallar Kahar Lake and its catchment are the main contributors of EC and RSC water, no water should be allowed to spill from the lake. This may be done by raising the dikes of the Kallar Kahar Lake and storing as much as water from the catchment as possible.
- Use chemical amendments, such as gypsum, in the field to reduce the negative effects of the sodic water
- Adopt an appropriate cropping pattern. Ashraf and Saeed (2006) found that Dhaincha (*Sesbania aculeate*) was a good short duration crop to incorporate into the cropping pattern, particularly where low quality sodic water was used for irrigation. Although dhaincha is not a salt tolerant crop it is used as a fodder and green manure for reclaiming land and adding organic matter to the soil. The addition of organic matter to a saline environment reduces ammonia volatilization losses, improves nitrogen use efficiency, and supports nutrient retention against leaching losses (Gupta and Abrol, 1990).

Table 4.9 shows that most of the samples exceeded the permissible limits for Ca^{2+} and Mg^{2+} . However, all the samples were within the permissible limit with respect to the Mg^{2+}/Ca^{2+} ratio. Mg^{2+}, when present in excess levels in the cation exchange complex, in combination with Na^{+} or alone, may result in soil degradation through its effects on the physical properties of the soil (Qadir and Schubert, 2002; Zhang and Norton, 2002). A high level of Mg^{2+} in the soil tends to increase surface sealing and erosion during rainfall events (Dontsova and Norton, 2002). It has also been shown that Mg^{2+} enhances the effect of Na^{+} on clay particle dispersion, thereby lowering the infiltration rate and hydraulic conductivity and increasing compaction in the top soil, ultimately affecting crop growth and yield. The process is insidious and takes years for its effects to be manifest in a structural decline (Karimov *et al.,* 2009; Vyshpolsky *et al.,* 2010).

The productivity of Mg^{2+}-affected soils can be enhanced by increasing the Ca^{2+} cation exchange sites to mitigate the effects of excessive exchangeable Mg^{2+} (Vyshpolsky *et al.,* 2008). This can be accomplished by applying a sufficient amount of Ca^{2+} to the soil (Qadir and Oster, 2004). Phosphogypsum, the main by-product of phosphate fertilizer from phosphate rock, is a source of Ca^{2+} as it is mainly composed of gypsum ($CaSO_4.2H_2O$).

Rashid *et al.* (2008) reported that the application of gypsum at 2.5 t/ha before the monsoon in a rainfed environment resulted in an increased moisture content in the soil profile at the time of sowing which helped increase wheat yields up to 46%. The application of gypsum increases the Ca^{2+} cation exchange in the soil and reduces the effect of Mg^{2+} . It helps to increase the infiltration rate of the soil and hence helps in moisture conservation.

The variability of water quality with time (based on the WAPDA standards) is shown in Table 4.10. Of the approximately 480 surface water samples, 161 were completely unfit with respect to their EC reading, 25 for the SAR value, and 43 for the RSC value.

The surface water quality of the other main water bodies (Figure 4.5) was also determined (Table 4.11). The water quality of most of the mini-dams/ponds was found to be fit for irrigation except for the Ahmad Faran mini-

Table 4.9. Mg^{2+}, Ca^{2+} and Mg^{2+}/Ca^{2+} ratio of the surface water samples (mg/L)

Location	July 2010			August 2010			September 2010			October 2010		
	Mg^{2+}	Ca^{2+}	Mg^{2+}/Ca^{2+}	Mg^{2+}	Ca^{2+}	Mg^{2+}/Ca^{2+}	Mg^{2+}	Ca^{2+}	Mg^{2+}/Ca^{2+}	Mg^{2+}	Ca^{2+}	Mg^{2+}/Ca^{2+}
1	40.8	19.2	2.1	48.0	56	0.9	8.4	56	0.2	28.8	64	0.5
2	96	98.4	1.0	54.0	104	0.5	40.8	100	0.4	36.0	120	0.3
3	136.8	74.4	1.8	36.0	126	0.3	51.6	108	0.5	46.8	112	0.4
4	103.2	110.4	0.9	32.4	106	0.3	37.2	110	0.3	33.6	110	0.3
6†	136.8	103.2	1.3	28.8	90	0.3	21.6	110	0.2	39.6	90	0.4
7	76.8	60	1.3	39.6	76	0.5	30.0	90	0.3	39.6	78	0.5
8	60	48	1.3	26.4	100	0.3	42.0	80	0.5	37.2	78	0.5
9	‡	‡	‡	15.6	110	0.1	84.0	210	0.4	198.0	410	0.5
10	120	72	1.7	42.0	100	0.4	46.8	112	0.4	51.6	120	0.4
11	81.6	112.8	0.7	44.4	116	0.4	40.8	82	0.5	50.4	116	0.4
12	96	108	0.9	38.4	110	0.3	42.0	110	0.4	60.0	120	0.5
13	60	19.2	3.1	31.2	80	0.4	21.6	56	0.4	30.0	60	0.5
14	60	2.4	25.0	30.0	80	0.4	24.0	60	0.4	28.8	56	0.5
15	52.8	21.6	2.4	34.8	86	0.4	24.0	50	0.5	34.8	70	0.5
16	60	4.8	12.5	6.0	40	0.2	14.4	36	0.4	14.4	44	0.3

† Source No 5 was completely choked, ‡ No flow of water

dam where the water was saline sodic and unfit for irrigation.

4.4.2 Groundwater Quality

Actually the water table is very deep in the area and groundwater has developed (mostly perched) in the vicinity of the recharging sources. The groundwater is used for both drinking and irrigation purposes and was monitored at 10 different locations in the watershed (Annexures 5-7). The water quality for irrigation is shown in Figures 4.6, 4.7, and 4.8. The behavior of the groundwater quality is almost similar to that of surface water. It shows high spatial and temporal variability. Figure 4.6 shows that at points 1, 3, 5, 7, and 8 the EC was within the acceptable limit, at point 6 it was slightly higher, while it was about 1.5 times higher than the threshold at points 2, 4, 9, and 10. Therefore, four out of 10 samples exceeded the permissible EC limit. Similarly, three out of 10 exceeded the permissible limits for SAR and six out of 10 for RSC at certain locations, reflecting the sodicity in the groundwater. As discussed before, the use of such water may cause deterioration of the soil structure and, ultimately, affect crop yields.

Table 4.12 shows that most of the groundwater samples exceeded the permissible limit for Mg^{2+} during the month of September 2010 while the Ca^{2+} and the Mg^{2+}/Ca^{2+} ratio were within the permissible limits for the monitored period.

Drinking water quality is judged from aesthetic, chemical, and microbiological points of view. The chemical quality of the monitored groundwater sources was within the permissible limits except at two

Table 4.10. Variability of water quality with time (based on WAPDA standards)

Month	EC (dS/m)			SAR			RSC (meq/L)		
	Fit	Marginal	Unfit	Fit	Marginal	Unfit	Fit	Marginal	Unfit
Nov 07	26	10	1	29	8	0	21	10	6
Feb 08	13	1	1	15	0	0	10	4	1
Mar 08	11	5	0	15	1	0	2	13	1
Jun 08	0	1	15	4	0	12	6	5	5
Aug 08	0	0	16	13	3	0	15	1	0
Oct 08	8	7	1	15	1	0	4	12	0
Dec 08	0	0	14	11	3	0	10	4	0
Feb 09	0	0	16	15	1	0	5	9	2
Mar 09	0	0	16	14	2	0	4	11	1
Apr 09	0	0	16	15	1	0	6	10	0
May 09	0	0	16	15	1	0	8	6	2
Jun 09	0	0	13	10	3	0	6	5	2
Jul 09	5	6	4	11	3	1	6	8	1
Aug 09	8	1	4	10	3	0	5	6	2
Sep 2009	11	3	1	14	0	1	4	0	11
Oct 09	7	2	4	12	0	1	11	1	1
Nov 09	5	4	4	12	0	1	13	0	0
Dec 09	7	6	2	14	0	1	14	0	1
Jan 10	6	6	0	12	0	0	12	0	0
Feb 10	14	0	0	14	0	0	14	0	0
Mar 10	7	7	1	14	0	1	13	0	2
Apr 10	4	4	3	10	0	1	10	1	0
May 10	4	4	4	11	0	1	9	1	2
Jun 10	5	2	4	11	0	0	8	1	2
Jul 10	7	7	0	14	0	0	6	8	0
Aug 10	9	5	1	14	0	1	11	4	0
Sep 10	11	3	1	14	0	1	11	4	0
Oct 10	4	10	1	14	0	1	11	3	1
Nov 10	9	4	2	14	0	1	12	3	0
Dec 10	10	4	1	14	0	1	13	2	0
Total	191	102	162	400	30	25	280	132	43

Table 4.11. Surface water quality of the water bodies located in the watershed

Stage no	Farmer or location	Type of water body	EC (dS/m)	SAR	RSC (meq/L)	Remarks
1	Malik Nasir Majeed	Mini-dam	0.68	4.8	0.4	Fit
2	Sher Muhammad Khan	Pond	0.98	1.01	0.0	Fit
3	Pel Upper	Mini-dam	1.00	2.31	1.1	Fit
4	Ahmed Farhan	Mini-dam	1.97	13.7	13.7	Unfit
5	Nikka dam	Small dam	0.61	3.07	0.8	Fit
6	Mumtaz H. Shah	Mini-dam	0.32	1.08	0.0	Fit
7	Naeem-ul-Hassan Shah	Mini-dam	0.37	0.57	0.2	Fit
8	Istaqlal	Mini-dam	0.67	3.00	0.9	Fit
9	Malik Sikander Khan	Mini-dam	1.03	1.33	0.0	Fit
10	Kallar Kahar	Mini-dam	0.71	4.02	0.7	Fit

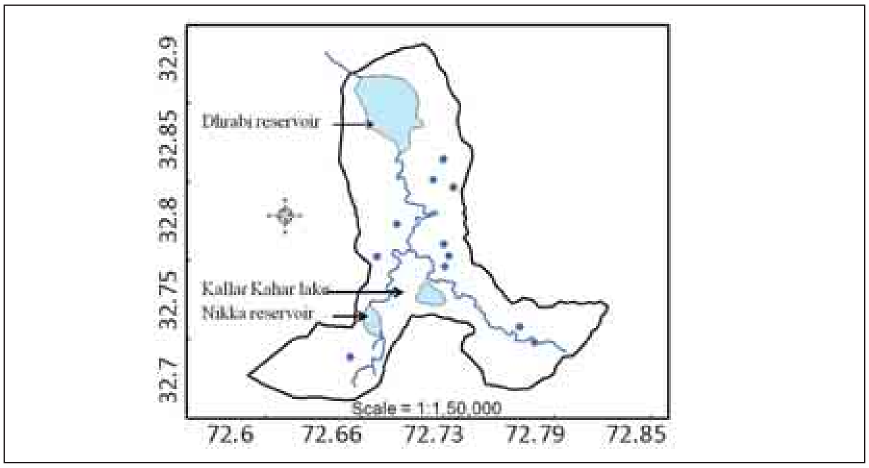

Figure 4.5. Map showing the locations of the water bodies

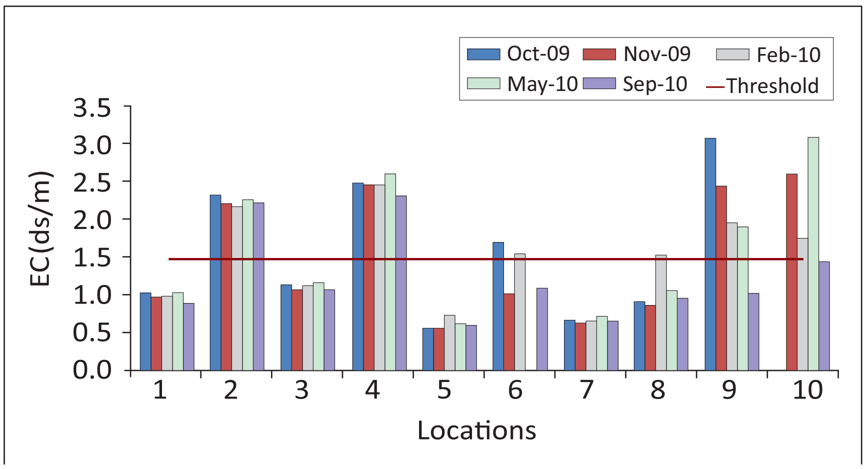

Figure 4.6. EC of the groundwater

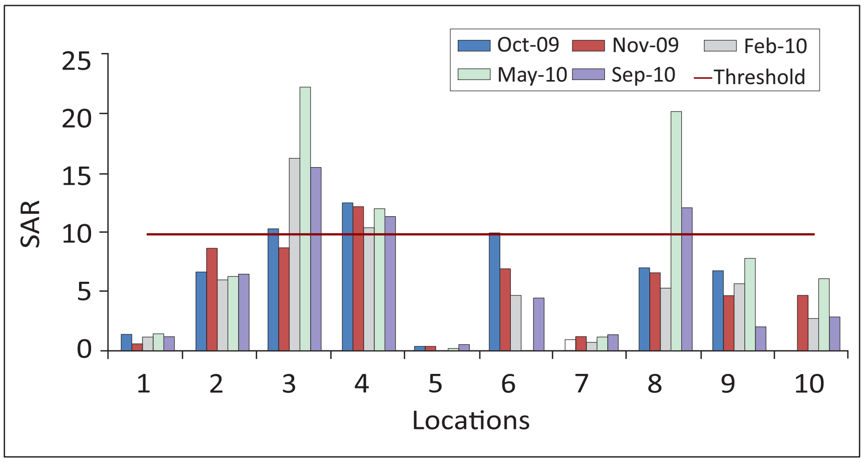

Figure 4.7. SAR of the groundwater

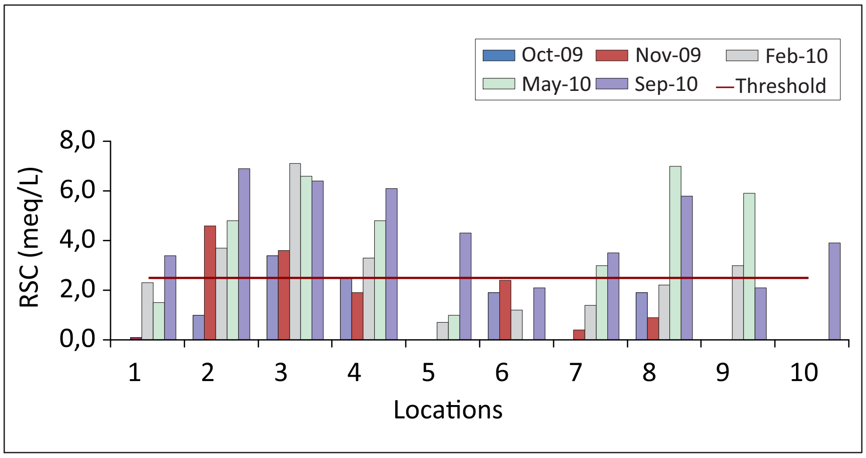

Figure 4.8. RSC of the groundwater

locations (Table 4.13) where the Cl limit was exceeded. Chloride toxicity has not been observed in humans except in the special case of impaired sodium chloride metabolism, e.g. in congestive heart failure. Healthy individuals can tolerate the intake of large quantities of chloride provided that there is a concomitant intake of fresh water. Little is known about the effect of a prolonged intake of large amounts of chloride in the diet. As in experimental animals, hypertension associated with sodium chloride intake appears to be related to the sodium rather than the chloride ion (WHO, 1996).

Microbiologically, two of the eight points sampled during August 2009, one out of eight samples during February 2010, and one out of 10 samples during June 2010 were found fit (Table 4.14). Microbiological contamination is one of the major forms of contamination found in drinking water of Pakistan. A study of PCRWR in Chakwal shows that all the drinking water sources sampled in the Dhrabi watershed were microbiologically contaminated (Table 4.15).

Table 4.12. Mg^{2+}, Ca^{2+}, and Mg^{2+}/Ca^{2+} ratio of the groundwater samples

Location	Mg^{2+} (mg/L)					Ca^{2+} (mg/L)					Mg^{2+}/Ca^{2+}				
	Jul 2010	Aug 2010	Sep 2010	Oct 2010	Nov 2010	Jul 2010	Aug 2010	Sep 2010	Oct 2010	Nov 2010	Jul 2010	Aug 2010	Sep 2010	Oct 2010	Nov 2010
1	25	20	36	38	32	90	76	70	90	80	0.3	0.3	0.5	0.4	0.4
2	6	20	41	48	47	40	60	104	116	110	0.2	0.3	0.4	0.4	0.4
3	2	2	2	8	5	6	10	12	36	28	0.4	0.2	0.2	0.2	0.2
4	5	22	22	24	30	44	64	64	74	76	0.1	0.3	0.3	0.3	0.4
5	19	11	24	20	29	56	76	60	70	60	0.3	0.1	0.4	0.3	0.5
6	11	14	16	30	42	52	48	60	60	80	0.2	0.3	0.3	0.5	0.5
7	24	10	18	20	24	50	70	56	66	60	0.5	0.1	0.3	0.3	0.4
8	26	6	2	6	20	40	20	16	30	64	0.7	0.3	0.2	0.2	0.3
9	12	32	34	42	48	70	60	74	130	160	0.2	0.5	0.5	0.3	0.3
10	40	53	48	37	68	100	112	92	140	120	0.4	0.5	0.5	0.3	0.6

Table 4.13. Groundwater quality (mg/l) of drinking water sources (November 04, 2009)

Site	Cl	Mg	SO_4	NO_3	NO_2	As (ppb)	Mn
Permissible limit WHO, 2004	**250**	**150**	**250**	**10**	**3**	**10**	**0.1**
Chak Khushi hand pump	35	58	50	5	0.052	4.67	BDL
Ghulam Haider hand pump	174	75	165	51	BDL	0.57	BDL
Ratta hand pump	95	6	48	0.2	BDL	4.9	BDL
Dhoke Mori dug well	418	50	124	17	0.259	0.71	BDL
Dhoke Zawar dug well	5	40	28	2	0.055	0.65	BDL
Dhoke Choie stream	122	29	60	1	0.066	7.08	BDL
Sadat turbine	17	29	10	5	0.052	0.86	BDL
Shahid Abbasi Ratta	71	9	41	0.3	0.038	8.94	BDL
Downstream from KK town	456	46	229	2	BDL	2.82	BDL
Upstream from KK	19	4	224	10	0.029	3.23	BDL

BDL: Below detection limit

Microbiological contamination of drinking water is responsible, directly or indirectly, for spreading major infections and parasitic diseases, such as cholera, typhoid, dysentery, hepatitis, giardiasis, cryptosporidiosis, and guinea-worm infections. The United Nations Commission for Environmental Development (UNCED) estimates that about 80% of all diseases are water-borne, and that 33% of the total deaths in developing countries result from drinking polluted water and 10% of each person's productive time is wasted as a consequence of water-related diseases. The chemical quality of the Dhrabi reservoir drinking was relatively good (Table 4.16).

Table 4.14. Microbiological quality of the drinking water sources

Site	August 28, 2009		February 22, 2010		June 22, 2010	
	Total coliform	Fecal coliform	Total coliform	Fecal coliform	Total coliforms	Fecal coliform
Permissible limit (cfu/mL)†	**0**	**0**	**0**	**0**	**0**	**0**
Chak Khushi hand pump	350	280	3.6	3.6	20	4
Ghulam Haider hand pump	4	4	1.1	1.1	0	0
Ratta Hand pump	280	220			1,100	1,100
Dhoke Mori dug well	220	130	2.2	2.2	1,100	1,100
Dhoke Zawar dug well	1,600	350	> 23	> 23	1,100	1,100
Dhoke Choi/Mori stream	1,70	170	2.2	2.2	1,100	1,100
Sadat turbine	0	0	12	12	93	43
Shahid Abbasi Ratta	0	0	23	23	1,100	11
Dhrabi reservoir	na	Na	12	12	1,100	23

na – not available or data could not be collected
† WHO, 1996

Table 4.15. Quality of drinking water sources in the watershed

Location	U/C †	Color	Odor	pH	EC (dS/m)	Turbidity (NTU)	Bacteriological contamination	Status
Rehna Sadat	6	Colorless	Odorless	7.57	0.69	0	+ ve	Unfit
Bhoun	8	Colorless	Odorless	7.61	1.22	2.2	+ ve	Unfit
Hastal	7	Muddy	Odorless	7.47	1.10	23	+ ve	Unfit
Thoa Bahadar	7	Colorless	Odorless	7.69	2.46	0	+ ve	Unfit
Uderwal	9	Colorless	Odorless	8.09	1.23	0	+ ve	Unfit
Bekhri	11	Muddy	Odorless	7.86	0.34	12.6	+ ve	Unfit
Chak Bhown	12	Colorless	Odorless	8.04	1.11	0.1	+ ve	Unfit
Balkasar	20	Colorless	Odorless	7.79	0.91	2.3	+ ve	Unfit
Bikhari Kalan	20	Colorless	Odorless	7.6	0.84	4.5	+ ve	Unfit
Warwal	22	Colorless	Odorless	8.27	3.31	1.7	+ ve	Unfit
Kallar Kahar	6	Colorless	Odorless	8.24	1.32	0	+ ve	Unfit
Kot Chohdrian	25	Colorless	Odorless	8.27	1.44	0	+ ve	Unfit

Source: PCRWR, 2008 ; † Union Council

Table 4.16. Chemical water quality of the Dhrabi reservoir for drinking purpose

Parameter	Unit	Water quality	Permissible limit†
pH		7.2	6-10
Conductivity	dS/m	1.1	ND‡
Turbidity	NTU	3	5
Total alkalinity	(mg/L)	280	ND‡
Total hardness	(mg/L)	228	ND‡
Total solids	(mg/L)	534	ND‡
Total suspended solids	(mg/L)	4	150
Chloride	(mg/L)	130	250
Fluoride	(mg/L)	0.75	20
Calcium hardness	(mg/L)	132	250
TOC	(mg/L)	11.2	ND‡
Total nitrogen	(mg/L)	1.5	15

† WHO Guidelines, ‡ ND: Not defined

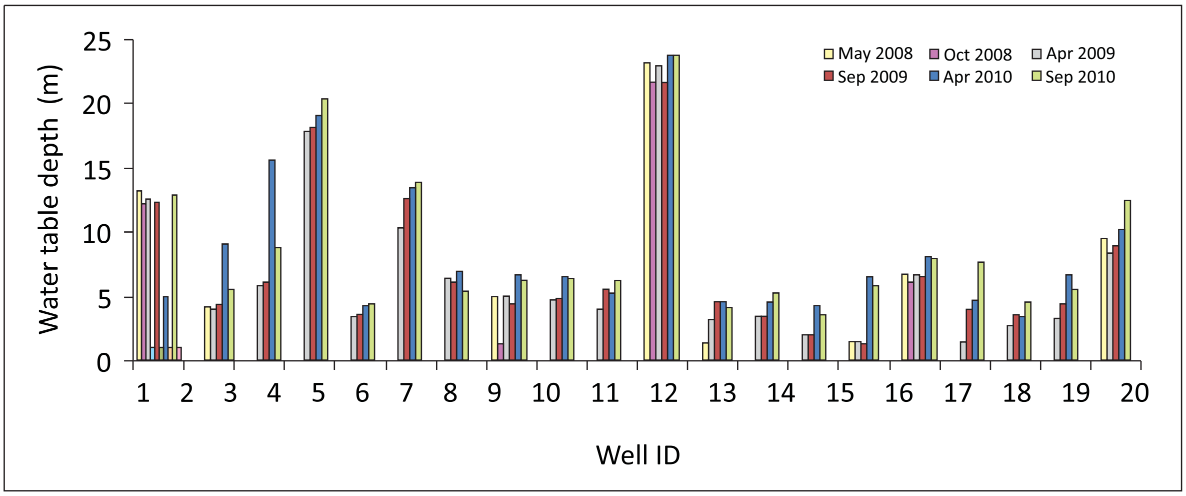

Figure 4.9. Water-table depth in the watershed (Refer to Figure 4.1 for well ID)

4.4.3 Water-table depth

The water-table depth may have significant influence on groundwater quality depending upon the extent and locations of the recharging sources. Figure 4.9 shows the water-table depth with respect to the soil surface. There was high spatial variation in water-table depth mostly a result of the topography and location near the recharging sources.

However, there is very small temporal variation, most probably because of the small extraction of groundwater in the area.

4.4.4 Wastewater situation

Wastewater is an important component of integrated watershed management. In the Dhrabi watershed, however, most of the villages do not generate much wastewater because water is relatively less available in their home – most farmers have to fetch water for their domestic uses. Only one village, Khandoa, had a wastewater pond outside the village. This pond also stores rainwater and is used for watering animals and small scale agriculture. Table 4.17 shows that the BOD and COD of the wastewater were within permissible limits except for the Khandoa wastewater pond. The high BOD and COD of the pond may be because the water has been stagnant for a longer period of time. The pond was renovated and bio-remedial material (water lattice and duckweed) was used to clean the water. Additionally, perforated pipe along with gravel material was used for the small portion of the pond perimeter where the animals drank. The quality of the pond water is given in Table 4.18.

4.4.5 Sources of salinity for the water

There could be two sources that are contributing to the salinity and sodicty in the surface and groundwater, perennial streams (since rainwater is always free from such impurities) and salts present in the soil profile that are detached and transported to the water bodies with the runoff. To identify the sources of salinity for the surface water, samples were collected from two perennial streams during low flow periods (November 2009). Table 4.19 shows that the water quality in the perennial streams was relatively good. Soil samples were also collected from the catchment areas of the major polluting streams and from the beds of Kallar Kahar Lake and Dhrabi reservoir. The soil samples from the catchments show relatively high salinity and sodicity that might arise from the high salinity and sodicity of the streams (Table 4.20). It is interesting to note that the

Loss of Kallar Kahar Lake capacity due to sedimentation and vegetation

Table 4.17. BOD and COD analysis of the wastewater (mg/L)

Location	September 3, 2009		February 22, 2010		June 22, 2010		September 27, 2010	
	BOD	COD	BOD	COD	BOD	COD	BOD	COD
Permissible limit (ppm)†	**80**	**150**	**80**	**150**	**80**	**150**	**80**	**150**
Downstream of Kallar Kahar	16	10	36	62	44	79	21	34
Upstream of Kallar Kahar	11.0	8.0	20	34	60	109	32	54
Khandoa wastewater pond	na	na	104	180	443	739	36	61
Dhok Choi	na	na	19	34	14	29	17	28
Dhrabi reservoir	na	na	18	31	20	33	54	88

† National Environment Quality Standards (NEQS)
na – not available or data could not be collected.

highest EC, SAR, and ESP in the bed samples from Kallar Kahar Lake were about 43 dS/m, 56, and 45, respectively. Similarly, the EC of the bed samples from the Dhrabi reservoir was 5.1 dS/m. The high EC, SAR, and ESP in the bed of Kallar Kahar Lake is caused by the saline water brought into the lake with the runoff. The evaporation from the lake results in an increased salinity of the water. The salts ultimately settle to the bed increasing the salinity and sodicity of the bed. The EC of the bed of the Dhrabi reservoir is also high (up to 5.1 dS/m). The Dhrabi reservoir became operational during 2007. Bearing in mind the

Table 4.18. Chemical water quality of the Khandoa wastewater pond

Month	EC (dS/m)	SAR	RSC (meq/L)
October 2009	1.06	2.05	0.8
February 2010	0.67	2.1	0.0
June 2010	1.73	2.2	3.4
July 2010	0.50	2.0	4.0
August 2010	0.50	0.6	1.5
September 2010	0.50	1.2	2.5
October 2010	0.60	0.7	1.4

Table 4.19. Water quality in the perennial stream

Location	EC (dS/m)	SAR	RSC (meq/L)
Inflow to Kallar Kahar Lake (point-1)	1.51	1.96	0
Inflow to Kallar Kahar Lake (point-2)	1.56	1.4	0
Drain surrounding the lake	1.64	1.75	0
Nikka dam	0.68	2.61	1.6

Table 4.20. Soils analysis of the watershed in relation to water quality

Site	Date of sampling	pH	ECe (dS/m)	SAR	ESP
Right side of the Dhrabi reservoir bed	4.11.09	7.9	2.4	1.0	0.2
Left side of the Dhrabi reservoir bed	4.11.09	7.8	5.1	3.9	4.3
Right side of KK lake bed	4.11.09	8.7	41.9	56.2	44.9
Left side of the KK lake bed	4.11.09	8.6	32.8	44.6	39.2
Catchment of water point No.1 †	15.11.09	9.7	2.4	12.6	14.7
Catchment of water point No.1 †	15.11.09	9.0	0.6	3.5	3.7
Catchment of KK lake (right)	23.11.09	8.0	2.7	3.6	3.8
Catchment of KK lake (middle)	23.11.09	8.4	0.3	0.2	0.0
Catchment of KK lake (left)	23.11.09	8.3	2.7	7.7	9.1

† Two different locations in the same catchment

Table 4.21. Soil salinity status in the watershed

Site	Land use	pH	ECe (dS/m)	SAR	ESP
Bharpur Road near surface water sampling point No. 1	Uncultivated	7.89	1.36	1.94	4.05
	Cultivated	8.01	0.47	1.53	3.48
Chak Khushi near surface water sampling point No. 7	Uncultivated	7.69	0.93	0.68	2.27
	Cultivated	7.83	0.55	0.69	2.28
Kallar Kahar near surface water sampling point No. 8	Uncultivated	8.56	2.23	9.64	13.70
	Cultivated	8.10	0.43	3.36	5.99
Ratta bridge near surface water sampling point No. 14	Uncultivated	7.90	1.22	3.55	6.25
	Cultivated	8.22	1.07	4.43	7.40

salinity and sodicity levels in the reservoir, it is expected that the salinity and sodicity of the bed of the Dhrabi reservoir will also increase with time.

The small dams, mini-dams, and ponds are the main sources of groundwater recharge in the area. However, with such a high sodicity in the bed of the Dhrabi reservoir, the recharge to the groundwater will be reduced substantially. It is necessary to conduct a systematic study of the effect of saline-sodic water on groundwater recharge.
To understand how the catchments were contributing to the salinity of the water, soil samples were collected to a depth of 15 cm from both uncultivated and cultivated fields. Table 4.21 shows that there is a substantial amount of salts present in the soil profile particularly in the catchment areas of Kallar Kahar Lake. Since the main source of water to Kallar Kahar Lake and the Dhrabi reservoir is the runoff water, these salts are being transported to the water bodies.

4.4.6 Review of policy documents

National water strategy and policies

Although Pakistan has the world's largest contiguous irrigation system it does not have any approved national water policy. A draft National Water Policy was prepared in 2002, but it has not been approved so far. There is a National Water Policy Vision and a Water Sector Strategy. The National Water Policy Vision is to have adequate water available through proper conservation and development, with water supplies of good quality which are equitably distributed. The Water Sector Strategy provides a roadmap for sector planning, development, and management up to 2025. The draft National Water Policy prioritizes water rights, commits to clean potable water to all by 2025, promotes public-private partnerships, and targets full financial sustainability in urban water supply.

National environmental policy

Environmental legislation was first introduced in 1977 and since then a number of policy initiatives governing regulatory frameworks and institutions have been introduced. Following the Pakistan Environmental Protection Act of 1997, the National Environment Action Plan was introduced in 2001 to safeguard public health and promote sustainable livelihoods. More recently, the National Environmental Policy 2005 includes a framework for sustainable development and addresses water management and conservation, pollution and waste management, agriculture and livestock, forestry and plantations, biodiversity and protected areas, and climate change issues. There is no separate policy for land management. However, it is covered in the National Environmental Policy where great emphasis is given to protecting and preserving prime agricultural land from conversion to other uses through land-use planning and zoning, preventing soil degradation and restoring and improving degraded lands, and developing strategies and programs to tackle desertification, etc.

National drinking water policy

The National Drinking Water Policy 2009 recognizes access to safe drinking water as a basic human right of every citizen, placing responsibility on the state to ensure its provision, and with drinking water taking precedence over all other water uses. It also provides guidelines for the protection and conservation of water resources, water treatment and safety, appropriate technologies and standardization, community participation and empowerment, public awareness and capacity building, etc. A Safe Drinking Water Act is proposed to be enacted to cover technical and supply standards and legislation approved to ensure compliance with the Pakistan Drinking Water Quality Standards.

National sanitation policy

The National Sanitation Policy 2006 provides a broad framework and policy guidelines to support sanitation coverage through the development of strategies, plans, and programs. The primary focus is on the safe disposal of excreta using sanitary latrines and includes creation of an open, defecation-free environment, together with the safe disposal of solid and liquid wastes. The Policy promotes community-led total sanitation (CLTS) in smaller communities and the component sharing model in larger ones.

National wetlands policy

The wetlands of Pakistan cover about 780,000 ha which constitute 9.7% of the total surface area of the country. More than 225 significant wetlands sites are on record, 19 of which have been internationally recognized by the Ramsar Convention Bureau as being of global importance. There is no separate national policy for the wetlands. However, it is covered under the National Environmental Policy. In this policy, along with other protective measures for wetlands, it has been proposed to develop and implement a comprehensive national wetlands policy.

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Chapter 5: Soil erosion assessment in Dhrabi watershed

A. Klik, W. Rattanaareekul, and T. Bushsbaum

5.1 Introduction

Erosion is the main threat to soil resources worldwide. Soil erosion implies loss or removal of surface soil material through the action of moving water, wind, or ice. Soil erosion by wind and water are major problems in Pakistan. The extent to which different areas of Pakistan are affected by water erosion is given in Table 5.1 and by wind erosion in Table 5.2. Of a total geographical area of 80 million hectare (Mha) in Pakistan, the area suitable for agriculture is about 29.6 Mha and about 50.4 Mha are uncultivated. About 13.05 Mha are affected by water erosion and about 6.17 Mha are affected by wind erosion. Soil erosion is taking place at an alarming rate and is mainly a consequence of deforestation in the north. Water erosion is prominent on steep slopes, such as the Pothwar track and surrounding areas, an area extensively used for cultivation. The highest recorded rate of erosion is estimated to be between 150 t/ha/year and 165 t/ha/year. The Indus River carries the 3rd largest load of sediment (4.49 t/ha) in the world in 1990. According to some estimates, annually the Indus is adding 132 billion m^3 of sediment to the Tarbela reservoir (Haq and Abbas, 2007). This corresponds to a daily rate of about 500,000 tonne, reducing the life of the dam by 22% and the capacity of the reservoir by 35%.

Information about soil erosion measurements and assessments in Pakistan effectively do not exist. Nasir *et al.* (2006) evaluated soil erosion for a small mountainous watershed by using RUSLE (Revised Universal Soil Loss Equation) (Renard *et al.,* 1995). Calculated soil loss ranged from 0.1 t/ha/year to 8 t/ha/year for flat soils. The average rate of soil loss from the entire 13 ha watershed was 19.1 t/ha/year. Steep slopes generated 74% of the total soil loss. Ahmad *et al.* (1990) reported that for slopes of between 1% and 10%, soil is being lost at a rate of between 17 t/ha/year and 41 t/ha/year under fallow conditions and at a rate of between 9 t/ha/year and 26 t/ha/year under vegetative cover in the Fateh Jang watershed.

Table 5.1. Area affected by water erosion (in 1000 ha)

Degree of erosion	Punjab	Sindh	NWFP/FATA	Balochistan	Northern Area	Pakistan
Slight (sheet and rill erosion)	61.2		156.3		110.5	328.0
Moderate (sheet and rill erosion)	896.8		853.8	1858.6	25.8	3,635.0
Severe (rill, gully and/or stream bank erosion)	588.1	58.9	1765.1	2724.4	504.2	5,640.7
Very severe (gully, pipe and pinnacle erosion)	357.9		1517.0		1571.6	3,446.5
Total	1,904.0	58.9	4,292.2	4,583.0	2,212.1	13,050.2

Source: Shah and Arshad, 2006.

Table 5.2. Area affected by wind erosion (in 1000 ha)

Degree of erosion	Punjab	Sindh	NWFP/FATA	Balochistan	Pakistan
Slight	2,251.4	295.0	13.1	36.0	2,595.5
Moderate	279.1	70.2	3.8	143.6	469.7
Severe to very severe	1,274.0	1,686.8	19.6	100.9	3,081.3
Total	3,804.5	2,052.0	36.5	280.5	6,173.5

Source: Shah and Arshad, 2006

The rainfed areas (*barani*) are located in the northern part of Punjab and cover an area of about 84,500 km². This is equivalent to about 40% of the total area of the Pakistan Punjab. It consists of hilly to semi-hilly watersheds at altitudes of between 300 m and 800 m above sea level. Hot summers and moderate winters prevail. The climate is mainly affected by two rainy periods – the rainy summer season (July-September) delivers from about 70% to 80% of the annual rainfall, and the winter rainy season (December-March), delivering about 20% to 25%. The average annual rainfall is highly spatially distributed and ranges from 400 mm in the southwest to more than 850 mm in the northeast (Figure 5.1) (ICARDA, 2009). Longer dry periods alternate with heavy rainstorms. Very often the rainfall intensities exceed the infiltration rates of the soils.

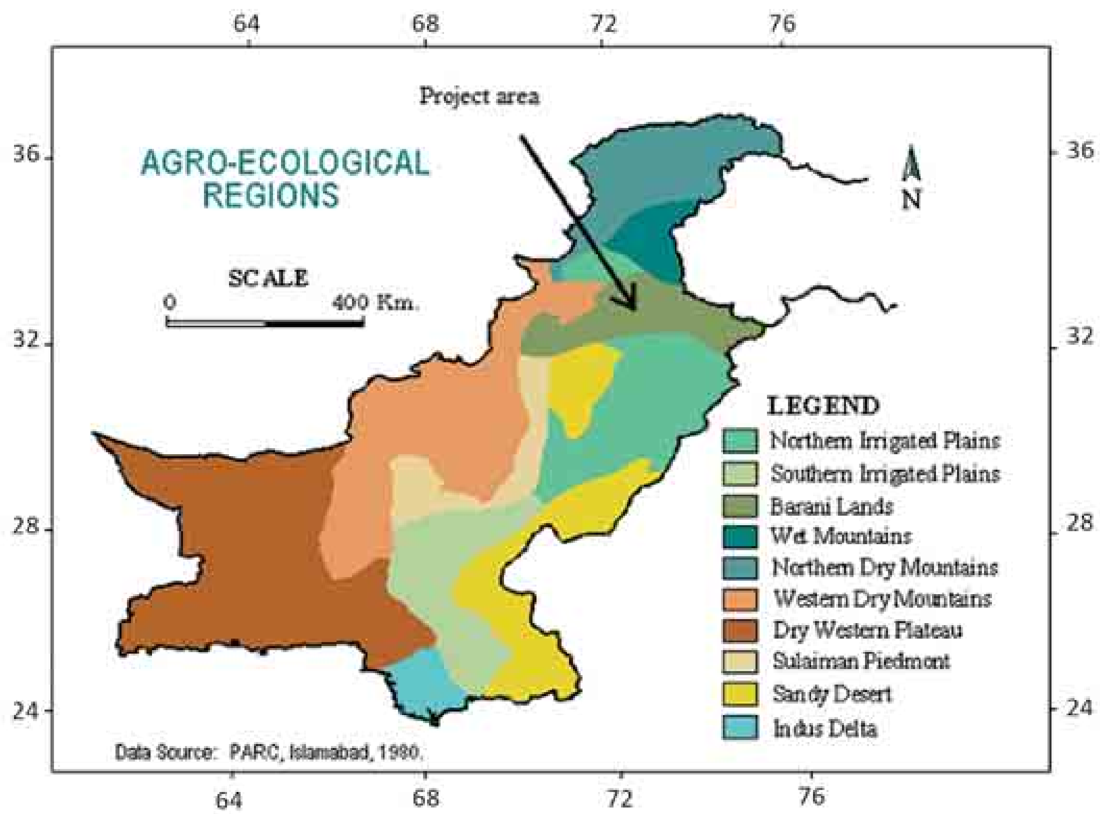


Figure 5.1. Location map of the Barani area in northern Punjab province of Pakistan

5.2 Main research objectives

This cooperative project was financed by the Austrian Development Agency (ADA) and coordinated by the International Center for Agricultural Research in the Dry Areas (ICARDA).
The main objectives of the project were:

- Assessment of runoff and soil erosion rates by water within the Dhrabi watershed under current land-use and soil-management systems
- Evaluation of the impact of different land-use and soil types on soil erosion
- Estimation of runoff and soil erosion rates with the application of interventions (soil conservation measures) in fields used for agriculture.

5.3 Materials and methods

5.3.1 Description of the investigated watershed

The Dhrabi watershed has a total drainage area of 196 km² and is located from latitudes 32° 42´ 36″ N to 32° 55´ 48″ N and from longitudes 72° 35´ 24″ E to 72° 48´ 36″ E in Chakwal district. It has a length of 25 km in the north-south direction and its width varies from 5.5 km to 21 km in an east-west direction (Figure 5.2). The watershed contains diversified agro-ecologies and production systems starting from the higher elevation areas in the south to the lower areas in the north. The altitude ranges from 466 m above sea level (asl) in the north to 800 m asl in the south. The watershed drains through a perennial stream – the Dhrab Kass – into the Dhrabi reservoir which is located in the northern end of the watershed.

The geomorphologic characteristics of the watershed affect the entire hydrological cycle which includes total runoff volume, peak runoff rate, runoff duration, and hydrological parameters that have a direct effect on the variation in soil erosion by water. The watershed consists of low to medium hills with elevations of 445 m to 898 m above sea level. The source of elevation information was evaluated using Digital Elevation Models (DEMs) obtained from ASTER satellite images in 2007. Low to medium relief hills dominate

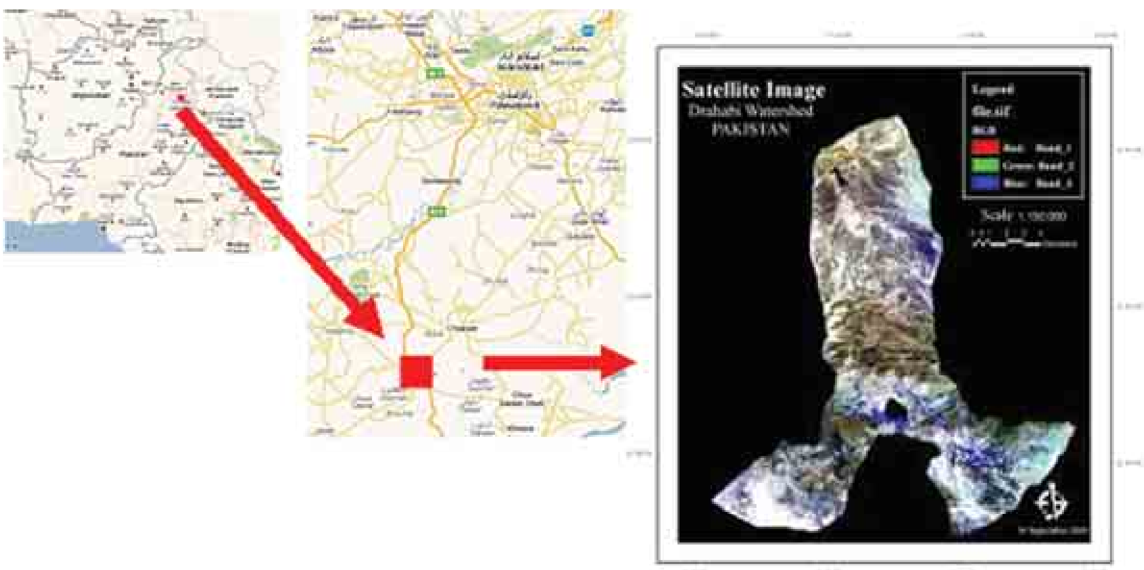


Figure 5.2. Location of Dhrabi watershed, Chakwal district, Pakistan

in the watershed. A dendric type drainage pattern is present in the catchment area. Slope steepness varies between 2% in the plain areas to more than 30% along hillsides (Figures 5.3, 5.4, and 5.5).

Pakistan is blessed with different topographic land, and is one of the world's most arid countries with an average annual rainfall between 465 mm and 595 mm per a year. The average minimum temperature varies from -0.5 °C in January to 16 °C in July and August. The maximum temperatures were 24 °C in January and 48 °C in June. The climate in Punjab , where Dhrabi watershed is located, is generally cold in winter and hot in summer. Summer runs from April to September with June and July the extremely hot months in which temperatures reach between 30 °C and 35 °C. Winter runs from October to March with December and January being extremely cold months in which the temperature falls to its minimum of between 0 °C and 5 °C. Most rain is received during the monsoon season (ICARDA, 2009).

Figure 5.6 shows the rainfall amounts for a climatic station in Islamabad. Data were obtained from a CLIGEN database and were generated from a 100-year simulation run. The average long-term annual rainfall is 989 mm (+/- 109 mm). In Figure 5.6 the monthly precipitation is displayed against monthly temperature in a climatic diagram. It can be seen that, despite the high rainfall amounts, dry periods occur in May and June as well as in November. The frequency distribution of different rainfall classes is displayed in Figure 5.7. Annual rainfall ranges from 600 mm to 1500 mm with a long-term average of 989 mm. In most years, the precipitation ranges between 800 mm and 1200 mm. Annual rainfall amounts exceeding 1200 mm do not occur often (Figure 5.7).

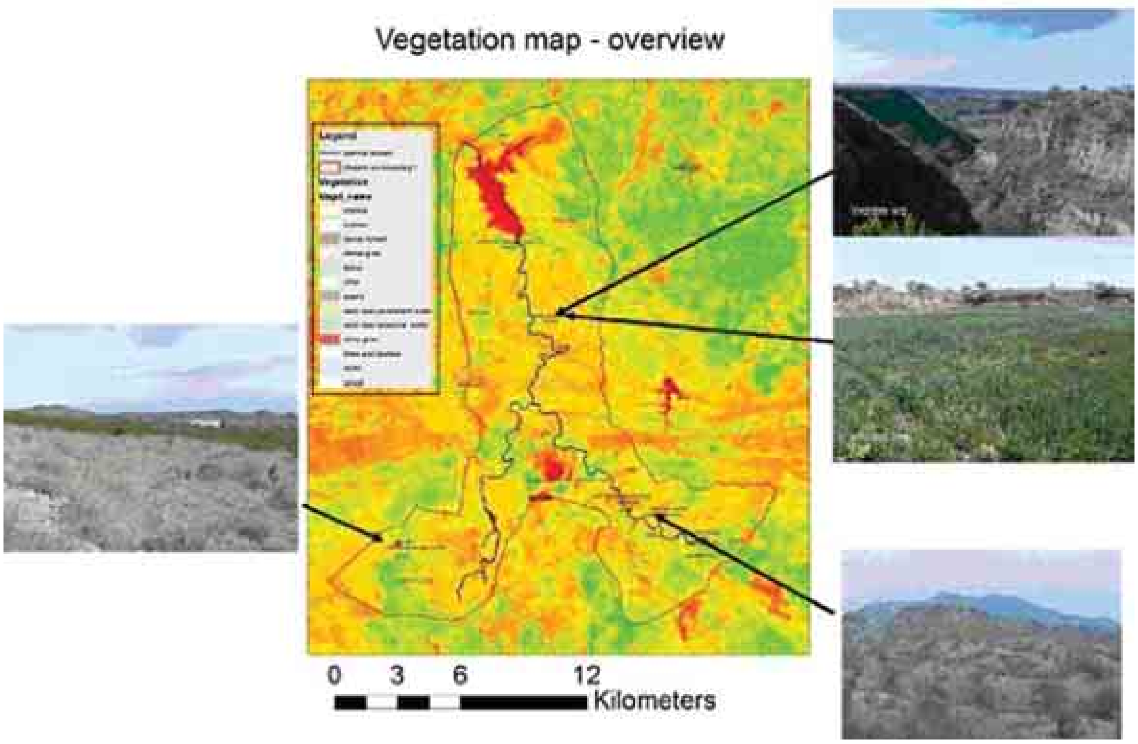


Figure 5.3. Landscape map with impressions from different areas

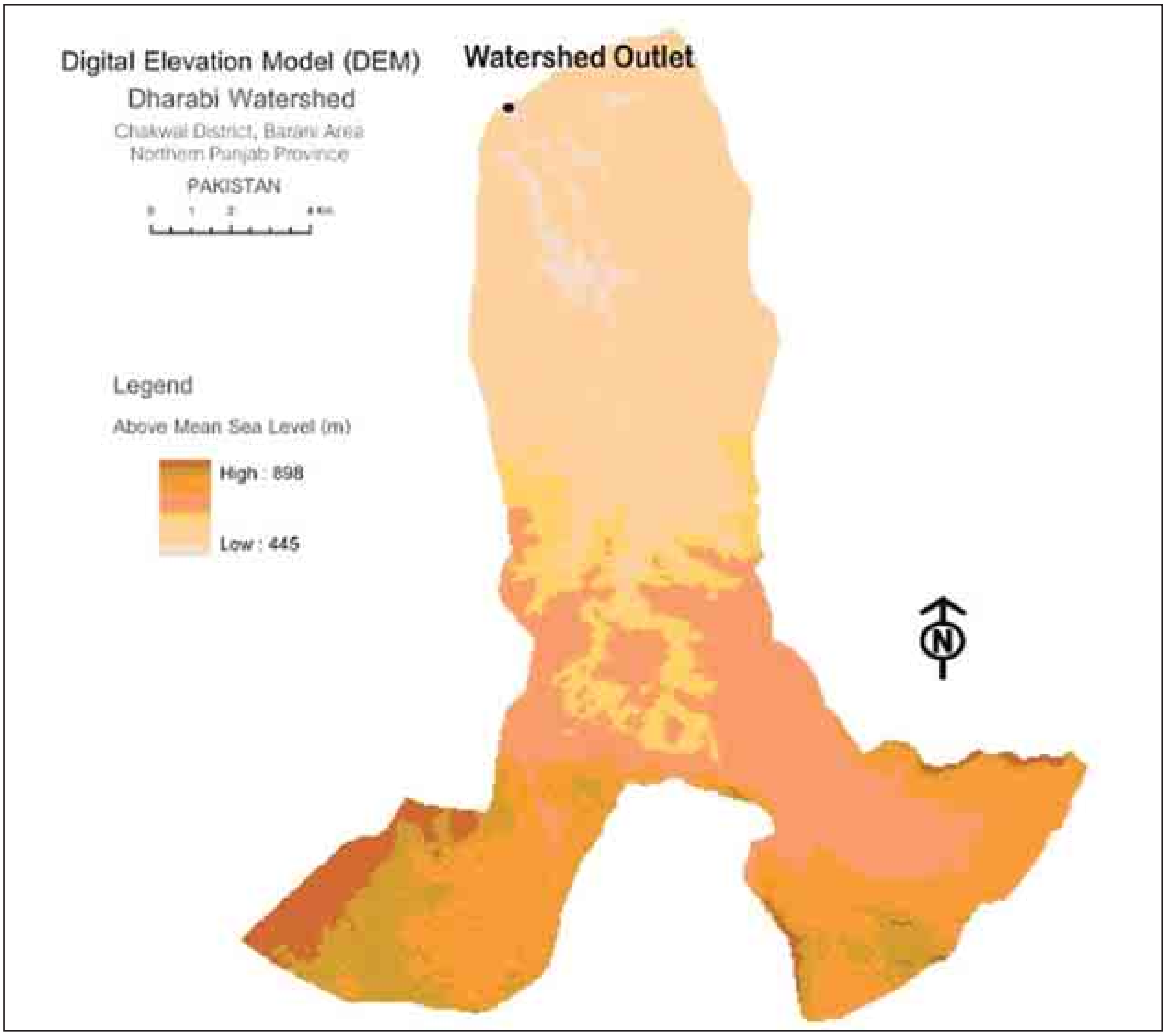


Figure 5.4. Digital elevation model of Dhrabi watershed

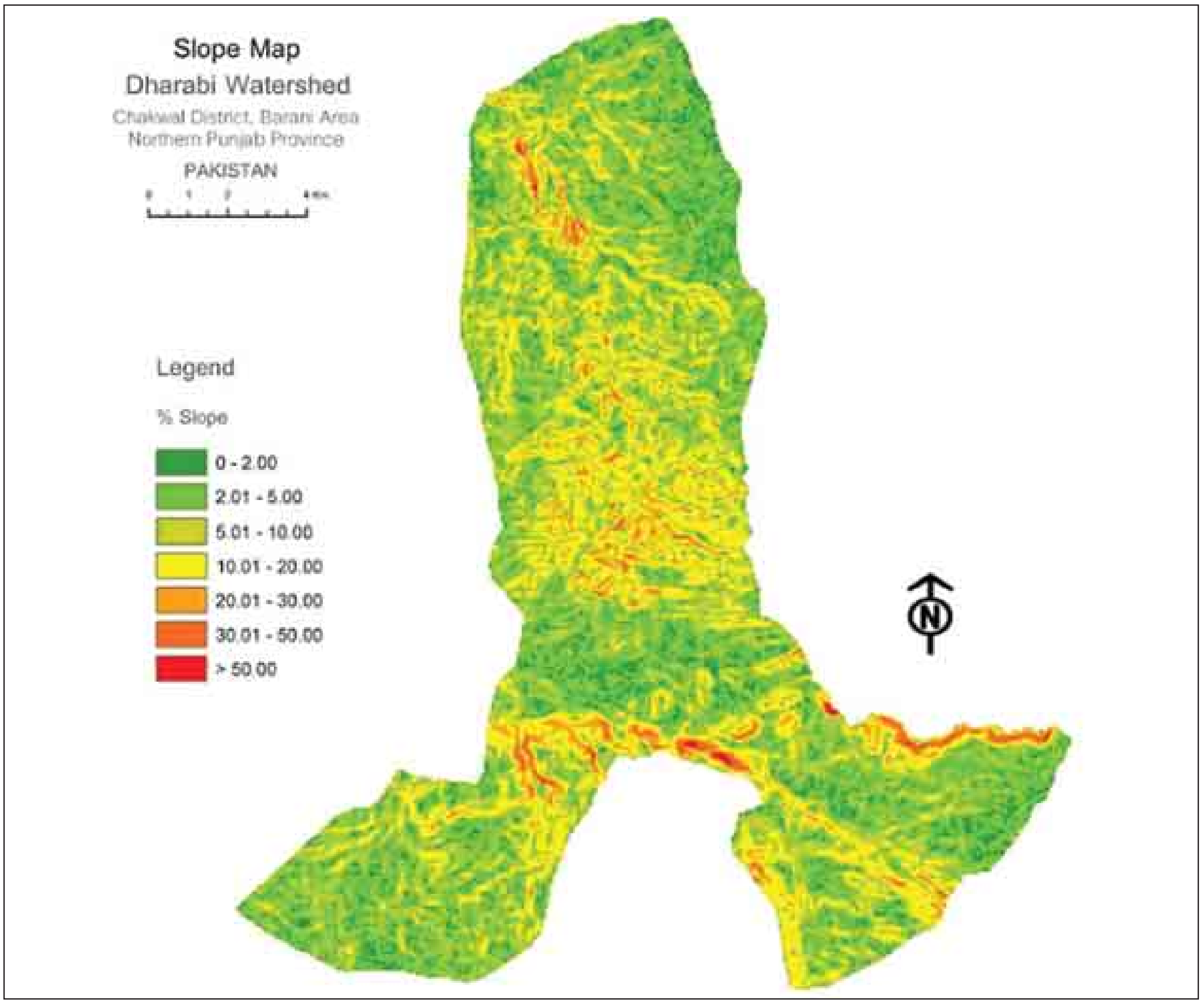


Figure 5.5. Slope map of the investigated watershed

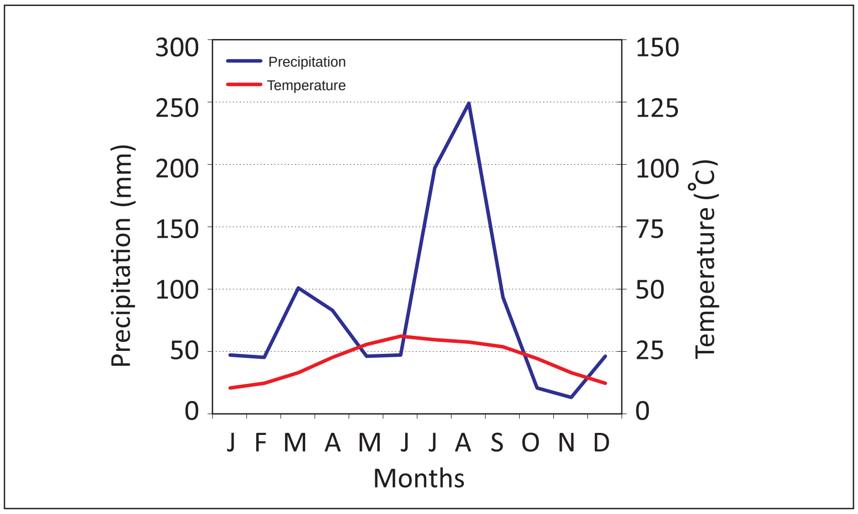


Figure 5.6. Precipitation and temperature variation for Islamabad generated by CLIGEN for a 100-year period

Table 5.3. Average monthly and yearly precipitation and temperature of Islamabad, Pakistan

Month	Average precipitation	Average maximum daily air temperature (°C)	Average minimum daily air temperature (°C)	Average daily air temperature (°C)	Average daily solar radiation (langley/d)
January	46.9	17.1	3.8	10.5	293
February	45.6	18.8	6.0	12.4	369
March	100.5	22.5	10.3	16.4	455
April	83.0	29.8	15.9	22.0	505
May	46.3	35.2	20.2	27.7	598
June	47.5	38.4	23.4	30.9	649
July	197.6	34.4	24.7	29.6	635
August	248.7	33.1	24.0	28.6	597
September	93.8	33.2	20.9	27.1	509
October	20.3	30.1	14.7	22.4	417
November	13.0	24.9	8.5	16.7	311
December	45.9	19.0	5.4	12.2	276
Sum/Average	989.2	28.0	18.4	21.4	468

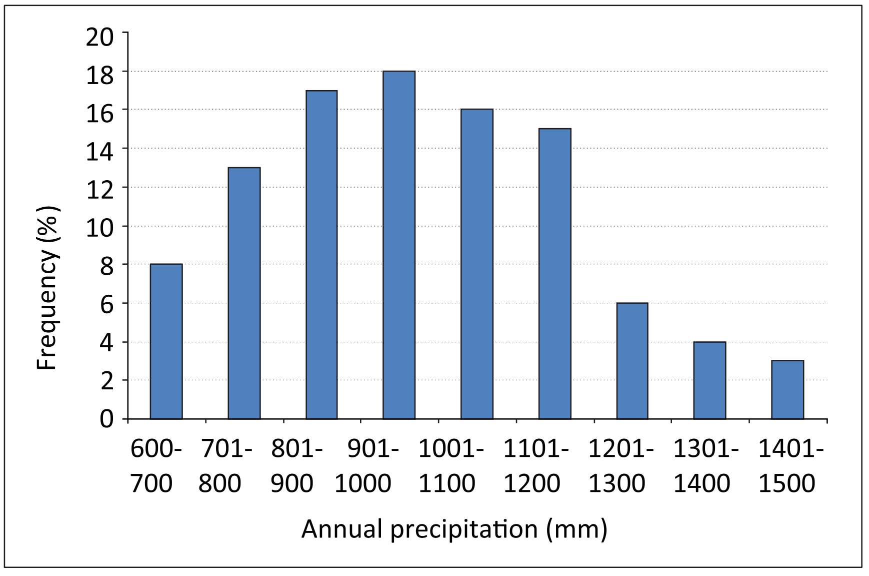


Figure 5.7. Frequency of different annual rainfall classes

The watershed area falls in the southern part of Pothwar plateau. The rocks exposed in this area belong to the Kamalial formation (Rawalpindi group) of a late Miocene age. A section south west of Kamalial in Attock district is type locality and the formation is distributed in the Pothwar area. This formation is typically represented by alternate beds of sandstone/shale with interbeds of sandstone, and silt stone shale with interbeds of conglomerate. Loess parent material also occurs in this region. The sandstone is purple grey in color and medium to coarse textured while the siltstone is purple in color. Stratigraphically, the Kamalial formation overlies the Muree formation (ICARDA, 2009).

Generally soils in the Chakwal district are mostly sandy and clayey. Minerals like stones, which are dolomite and granite, are available in Chakwal district. Soil erosion is the most important form of soil degradation in this area and causes formation of gullies of from 3 feet to 5 feet deep. Soil degradation and erosion are the major factors responsible for the decrease in the agricultural area and for the reduction in the productivity level.

Based on the reports of the Soil Survey of Pakistan (1967, 1975), thirteen land-use forms and soil series can be distinguished in the watershed (Table 5.4). Major land-use forms are rough broken land (# 39), stony land (# 22), and ridge and trough plain (# 20), which cover nearly 75% of the total watershed area.

5.3.2 Dominant soil series and their common properties in the investigated watershed

Balkassar series

The Balkassar series consists of deep and moderately deep, well drained, calcareous, moderately fine textured soils developed in materials derived from the underlying tertiary sandstone. These soils have a weak argillic B horizon. They have a brown to dark brown, very friable, massive to single grain , slightly calcareous, sandy loam top soil. This overlies a dark grayish brown, friable, strongly calcareous sandy loam B horizon with a weak, coarse, sub-angular blocky structure. The sub-stratum is a light grey, strongly calcareous, semi-consolidated, sandstone.

Chakwal series

The Chakwal series consists of deeply developed, well and seasonally moderately well drained, moderately fine to fine textured, calcareous soils developed in late Pleistocene loess. These soils have an argillic B horizon with a moderate sub-angular blocky structure. They have a brown to dark brown friable, slightly calcareous, silt loam top soil with massive and weak angular structure. This is underlain by dark grayish brown, friable, moderately calcareous, silty clay loam approaching silty clay B horizon with moderate, medium, and fine sub-angular blocky structure. The sub-stratum is brown, friable, strongly calcareous, massive, silty clay loam with many times the concentrations.

Dhuman series

The Dhuman series consists of very deep, well-drained, moderately fine textured, calcareous soils developed in sub-recent mountain outwash deposits. These soils have an argillic B horizon with a weak sub-angular blocky structure. They have a dark yellowish-brown, friable, massive, slightly calcareous, loamy top soil. This is underlain by a brown to dark brown, friable, moderately calcareous, clay loam, having a B horizon with a weak sub-angular blocky structure. The sub-stratum is brown to dark brown, friable, strongly calcareous, massive loam.

Dhulian series

The Dhulian series consists of deep well drained, medium textured, calcareous soils with a structural cambic B horizon. The soil is developed in calcareous residual materials derived from white and grey sandstone of the lower and middle Siwalik age. It occurs under semi-arid sub-tropical continental climates and occupies a nearly level to gently sloping position in the undulating rock plains and ridge and trough upland.

The series has brown/dark brown loamy sand, massive, calcareous. A P horizon, underlain by a brown to dark brown, loam weak, coarse sub-angular blocky, strongly calcareous B horizon, which, in turn, overlays a brown to dark brown sandy loam, massive, strongly calcareous C horizon.

Shahdara series
The Shahdara series consists of deep and very deep, well drained, calcareous, medium textured soils formed in recent mixed alluvium derived from the Himalayas. It has no B horizon. It occurs in a semi-arid sub-tropical continental climate and occupies the nearly level parts of active and recent flood plains. It has a brown to dark brown, friable, calcareous, massive silt loam, top soil. The sub-soil and sub-stratum have laminated layers of various textures, predominantly brown, friable, massive silt loams and very fine sandy loams. The horizon boundaries are abrupt or clear and smooth.

Guliana series
The Guliana series consists of deeply developed, well-drained, and seasonally moderately well drained, non calcareous, moderately fine to fine textured, soils developed in late Pleistocene loess. The soils have an argillic B horizon with a moderate blocky structure. They have brown to dark brown, friable, non calcareous, silt loam top soil with massive and weak angular structure. This overlays a dark grayish brown friable, non calcareous, silty clay loam approaching silty clay thick B horizon with moderate sub-angular blocky breaking into a moderate granular structure. The sub-stratum is dark yellowish brown, strongly calcareous, massive silt loam with many time concretions within 5 feet.

Missa series
The Missa series consists of very deep; will drained calcareous, medium textured soils developed in late Pleistocene loess with sub-recent surface. These soils have a weak structural B horizon. They have a yellowish brown, friable, moderately calcareous, silt loam sub-soil with weak, coarse sub-angular blocky structure. The sub-stratum is yellowish brown, friable, strongly calcareous, massive silt loam with common lime concretions.

Badland
This land type occurs extensively in the dissected basin plains. It is steep or very steep, nearly barren land, ordinarily not stony, broken by numerous intermittent drainage channels. The geologic erosion has been active for centuries with the result that the streams, with their associated ravines, have entrenched themselves in soft materials, generally loess.

Rough broken and stony land
This land type is extensively mapped on the flanks of the Soan River. The two components of the unit, rough broken land and stony land, occur in roughly equal proportions, either being dominant locally, Rough broken land consists of very steep, rocky land, broken by numerous intermittent drainage channels.

Rough mountainous land
This land type comprises mountainous areas, dominantly rocky or stony and includes very minor areas of shallow and very shallow phases of unidentified soils, partly suitable for cropping.

Gullied land
This land type consists of a network of intricate gullies, deeply dissected by streams and their associated ravines, in soft alluvial and loessial materials deposited during the late Pleistocene

epoch. The runoff is high and geological erosion is active. The vegetation consists of sparse scrub and grasses. (ICARDA, 2009).

The main land cover type in Dhrabi watershed is rangeland (bad or wasteland); more than 130 km^2 is predominantly unused land and mainly rough grazing land. An area of just 38.6 km^2 is suitable for agriculture. This comprises irrigated land (2.2 km^2), dry-farmed land (9.4 km^2), and some land for grazing. For this research, the land-cover information was created as a land-cover map by using the classification process to interpret the ASTER imagery which was obtained from the NASA Terra satellite. The classification of the imagery data was carried out by the Institute of Surveying, Remote Sensing and Land Information of the University of Natural Resources and Applied Life Sciences, Vienna using the ERDAS program. Two normalized difference vegetation indices (NDVIs), from May 2006 and December 2007, with a resolution of 15 m, were available to determine the different vegetation forms appearing in the watershed. Then the land-cover map was created by overlaying the winter and summer land-cover maps. The land-cover map showed eleven land-cover types which were classified into three types of agricultural land use, three types of forest land use, two types of bare soil area, one type

Table 5.4. Land-use forms and soil series in the investigated watershed

Map Unit	Land form and soil class	Area (km^2)	Area (%)	No. of samples for soil texture	No. of samples for saturated hydraulic conductivity
7	Weathered rock plains: Balkassar association	6.10	3.1	3	1
11	Piedmont alluvial plains and dissected piedmont plains	3.20	1.6	1	1
13	Level to nearly level plains: Guliana association	2.50	1.3	1	1
14	Missa association	0.60	0.3	0	0
16	Weathered rock plains: undulating and gently sloping plains, Balkassar association	0.80	0.4	0	0
17	Weathered rock plains: undulating and gently sloping plains	4.35	2.2	1	1
19	Dhulian association	14.30	7.3	5	3
20	Ridge and trough plain Balkassar complex, badland	35.40	18.0	4	3
22	Rough broken and stony land	33.00	16.8	5	3
36	Miscellaneous areas: gullied land	8.00	4.1	3	2
38	Open water	2.10	1.1		
39	Rough broken land	78.70	40.1	5	6
40	Rough mountainous land	7.20	3.7	1	1
	Total	196.25	100.0	29	22

of vegetation along water courses, one type of wetlands, and one type of built-up area (Figure 5.8 and Table 5.5).

The major area in Dhrabi watershed (32.3 %) has perennial trees and bushes. The agricultural-use fields cover 43.3 % of the Dhrabi watershed area (Table 5.5, rows 2, 5.3, and 5.4) and they are mainly planted with winter wheat and canola (rapeseed) as winter cultivation crops and groundnut, sorghum, and millet as summer crops. A small part of the agricultural area is also planted with mung bean and chickpea. Generally, the winter crops, like winter wheat and canola, are planted during September and October and harvested during April and May. The monsoon starts in June or early July, therefore, the summer crop will start at the same time and be harvested in October. The vegetation period and productivity of different crops are shown in Table 5.6.

The agricultural crops were divided into two crop management groups – winter crops and summer crops. The winter crop consisted of four crop rotation systems which were differentiated by the annual vegetation types and the level of fertilization as follows:
High fertilization

Table 5.5. Land-cover areas of the Dhrabi watershed

Type of land cover	Number of cells	Area (ha)	Cover area (%)
Buildings and streets	1,007	362.52	1.86
Fields with dense vegetation (50-75%)	5,171	1,861.56	9.55
Fields with spare vegetation (35%)	4,817	1,734.12	8.90
Fields without vegetation (< 5%)	13,433	4,835.88	24.81
Dense forest (> 90%)	2,132	767.52	3.94
Perennial trees and bushes (75-90%)	17,494	6,297.84	32.31
Grass and bushes (50-75%)	1,560	561.60	2.88
Spare grass land (15-35%)	6,110	2,199.60	11.28
Gravel without vegetation (0-5%)	596	214.56	1.10
Vegetation along water courses (> 90%)	1,181	425.16	2.18
Open water	643	231.48	1.19
Total	54,144	19,491.84	100.00

Table 5.6. Vegetation periods and productivities of the main crops in Dhrabi watershed

Types of vegetable	Planting period	Harvesting period	yield (kg/ha)
Winter wheat	October 20-November 10	May	1,600
Canola (rapeseed)	September	April	700
Groundnut	March 20-April 15	October	1,200
Millet	July	October	
Sorghum	July	October	

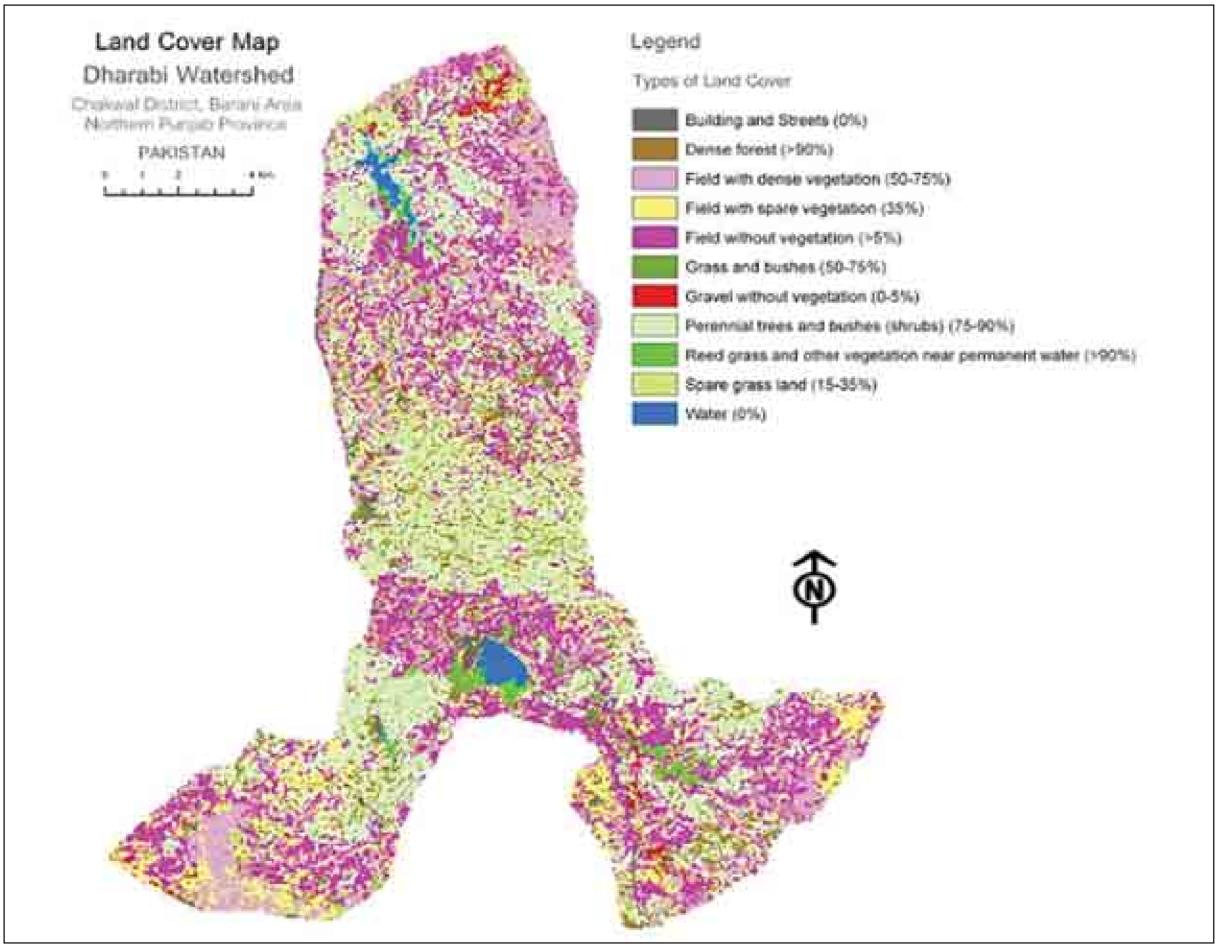


Figure 5.8. Land cover map of the Dhrabi watershed in the ArcGIS program

- Canola-fallow-canola-fallow-winter wheat-fallow
- Winter wheat-fallow-winter wheat-fallow-canola-fallow

Low fertilization

- Canola-fallow-canola-fallow-winter wheat-fallow
- Winter wheat-fallow-winter wheat-fallow-canola-fallow.

The summer crop consisted of two crop rotation systems; the main crops were defined as groundnut, millet, and sorghum. The following main crop rotations were assumed:

- Groundnut-fallow-groundnut-fallow-millet-fallow-groundnut-fallow-groundnut-fallow-sorghum-fallow
- Millet-fallow-groundnut-fallow-groundnut-fallow-sorghum-fallow-groundnut-fallow-groundnut-fallow.

5.3.3 Field investigation

To obtain the necessary input parameters for the soil erosion simulation models a soil sampling and field test campaign was carried out in February 2010.
The following tasks needed to be fulfilled:

- Investigation of soil parameters – soil texture, organic matter content, and saturated hydraulic conductivity
- Crop rotation, farming methods, and tillage implements
- Vegetation cover. This involved visual assessment of the vegetation classes, characterization of the main vegetation parameters, residue cover, canopy cover, canopy height, surface random roughness, and stone cover
- Calibration of the ASTER satellite images from June 2006 and December 2007.

A landform classification map, based on geomorphic maps, was elaborated by Mr. Bashir from SAWCRI. This map was the basis for the selection of the investigation sites (Figure 5.9). For each map unit, at least one sampling point to be investigated should be selected.

Overall, 29 sites were investigated in the watershed with up to eight sites per map unit (Table 5.3). A total of eight ring infiltration measurements and 42 (3*14 sites) core samples for saturated hydraulic conductivity

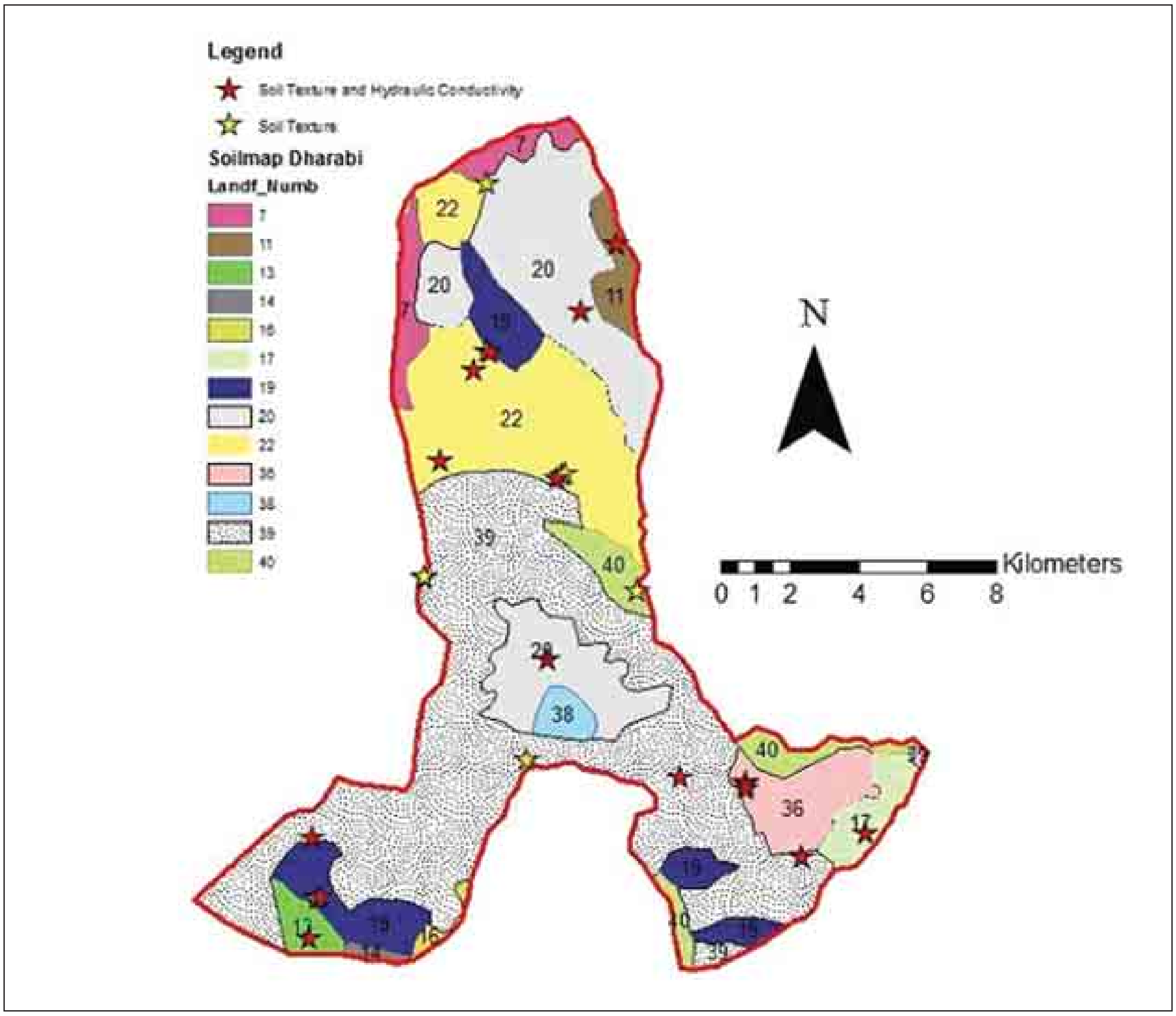


Figure 5.9. Landform classification map with important water bodies and sampling points (yellow: soil texture samples, red, soil texture and saturated hydraulic conductivity)

(total 22 samples). Soil texture and organic matter assessments were conducted on 29 disturbed soil samples. All sites were marked with GPS points in the Universal Transverse Mercator (UTM) coordinate system.

Soil texture

The soil texture or particle size distribution has a significant influence on soil erosion. For the determination, 29 disturbed soil samples were taken from the top 2.5 cm of the soil with a sample weight of between 0.5 kg and 1 kg. These were analyzed in the SAWCRI laboratory.

The samples were first air dried in the soil storage room of the institute for from three to five days, depending on the prevailing weather conditions. The second step was to separate, with a sieve, soil particles of less than 2 mm. For the texture analyses, a hydrometer testing method was used. A dispersing solution of 100 g sodium hexametaphospate $(NaPO_3)^6$ and 2 L of distilled water was mixed. For each sample, 50 ml of the dispersing solution was again mixed with 50 g of the sieved soil and 150 ml of distilled water, then covered and set aside in a safe place for at least 24 hours. Next the dispersion was automatically shaken for 10 minutes and then transferred to a measure cylinder with a volume of 1000 ml (Figure 5.10). The hydrometer was placed in the cylinder which was filled to the 1000 ml mark with distilled water. The hydrometer was removed from the cylinder, the solution was mixed by hand for one minute, and the first hydrometer reading, showing the percentage of silt and clay, was taken 40 seconds after the beginning of deposition. To factor in the dynamic viscosity, the temperature of the liquid was taken.

To determine the percentage of clay, the solution was mixed for another minute and second readings of the hydrometer and temperature were taken after exactly 2 hour of deposition. The equation for the percentage of silt and clay is:

$$\text{Silt + Clay} = \{A * (T1 - T0) *0.3\} * 2 \qquad (1)$$

were A is the hydrometer reading after 40 seconds, T1 the temperature of the liquid while testing (°C) and T0 is the reference temperature of 19.40 °C. The same equation was used to determine the percentage of clay after 2 hours.

Figure 5.10. Sedimentation method

The percentages of sand, silt, and clay, as well as the soil texture of the investigated soil classes, are compiled in Table 5.7.

Significant stone cover was apparent only in soil units 19, 22, and 39 which form 64% of the total area. Stone cover for these soils ranged between 11% and 44% (Figure 5.11).

Saturated hydraulic conductivity

Saturated hydraulic conductivity was determined by eight single ring infiltration measurements and 42 core soil samples (3 samples at 14 places). To be able to compare the results obtained by the two different methods, the ring infiltration and core samples were taken at three sites.

Single ring infiltration

Single ring infiltration measurement is a method of determining the infiltration

Table 5.7. Texture of the investigated soil classes (based on the Austrian texture triangle)

Landform	Land-use	Sand (%)	Silt (%)	Clay (%)	Soil texture
7	Terrace	54 - 69	16 - 25	4 - 22	Loamy sand - sandy clay loam
13	Terrace	25 - 78	16 - 54	5 - 21	Loamy sand - silt loam
17	Terrace/slope	47	39	14	Loam
19	Terrace/slope/gully	56 - 89	11 - 25	0 - 18	Sand - sandy loam
20	Terrace/slope/gully	69 - 82	10 - 28	2 - 16	Loamy sand - loam
22	Terrace/slope/gully	67 - 89	10 - 20	0 - 14	Sand - sandy loam
36	Terrace/gully	47 - 67	5 - 26	28 - 30	Sandy clay loam
39	Terrace/slope	31 - 80	13 - 46	8 - 14	Loamy sand - silt loam
40	Slope	87	13	0	Loamy sand

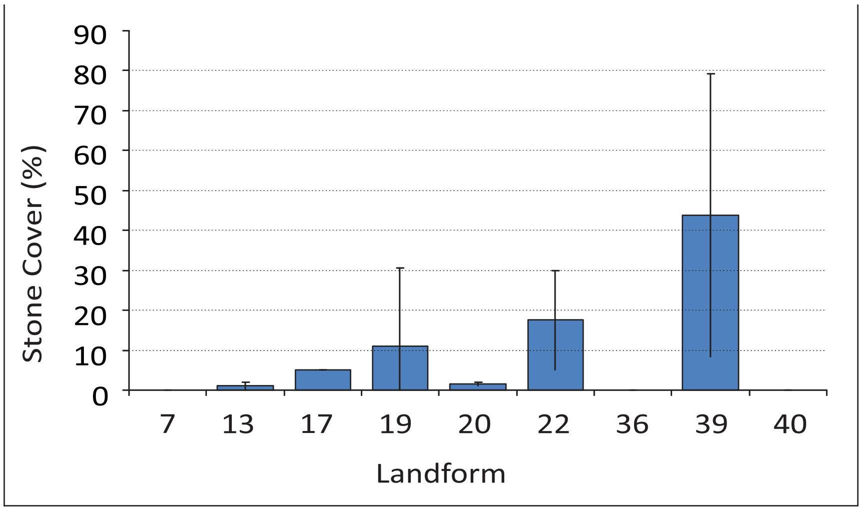


Figure 5.11. Average stone cover (and standard deviation) of the investigated soil units/land forms

rate of water and the saturated hydraulic conductivity. For its input parameters, erosion models like Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995) and the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.,* 1997) require knowledge of the saturated hydraulic conductivity.

The ring size was 28.3 (+/- 0.1) cm diameter with a height of 25.3 cm (Figure 5.12). At each site the procedure started by inserting the ring 6 cm to 10 cm into the soil and adjusting it with an air lever. Then a ruler with millimeter spacing was installed and fixed to the ring with a tape, so that it was not possible to displace it. Plastic foil was then put into the ring and water poured in. The plastic foil was necessary so that the soil surface was not disturbed and in this way degrade the results. When the foil was taken away, infiltration of the water began, the clock was set to zero, and the first height reading was taken. In the first 5 minutes the water level was taken at 30 seconds intervals.

After that, a time step of between one and five minutes was chosen, depending on the rate of infiltration. When the water level was near the soil surface, the plastic foil was again put into the ring and fresh water added. The measurement finished when the infiltration rate was determined to be constant.

Core samples

Undisturbed core samples were taken to determine the hydraulic conductivity, when it became apparent that it would not be possible to arrange all the necessary ring infiltrations within the proposed time.

The core samples were taken with a steel ring 55 mm diameter and 45 mm high (Figure 5.13). At each site, three cores were taken to determine a mean value and the standard deviation of the measured saturated hydraulic conductivities. Some sites (mostly in the southern parts of the watershed) showed a large distribution, a result of the stones (up to 3 cm diameter) imbedded in the core. Measurements were undertaken in the soil laboratory with the devices shown in Figure 5.14 and Figure 5.15. This device was a small table with 12 sieves adapted to the steel rings and a water outlet at the bottom. For the measurement, a ring was placed on a sieve, and a second ring of the same dimensions was attached to its top by a 3 cm broad rubber ring. Then, blotting paper was put on top of the soil, the upper steel ring was filled with water and the paper removed. It took some time until the first drop of water

Figure 5.12. Single ring infiltrometer

Figure 5.13. Sampling of undisturbed soil samples in the field

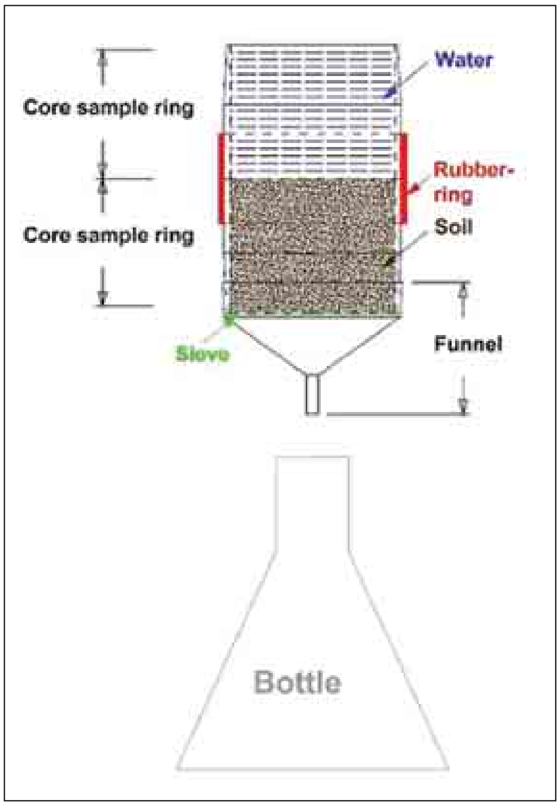


Figure 5.14. Schematic of the equipment to determine the saturated hydraulic conductivity

Figure 5.15. Equipment to determine the saturated hydraulic conductivity using the falling head method

came out of the funnel. At that moment it was assumed that the soil in the lower ring was saturated. Then the clock was started and allowed to run until the water level of the upper ring was nearly at the bottom. The measuring bottle was then removed, the time recorded and the amount of water measured. On the basis of this procedure, the water flow in the core was assumed to be constant and the soil saturated. The saturated hydraulic conductivity was then calculated as:

$$Ksat = V_{total/}[A_{ring} * T_{total}] \quad (2)$$

where Ksat (cm/s) is the saturated hydraulic conductivity, V_{total} (cm³) the cumulative amount of water in the bottle, A_{ring} (cm_2) the area of the ring, and T_{total} (s) the time from the first drop falling until the measurement stopped – mostly the moment when the water level reached the top of the soil.

The analyses of the saturated hydraulic conductivity delivered very high values for all the soils (Figure 5.16). The values ranged between 28 cm/day (# 40) and 346 cm/day (# 19).

Organic carbon content

The organic matter content (OM) of the soil is a parameter which affects soil aggregation and therefore influences soil erodibility.

The OM was determined at SAWCRI using a titration method with the following steps (Figure 5.17). First, 1 g of the air-dried and sieved soil was taken and mixed with 10 ml of potassium dichromate ($K_2Cr_2O_7$(IN)) in a 50 ml bottle. To calibrate the titration test two

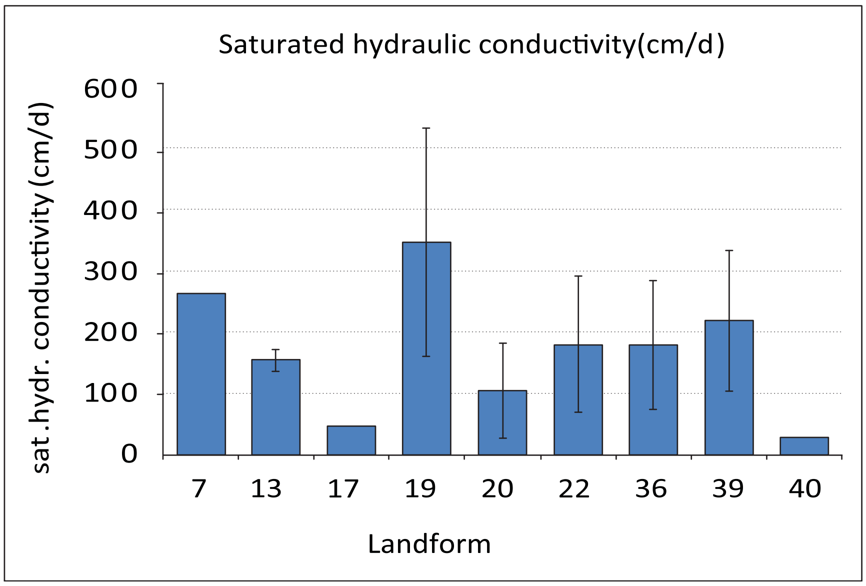


Figure 5.16. Average saturated hydraulic conductivities (and their standard deviations) for the investigated soil classes/landforms

Figure 5.17. Analysis of organic carbon content

blank samples without soil were prepared for each test series as well. After adding 20 ml of sulfuric acid (H_2SO_4) the samples were set aside for 30 minutes. Then 200 ml of tap water and 0.5 g of sodium fluoride (Na F) were added. After adding 1 ml of an indicator fluid, iron(II) sulfate ($FeSO_4$ $7H_2O$) was added to the solution, and the bottle was continuously shaken until the fluid color changed from red to green (Figure 5.9). The volume of iron(II) sulfate needed to achieve the color change, is proportional to the OM of the sample.

The organic matter content (%) was then calculated from the equation:

$$OM = (R_1 - R_0) * (6.7236 / R_0) \qquad (3)$$

were R_1 (ml) is the volume of iron(II) sulfate for the sample, R_0 (ml) is the average volume of iron(II) sulfate used in the two blank samples and 6.7236 is a constant.

Organic carbon contents were low and found to be in a range between 0.25% and 0.88% (Figure 5.18).

5.3.4 Simulation models

Revised Universal Soil Loss Equation (RUSLE)

RUSLE is an erosion model designed to predict long-term average annual soil loss (A) carried by runoff from specific field slopes in specified cropping and management systems. Wischmeier and Smith (1978) found that the soil loss (A) can be sufficiently described by

$$A = R \times K \times L \times S \times C \times P \qquad (3)$$

where

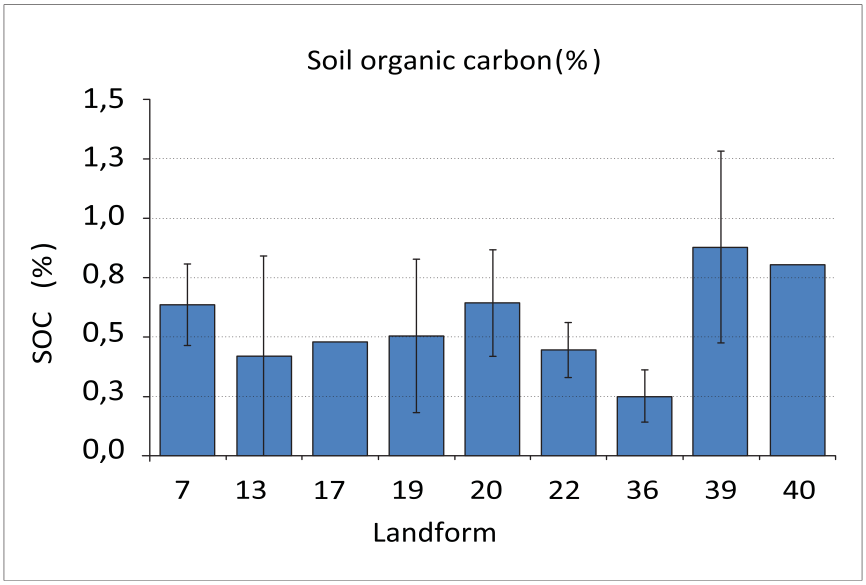


Figure 5.18. Average organic carbon content (and standard deviation) of investigated soil classes/landforms

A is the long-term average annual soil loss [t/ha/year]
R is the rainfall/runoff erosivity factor [kJ/ha.mm/hour]
K is the soil erodibility [t/ha.hour/N]
L is the slope length factor
S is the slope degree factor
C is the cropping management factor
P is the conservation practice factor
The parameters can be grouped as those causing erosion (R), and those resisting erosion (K,L,S,C,P).

For each factor, a digital, grid-based map was created. To obtain a final map of the potential average annual erosion these six maps were combined within ArcView using equation (3).

R-factor
The trigger for soil erosion by water is always rain. The falling raindrops hitting the ground cause destruction of soil aggregates and particles are splashed away. Subsequently, the surplus water cannot infiltrate when the precipitation rate is higher than the infiltration rate. This surplus water transports the loosened particles downhill and shears off more soil material.

To quantify the erosive force of a rain event, Wischmeier and Smith (1978) defined the R-factor as the product of the kinetic energy (KE) of an erosive rainstorm event (responsible for soil detachment by raindrops) and its maximum 30 minute intensity (I30 – describing the erosive force of the runoff).

An erosive rainstorm event is defined as a rainstorm of minimum 10 mm precipitation or as rains an I30 value of more than 10 mm/hour when the precipitation amount is less than 10 mm. Rains outbreaks with less than six hours of no precipitation between them are regarded as one rainstorm. Rainfall kinetic energy was calculated using unit kinetic energy in MJ/ha/mm (Brown and Foster, 1987)

$$KE = 0.29 (1 – 0.72 \exp (-0.05 \times Im) \qquad (4)$$

where Im is the rainfall intensity in mm/hour.

The R-factor of a single rainstorm event is calculated by multiplying KE by I30. Adding up the (KE)(I30) values for all rainstorms of a year gives the R-factor.

K–factor
Soils differ in their susceptibility to erosion by water. The erodibility of a soil depends on various properties, however Wischmeier and Smith (1978) found that erodibility can be sufficiently described with five parameters:

- Silt and very fine sand (fraction size 0.002 – 0.1 mm) content [%]
- Modified sand (fraction size 0.1 - 2 mm) content [%]
- Organic matter content (OM) [%]
- Soil structure class (s)
- Soil permeability class (p).

Table 5.8. Soil permeability classes for RUSLE

Permeability code	Hydraulic conductivity (cm/day)	Description
1	< 1	very low
2	1– 0	low
3	10–40	medium
4	40–100	high
5	100–300	very high
6	> 300	extremely high

Table 5.9. Soil structure classes for RUSLE

Structure code	Mean aggregate size (mm)	Description
1	< 1	very fine
2	1–2	fine
3	2–10	coarse
4	> 10	blocky, platy, dense

For soils where the silt fraction does not exceed 70%, the following equation can be used (Schwertmann *et al.,* 1987)

K = 2.77x10-6 x M 1.14(12 – OM) + 0.043(s – 2) + 0.033(4 – p) (5)

where M is the product of the primary particle size fractions – (% modified silt) x

(% silt + % very fine sand). K is expressed in t/ha per unit R-factor.

The classifications of soil structure and permeability can be seen in Tables 5.8 and 5.9 respectively.

In the Universal Soil Loss Equation (USLE), these soil properties are considered not to vary significantly with time (Pall *et al.,* 1982). The effects of tillage and other agricultural operations are incorporated in the C-factor. Nevertheless, it was found that the K-factor does vary during a season. Primarily this is due to soil freezing. Freeze-thaw circling generally leads to low bulk density of the surface soil (Pall *et al.,* 1982). Conditions of low bulk density and high soil water content provide a soil surface that is very susceptible to detachment and transport. After a freezing period, when the surface of the still frozen top soil layer thaws, the erosivity of the soil is extremely high since the infiltration is practically zero.
RUSLE incorporates this seasonal variation by the calculation of half-month K-factors based on

$K_r = 1 + a.\cos(b.t - c)$ (6)

where Kr is the ratio between the average seasonal K value over the average annual K value, t is the mean monthly temperature and a, b, and c are location specific constants.

Generally, the susceptibility of a soil to erosion by water rises with

- A high content of silt and very fine sand
- A low content of clay
- A low organic matter content
- Bigger aggregate size
- A lower permeability.

LS–factor
Soil loss increases with the length and inclination of the slope. The steeper the slope, the earlier the surface runoff during a rainfall event will start, and the higher the velocity of the runoff. The same happens with an increased length of slope, since more water with a higher velocity erodes and transports more soil downhill. The amount and velocity of the runoff determine the shear-stress and the transport capacity of the water.

The slope length (L) and the slope degree factor (S) are typically combined together and defined as the topographic factor, which is a function of both the slope and the length of a land segment. The LS-factor of the USLE describes the ratio of the soil loss on a given slope length and steepness to the soil loss of a slope with a length of 22.13 m and a steepness of 9%.

The original Wischmeier equation for the computation the LS-factor is

$$LS = (l/ 22.13)m \times (65.41*\sin^2\theta + 4.56*\sin\theta + 0.065) \quad (7)$$

Where l is the erosive length of the slope (from the point where surface runoff starts to the point of sedimentation, ɵ is the average slope angle (arc) of the plot and m is an exponent varying with different slopes.

Since the USLE/RUSLE formulas have been derived for just single plots and not for a complex terrain like the study area, a different approach for generating the topographic factor for each cell of the digital elevation model had to be found.

Schäuble (1999) developed a 'RUSLE Light Concept' where l was taken as the raster cell size of the digital elevation model (DEM) and the derived slope angle map used. This work also calculated the soil loss A and the net erosion.

To deal with the problem of the L factor, different algorithms were developed. Three will be discussed in this paper, while two of them were used to calculate the potential soil erosion (A factor) and net erosion.

We can include the upslope conditions based on the irregular slope concept of Foster and Wischmeier (1974), where the L of a slope segment is defined as

$$L_i = (l_i^m+1 - l_i\text{-}1^{m+1})/[(l_i - l_{i-1})\ (22.13)^m] \quad (8)$$

Different investigations preceded the unit contributing area concepts. Schäuble (1999) developed the equation

$$L_i = (l_i^{m\ \theta i+1} - l_{i-1}^{m\ \theta i+1})/[(l_i - l_{i-1})\ (22.13)^{m\theta i}] \quad (9)$$

where l_i is the potential water mass flowing through the objective cell, calculated with a multiple flow direction algorithm from FLOW95, $m_{\Theta i}$ is the mean m value from the upslope watershed area and calculated as a $m_{\theta i}$ weighted flow length map divided by a non weighted flow length map.

Desmet and Govers (1996) developed the following equation:

$$L(i,j) = (A(i,j) + D^2)^{m+1} - A(i,j)^{m+1}/ (xm * D^{m+2} *22.13^m) \quad (10)$$

where L(i,j) is the slope length factor of a certain cell, A(i,j) is the associated contributing area, and D is the cell size in meter (D^2 is the cell area).

On closer examination, equations (9) and (10) are seen to be derived from the same origin, equation (8). Differences exists in the use of $m_{\theta i}$ in equation (9) while Desmet and Govers (1996) use the equal m as shown in equation (13), and that formula (10) uses the real area in square meters while equation (9) uses "area per meter". During the practical application this means nothing more than the weighted flow length, which is the input for A(i,j), and li, is multiplied by the cell area (or 900 m^2 in this work), while equation (9) uses just the cell width (here, 30 m). The last difference is in the use of the correction factor x in equation (10).

For the calculations in Dhrabi watershed, the equation developed by Mitasova *et al.* (1998) –see equation (13) below – was used. The reason was that the other algorithms needed special programs. While for the application of equation (13), FLOW95 worked well and was really easy to handle. For the application of equation (10), the so-called Watem/Sedem, developed at the University Leuven, Belgium, FLOW 95 did not work properly.

The S-factor in RUSLE mirrors the effect of the steepness of a given slope. In the past, this factor has been the subject of many investigations. Within the RUSLE equations developed by McCool *et al.* (1987, 1989) are used:

$S = 10.8 \sin Q + 0.03$ for $s < 9$ %
(for $Q < 5.143°$) (11)

and

$S = 16.8 \sin Q – 0.50$ for s 9 %
(for Q 5.143°) (12)

Hillslope was calculated in ArcGIS with the function *slope* from the Arc Toolbox. The result was equated to the degree and percent slope of each cell and compared to that of its neighbor to show the maximum difference in altitude . In this way *slope* identifies the steepest downhill *slope* for a raster cell.

Mitasova *et al.* (1998) found a simpler form of equation which calculates not only L, but also the steepness factor, S:

$$LS = (m+1) * [A(i,j)/a_0]^m * [\sin\theta(i,j)/b_0]^n \qquad (13)$$

with
$a_0 = 22.13$ m (standard plot length), $b_0 = 9$ % (standard plot slope), m = 0.6, and n = 1.3.

A(i,j) (m^2/m) is the unit contributing area of a grid cell (i,j) and θ(i,j) is the slope angle. The values for m and n give results consistent with RUSLE for slopes < 100 m and slope angles < 14° (Moore and Wilson, 1992). It need to be noted that equations (13) and (16) and equations (9) and (14) use the unit contributing area ℓ (in m^2/m) while equation (10) uses the same parameter A(i,j) (in m^2).

The proposed values for m and n give results consistent with RUSLE for slopes < 100 m and slope angles < 14° (Moore and Wilson, 1992).

It must be considered that both the standard and modified equations can be properly applied only to areas experiencing net erosion, so the direct application of USLE/RUSLE to a complex terrain within a GIS is rather restricted. Depositional areas should be excluded from the study area because the model assumes that the transport capacity exceeds detachment capacity everywhere, whereas erosion and sediment transport is detachment capacity limited. The results can be interpreted as an extreme case with the maximum spatial extent of erosion possible.

Flow95 algorithm
As explained before, the value of a raster cell in the L-factor calculation is not just dependent on on-site parameters. In fact, it depends on the properties of the upstream watershed of each raster cell. To deal with this problem, the parameters of A(i,j) and li have to be calculated by a flow accumulation tool. This means that the contributing area, according to each raster cell, has to be determined by using the Digital Elevation Map (DEM) and a special calculation tool. ArcGIS provides such a tool, but it uses a single flow algorithm, while FLOW 95 (Schäuble, 1999) uses a multiple flow algorithm. The function of such flow accumulation tools is to find out how much water the raster cells would drain into the cell under consideration.

60	62	62
60	58	60
58	57	58

Figure 5.19. Example of a DEM representing the altitudes of each cell

To mark the difference between these, both have to be explained. A single flow algorithm uses the DEM as input, where each raster cell has a value, representing its altitude.

An example is given in Figure 5.19. A single flow algorithm would calculate, that the total rainfall amount of the middle cell in the upper row (Altitude = 62) would run into the cell in the centre of the matrix with the height of 58. In contrast, the multiple flow algorithm used in FLOW95, divides the rainfall depending on the relative descents to each neighbor as shown in Figure 5.20.

0.2	x	0.0
0.2	0.4	0.2

Figure 5.20. Principle of the multiple flow algorithm. This matrix shows, that 40% of the rainfall will run into '58' while the rest will flow into other cells

With this procedure, FLOW 95 calculates the contributing area of each raster cell. To calculate the A(i,j) and li (which are indeed parameters of the same origin) the resulting flow accumulation file has to be multiplied by the raster size (30 m).

C–factor

The cover management factor (C-factor) reflects the cropping and management systems and depends on several sub-factors. C itself is a dimensionless factor, representing long term conditions, though the input parameters for it – mainly the agricultural land, but on a small scale also rangeland, pasture, etc. – vary significantly during a year. To imply the change of vegetation and soil conditions during the year, C is calculated as the mean of half-month period constants, weighted by the amount of rainfall energy EI_{30} in this period:

$$C = (SLR_1 * EI_1 + SLR_2 * EI_2 + ... + SLR_n * EI_n)/\sum EI_n \qquad (14)$$

In the C-factor, the protective effect of vegetation as well as the effect of farming practices, including type of crop and rotation patterns, is considered. For agricultural land both factors vary significantly during a year. Canopy cover reduces erosion. First it protects the soil from the 'splash' effect and second, the plant roots stabilize the top soil layers. Tillage changes the structure and roughness of the soil surface. The modified C-factor calculations in RUSLE and the original USLE are based on the concept of deviation from a standard, under clean-tilled, continuous-fallow conditions. The soil loss ratio (SLR) is then an estimate of the ratio of soil loss under actual conditions to the losses experienced under reference conditions. In RUSLE the soil loss ratio is calculated for a 15 day time period and then weighted by the fraction of rainfall and runoff erosivity (EI) associated with the corresponding time period. Finally these weighted values are combined into an overall C-factor value. The soil loss ratio is computed as

$$SLR = PLU * CC * SC * SR * SM \qquad (15)$$

where

PLU is the prior land-use sub-factor, CC is the canopy cover sub-factor, SC is the surface cover sub-factor, SR is the surface roughness sub-factor and SM is the soil moisture sub-factor.

Each sub-factor contains cropping and management variables that effect soil erosion, like residue cover, canopy cover, canopy height, surface random roughness, below-ground biomass, prior cropping, soil moisture, and time. The calculations of these sub-factors are described in the literature (Renard *et al.,* 1997).

For areas like rangeland and pasture, where the natural conditions show seasonal cycles such as winter knockdown and spring growth, the soil loss ratios and C-factors can be computed in a similar way. If the natural conditions reach a relative equilibrium, so that the input parameters of the soil loss ratio change very slowly with time, it may be sufficient to assess a single SLR for the entire year. This simplifies the calculations and reduces the number of necessary input parameters.

The input parameters for calculating a time invariant SLR are:

- Average annual root mass in the top 4 inch layer (pound/acre)
- Average annual canopy cover (%)
- Average annual fall height (inches)
- Random roughness for the field condition (inches)
- Total percentage ground cover (rocks and residue %)
- B-value index (rill/interrill erosion ratio from 0.025 to 0.6).

P-factor

The P-factor describes the reduction in soil erosion achieved by using soil conservation measures. Based on experimental data, the P-factor is calculated as the ratio of soil loss with a specific support practice to the corresponding soil loss with up-slope and down-slope tillage.

For cultivated land, the support practices considered include contouring (tillage and planting on or near the contour), strip cropping, terracing, and subsurface drainage. On dryland or rangeland areas, soil-disturbing practices oriented on or near the contour that result in storage of soil moisture and reduction of runoff are also used as support practices (Renard *et al.,* 1997).
An overall P-factor value is computed as a product of the P sub-factors for individual support practices, which are typically used in combination. The P-factor values range from 0 to 1, where 0 means that no soil erosion can be expected and 1 that no conservation practices are used.

Water erosion prediction project model (WEPP) (Flanagan and Nearing, 1995)

<u>Overview</u>

For simulation of surface runoff, soil loss within the watershed, and sediment yield from the watershed the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) was used in combination with its geo-spatial interface (GeoWepp) (Renschler, 2003). WEPP is a continuous simulation, process-based model that allows the simulation of small watersheds. The geo-spatial interface uses digital, geo-referenced information, like digital elevation models and soil and land-use maps, to derive and prepare valid model input parameters.

The model can be subdivided into six conceptual components – climate generation, hydrology, plant growth, soils, irrigation, and erosion.

The climate generator is a model called CLIGEN and is run separately from the WEPP model. It generates the rainfall amount, duration, maximum intensity, time to peak intensity, maximum and minimum air temperature, and solar radiation for the on-site location. The generated data are written to a climate file which is read by the WEPP model. Rainfall is disaggregated into a time-rainfall intensity format for use by the infiltration and erosion component.
The hydrology component calculates infiltration and the daily water balance, including runoff, evaporation, and deep percolation. Infiltration is calculated using the Green and Ampt (1911) infiltration equation. Runoff is calculated using the kinematic wave equations or by an approximation to the kinematic solution for a range of rainfall intensity distributions, hydraulic roughness, and infiltration parameter values.

The crop growth component of the model calculates growth, senescence, and decomposition of plant material. In the case of croplands, a particular crop or crops are grown as a function of growing degree days and soil moisture. The pattern of growth is controlled by crop specific parameters. After harvest, decomposition of the vegetative residue, if present, is simulated. In the case of rangelands, a plant community is simulated for a growing season. The component calculates the leaf area index for transpiration calculations.

Many of the soil parameters which are used in the hydrology and erosion calculations change with time as a result of tillage operations, compaction, weathering, or history of precipitation. The soil components make adjustments to the soil properties on a daily time step. Examples of time varying factors include soil bulk density, saturated hydraulic conductivity, surface roughness, and erodibility.

The WEPP erosion model computes soil loss along a slope and sediment yield at the end of a hillslope. Interrill and rill erosion processes are considered. Interrill erosion is described as a process of soil detachment by raindrop impact, transport by shallow sheet flow, and sediment delivery to rill channels. Sediment delivery rate to rill flow areas is assumed to be proportional to the product of the rainfall intensity and the interrill runoff rate. Rill erosion is described as a function of the flow's ability to detach sediment, its sediment transport capacity, and the existing sediment load in the flow. Net soil detachment in rills occurs when the hydraulic shear stress exceeds the critical shear stress and when the sediment load is less than the sediment transport capacity. When the sediment load is greater than sediment transport capacity, sediment deposition occurs.

Overland flow processes are conceptualized as a mixture of broad sheet flow occurring in interrill areas and concentrated flow in rill areas. Broad sheet flow on an idealized surface is assumed for overland flow routing and hydrograph development. Overland flow routing procedures include both an analytical solution to the kinematic wave equations and regression equations derived from the kinematic approximation for a range of slope steepness and lengths, friction factors (surface roughness coefficients), soil texture classes, and rainfall distributions.

The Geo-spatial interface for WEPP (GeoWEPP) was developed by the Agriculture Research Service, Purdue University and the USDA National Soil Erosion Research Laboratory (Renschler, 2003). It should integrate the advanced features of the Geographic Information System (GIS) within the WEPPWIN program. The program requires necessary input data, such as land cover, climate, soil, and crop management that are generated within the WEPPWIN program as a text file. It uses the GIS to generate the map as an ASCII file. GeoWEPP integrates WEPPWIN and TOPAZ (Topography Parameterization) software within ArcGIS 9.3. The WEPP Windows program is used to prepare the WEPP input data. The program has two parts, the WEPP program and a climate generator program which are written in FORTRAN. The other one, written in Visual C++, was used for a Windows interface (WEPPWIN) (Flanagan and Frankenberger, 2002).

Description of main processes represented in WEPP

<u>Infiltration</u>

For simulation of the infiltration rate (i) for unsteady rainfall the Green and Ampt (1911) approach is used as presented by Chu (1978):

$$i = K_e\left(1 + \frac{(n-\theta_0)\cdot\psi}{I}\right) \qquad (16)$$

where i is the actual infiltration rate (m/s), Ke the effective hydraulic conductivity of the wetted zone (m/s), n the effective porosity (m^3/m^3), θ_0 the initial saturation (m^3/m^3), Ψ the average capillary tension or matric potential of the wetting front (m), and I the cumulative infiltration depth (m).

It describes the approach of the actual infiltration rate, i, to the hydraulic conductivity, K_e, when i approximates infinity. The main assumptions of this approach are the piston-like entry of the water into the soil and a sharply defined wetting front which separates the fully saturated and unsaturated zones. The driving parameters of the Green and Ampt model are the matric potential of the wetting front, the soil moisture deficit ($n-\theta_0$), and the effective hydraulic conductivity K_e.

The wetting front term is calculated from the soil type, the soil water content, and the soil bulk density using a pedotransfer function modified from the one developed by Rawls and Brakensiek (1983). The moisture deficit is determined in a similar manner from empirical functions which were developed during extensive WEPP rainfall simulation studies (Elliot *et al.,* 1989). The effective hydraulic conductivity is calculated from sand and clay contents and the cation exchange capacity of the topsoil (USDA-ARS 1994; Flanagan and Livingstom, 1995).

Runoff routing

Dynamic infiltration-hydrograph models for overland flow consist of an infiltration function that computes the infiltration rate as it varies with time from an unsteady rainfall input and a routing function that transforms rainfall excess into flow depths on a flow surface. The choice of the infiltration function is somewhat arbitrary, but the routing function is generally some form of the St. Venant shallow water equations. One such form, the kinematic wave model, has been shown (Woolhiser and Liggett, 1967) to be a valid approximation for most overland flow cases.

WEPP uses two methods of computing the peak discharge; a semi-analytical solution of the kinematic wave model (Stone *et al.,* 1992) and an approximation of the kinematic wave model. The first method is used when the WEPP is run in a single event mode while the second is used when the WEPP is run in a continuous simulation mode.

The kinematic equations for flow on a plane are the continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = v \qquad (17)$$

and a depth-discharge relationship

$$q = \alpha . h^m \qquad (18)$$

where h is the depth of flow (m), q the discharge per unit width of the plane ($m^3/m/s$), v the runoff or rainfall excess rate (m/s), α the depth-discharge coefficient by Chezy ($m^{1/2}/s$), m the depth-discharge exponent, and x the distance from top of the plane (m).

Both equations are solved analytically by the methods of characteristics (Eagleson, 1970) and rewritten as differential equations on characteristic curves on the x^{th} plane :

$$\frac{dh}{dt} = v(t) \qquad (19)$$

and

$$\frac{dx}{dt} = \alpha . m . h(t)^{m-1} \qquad (20)$$

These equations are solved together with the infiltration calculations by using a Runge-Kutta iteration scheme. The recession limb of the hydrograph is calculated until the routed runoff volume equals 95% of the total infiltration excess volume, or the discharge rate equals 10% of the peak discharge rate. The approximate method used for calculating the runoff volume, peak runoff rate, and runoff duration is based on the empirical relationships among these parameters developed from the kinematic wave simulations.

Erosion and deposition

The movement of the sediment along a hillslope is described on the basis of the steady-state sediment continuity equation (Foster and Meyer, 1972):

$$\frac{dG}{dx} = D_f + D_i \tag{21}$$

where x represents distance down-slope (m), G the sediment load (kg/s/m), D_f the net rill detachment (kg/s/m) and Di is the interrill erosion rate (kg/s/m^2).

The interrill erosion rate is assumed to be independent of distance, which means that it occurs at a constant rate down the slope. Rill erosion, D_f, is positive for detachment and negative for deposition.

The interrill detachment, Di, is calculated from:

$$D_i = K_{iadj} \times L \times q \times SDR_{RR} \times F_{nozzle} \times (r_s/w) \tag{22}$$

with K_{iadj} the adjusted interrill soil erodibility (kg.s/m^4), l/the effective rainfall intensity (m/s), q the interrill runoff rate (m/s), SDR_{RR} the sediment delivery ratio as a function of the random roughness, the row side-slope, and the interrill sediment particle size distribution, F_{nozzle} an adjustment factor to account for sprinkler irrigation nozzle energy variation, and r_s and w the rill spacing and width (m) (Foster *et al.,* 1995).

Erosion processes in rills are determined by:

$$D_c = K_r \cdot (\tau_f - \tau_c)(23) \tag{23}$$

where Dc is the detachment capacity of rill flow (kg/s/m^2), Kr the rill erodibilty of the soil (s/m), τ_f the flow shear stress acting on soil particles (Pa) and τ_c the critical shear stress to initiate particle detachment (Pa). Rill detachment is zero if the shear stress is less than the critical shear stress of the soil.

The interrill erosion rate is always greater than or equal to zero and is added to the rill erosion rate. A rill spacing of 1 m is assumed if no rills are specified by the user. Whether detachment or deposition occurs in a rill segment is decided by the sign of the rill erosion rate D_f:

For erosion

$$D_f = D_c \cdot \left(1 - \frac{G}{T_c}\right) \quad (if\ G < T_c) \tag{24}$$

For deposition

$$D_f = \frac{\beta \cdot v_f}{q} \cdot (T_c - G)\ (if\ G \geq T_c) \tag{25}$$

where D_f is the net detachment or deposition, raindrop-induced, turbulence coefficient (assigned a value of 0.5 for rain-impacted rill flows), v_f is the effective transport capacity of rill flow (kg/s/m^2), G is the sediment load (kg/s/m^2), and T_c is the transport capacity (kg/s/m). β is the fall velocity for sediment particles (m/s) calculated by Stoke's Law and q is the discharge per unit width (m^2/s).

WEPP uses a simplified form of the Yalin (1963) transport capacity equation developed by Finkner *et al.* (1989)

$$T_c = k_t \cdot \tau_f^{3/2} \tag{26}$$

where T_c is the transport capacity (kg/m/s), k_f the transport coefficient (m$^{1/2}$.s^2/kg$^{1/2}$) and τf the hydraulic shear acting on soil (Pa).

5.3.5 Model calibration

Model calibration is the first stage of testing or tuning the model to a set of field data not used in the original construction of the model. Such tuning is to include a consistent and rational set of theoretically defensible parameters and inputs. Model calibration is actually the process by which one obtains estimates for the model parameters through the comparison of field observations and model predictions (Himesh *et al.,* 2000).

The model calibration was carried out for a 2 ha large agricultural watershed (catchment 25) where runoff and soil loss data were observed in 2009 and 2010. Data from January 2009 to July 2010 were available. Climate data collected with the automatic weather station were used to build the climate input file and the model was run with existing land-use and soil information.

5.3.6 Soil conservation measures

In the Dhrabi watershed the impact of soil conservation measures and interventions should be estimated. For this study, stone Überfalle were used as interventions for terraces. Under the current systems, the terraces fail when heavy rainstorms occur. This is mainly caused by hydraulic shear failure of the soil under saturated conditions. The disturbance of soil organisms can aggravate the impact. Figure 5.21 shows such terrace failures which cause an increase in surface runoff and soil erosion especially in the Pothwar area.

To reduce this problem, stone spillways were designed and installed in some areas of the watershed (Figures 5.22 and 5.23). The idea is to retain water in the terrace until a

Figure 5.21. Soil hydraulic shear failure at the edge of a terrace

certain rainfall amount is reached (without overboarding the terrace), and then to divert the excess rainfall in a non-erosive way. Firstly this increases the infiltration and improves the amount of plant available water and secondly it reduces soil erosion by reducing the kinetic energy of the runoff. On average a water height of between approximately 10 cm and 15 cm can be held back in the fields.
It was assumed that by using the stone spillways a heavy rainstorm of 100 mm would be retained on the terrace and would not overboard. Such rainstorms can occur during the monsoon. The water should infiltrate within 6 hours, which leads to an infiltration rate of 16.7 mm/hour or 4 m/day.

For the WEPP simulations, the saturated hydraulic conductivity of the soil units which form part of the agricultural area was increased to 15 mm/hour. To obtain the soil map for estimating the erosion rates with the soil conservation measures, the original soil map was overlaid with the land-cover map. Soil units which belong in both categories were assigned an effective hydraulic conductivity of 15 mm/hour.

Figure 5.22. Stone spillway to divert excessive rainfall in a non-erosive way

Figure 5.23. System of stone terraces

5.4 Results and discussion

5.4.1 Input parameters for RUSLE

Rainfall erosivity (R-factor)

The necessary data for the rainfall in Dhrabi watershed was provided by a rain gauge near Ratta village in the north eastern part of the watershed. The annual precipitation map shows an increase in rainfall from the southwest to the northeast part of the area. But given the absence of another gauge in or near the watershed, values for R were taken as constant over the whole area.

Record collection began December 17, 2004 and ended August 11, 2007. This data was compared with the series of an existing totalizer at SAWCRI Campus. Unfortunately, reliable data related to the Dhrabi watershed was available for just two long-term periods from August 1, 2005 to November 31, 2005 and from November 1, 2006 to August 11, 2007. Data was also available for May 2005, March 2006, and April 2006. All these data appeared to be reliable. For the remaining time from December 2004 to August 2007, data series were not available, meaning that the gauge did not work, or that there were major discrepancies when comparing to the monthly rain data from the SAWCRI weather station.

With the data sets from August 12, 2005 to October 31, 2005 and from November 1, 2006 to August 11, 2007, a virtual one-year time series with a total rainfall of 774.6 mm was developed. This value is somewhat higher than the mean annual rainfall of 624 mm between 1977 and 2005 and the 693.7 mm/year calculated for the years 1998 to 2007.

The rainfall and runoff factor (R-factor) was calculated as 2474 MJ.mm/(ha.hour.year) after Laws and Parsons (1943), and as 2141 MJ.mm/(ha.hour.year) after Brown and Foster (1987), which was used for later equation of annual soil loss (A).

As the R-factor is derived from just one year's data and not based on long-term data, it is not a sound basis for soil loss estimations; it should be controlled and compared with data from other rain gauges. Two other gauges in Sohawa and Fatehjang were analyzed. The objective was to compare E_{I30} values and expand the time series in this way. A first comparison showed that the time courses of both Sohawa and Fatehjang were even shorter than those of Chakwal. Nevertheless, these monthly rainfall amounts were analyzed as well.

Comparing the Chakwal and Sohawa observations for the period October 2005 to July 2007 showed that the data for each gauge was reliable and these were used for the calculation of a correlation coefficient of 0.7398. For Chakwal and Fatehjang seven months were used, with a calculated correlation coefficient of 0.0799. The fact that both series had less available data meant that they were not useful for further investigations.

Estimation of the long term R-factor using the correlation between total rainfall and EI_{30}

Because of inadequate agreement between the three gauges, a long term R-factor was established using the correlation between the daily rainfall, Nday, and the total daily storm energy, E_{I30},day. Thus, the simulated R-factor was taken from the virtual year and split into values for each day. Certainly some rainfall events would have occurred over midnight. If such was the case, E_{I30}, as well as the total rainfall of the event, were apportioned to the first day the rain occurred. Then, with those day values, scatter plots were created for each month and a linear trend function, equation (27), and the associated correlation coefficient were calculated.

$$EI_{30,day} = N_{day} * k + d \qquad (27)$$

where d was set to 0, since the kinetic storm energy must be zero if no rainfall occurs and k is a constant factor. Thence, the total rainfall and EI_{30} of each month could be calculated as:

$$\sum EI_{30,day} = \sum_{Nday} * k \qquad (28)$$

or

Table 5.10. Monthly rainfall amounts and EI_{30} values derived for Chakwal

Month	k: gradient of trend function	Virtual year				1977 - 2005	
		Total monthly rainfall (mm)	EI_{30}	Calc. EI_{30}	R^2	N: mean monthly rainfall† (mm)	$EI_{30,month} = N_{month}*k$
January	0.080	1.5	0.10	0.12	0.970	27	2.16
February	1.4636	158.5	206.58	231.92	0.992	40	58.54
March	2.1003	126.0	280.47	264.66	0.927	56	117.62
April	0.4866	8.1	3.43	3.93	0.995	44	21.41
May	3.4388	42.1	120.32	144.81	0.937	26	89.41
June	3.340	108.4	312.98	362.06	0.997	54	180.36
July	2.5039	79.4	168.72	198.86	0.971	121	302.97
August	4.2666	93.7	374.12	399.65	0.981	146	622.92
September	11.818	66.5	609.70	785.78	0.970	68	803.62
October	1.8880	13.5	24.97	25.41	1.000	21	39.65
November	0.8157	40.0	27.13	32.84	0.946	6	4.93
December	0.4780	33.8	12.38	16.15	0.927	15	7.17
		771.4	2141.2			624	2250.76

† Average total monthly rainfall from 1977 - 2005 at SAWCRI weather station

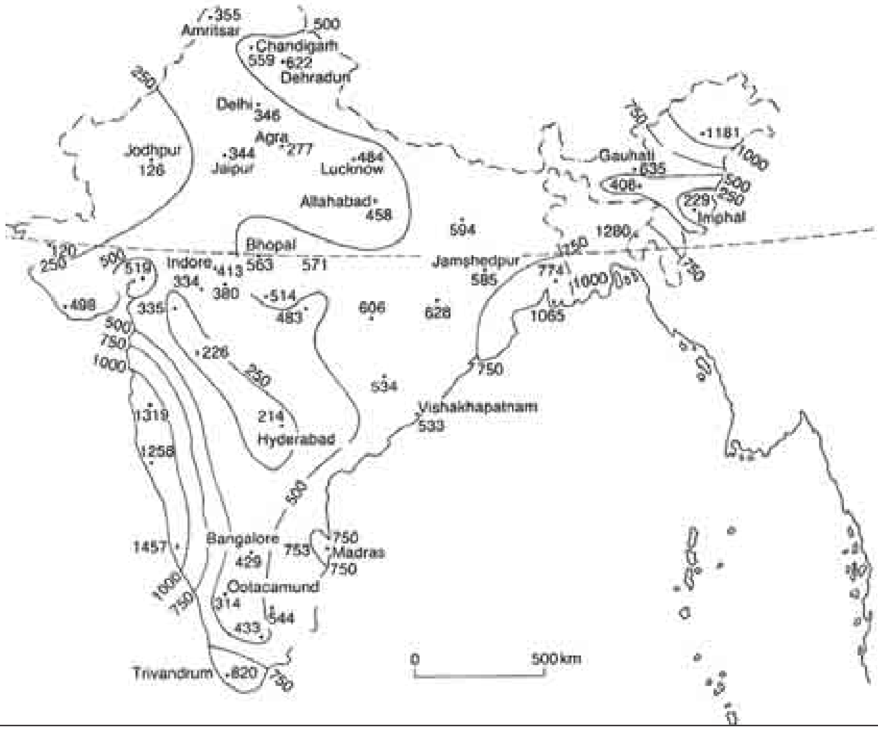


Figure 5.24. Annual EI30 (10^7 J.mm/(ha.hour.year)) for India (from Singh *et al.,* 1981)

Source: http://commons.wikimedia.org/wiki/File:India_annual_rainfall_map.svg
Accessed January 22, 2010

Figure 5.25. Annual precipitation of Pakistan based on data from the Pakistan Statistical Year Book 1988 found in Geology of Pakistan, Bender and Raza (1995)

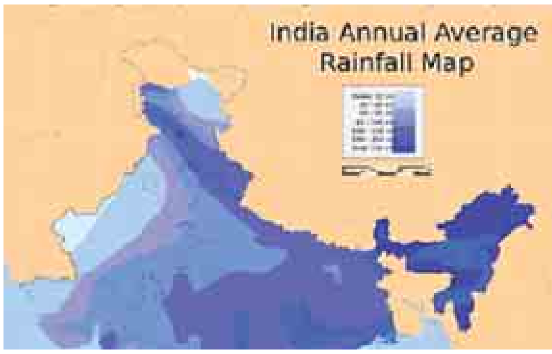


Figure 5.26. India annual average rainfall map

Table 5.11. Mean soil erodibility factor (K) for the different soil units

Landform No.	K
7	0.2768
13	0.4634
11	0.2460
17	0.3649
19	0.2607
20	0.2537
22	0.2305
36	0.1839
39	0.3202
40	0.1936

$$EI_{30,month} = N_{month} * k \qquad (29)$$

The analyses show a high correlation between daily rainfall and daily storm energy for each month, meaning that the rainfall events in these periods had the same characteristics. Therefore, for each month a corresponding monthly $EI_{30,month}$ was calculated based on the available average monthly rainfall of the watershed from 1977 to 2005. The overall

R-factor, as the sum of $EI_{30,month}$, was calculated to be 2250.76 MJ/ha.mm/hour. The detailed result is given in Table 5.10.

Comparison of EI_{30} Pakistan-India

Figure 5.24 shows the mean annual storm energy index (EI_{30}) for India, calculated by Singh *et al.* (1981). By executing a gross evaluation, the watershed is situated in the area of the red filled, black circle in the upper left area. Compared with the annual precipitation maps of Pakistan (Figure 5.25) and India (Figure 5.26), the contour lines of $200*10^7$ and $300*10^7$ J.mm/(ha.hour.year) can be developed in a northeast direction. The watershed is situated in between those two lines. The value 2141.2 MJ.mm/(ha.hour.year) is the same as $2141.2*10^6$ J.mm/(ha.hour.year); the result for the R-factor calculation fits with this map.

Soil erodibility (K-factor)

Soil properties can change slowly throughout the year. In the absence of a long-term field work program (samples were taken in a relative short period of time in February 2009) it was not possible to consider its variation. For this project the K-factor was considered as constant. Values of the mean K-factor for each landform are shown in Table 5.11. A graphical display of the spatial distribution of the C-factors in the watershed is shown in Figure 5.29 .

Topographic factor (LS-factor)

The topographic LS-factor was calculated based on the equations of Schäuble (1999) (Figure 5.27), Mitasova *et al.* (1998) (Figure 5.28), and McCool *et al.* (1987, 1989) using the digital elevation map of the area under investigation.

The LS-factors based on the equations of Schäuble (1999) and McCool *et al.* (1989) range from 0.1 to a maximum of 354.4 with a mean of 12.0. The equation of Mitasova *et al.* (1998) results in higher values ranging from 0 to 1561.7 with a mean of 26.7.

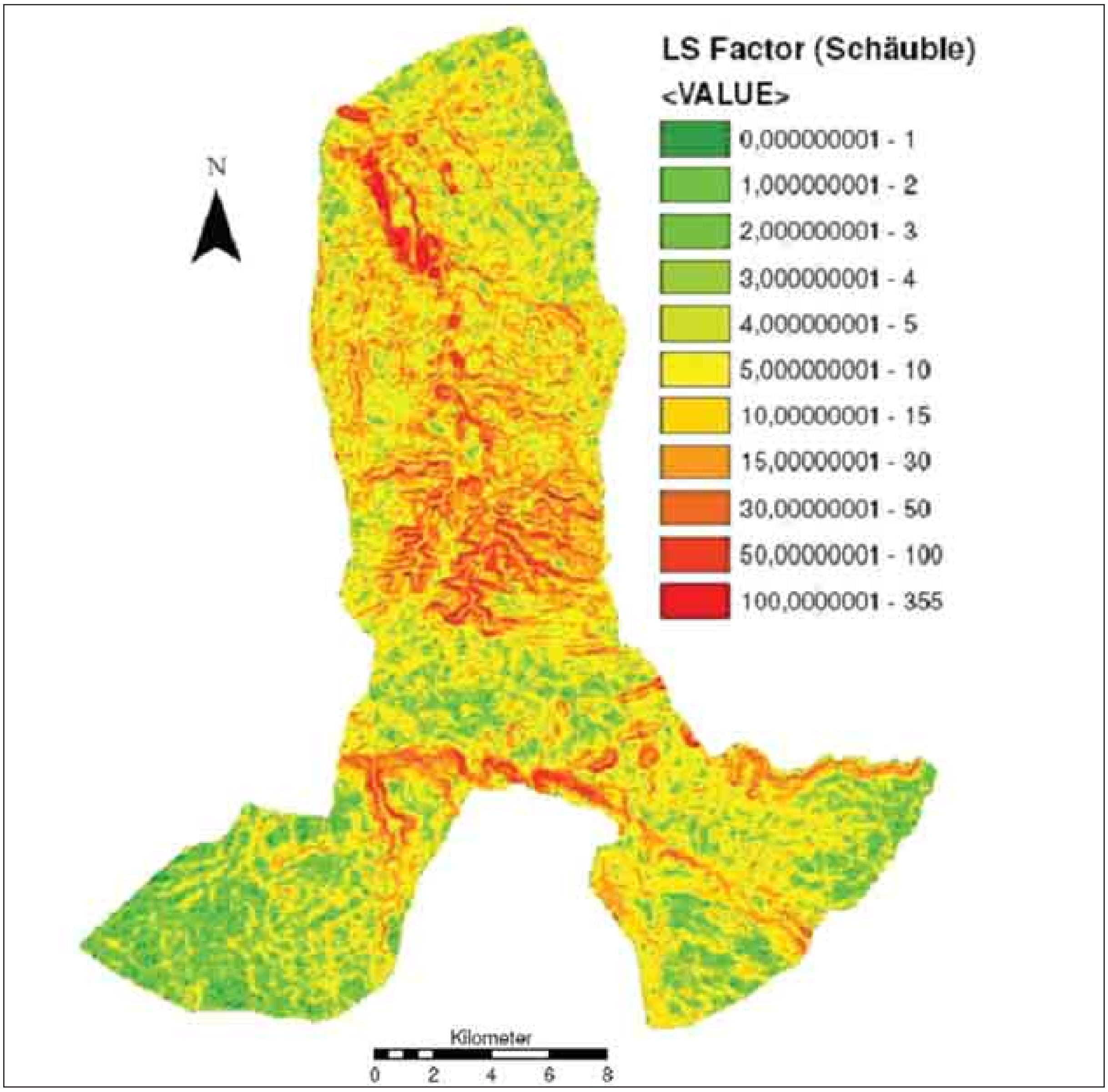


Figure 5.27. LS-factor map derived from Schäuble (1999)

Table 5.12. Main RUSLE input parameters for winter crops

High yield winter crops	Date of seeding: 1. November
Date of seeding: 1. October	Date of harvesting: 1. May
Date of harvesting: 15. May	Crop yield: 1,000 kg/ha
Crop yield: 1,600 kg/ha	Residue/yield ratio: 1.7
Residue/yield ratio: 1.7	

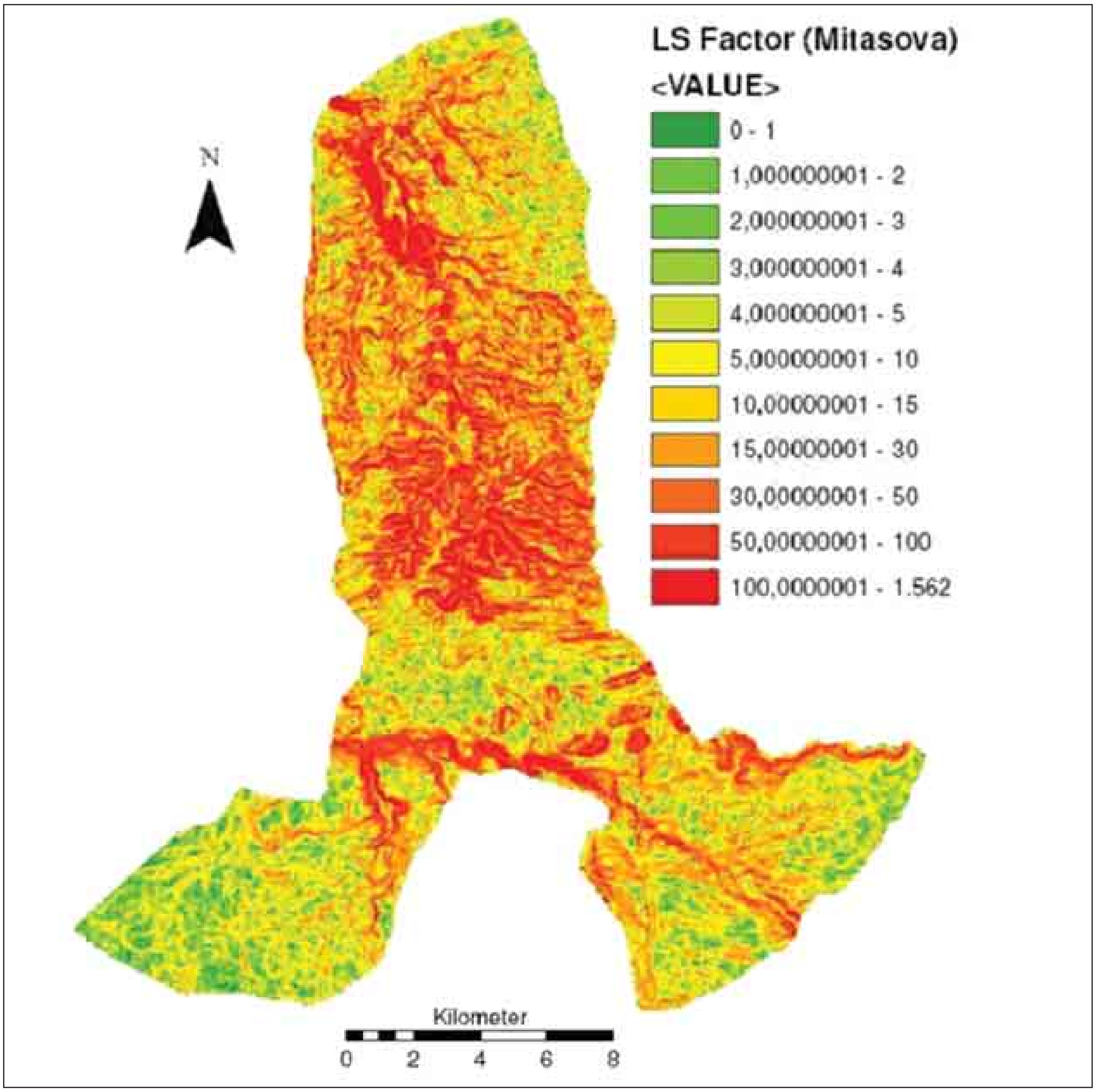


Figure 5.28. LS-factor map derived from Mitasova *et al.* (1998)

The LS-factors derived by Schäuble (1999) were used for further calculations because they were more realistic than those calculated by Mitasova *et al.* (1998).

Soil cover and management factor (C-factor)
According to the vegetation classification, the 11 vegetation classes stand for unique C-factors. For each class, the C-factor was calculated based on its properties. There was a difference in calculation between agricultural land and non-cultivated land. Therefore, these are described separately.

Agricultural areas
The main input parameters for the C-factor calculation of the cropping systems were obtained from BARI (Table 5.12). Based on

this data and on the results of the vegetation classification – ground truthing took place in February 2009 at selected areas within the watershed – it was separated into fields with 'high yield' and 'low yield' winter crop, both representing wheat, but under different growing conditions. These two classes were used because with the present NDVI images, a differentiation between varying crops was not possible. Adapted from this, other required values, like root mass and canopy cover development, etc., were taken from Tables 5.1 (wheat, winter) and 5.2 (winter small grain) of the RUSLE guide Chapter 5 (Renard *et al.,* 1997).

Non-cultivated areas

Non-cultivated areas were divided into six classes, following the results of the vegetation classification. To be able to follow the RUSLE procedure, it was necessary to make some assumptions about the above ground biomass, canopy cover, random roughness, and raindrop fall height after striking the canopy. The input data for those parameters were selected from knowledge of field research and from the Watershed Report 2008.

Above ground and root biomass

Calculation of the soil loss ratio was achieved using the above ground biomass data from Table 5.14 of the Watershed Report 2008 (ICARDA, 2009) and a visual determination of the canopy cover for each vegetation class. Biomass data (Table 5.13) are based on an investigation made in December 2008 on total forage (the biomass above ground) in different non-cultivated areas.

Table 5.13. Biomass and canopy cover in different landscapes of the investigated watershed

Kind of area	Biomass (kg/ha)	Canopy cover (%)
Flat area	782	48
Gentle slope	942	71
Steep slope	1,626	52
Gully area	1,100	61
Mean	1,112.5	58

Table 5.14. Above ground and root mass as input data for RUSLE

Vegetation class	#ID	CC (%)	Calculated BM = CC*k (kg/ha)	Ratio of root mass to above biomass*	Ratio of root mass in upper 4 inch to total root mass†	Root mass in top inch of soil (kg/ha/inch)
Very spare grass land	23	15	288	0.7	0.40	81
Dense forest	31	70	1343	2.5	0.56	1,880
Trees and bushes	32	45	863	2,5	0.56	1,208
Grass and bushes	33	35	671	2,5	0.56	940
Spare grass land	34	25	480	0,7	0.40	134
Dense vegetation near water (reed)	41	70	1343	0,.7	0.40	376

† Values taken from Table 5-4 of RUSLE (Renard et al., 1997).

Table 5.15. Input values for the canopy cover sub-factor: effective fall height H (feet)

Vegetation class and description		1 October	1 April
	H_{max} / H_{min}	H_{max}	H_{min}
#23 - very spare grassland	0.5	2	1
#31 - dense forest	1.0	10	10
#32 - trees and bushes	0.8	5	4
#33 - grass and bushes	0.6	3	1.8
#34 - spare grassland	0,5	2	1

Table 5.16. Input values for the canopy cover sub-factor: canopy cover Fc

Vegetation class and description		1 October	1 April
	Fc_{max}/Fc_{min}	Fc_{max}	Fc_{min}
#23 - very spare grassland	0.1	0.2	0.02
#31 - dense forest	0.5	0.7	0.35
#32 - trees and bushes	0.5	0.5	0.25
#33 - grass and bushes	0.2	0.4	0.08
#34 - spare grassland	0.1	0.3	0.03

Where there was a lack of a correlation between the measured biomass and the canopy cover, the mean values of these parameters was calculated and then used to generate a linear function of biomass to cover ratio. This function is

$$BM = CC * k \quad (30)$$

where BM is the total above ground biomass (kg/ha), CC the canopy cover (%), and k is the gradient of this linear function, calculated as $k = BM_{mean}/CC_{mean} = 1112.5/58 = 19.181$

Classes 31, 32 and 33 were defined as ‘south eastern grasses and forbs’; 23, 34, and 41 as ‘southern desert shrub’.

Canopy cover and effective fall height

During the field investigations, the mean canopy cover and mean plant height of the vegetation parameters were estimated by eye and recorded. With this basic data for each vegetation class, overall values for the maximum and minimum canopy cover and effective fall height were established.
The results are shown in Table 5.15 and Table 5.16.

Surface roughness

The surface roughness sub-factor for the non-cultivated areas was calculated as

$$SR = \exp[-0.66 (R_u-0.24)] \quad (31)$$

During the field investigations an overall roughness of 0.3 inch was observed in the non-cultivated areas. A relationship between this parameter and the landform classes was not evident. Rather, local geology suggested a higher roughness in the upper watershed, with its affiliation to the Tertiary period and the presence of limestone. Admittedly, the borders of the different geologic ages could not be assigned exactly and a closer investigation is not appropriate.

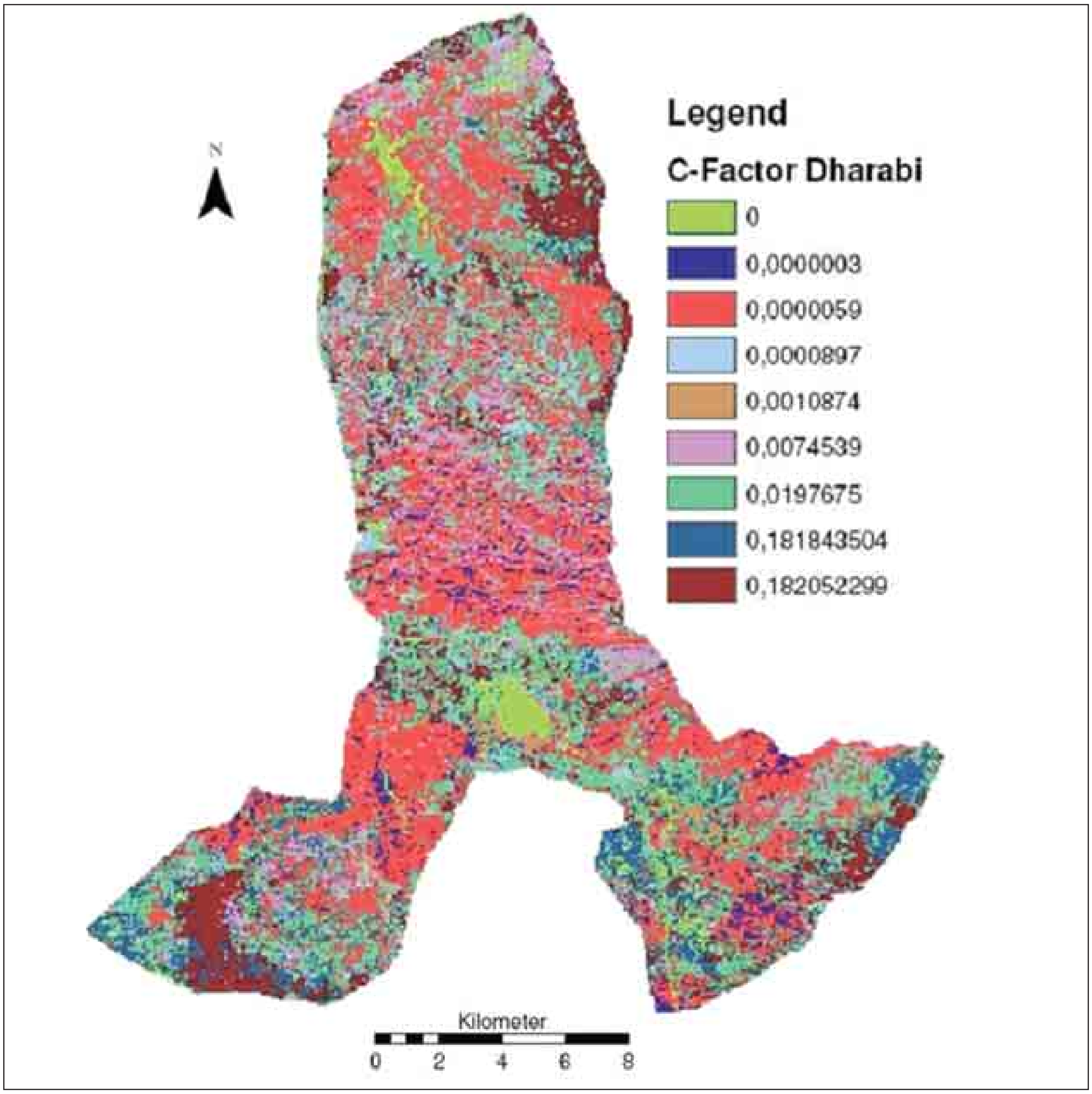


Figure 5.29. C-factor map of investigated watershed

Soil moisture sub-factor (SM)

The SM influences erosion by the immediate connection between soil moisture and infiltration rate. When soil is dry, more rainwater can infiltrate faster and less surface runoff occurs. As there is no equation for this factor the following formula was created to assess it:

$$SM = N_t/N_{max} \quad (32)$$

where Nt is the rainfall in current half-month period (mm) and Nmax is the maximum rainfall in a half-month period (mm). It embraces the fact that SM has a maximum count of 1 (when the soil moisture is nearly at field capacity), and is dependent on the medium-term rainfall, which here appears as

Table 5.17. C-Factors for each vegetation class

Vegetation class and description	C factor
#11 - buildings - streets	0
#21 - field with high vegetation	0.18205
#22 - field with spare vegetation	0.18184
#23 - very spare grassland	0.17655
#31 - dense forest	0.00052
#32 - trees and bushes	0.00762
#33 - grass and bushes	0.02047
#34 - spare grassland	0.14588
#35 - gravel, blank rock	0
#41 - dense vegetation near water	0.01436
#51 - water	0

the total rainfall in 15 (or 16) days (Renard *et al.,* 1997). The SM described in this chapter was also used for the agricultural land.

Cover management factor (C)
Based on these inputs, the cover management factor was calculated for each vegetation form (Table 5.17). Surprisingly, vegetation class #21 appears with a higher C-factor than #22. A detailed analysis showed that these fields are less disturbed during autumn and winter and therefore have greater strength against soil erosion in summer.

5.4.2 Input data for WEPP

Climate parameters
The WEPP model requires a climate file that contains monthly climate data – average maximum temperature, average minimum temperature, average monthly solar radiation, and average monthly precipitation. The file also contains daily data – precipitation amount, duration of precipitation, the ratio (time to rainfall peak)/(rainfall duration), the ratio (maximum rainfall intensity)/(average rainfall intensity), maximum daily temperature, minimum daily temperature, daily solar radiation, wind velocity, wind direction, and dew point temperature. The WEPP model uses CLIGEN (Climate Generator) which is a stochastic weather generation model. The climate parameters were obtained from the weather station in Islamabad. The rainfall data was then transformed into a PAR file, and was later generated in the WEPP as a climate file of CLIGEN (Figure 5.30). A climate input file for a period of 100 years was generated.

Soil input parameters
The physical and chemical properties of the soil were analyzed in the laboratory. The results showed that most soil types consisted of sand particles (more than 50%) and clay particles (not exceeding 20%) (Table 5.18).

The values for the 'baseline' effective conductivity (Kb) may be estimated using the following equations:
For soils with ≤ 40% clay content:

$$K_b = -0.265 + 0.0086*SAND^{1.8} + 11.46 * CEC^{-0.75} \quad (33)$$

For soils with > 40% clay content:

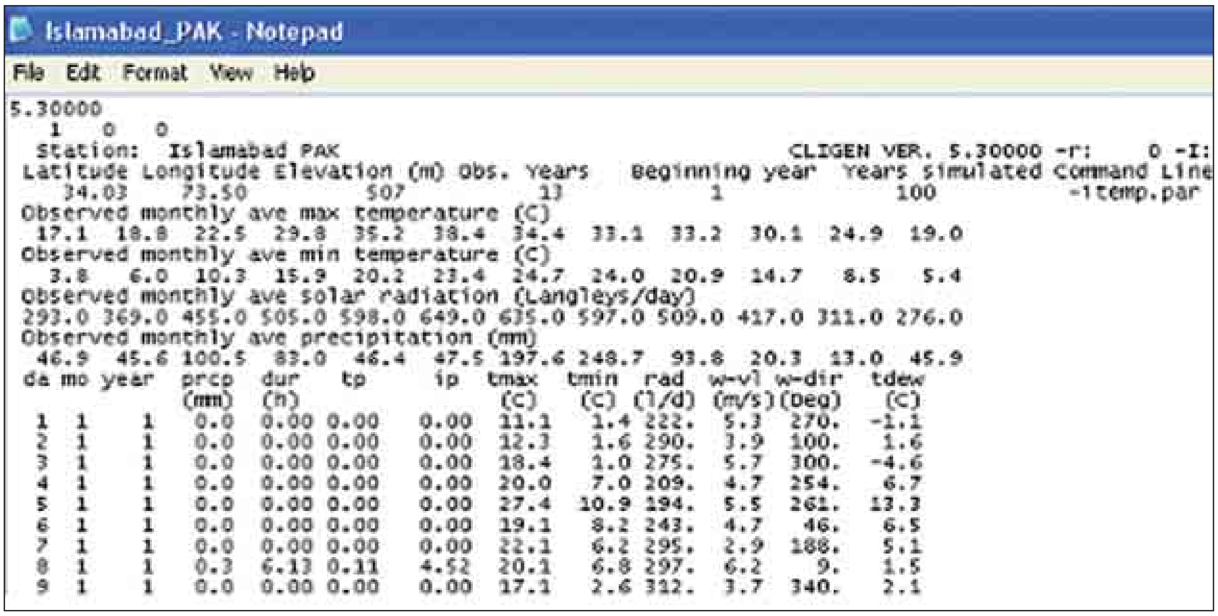
$$K_b = 0.0066\exp(244/CLAY) \quad (34)$$

where SAND and CLAY are the percent of sand and clay, and CEC (meq/100g) is the cation exchange capacity of the soil. In order for equation (33) to work properly, the input value for the cation exchange capacity should always be greater than 1 meq/100g.

For this research, the default Ke – a constant value – is estimated as a function of both abiotic and biotic components and may be computed using the following equations.

Table 5.18. Soil properties in the Dhrabi watershed

Number of soil type	Sand (%)	Silt (%)	Clay (%)	Organic (%)	CEC (meq/ 100 g)	Rock (%)	Albedo	Initial sat. level (%)
7	58	31	11	1.03	10	0	0.40	70
11	57	28	15	0.8	10	0	0.45	70
13	52	35	13	0.7	10	2	0.44	70
14	57	28	15	0.8	10	0	0.44	70
16	73	10	17	0.8	10	0	0.30	70
17	47	39	14	0.82	10	5	0.42	70
19	78	16	6	0.88	10	11.5	0.39	70
20	70	20	10	1.10	10	1.5	0.44	70
22	81	13	6	0.76	10	17.5	0.51	70
36	56	16	28	0.43	10	0	0.33	70
38	100	0	0	0.10	0	0	0.33	70
39	53	32	15	1.51	10	50	0.35	70
40	86	14	0	1.37	10	0	0.40	70



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5.30000
   1    0    0
  Station:  Islamabad PAK                                   CLIGEN VER. 5.30000 -r:     0 -I:
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line
    34.03    73.50          507          13               1             100         -1temp.par
 Observed monthly ave max temperature (C)
  17.1  18.8  22.5  29.8  35.2  38.4  34.4  33.1  33.2  30.1  24.9  19.0
 Observed monthly ave min temperature (C)
   3.8   6.0  10.3  15.9  20.2  23.4  24.7  24.0  20.9  14.7   8.5   5.4
 Observed monthly ave solar radiation (Langleys/day)
 293.0 369.0 455.0 505.0 598.0 649.0 635.0 597.0 509.0 417.0 311.0 276.0
 Observed monthly ave precipitation (mm)
  46.9  45.6 100.5  83.0  46.4  47.5 197.6 248.7  93.8  20.3  13.0  45.9
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)               (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1    1   0.0  0.00 0.00   0.00  11.1   1.4 222.   5.3  270.  -1.1
  2  1    1   0.0  0.00 0.00   0.00  12.3   1.6 290.   3.9  100.   1.6
  3  1    1   0.0  0.00 0.00   0.00  18.4   1.0 275.   5.7  300.  -4.6
  4  1    1   0.0  0.00 0.00   0.00  20.0   7.0 209.   4.7  254.   6.7
  5  1    1   0.0  0.00 0.00   0.00  27.4  10.9 194.   5.5  261.  13.3
  6  1    1   0.0  0.00 0.00   0.00  19.1   8.2 243.   4.7   46.   6.5
  7  1    1   0.0  0.00 0.00   0.00  22.1   6.2 295.   2.9  188.   5.1
  8  1    1   0.3  6.13 0.11   4.52  20.1   6.8 297.   6.2    9.   1.5
  9  1    1   0.0  0.00 0.00   0.00  17.1   2.6 312.   3.7  340.   2.1
```

Figure 5.30. CLIGEN data

For plant communities with rill cover less than 45%.

$$K_e = 57.99-14.05*\ln(CEC) + 6.2*\ln(ROOT10) - 473.39*BASR^2 + 4.78*RESI \quad (35)$$

For plant communities with rill cover equal to or exceeding 45%.

$$K_e = -14.29 - 3.40*\ln(ROOT10) + 0.3783*SAND + 2.0886*ORGMAT + 398.64*RROUGH -27.39*RESI + 64.14*BASI \quad (36)$$

where Ke is effective hydraulic conductivity (mm/hour), CEC is the cation exchange capacity (meq/100 g), ROOT 10 is root biomass in the surface top 10 cm of the soil profile (kg/m^2), BASR is the fraction of the rill surface area with basal cover, RESI is the fraction of the interrill area covered by litter, SAND is the sand content (%), ORGMAT is the OM content (%) of the surface horizon, RROUGH is the random roughness of the soil surface (m), and BASI is the fraction of the interrill surface area with basal cover.
The estimates for baseline interrill erodibility (K_i), rill erodibility (K_r), and critical hydraulic shear (τ_c), based upon extensive evaluation of the WEPP cropland and rangeland erodibility experimental results, are determined from the following:

For cropland soils containing 30% or more sand, the equations are:

$$K_i = 2728000 + 192100*VFS \quad (37)$$

$$K_r = 0.00197 + 0.00030*VFS + 0.03863*EXP(-1.84*ORGMAT) \quad (38)$$

$$\tau_c = 2.67 + 0.065*CLAY - 0.058*VFS \quad (39)$$

where VFS is thievery fine sand content (%) and ORGMAT is the OM content (%) of the surface soil.

For cropland soils containing less than 30% sand, the equations are:

$$K_i = 6054000 - 55130*CLAY \quad (40)$$

$$K_r = 0.0069 + 0.134*EXP(-0.20*CLAY) \quad (41)$$

$$\tau_c = 3.5 \quad (42)$$

In equations (39) and (41) [9] and [10] , CLAY must be 10% or greater (if the value for CLAY is less than 10%, then use 10% in the equations).

For rangeland soils, the baseline erodibility equations are:

$$K_i = 1810000 - 19100*SAND - 63270*ORGMAT - 846000*\Theta fc \quad (43)$$

$$K_r = 0.000024*CLAY - 0.000088*ORGMAT - 0.00088*BDdry - 0.00048*ROOT10] + 0.0017 \quad (44)$$

$$\tau_c = 3.23 - 0.056*SAND - 0.244*ORGMAT + 0.9*BDdry \quad (45)$$

where Θfc is the volumetric water content of the soil at 0.033MPa (m^3/m^3), BDdry is the dry soil bulk density (g/cm^3).

Albedo is the fraction of the solar radiation which is reflected back to the atmosphere. This parameter is used to estimate the net radiation reaching the soil surface, which is then used in the evapotranspiration calculations within the WEPP water balance routines. Soil albedo for a dry surface can be estimated by an equation proposed by Baumer (1990):

$$SALB = 0.6/\exp(0.4*ORGMAT) \quad (46)$$

where SALB is the soil albedo value, ORGMAT is the OM content (%) in the surface soil (Flanagan and Livingston, 1995).

Table 5.19. Characteristics of agricultural crops in Dhrabi watershed

Land cover type	Initial canopy cover (%)	Initial Interrill cover (%)	Initial rill cover (%)	Initial roughness after last tillage (cm)	Canopy cover coefficient	Maximum canopy height (cm)	Maximum leaf area index
11	0	0	0	2	14	15	1
31	90	30	30	10	14	500	6
32	50	20	20	10	14	250	3
33	40	50	50	10	14	100	2
34	30	30	30	2	6	50	7
35	0	0	0	0	14	15	1
41	29	56	61	0.8	5	60	6
51	0	0	0	0	14	15	1

Table 5.20. Characteristics of land cover types in Dhrabi watershed

Land cover type	CW (H-fer)	CW (L-fer)	WC (H-fer)	WC (L-fer)	GMS	MGS
	C-C-W	C-C-W	W-W-C	W-W-C	G-G-M -G-G-S	M-G-G -S-G-G
Initial canopy cover (%)	0	0	0	0	0	0
Initial Interrill cover (%)	5	5	5	5	90	90
Initial ridge height after last tillage (cm)	8	8	8	8	2	2
Initial rill cover (%)	5	5	5	5	90	90
Initial roughness after last tillage (cm)	5	5	5	5	2	2
Canopy cover coefficient	5.2	5.2	5.2	5.2	12	12
Maximum canopy height	100	50	90	50	66	66
Maximum leaf area index	5	5	4.5	4.5	4.5	4.5

Note: W - winter wheat; C - canola; G - groundnut; M - millet; S - sorghum; H-fer - high fertilization; L-fer - low fertilization

Land cover information

Depending on the information derived from the ASTER satellite images, the WEPP input parameters were derived for each land-use class. The most important inputs with respect to soil erosion are the initial canopy cover, the initial rill cover and interrill cover, the canopy cover coefficient, maximum canopy height, maximum leaf area index, and surface roughness. For most of the agricultural crops these parameters are already defined and available in a WEPP database. In addition some of them were defined based on observations in the watershed area.

In Table 5.19 the input parameters for the land-use types are displayed. Figure 5.20 shows the input parameters for the agricultural crops. Figure 5.31 provides a graphical presentation of land use in the investigated watershed.

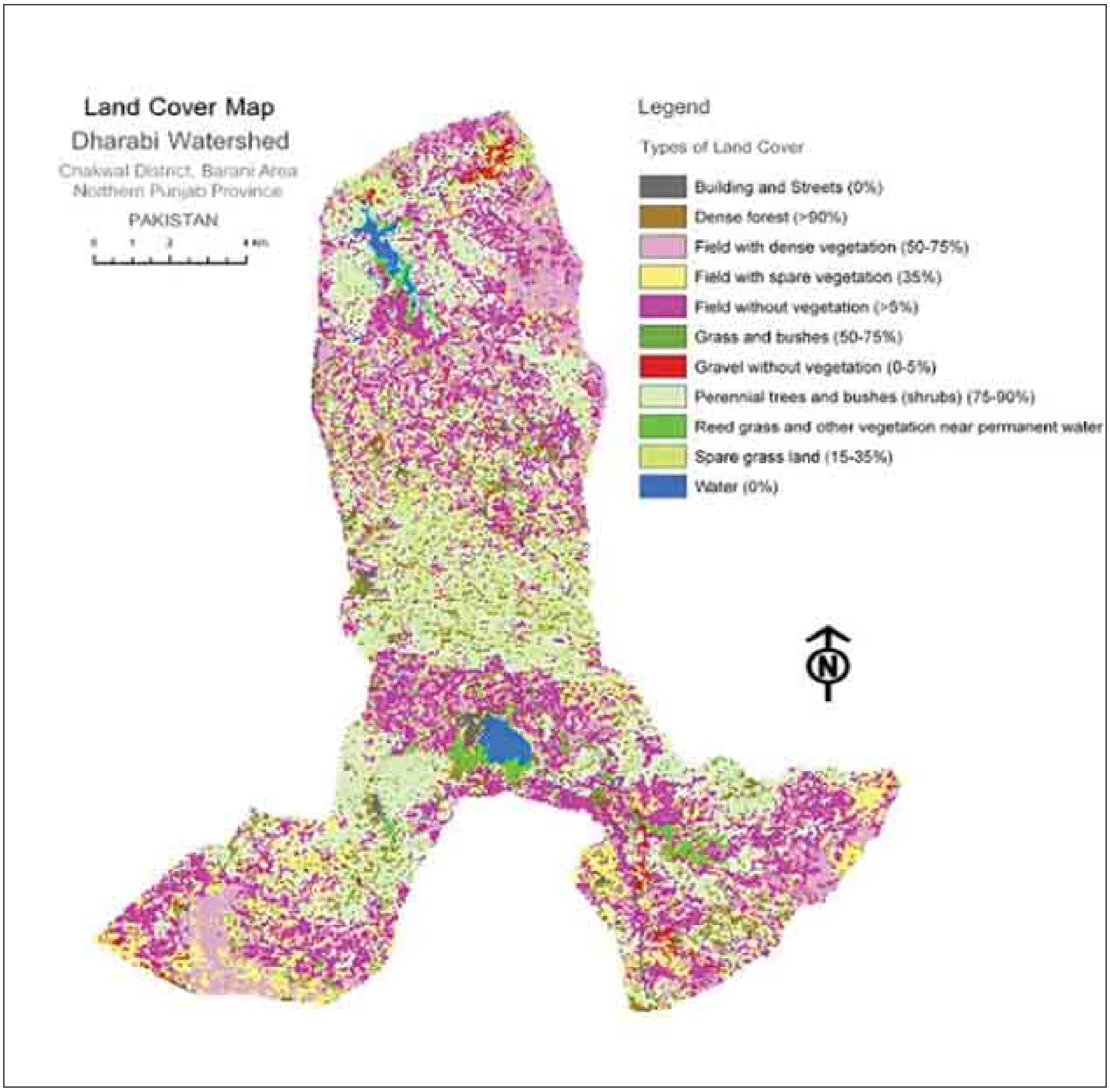

Figure 5.31. Land cover map of the Dhrabi watershed in the ArcGIS program

Note: 11 - buildings and streets; 21 - field with dense vegetation (50-75%); 22 - field with spare vegetation (35%); 23 - field without vegetation (<5%); 31 - dense forest (>90%); 32 - perennial trees and bushes (75-90%); 33 - grass and bushes (50-75%); 34 - spare grass land (15-35%); 35 - gravel without vegetation (0-5 %); 41 - vegetation along the water courses (>90%); 51 - open water area.

5.4.3 Model calibration and verification

The location of a small watershed (number 25) which was used as the representative source of field observation data is shown in Figure 5.32. The coordinates of the watershed outlet, which is also the measuring point, are 32.8946380 N and 72.7094070 E.

Table 5.21. Observed runoff and soil loss data from a small watershed (#25) used for calibration

2009	Rainfall (mm)	Rainfall intensity (mm/hour)	max I30 (mm/hour)	Runoff (mm)	Sediment yield (kg/ha)
Apr am	25.8	5.0	31.0	6.8	21
Apr pm	46.0	14.2	81.3	26.3	1343
Jul	38.9	37.7	54.9	7.0	127
Jul	32.3	15.7	41.2	3.1	71
Jul	31.8	13.9	56.4	4.8	97
Jul	22.6	7.7	37.6	2.6	2778
Jul	42.7	60.1	84.8	21.7	
Aug	26.9	33.7	49.2	2.0	103
Sep	25.4	13.4	37.6	0.7	73
Total	**292.4**			**75.0**	**4613**
2010					
Feb	38.9	13.9	31.0	2.8	154
May	60.5	10.5	89.4	24.8	2125
Jun	24.4	20.3	46.8	3.6	114
Jun	32.5	34.2	55.4	6.2	371
Jul	59.9	41.3	85.9	31.5	3526
Jul	25.9	30.5	43.2	1.9	115
Jul	19.3	24.4	31.5	0.6	12
Jul	21.3	28.8	38.6	5.7	592
Jul am	41.9	40.7	56.9	11.6	711
Jul am	16.3	41.7	83.3	0.3	
Jul pm	64.1	37.3	64.1	14.0	
Aug	26.2	15.0	47.8	3.6	199
Aug	10.9	27.3	54.6	0.5	6
Aug am	50.3	10.8	40.1	1.1	22
Aug pm	12.5	31.1	62.2	1.0	39
Total	**404.1**			**108.0**	**7986**

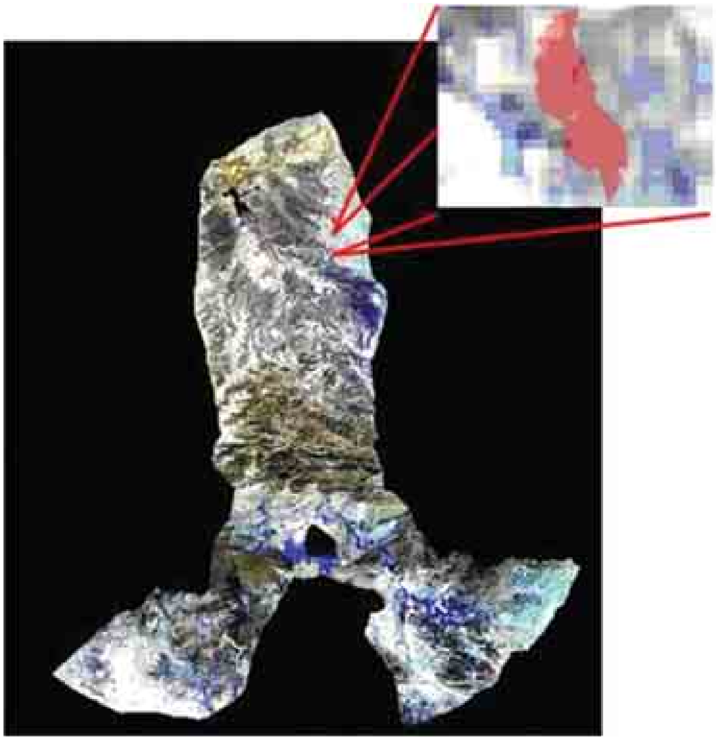

Figure 5.32. Location of the 2 ha agricultural watershed used for model calibration

In Table 5.21 rainfall amounts, average rainfall intensity, maximum 30-min intensity (I30), and runoff and sediment yield data, measured in catchment 25, are compiled for all observed erosive events in 2009 and 2010.

In 2009, nine erosive rainstorms were observed with an overall amount of 292 mm. The average rainfall intensities of these erosive rainfall events ranged between 5.0 mm/hour and 60.1 mm/hour with I30-values between 31.0 mm/hour and 84.8 mm/hour. The runoff events were measured with amounts between 0.7 mm and 26.3 mm, with an overall runoff of 75.0 mm (Table 5.21). Soil losses for the corresponding events ranged between 21 kg/ha and 2778 kg/ha. For the period of the investigation, the total sediment yield was 4.61 t/ha.

From January to September 2010, 15 erosive storms occurred with a total rainfall of 404.1 mm. Rainfall intensities were measured between 10.5 mm/hour and 41.7 mm/hour. The maximum I30 ranged from 31.0 mm/hour to 85.9 mm/hour. Overall runoff during the 2010 measuring period was 108 mm with runoff events ranging from 0.5 mm to 31.5 mm. The corresponding erosion rates were from 0 t/ha to 3.53 t/ha, resulting in a total soil loss during the investigation period in 2010 of 7.99 t/ha. Rainfall on July 29 (122.3 mm) and August 24 (62.8 mm) delivered relatively low runoff amounts – 25.9 mm and 2.1 mm, respectively – although the soil must have been wet from prior rainfall events. For these two events also very low erosion rates of 0.71 t/ha and 0.05 t/ha were observed.

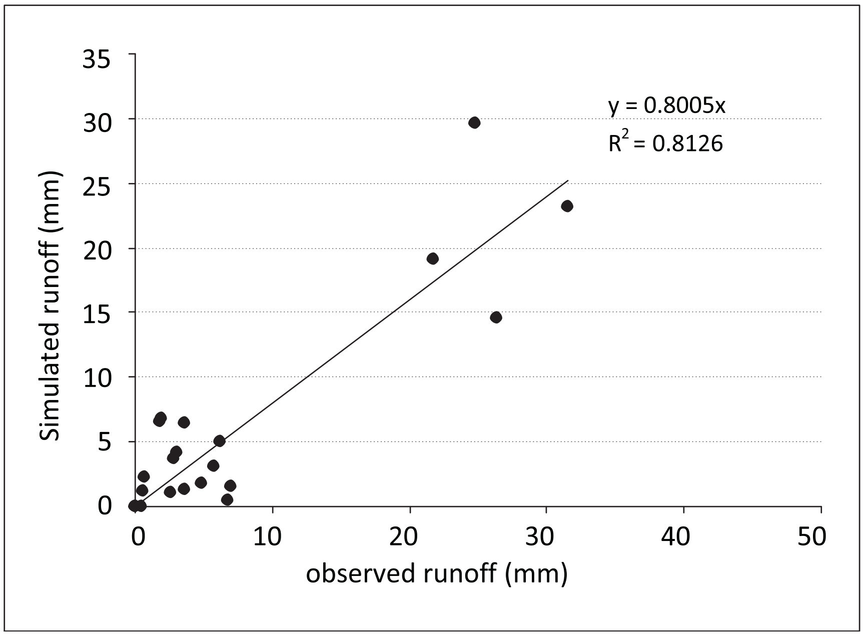

Figure 5.33. Relationship between observed and WEPP simulated surface runoff

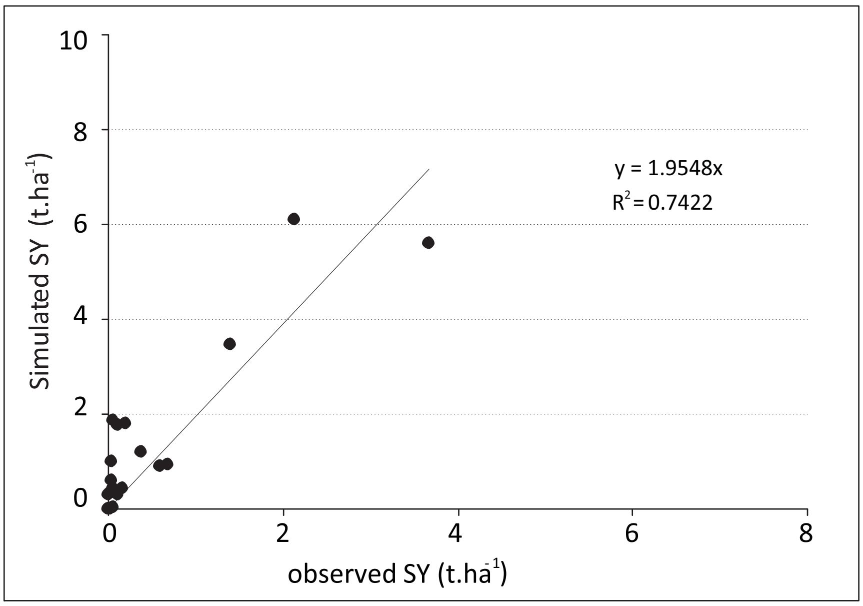

Figure 5.34. Relationship between observed and WEPP simulated sediment yield

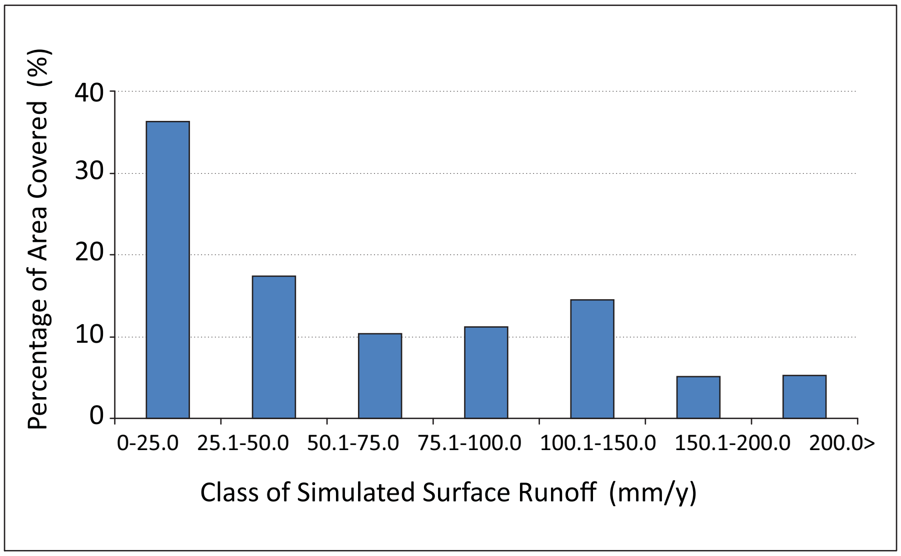

Figure 5.35. Distribution of areas with different surface runoff classes

The average simulated runoff value (6.42 mm) is close to the measured one (6.58 mm). Additionally, the mean values and the standard deviations exhibited good agreement. Nevertheless the WEPP model over-estimated sediment yield from the watershed.
The RMSE (Thomann, 1982) is defined as:

$$RMSE = \left(\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n} \right)^{1/2} \qquad (47)$$

where O_i and P_i are the observed and predicted values for the ith pair, and n is the total number of paired values. The smaller the RMSE, the closer the simulated values are to the observed ones. For all events, the RMSE is 13.5 mm for runoff and 4.5 t/ha for sediment yield. If the two events of July 29 and August 25, 2010 are not considered, the RMSE improves to 4.0 mm and 1.2 t/ha. Figures 5.33 and 5.34 provide graphical displays of the measured and simulated values of the surface runoff and sediment yield for the whole period of investigation. (Data for the two erosive events in 2010 are not included.) The graphs show that WEPP under-estimates surface runoff by about 20%, but over-estimates sediment yield. However, it must be remembered that field measurements suffer from errors.

The large resolution of the digital elevation model (DEM) also caused problems for the simulation results. For this research, a resolution 30 m was the best available, and the small watershed was covered by just 23 cells. This means that an area of 900 m^2 was represented by a single elevation point, which results in a longer slope length, but maybe a shallower slope than actually exists in the small watershed. These assumptions can have an effect, especially on the soil loss results.

5.4.4 Surface runoff calculations

The investigated watershed was divided into 319 sub-catchments which were connected by 129 channels. The representation of the watershed by the WEPP model resulted in an area of 157.01 km^2, which is smaller than the actual value of 194.9 km^2. The elevation ranged between 445 m and 898 m above sea level.

Table 5.22. Comparison between observed and simulated runoff and soil loss for all events in 2009 and 2010

Date	Precip Depth (mm)	Runoff (mm)	Sediment Yield (t/ha)	Runoff (mm)	Sediment Yield (t/ha)
Feb 13, 09	25.9	0.00	0.00	0.00	0.00
Apr 1, 09	11.7	0.00	0.01	0.00	0.00
Apr 5, 09	25.9	6.81	0.05	0.43	0.03
Apr 6, 09	48.5	26.34	0.67	14.58	0.93
Jul 1, 09	28.9	6.98	0.06	1.54	0.37
Jul 12, 09	32.3	3.10	0.04	4.15	1.00
Jul 13, 09	8.4	0.00	0.00	0.00	0.00
Jul 12, 09	30.2	4.80	0.05	1.79	0.45
Jul 28, 09	22.6	2.59	0.00	1.03	0.30
Jul 29, 09	42.7	21.68	1.39	19.13	3.46
Aug 8, 09	26.9	1.96	0.05	6.84	1.88
Aug 18, 09	14.5	0.00	0.00	0.00	0.00
Sep 2, 09	29.5	0.66	0.04	2.22	0.61
Feb 8, 10	38.9	2.80	0.15	3.74	0.45
May 7, 10	58.2	24.75	2.12	29.57	6.11
Jun 9, 10	24.4	3.55	0.11	1.34	0.29
Jun 29, 10	32.5	6.20	0.37	4.97	1.19
Jul 20, 10	59.9	31.50	3.66	23.21	5.61
Jul 21, 10	25.9	1.85	0.12	6.60	1.77
Jul 22, 10	18.5	0.55	0.02	1.25	0.34
Jul 27, 10	21.3	5.75	0.59	3.11	0.91
Jul 29, 10	122.2	25.85	0.71	87.07	21.78
Aug 13, 10	26.2	3.60	0.20	6.42	1.80
Aug 21, 10	10.9	0.45	0.01	0.00	0.00
Aug 24, 10	62.7	2.05	0.06	22.10	4.89
Sum		183.79	10.48	241.09	54.19
Average		7.35	0.42	9.64	2.17
s.d.		9.67	0.82	17.83	4.37
RMSE				13.50	4.37
Average w/o Jul 29,10 and Aug 24, 10		6.58	0.41	6.42	1.35
s.d.		9.08	0.84	8.42	1.78
RMSE				4.00	1.20

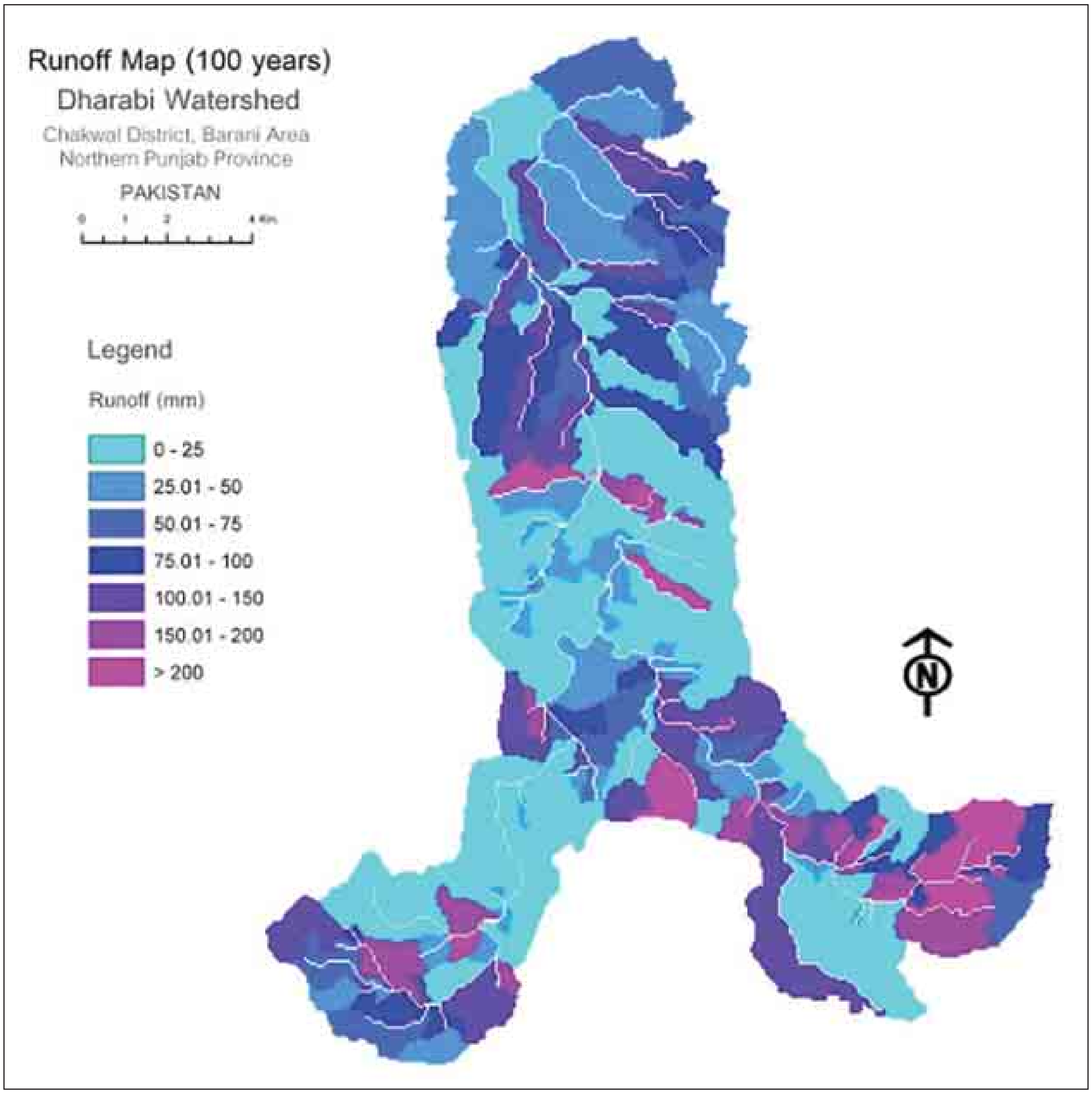

Figure 5.36. Surface runoff classification map for the Dhrabi watershed (simulation period 100 years)

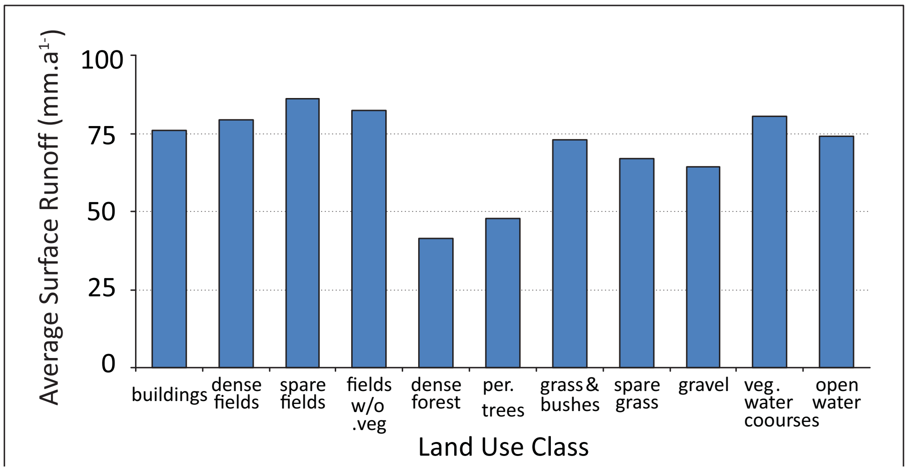

Figure 5.37. Average annual surface runoff from different land-use classes

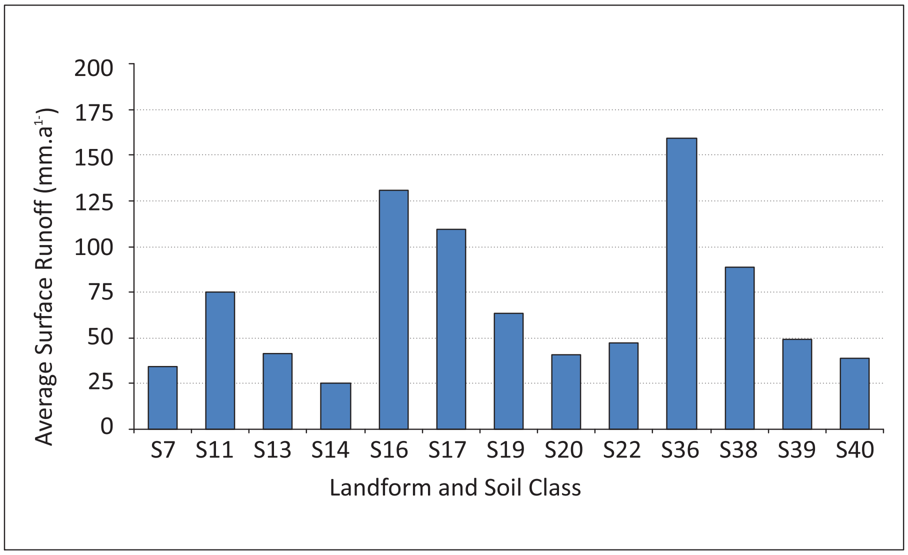

Figure 5.38. Average annual surface runoff from different landform/soil classes

The 100-year average surface runoff for present conditions without conservation measures is 66.4 mm/year. This result was obtained from the runoff values for each 30x30 m raster grid. Around one-third of the area (36%) delivered a runoff of up to 25 mm/year and more than one-half of the watershed (53%) did not exceed a value of 50 mm/year. In contrast, 25% of the watershed yielded a surface runoff of more than 100 mm and a 5% segment yielded more than 200 mm (Figure 5.35).

The surface runoff classification map (Figure 5.36) indicates the source areas of high surface runoff. A detailed analysis shows that areas with intensive cultivation (fields with dense, sparse, and without vegetation) contribute mainly to the high runoff (Figure 5.37). Dense forests and perennial

Table 5.23. Average, maximum and minimum runoff from the whole Dhrabi watershed and from agricultural-use areas only, both without and with soil conservation measures (SC) for different simulation periods

Parameter	Dhrabi watershed 100 years	Dhrabi watershed 2009		Agricultural area 2009	
		w/o SC	with SC	w/o SC	with SC
Average (mm)	66.4	24.9	18.1	29.5	18.5
Standard deviation (mm)	60.2	27.4	20.7	27.8	19.2
Maximum (mm)	262.6	154.7	154.7	154.7	154.7
Minimum (mm)	0.22	0.0	0.0	0.0	0.0
Median (mm)	29.1	12.8	10.5	20.5	11.4

Table 5.24. Maximum, minimum, and mean average potential soil loss as well as net soil loss in the watershed

Parameter	Schäuble	Mitasova
Potential soil loss (t/ha/year)		
Maximum	0	0
Minimum	27,188	122,772
Mean	561.0	1,222.7
Net soil loss (t/ha/year)		
Maximum	-53,782	-232,843
Minimum	24,008	100,190
Mean	13,6	22,3

Table 5.25. Average maximum and minimum soil loss rates from the whole Dhrabi watershed and from just the agricultural-use areas, with and without soil conservation measures (SC), for different simulation periods

Parameter (t/ha)	Dhrabi watershed 100 years	Dhrabi watershed 2009		Agricultural area 2009	
		w/o SC	with SC	w/o	with SC
Average	82.43	47.76	37.98	65.19	44.73
Standard deviation	210.56	114.93	93.69	128.63	90.13
Maximum	3,725.51	2,716.17	1,731.94	2,716.17	1,731.94
Minimum	0.00	0.00	0.00	0.00	0.00
Median	8.74	6.11	5.06	25.37	17.00

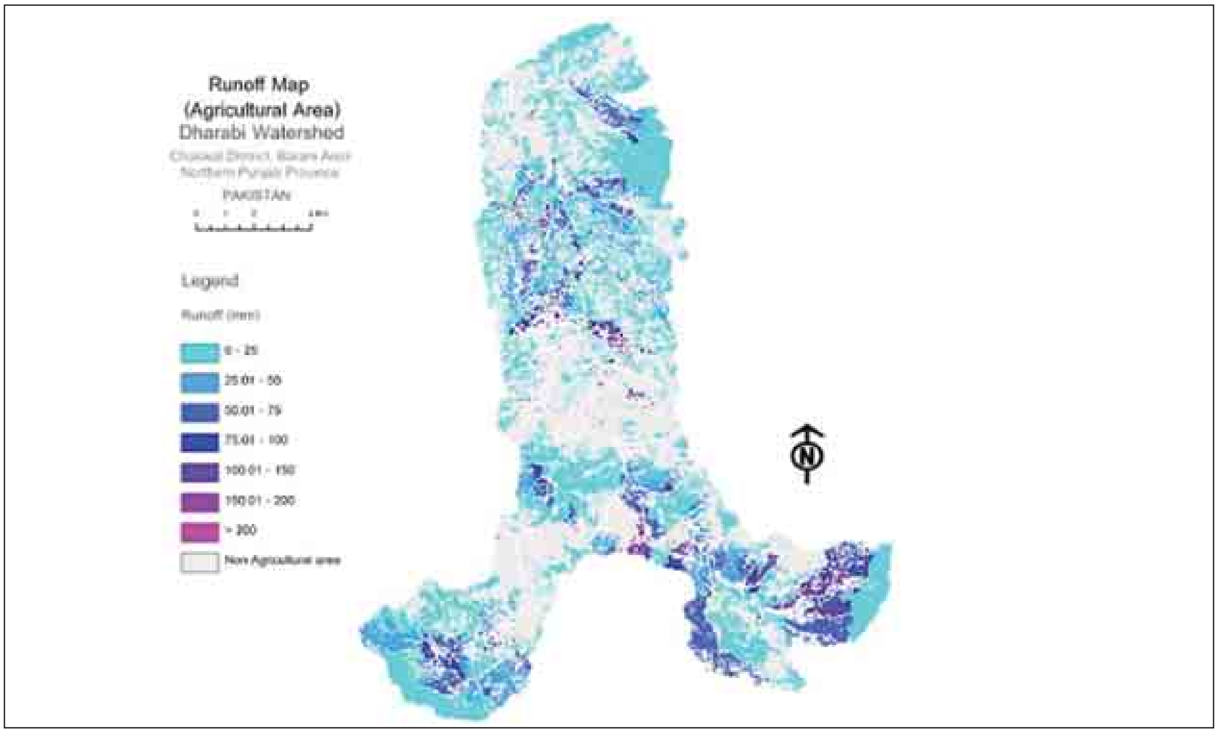

Figure 5.39. Average annual surface runoff from agricultural land without soil conservation measures (simulation period 2009)

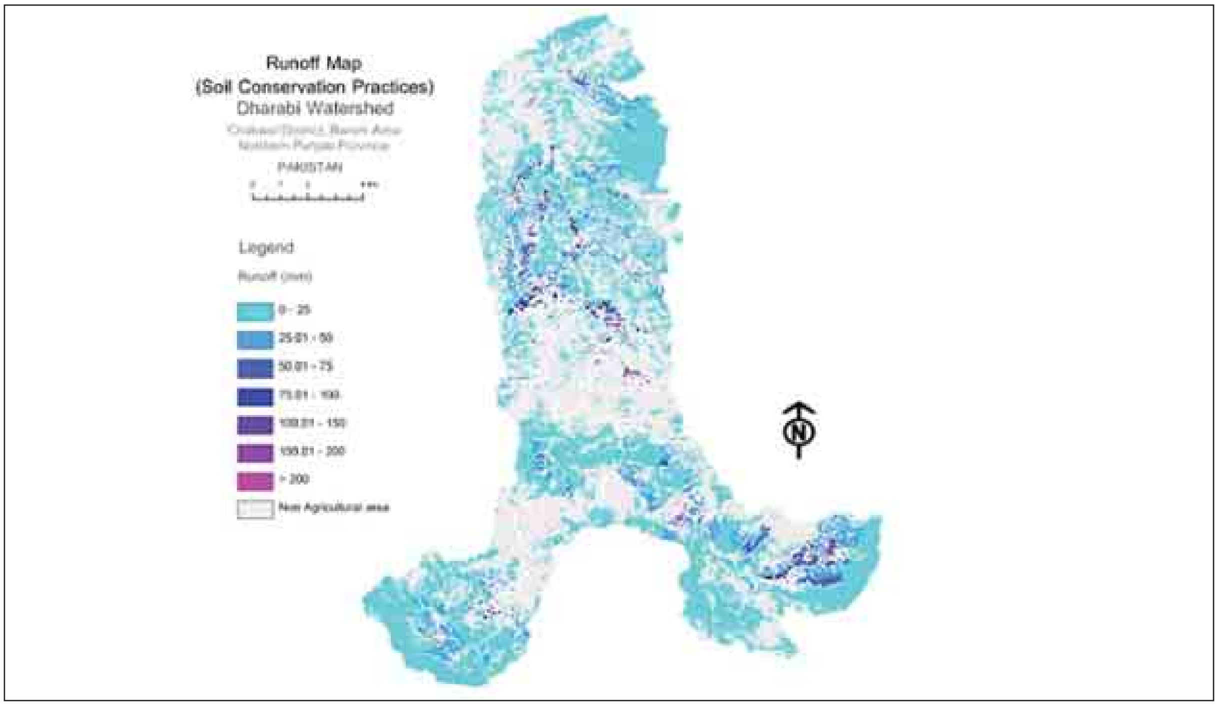

Figure 5.40. Average annual surface runoff from agricultural land with soil conservation measures (simulation period 2009)

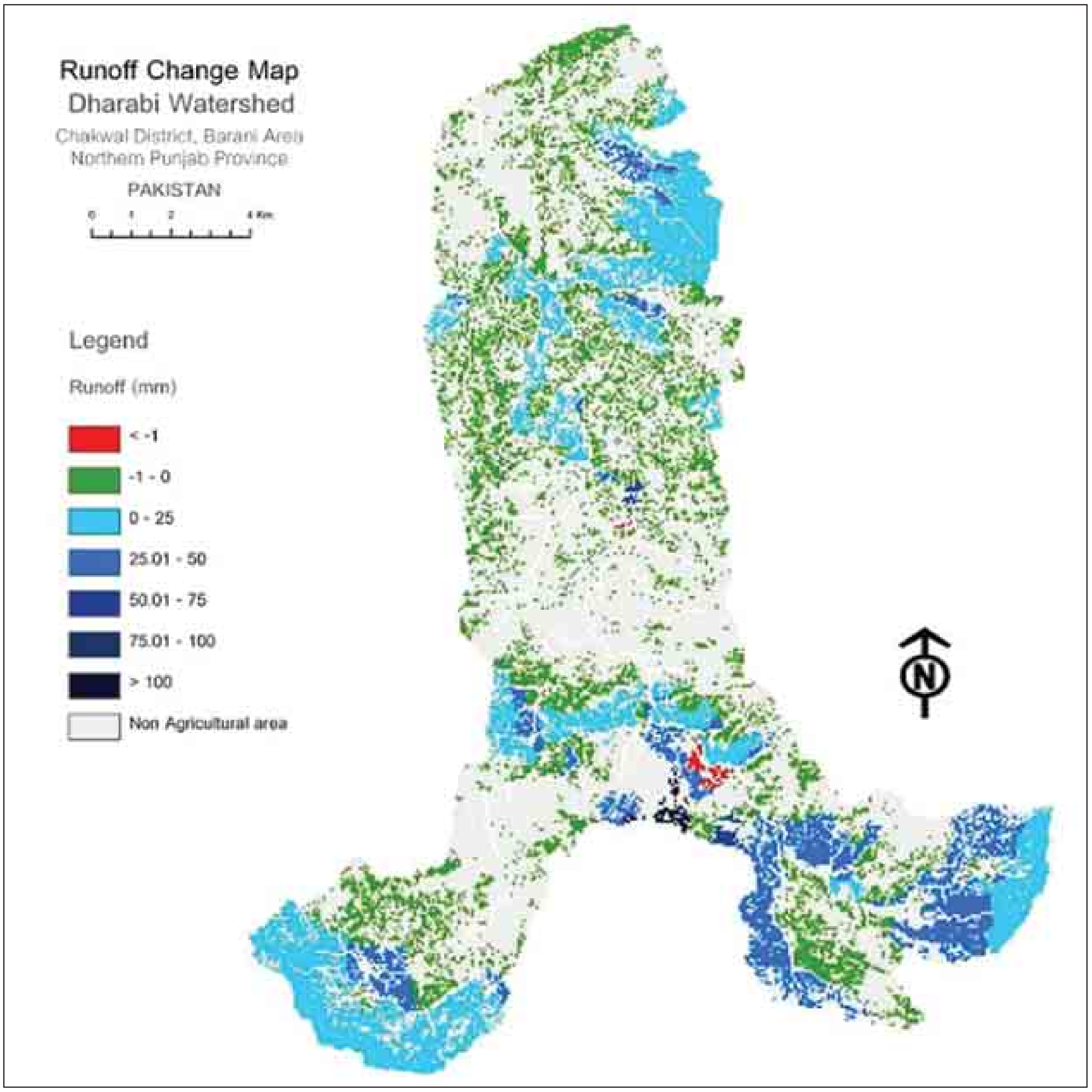

Figure 5.41. Runoff change map displaying the difference between annual runoff with and without soil conservation practices (simulation period 2009; negative values indicate a decrease in runoff, positive values indicate an increase)

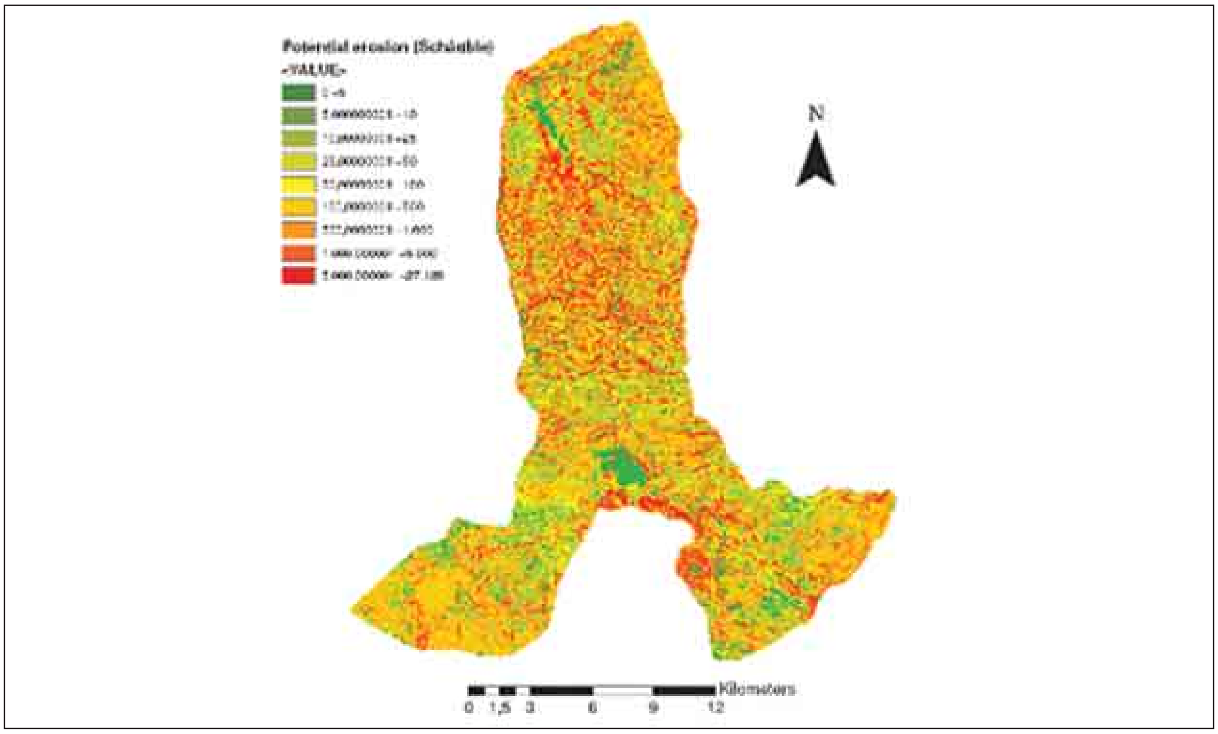

Figure 5.42 . Spatial distribution of potential soil loss derived by Schäuble (1999)

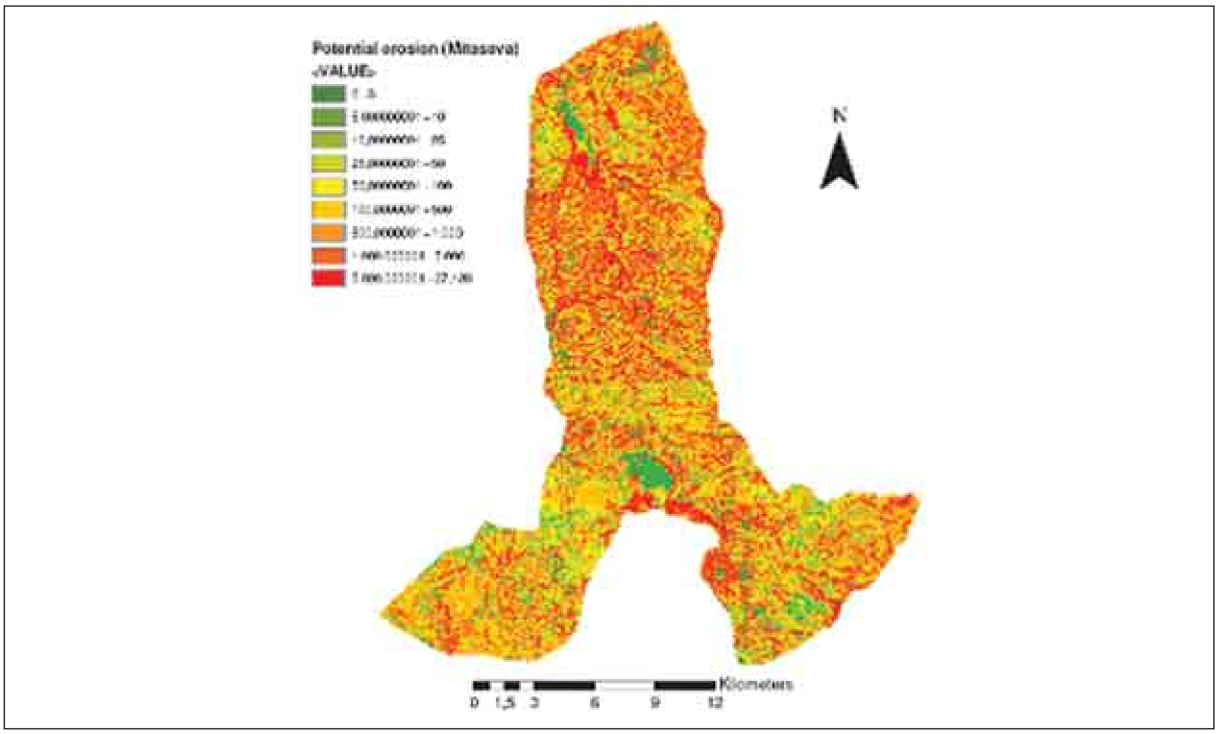

Figure 5.43. Spatial distribution of potential soil loss derived by Mitasova *et al.* (1998)

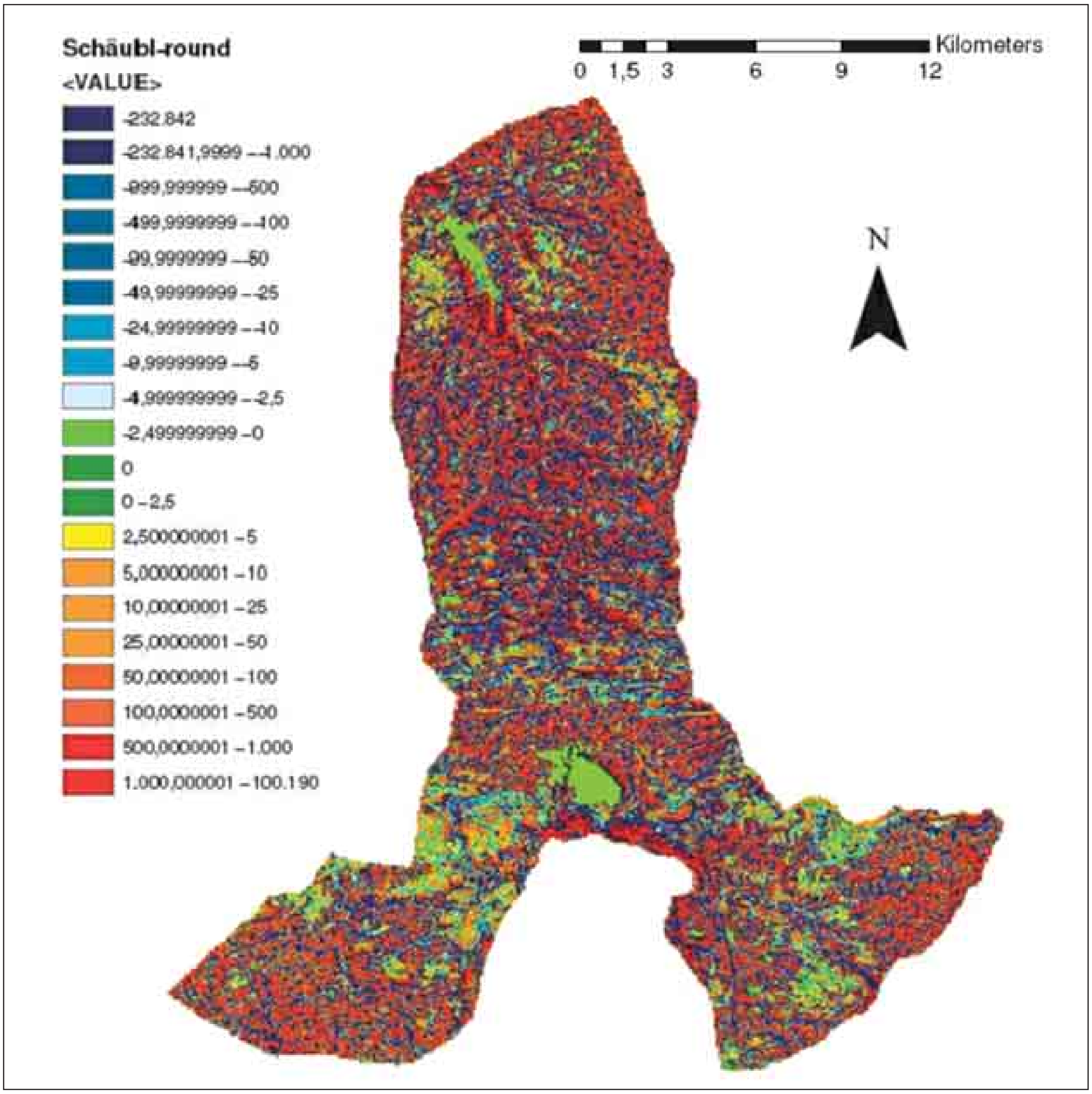

Figure 5.44. Net erosion map of the investigated watershed (based on LS-factor derived by Schäuble, 1999)

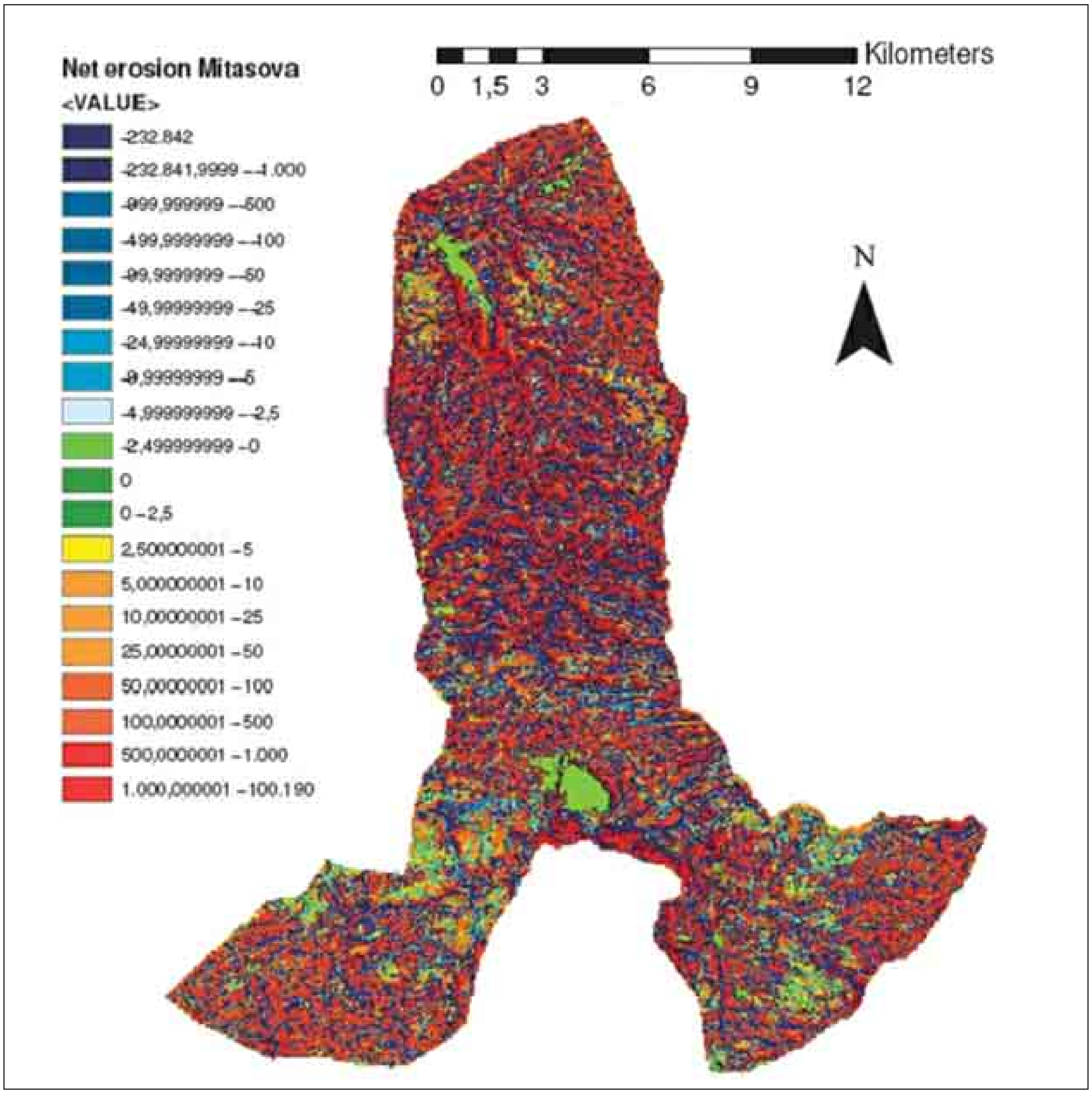

Figure 5.45. Net erosion map of the investigated watershed (based on LS-factor derived by Mitasova *et al.,* 1998)

trees and bushes have a high infiltration rate and therefore low surface runoff. In these areas, retention of rainwater will occur. For the different soils, landform/soil classes 11, 16, 17, 19, and 36 are the main contributors to the high surface runoff (Figure 5.38), but they cover only 15% of the total area. Low runoff volumes from soils classes 20, 22, and 39, which appear on about 75% of the watershed, are mainly responsible for the average value of 66.4 mm/year.

The simulation runs for 2009, with a precipitation of about 650 mm, delivered an average runoff of 24.9 mm from the whole watershed. When applying stone terraces as soil conservation measures (SCM) this value can be reduced by 28% to 18.1 mm. When considering only the agricultural-use area of the watershed, a reduction by 38%, from 29.5 mm to 18.5 mm, can be achieved with such protection measures (23).

By comparing Figure 5.39, which shows the runoff from agricultural fields without soil conservation measures, and Figure 5.40, which displays the runoff from agricultural fields with stone terraces, the effect of these soil conservation measures on surface runoff from agricultural areas can be seen. In both simulations, the stone terraces were installed on all agricultural-use fields in the Dhrabi watershed and the calculations were run with the climate data of 2009.

In the runoff change map (Figure 5.41) the difference between the runoff with and without soil conservation practices is displayed. In many of the agricultural fields a decrease in annual runoff is calculated. Nevertheless, in a small area south of the watershed near Kallar Kahar Lake, the installation of stone terraces lead to an increase in runoff.

5.4.5 Soil erosion and sediment yield calculations

RUSLE assessment

Soil loss in the watershed was calculated using the LS-factors derived by Schäuble (1999) and Mitasova *et al.* (1998). Average potential soil loss was 561 t/ha using the Schäuble derived LS-factor and 1222.7 t/ha using the Mitasova *et al.,* derived LS-factor. Within the watershed, high variability occurred with values up to

27,188 t/ha/year for Schäuble and 122,772 t/ha/year for Mitasova (Figures 5.42 and 5.43). To derive the net erosion, FLOW95 was applied again. To calculate erosion and deposition, the potential erosion maps were used as weight map for the function *weighted flow accumulation* in FLOW95. With this function, the program calculates the inflow and outflow of soil in each cell, based on the potential erosion maps. The results are shown in Figures 5.44 and 5.45.

Deforestation, urbanization, and other land-use activities can significantly alter the seasonal and annual distribution of stream flow within a watershed (Dunne and Leopold, 1978). Land-use change is expected to have a greater impact on gully erosion than climate change (Walling and Fang, 2003; Valentin *et al.,* 2005) which, therefore, represents an important sediment source in a range of environments and an effective links for transferring runoff and sediment (Poesen *et al.,* 2003). Land-use change effects on water, sediment, solutes, and nutrients can be evaluated (Slaymaker, 2003).

WEPP results

Soil loss

The soil loss results of the 100-year simulation run are displayed in Figure 5.46. Soil erosion occurs on 74.7% of the watershed and results

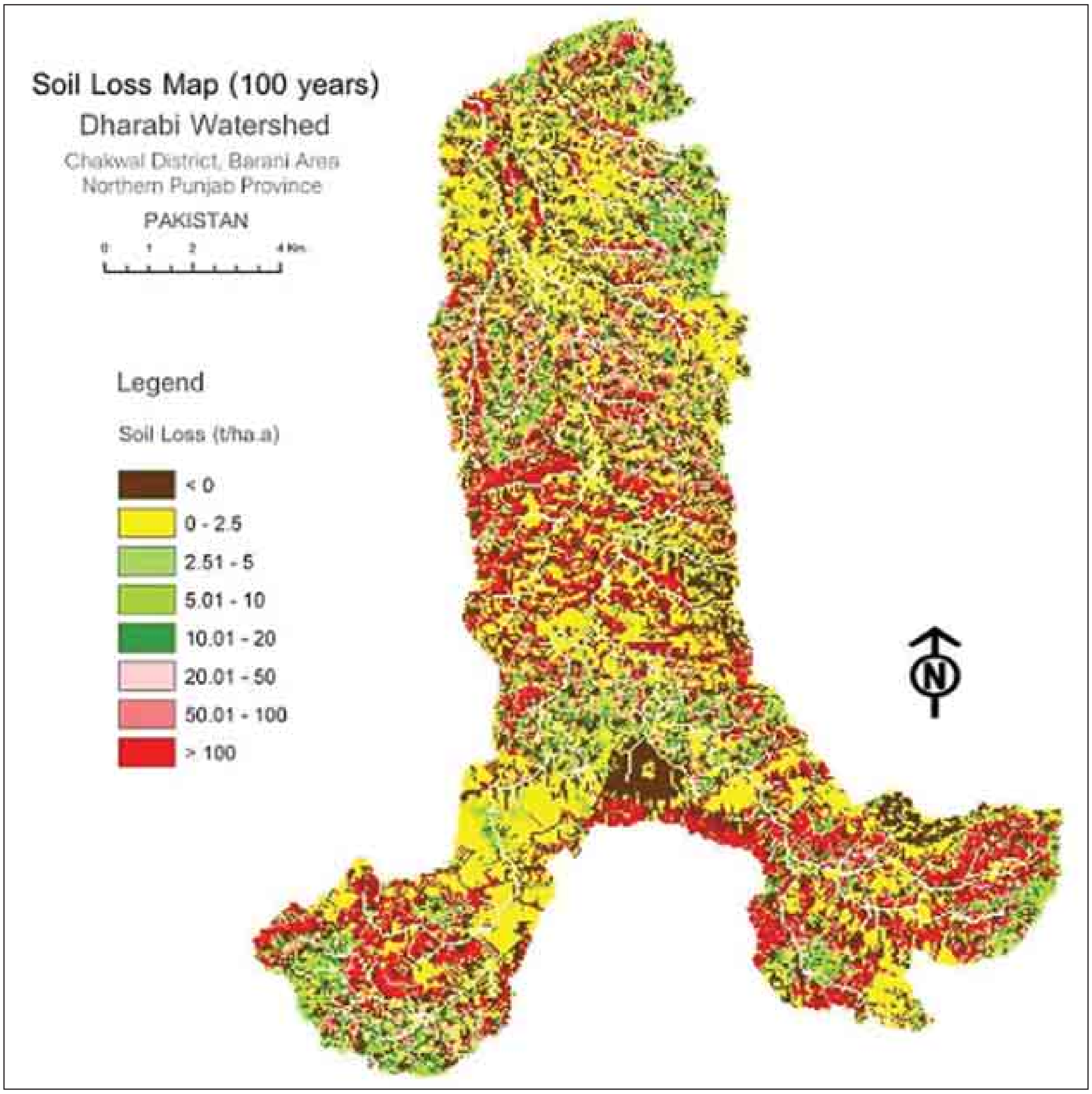

Figure 5.46. Spatial distribution of soil erosion in the Dhrabi watershed

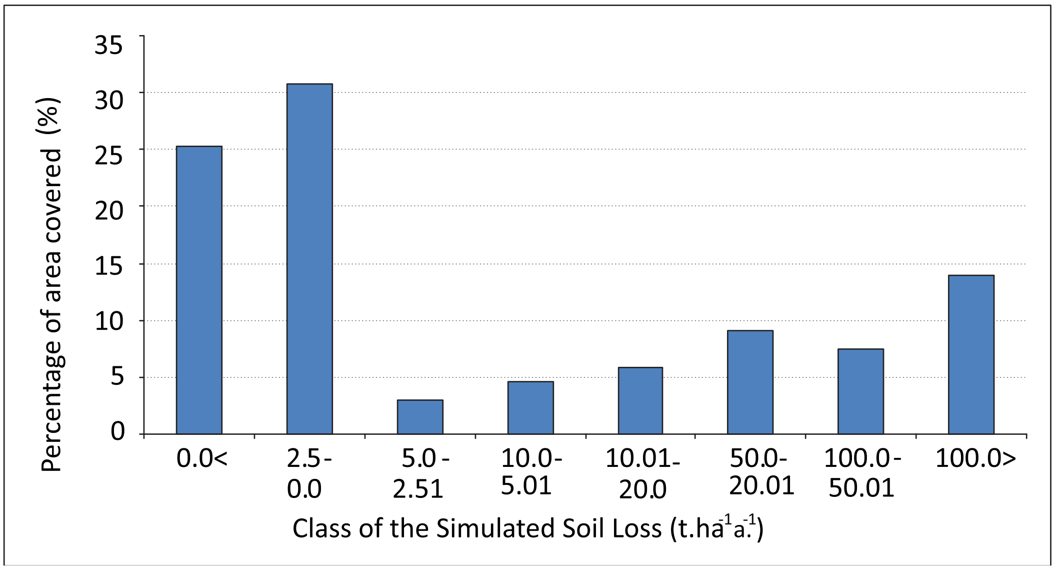

Figure 5.47. Distribution of different soil erosion classes in the investigated watershed

in an average annual rate of 82.42 t/ha. This relates to a mean loss of between 5 mm and 6 mm annually. On 25.3% of the Dhrabi watershed, some of the eroded soil is deposited resulting in a mean value of 97.11 t/ha.

Annual soil loss rates on 31% of the area are below 2.5 t/ha/year (Figure 5.47). This value relates to an annual soil loss of about 0.2 mm, which can also be considered as the annual soil formation rate. Therefore, this value is recommended by the OECD (2001) as the soil loss tolerance level. At the other extreme, the annual erosion rates for 22% of the watershed are calculated to exceed 50 t/ha/year.
Dense forests, perennial trees, and grassland are the best land-use systems in the watershed for protecting the soil against erosion (Figure 5.48). Agricultural fields with low fertilization or low biomass production, bare fields, as well as sparse grassland are major sediment sources. Most soils with high runoff potential (land-uses/soil classes 16, 17, 36) also show high erosion rates. Soils in rough broken land (39), which are widely spread in the watershed and cover 40% of the area, lead to the highest soil losses. The mean erosion rate for this land-use/soil class is calculated at 153 t/ha/year (Figure 5.49).

For the agricultural area, the soil loss rates, with and without implementation of soil conservation practices, are shown in Table 5.25 and Figures 5.50 and 5.51. Major reductions in soil loss as a result of the stone terraces are simulated in the central and the southern part of the watershed. This effect is displayed in the soil loss change map (Figure 5.52). On average, a reduction in soil erosion by 31% is calculated for the whole watershed and by 32% for the agricultural-use area.

Sediment yield
Not all detached and eroded soil reaches the watershed outlet. Depending on the topography and size of the watershed and sub-watershed, more or less sediment is deposited within it. The overall average amount of sediment leaving the total watershed amounts to 24.4 t/ha (Table 5.26). This means that only a small portion of the eroded soil leaves the area and reaches the

Table 5.26. Average maximum and minimum sediment yields from Dhrabi watershed as a whole and from agricultural use areas, with and without soil conservation measures, (SC) for different simulation periods

Parameter (t/ha)	Dhrabi watershed 100 years	Dhrabi watershed 2009		Agricultural area 2009	
		w/o SC	with SC	w/o	with SC
Average	24.40	13.08	8.19	14.72	8.25
Standard deviation	124.42	40.37	34.58	36.75	28.26
Maximum	1,240.20	672.40	672.40	672.40	672.40
Minimum	0	0	0	0	0
Median	4.30	0.70	0.60	1.60	1.00

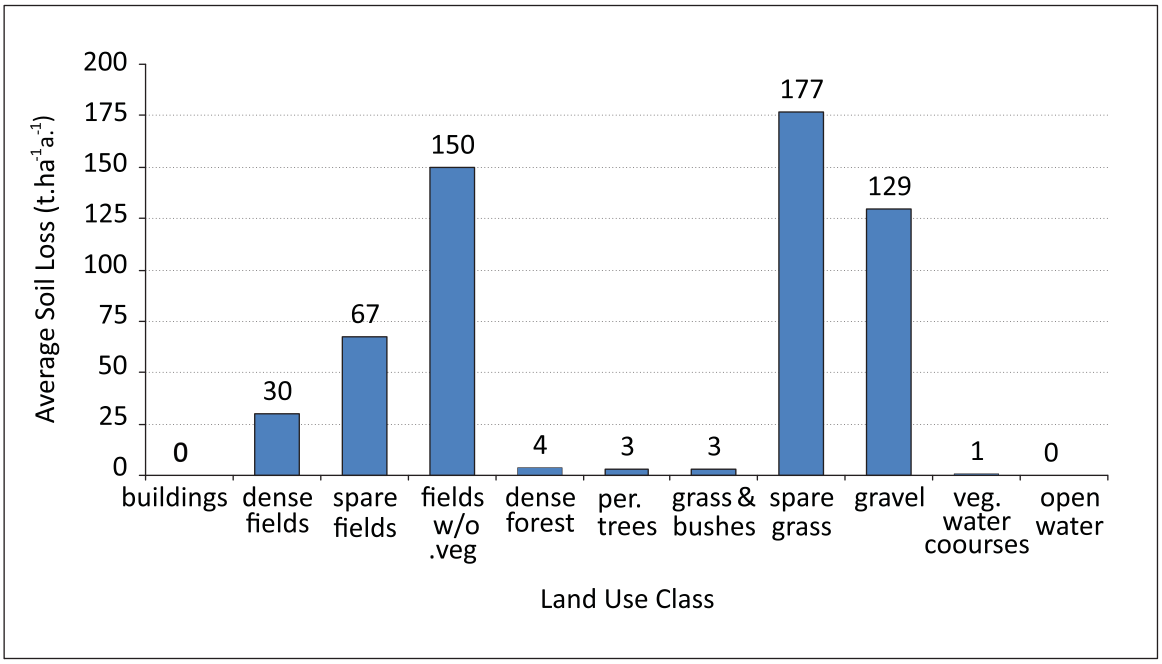

Figure 5.48. Average annual soil loss from different land-use classes

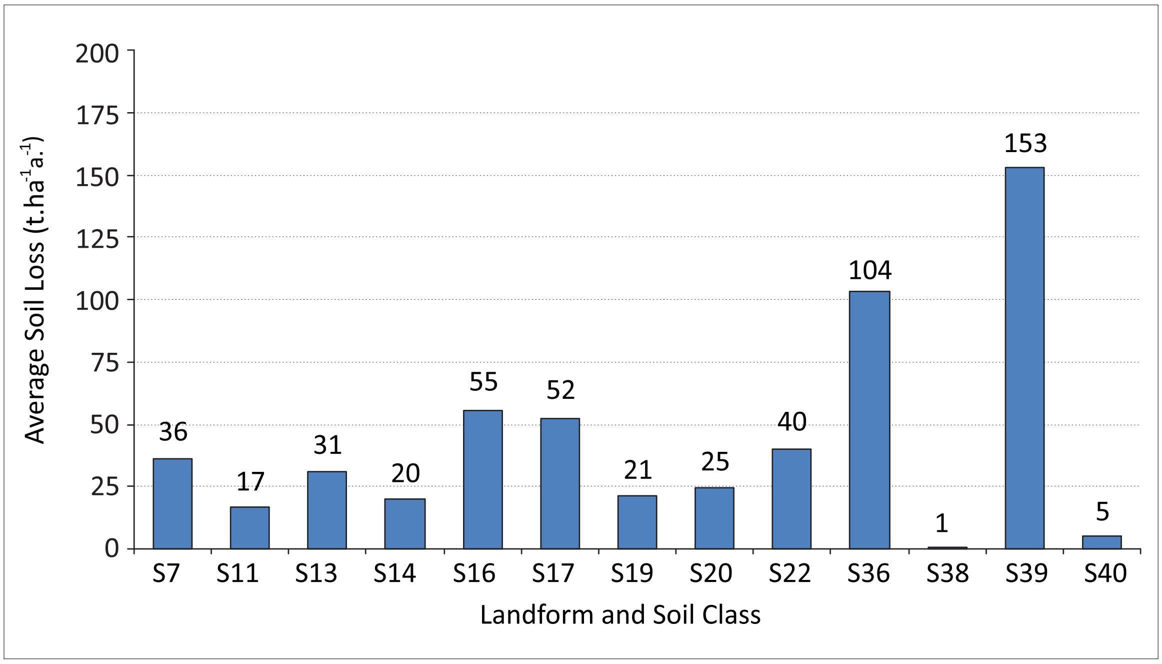

Figure 5.49. Average annual soil loss for different landform and soil classes

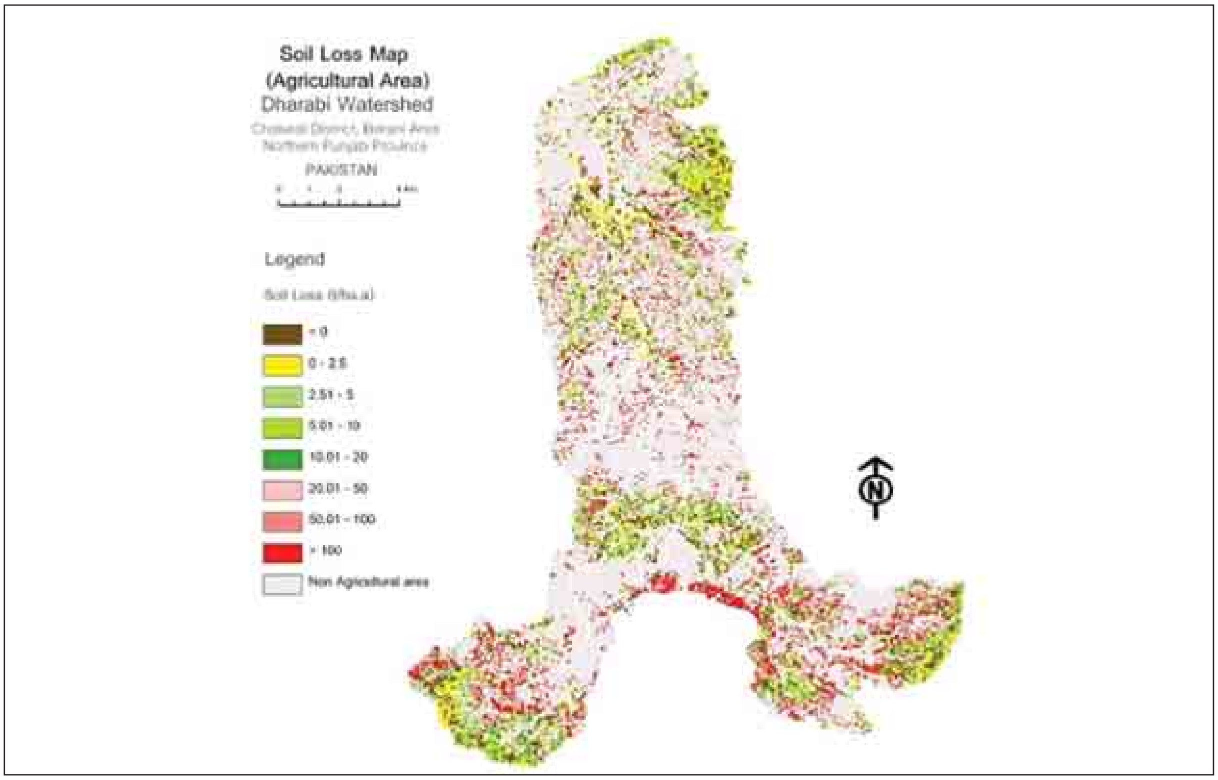

Figure 5.50. Average annual soil loss from agricultural land without soil conservation measures (simulation period 2009)

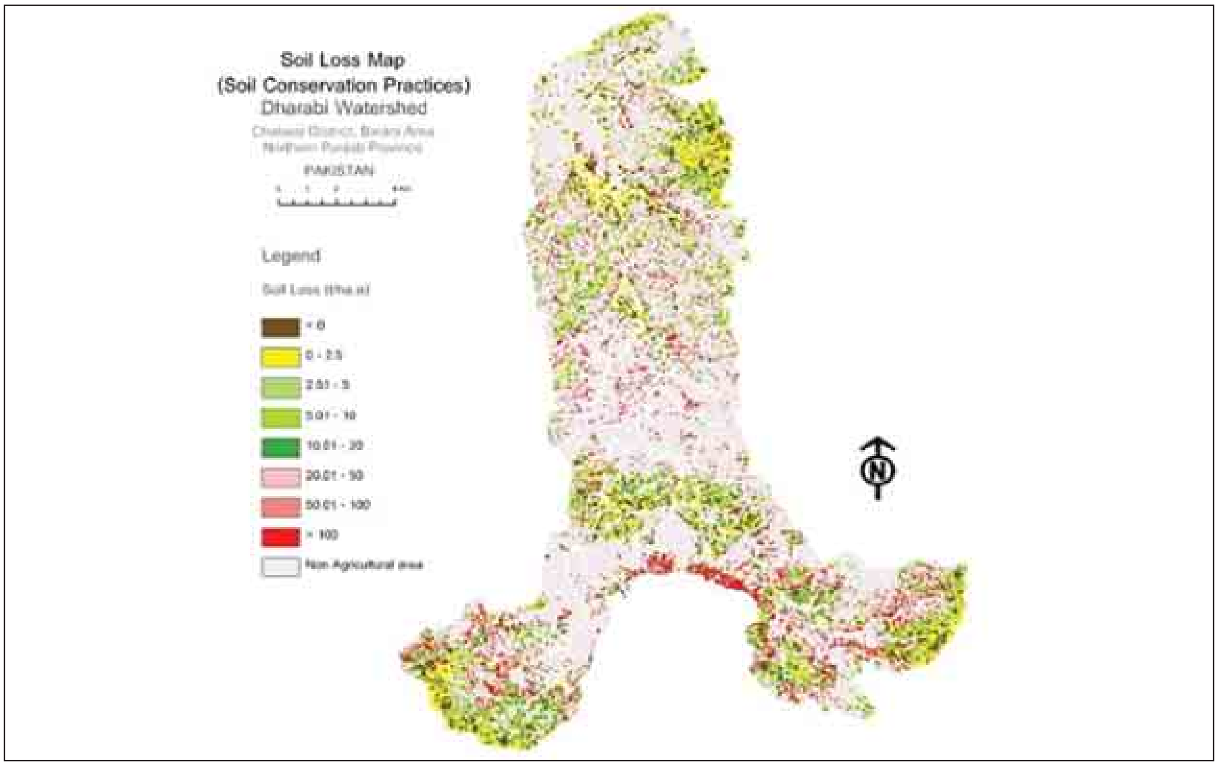

Figure 5.51. Average annual soil loss from agricultural land with soil conservation measures (simulation period 2009)

outlet of the watershed while the major part is deposited within the area. This leads to a redistribution of soil and to changes in soil depth, soil productivity, and the related effects on water storage and the filtering function of the soil.

For the 100-year simulation period, 57% of the area produces annual sediment yields less than 2.5 t/ha (Figure 5.46). Nevertheless about 11% of the watershed exceeds sediment yields of 100 t/ha/year. These areas are the hot spots in the watershed which cause off-site damage and where soil protection measures will be most effective. High sediment yields like this have major impacts on water quality and on the silting up of the reservoir located at the watershed outlet. Figure 5.54 shows the average sediment yields for the 319 sub-watersheds. It can be seen that the highest values are found in the southern part of the watershed where the highest surface runoff occurs.

Calculations for 2009 show that the sediment yield was much lower and ranged between 13.08 t/ha/year for the area as a whole and 14.72 t/ha/year when only agricultural fields are taken into account. The scenario in which soil conservation practices are implemented indicates that these structures lead to a decrease of 38% in the average annual sediment load for the area as a whole and of 44% for the agricultural area (Table 5.26).

The effect of soil conservation practices on sediment yield can be seen by comparing the results for simulation runs with and without soil protection measures for the year 2009 (Figures 5.55 and 5.56). The decrease in

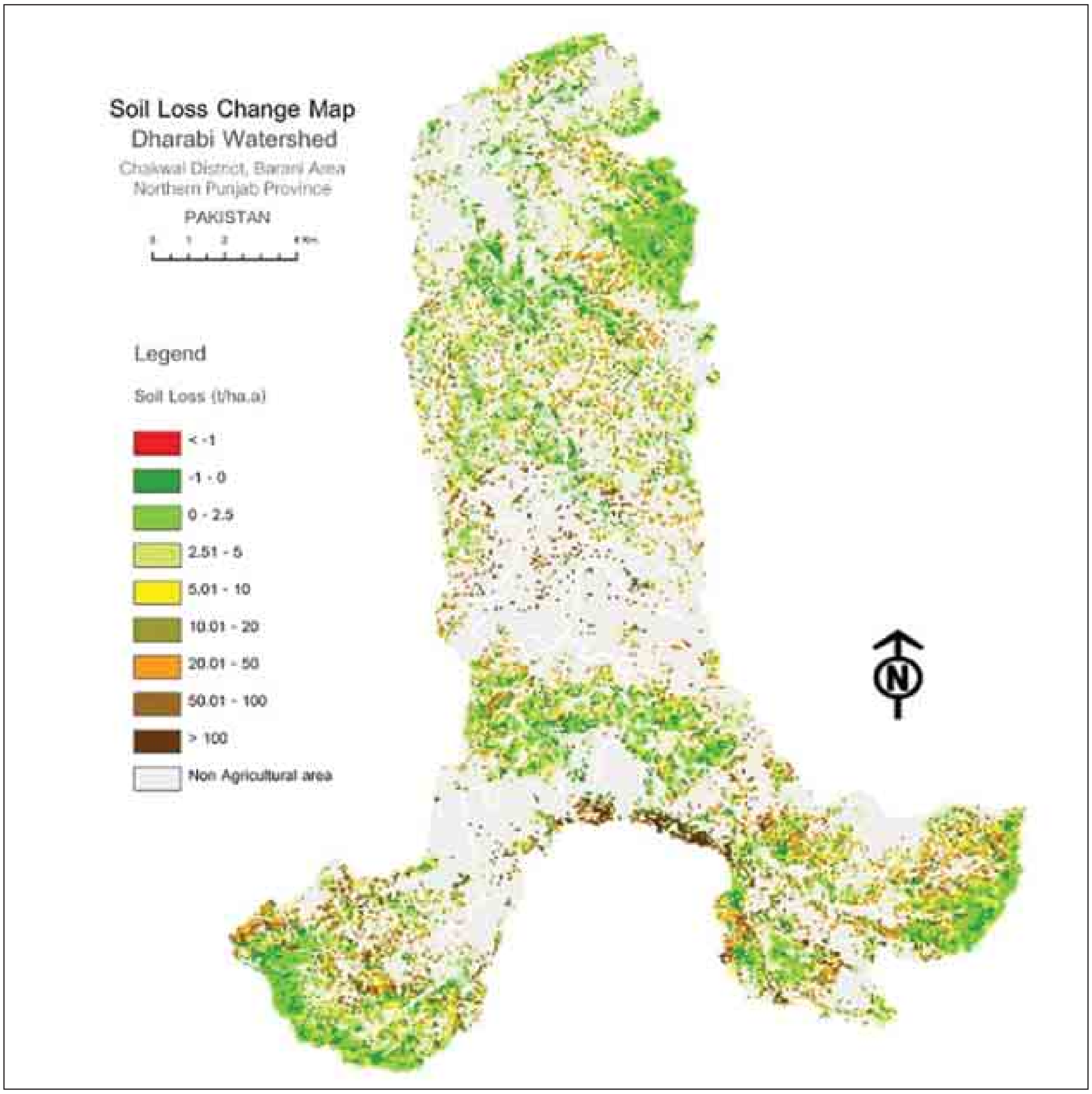

Figure 5.52. Soil loss change map displaying the difference between annual soil loss with and without soil conservation practices (simulation period 2009; positive values indicate a decrease in soil erosion, negative values indicate an increase)

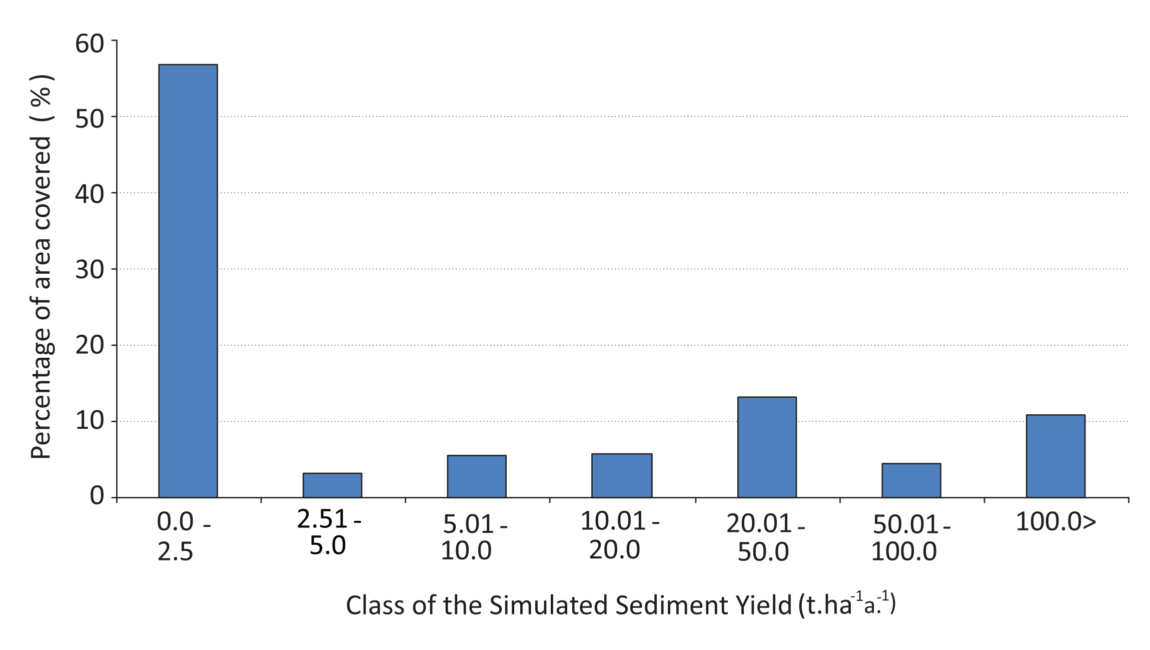

Figure 5.53. Distribution of sediment yield classes in the investigated watershed

sediment yield appears mainly in those areas where soil erosion is already high. These areas, where the stone terraces are most effective, are located in the south-western and south-eastern part of the watershed as well as around Lake Kallar Kahar (Figure 5.57).

5.5 Summary and conclusions

Erosion by water is the main threat to the soil resource in the Dhrabi watershed, Chakwal District. High intensity rainstorms during the monsoon period, together with low soil and canopy cover, result in average soil erosion rates exceeding the tolerance level of 2.5 t/ha/year, as recommended by the OECD (2001).

Long-term annual runoff and soil loss in the 196 km² watershed, as well as the sediment yield leaving the area, were calculated using the simulation models RUSLE and WEPP. The necessary climate input data were obtained from a nearby weather station and from long-term observations in Islamabad. The digital elevation model and the land-use/land-cover map were derived from ASTER satellite images taken in June 2006 and December 2007.
For land cover and soil data, additional field measurements and laboratory analyses were carried out.
Simulation runs were performed for two time scenarios:

- For a period of 100 years generated from observations in Islamabad
- Using the measured climate data of Chakwal SAWCRI station from 2009.

Runoff and sediment yield measurements performed in 2009 and 2010 in a 2 ha watershed were used to verify WEPP simulations. The comparison between observations and simulations showed a satisfactory agreement.
For the 100-year simulation, current land use, without soil conservation measures, was used. For the 2009 scenario, soil protection

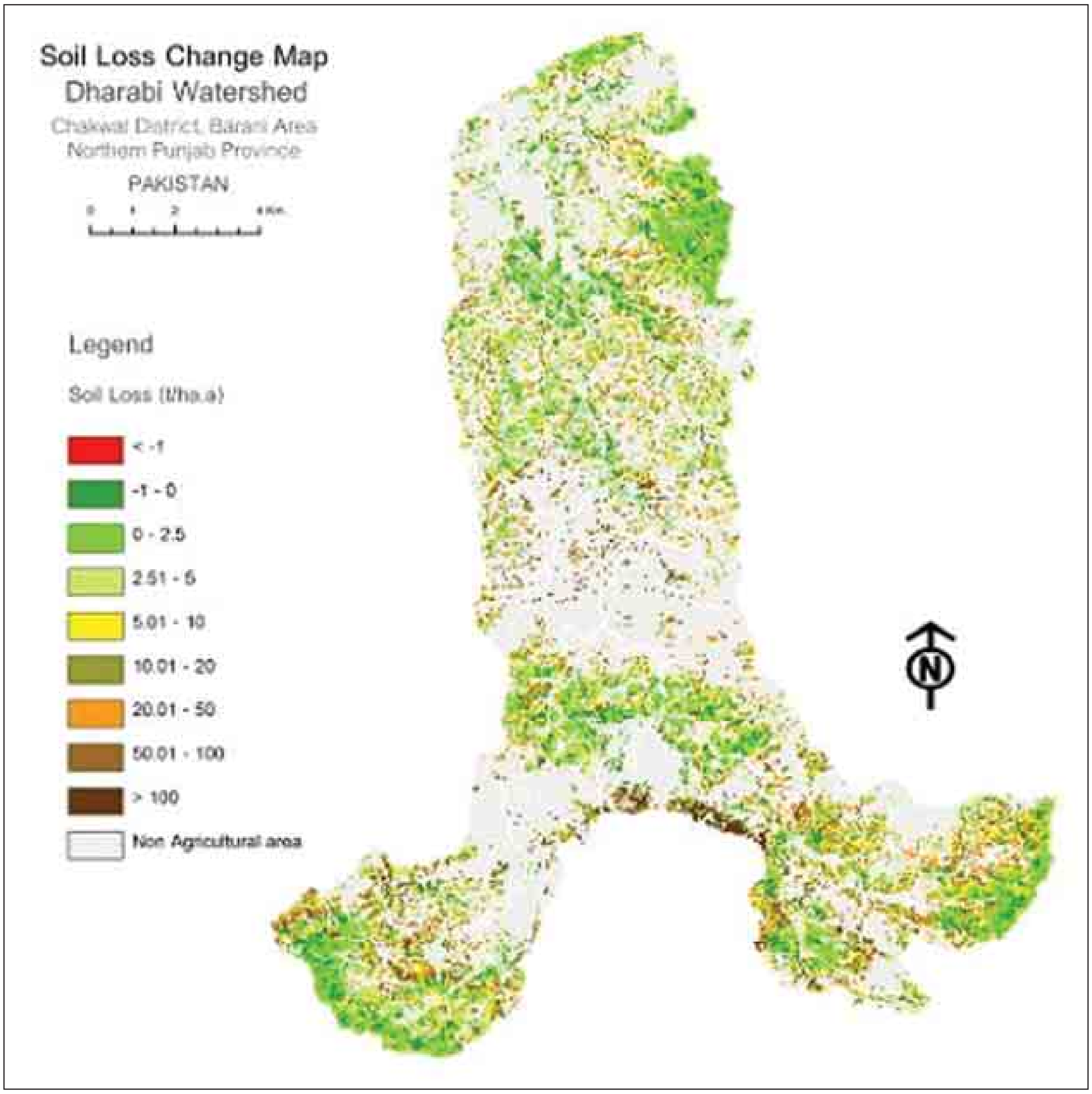

Figure 5.54. Spatial distribution of sediment yield delivered from sub-watersheds

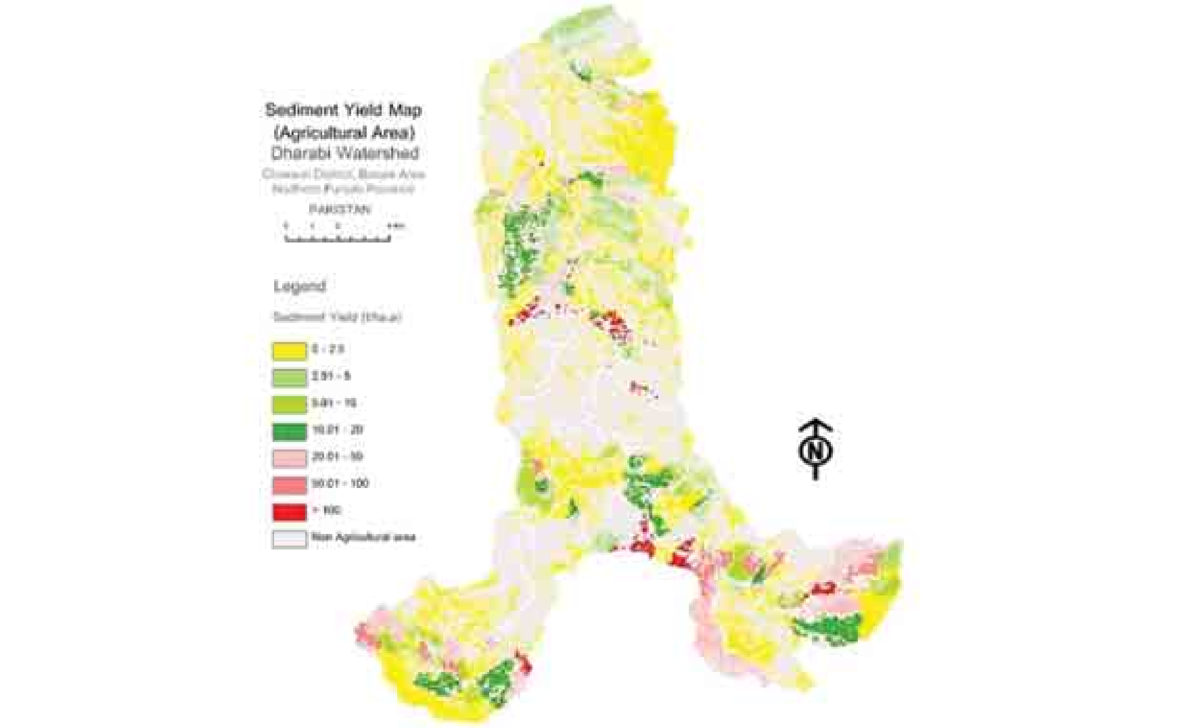

Figure 5.55. Average annual sediment yield from agricultural land without soil conservation measures (simulation period 2009)

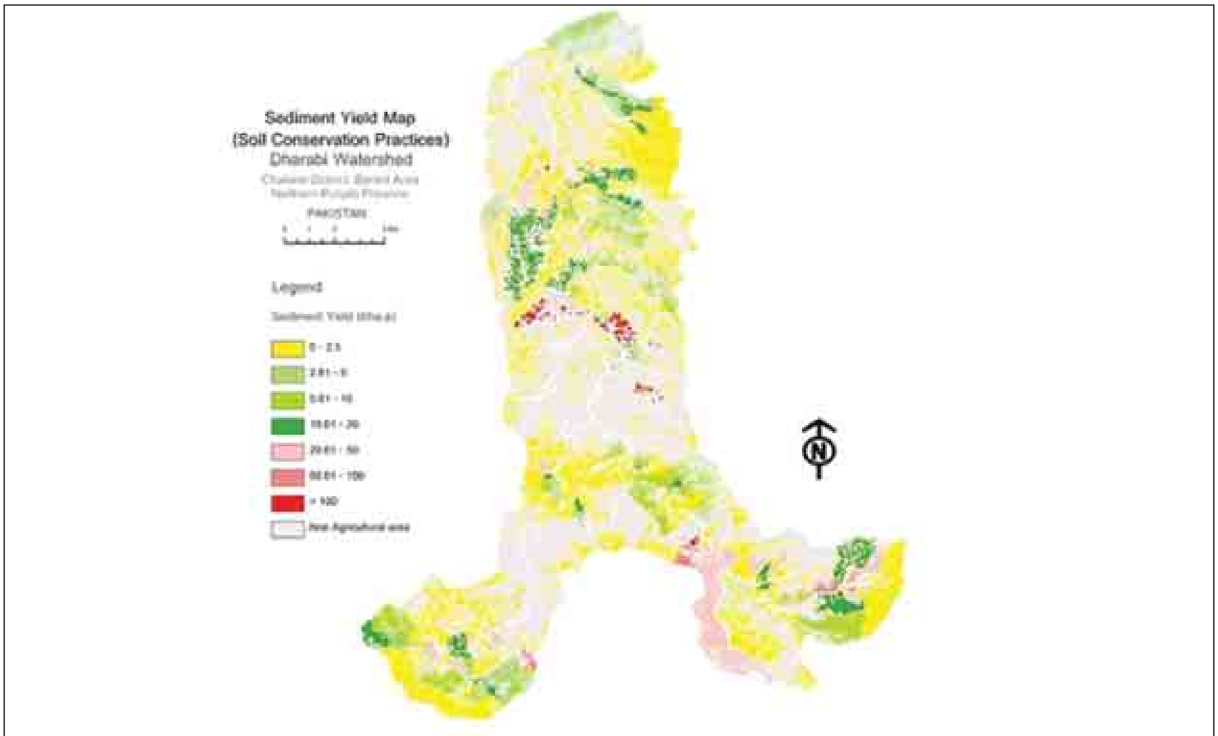

Figure 5.56. Average annual sediment yield from agricultural land with soil conservation measures (simulation period 2009)

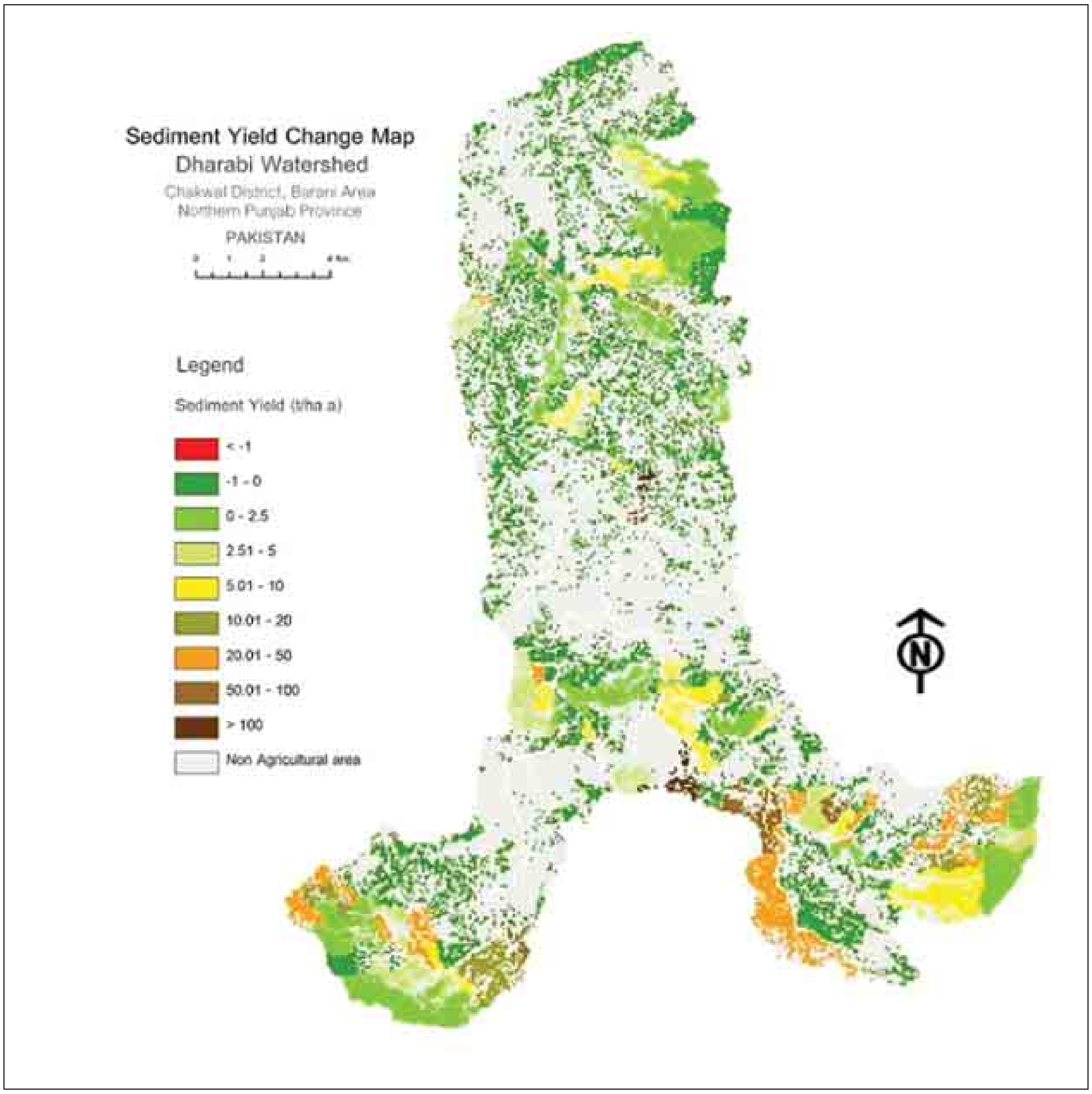

Figure 5.57. Sediment yield loss change map displaying the difference between annual sediment yield with and without soil conservation practices (simulation period 2009; positive values indicate a decrease in sediment yield, negative values indicate an increase)

structures in the agricultural-use areas were simulated. These structures consisted of stone spillways from the terraces which divert excessive rainfall in a non-erosive way. It was assumed that rainstorms of 100 mm with an intensity of about 15 mm/hour would not overboard .

For the 100-year simulation, an average surface runoff from the whole watershed without soil conservation structures was calculated at 66 mm/year. Using climate data from 2009, an annual surface runoff of 25 mm was predicted. But with protective structures applied in the agricultural-use areas, the annual runoff could be reduced by 28% to 18 mm. Retention of rainwater in the watershed leads to increased plant-available water and will increase crop yields.

Soil erosion processes occur on 75% of the Dhrabi watershed, with mean rates of 82 t/ha/year. This relates to an average loss of between 5 mm and 6 mm annually. It is estimated that 97 t/ha/year of eroded soil are deposited on 25% of the area. This dislocation of soil results in high variability in soil fertility and productivity within the area. Its effects diminish the storage and filtering functions of the soil.

Dense forests, perennial trees, and grassland are the best land-use systems for protecting the soil against erosion. Agricultural fields with low fertilization or low biomass production, bare fields, and sparse grassland are major sediment sources in the investigated watershed. Also, soils with high runoff potential show the highest erosion rates. Given the climatic conditions of 2009, average soil loss could have been reduced by 21%, from 48 t/ha/year to 38 t/ha/year, by installing soil conservation structures on all agricultural-use areas.

Not all of the eroded sediment is deposited within the area. For the 100-year simulation period a mean sediment yield of 25 t/ha/year was simulated. This quantity of sediment creates problems with siltation of the reservoir and impairs the water quality of the river and surface water bodies. For the 2009 scenario, a mean sediment yield of 13 t/ha/year was calculated. A reduction of 38% to 8 t/ha/year can be achieved by applying soil conservation measures.

The simulation results show that the suggested soil conservation measures would reduce surface runoff and soil loss. The decrease in sediment yield would lead to an improvement in water quality and reduce off-site damage caused by erosion processes.

However, land-use systems with annual erosion rates of more than 40 t/ha in major parts of the watershed and high deposition within the area cannot be called sustainable. Additional soil protection measures and – in some parts of the watershed – accompanying land-use changes need to be considered to achieve the ultimate goal of sustainable land management.

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Appendices

Annex 1

Initial surface water quality (2007)

Site No	Location	EC (dS/m)	SAR	RSC (meq/L)	Site. No.	Location	EC (dS/m)	SAR	RSC (meq/L)
1	Inflow to KK Lake	1.05	0.00	0.80	18	Near M2 bridge	1.05	1.96	0.7
2	Inflow to KK lake	1.11	0.00	0.10	19	Near Chuhi area	1.04	0.00	0.8
3	Inflow to KK lake	1.06	1.96	0.90	20	After mixing near Chak Khushi	1.04	0.00	0.6
4	Inflow to KK lake	1.05	0.00	0.70	21	Before D.G. Cement colony	1.25	5.88	1.50
5	Inflow to KK lake	1.03	0.00	0.70	22	Water of DG Cement colony	1.04	0.00	0.60
6	Inflow to KK lake	1.15	3.92	0.70	23	DG Cement colony effluent	1.05	0.00	0.40
7	Inflow to KK lake	1.02	0.00	0.50	24	DG. Cement colony effluent	1.10	1.96	0.90
8	Out flow from KK lake	1.03	0.00	0.70	25	Nikka stream (downstream)	1.03	0.00	0.50
9	Out flow from KK lake	1.02	0.00	0.60	26	Nikka dam reservoir	1.03	0.00	1.50
10	Out flow from KK lake	1.10	1.96	0.80	27	Spring in the perennial stream	1.10	0.00	0.90
11	Out flow from KK lake	1.15	1.96	0.80	28	Perennial stream at M2 bridge	1.17	1.96	0.70
12	Out flow from KK lake	1.18	1.96	0.70	29	KK Lake exit	1.10	0.00	0.10
13	Out flow from KK lake	1.18	1.96	0.60	30	Chak Khushi stream + box drain	1.09	0.00	0.80
14	Out flow from city	1.18	0.00	0.60	31	City drain + Chak Khushi	1.09	0.00	1.50
15	Out flow from KK lake	1.07	0.00	0.70	32	Baba Totanwali	1.07	0.00	0.50
16	Chumbi Nullah near FFC	1.02	1.96	0.80	33	Ratta Shrief bridge	1.08	1.96	0.50
17	Kallar Kahar city	1.04	7.84	0.40	34	Dhoke Choi	1.10	1.96	0.50

Annex 2

EC (dS/m) of the surface water monitoring points

Month/ Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Nov 2007	1.2	1.4	1.4	1.3	0.9	0.8	1.0	1.7	1.3	2.5	1.1	1.1	1.1	1.1	1.1	na
Feb 2008	1.3	2.1	1.3	1.3	1.7	0.8	0.9	1.2	1.1	n	nf	1.3	1.5	1.5	1.1	1.1
Mar 2008	1.5	1.3	1.3	2.1	0.9	0.0	0.9	1.6	0.8	1.8	2.9	0.7	0.6	0.7	nf	1.0
Jun 2008	0.8	1.4	0.8	1.3	1.5	1.3	1.0	0.0	4.1	4.8	0.8	2.0	1.4	1.5	nf	1.1
Aug 2008	1.3	1.5	1.5	1.4	0.9	0.9	1.1	1.2	3.4	3.5	2.5	2.0	1.7	1.6	1.2	1.2
Oct 2008	1.2	1.5	1.5	0.8	0.7	1.4	1.1	1.1	4.3	2.7	2.0	1.5	1.6	1.6	1.5	1.1
Dec 2008	1.6	1.4	1.3	nf	nf	0.7	0.9	1.0	4.6	3.4	2.4	1.9	1.6	1.6	1.5	0.9
Feb 2009	1.8	1.3	1.4	1.3	0.8	1.8	0.9	1.1	4.0	1.7	1.9	3.0	1.7	1.8	1.7	1.2
Mar 2009	2.2	1.3	1.2	0.8	0.8	1.6	0.9	1.1	4.0	2.0	2.7	2.1	1.7	1.6	1.6	0.9
Apr 2009	2.3	1.3	1.2	0.8	0.8	1.6	0.9	1.1	4.1	2.0	2.7	2.2	1.7	1.6	1.6	1.0
May 2009	1.0	1.4	1.3	0.8	0.8	1.5	1.0	1.1	4.7	2.0	2.8	2.1	1.5	1.5	1.5	1.0
Jun 2009	1.6	1.1	1.4	nf	0.8	1.5	1.0	1.1	6.5	1.3	4.1	3.6	nf	nf	1.5	1.1
Jul 2009	1.8	1.7	1.5	nf	0.9	1.6	1.1	1.1	7.7	2.9	3.7	2.8	1.1	2.1	2.3	1.2
Aug 2009	1.1	1.4	1.5	1.4	ps	0.8	1.0	1.1	7.5	4.1	3.6	3.9	1.9	nf	nf	1.0
Sep 2009	1.3	1.4	1.4	1.3	ps	0.7	0.9	1.0	9.3	2.3	2.9	2.0	1.5	1.4	1.1	1.0
Oct 2009	1.4	1.4	1.4	1.3	ps	0.8	1.0	1.5	18.8	3.5	3.0	2.9	2.6	nf	nf	1.0
Nov 2009	1.7	1.5	1.5	1.5	ps	0.8	1.0	1.9	23.1	4.2	3.0	2.9	nf	nf	nf	1.1

nf - no flow; ps - permanently sealed; na - sample was not collected

Annex 2 (Continued)

EC (dS/m) of the surface water monitoring points

Month/ Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Dec 2009	1.6	1.5	1.4	1.3	ps	0.8	0.9	1.1	40.3	4.1	2.7	2.6	1.8	1.9	1.8	1.0
Jan 2010	1.8	1.4	1.4	nf	ps	0.8	0.9	1.1	nf	nf	2.4	1.6	1.6	1.6	1.6	1.0
Feb 2010	0.5	1.4	1.4	1.3	ps	0.8	0.5	0.7	nf	1.0	0.7	1.0	1.0	1.0	1.0	1.0
Mar 2010	1.9	1.4	1.4	1.3	ps	0.8	0.9	1.1	16.4	1.9	2.5	1.8	1.6	1.5	1.6	1.0
Apr 2010	1.9	1.6	1.6	1.5	ps	0.9	1.0	1.5	44.2	nf	3.1	2.9	nf	nf	nf	1.1
May 2010	1.9	1.6	1.6	1.4	ps	0.8	1.0	1.7	49.7	4.2	3.1	3.1	nf	nf	nf	1.1
Jun 2010	1.7	1.6	1.5	1.5	ps	0.8	0.9	3.3	nf	3.9	2.8	2.8	nf	nf	nf	1.1
Jul 2010	0.9	1.5	1.6	1.5	ps	1.6	1.0	0.9	nf	2.1	2.1	2.1	1.3	0.9	1.3	1.1
Aug 2010	1.8	1.5	1.5	1.4	ps	0.8	1.0	1.1	6.2	1.7	1.7	1.8	1.1	1.1	1.1	1.0
Sep 2010	0.8	1.4	1.4	1.3	ps	0.8	1.0	1.1	7.4	1.5	2.4	1.5	1.0	1.0	1.0	0.9
Oct 2010	1.5	1.4	1.4	1.3	ps	0.8	0.9	1.0	1.6	1.8	1.8	1.8	1.4	1.4	1.4	0.9

nf - no flow; ps - permanently sealed; na - sample was not collected

Annex 3

SAR of the surface water monitoring points (refer to Chapter 4, Figure 4.1)

Month/ Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Nov 2007	2.9	4.4	8.3	5.0	4.4	2.7	3.2	12.7	7.5	13.1	7.0	7.1	5.7	6.0	7.8	na
Feb 2008	4.4	6.1	1.5	0.6	3.6	0.3	0.9	3.5	1.1	nf	nf	1.0	3.8	3.8	1.5	3.5
Mar 2008	5.1	3.7	3.2	7.7	2.0	0.0	2.6	7.6	1.7	6.4	10.6	2.2	1.8	8.3	nf	4.2
Jun 2008	5.3	3.8	0.7	3.4	3.4	4.3	3.2	2.5	21.1	15.1	6.0	5.6	4.8	4.0	nf	8.0
Aug 2008	4.7	3.6	2.6	2.5	1.5	1.7	1.8	2.3	14.3	14.2	12.0	6.0	6.0	5.4	4.8	6.3
Oct 2008	7.6	2.8	2.9	0.5	0.5	3.4	2.6	3.2	17.1	7.6	4.9	7.5	7.6	5.6	7.1	7.7
Dec 2008	8.9	4.8	4.3	nf	nf	2.1	3.4	4.0	17.5	12.1	9.0	6.2	8.8	9.5	10.0	7.5
Feb 2009	6.5	3.3	3.3	3.0	1.0	3.4	2.3	2.4	14.6	6.1	5.3	9.4	5.0	7.8	7.8	5.7
Mar 2009	10.2	4.5	2.9	1.1	0.9	3.1	1.5	3.0	13.8	6.6	8.4	6.7	7.1	7.2	6.0	6.0
Apr 2009	8.8	4.5	2.9	1.1	0.9	3.1	1.5	1.3	14.5	7.1	8.4	5.9	5.3	7.2	6.0	7.4
May. 2009	4.7	3.2	3.7	1.4	1.3	2.6	3.6	3.6	17.4	6.1	9.4	6.8	7.9	6.7	6.9	6.7
Jun 2009	7.5	1.4	4.2	nf	1.6	2.6	2.9	0.8	20.8	1.7	12.8	10.4	nf	nf	9.1	7.7
Jul 2009	9.9	5.0	5.1	nf	1.9	3.3	4.2	4.0	28.1	9.6	11.7	8.7	4.2	12.2	11.6	9.7
Aug 2009	5.2	3.7	4.1	3.8	ps	1.3	2.8	3.7	26.8	13.5	9.3	12.3	8.5	nf	nf	8.3
Sep 2009	6.0	3.0	3.6	4.0	ps	1.2	2.8	2.4	27.9	6.1	8.5	6.3	8.2	7.7	8.9	8.4
Oct 2009	5.3	1.6	1.5	1.8	ps	0.0	0.9	3.6	33.5	5.1	5.9	6.0	8.7	nf	nf	5.7
Nov 2009	7.5	1.4	4.2	nf	ps	2.6	2.9	0.8	20.8	1.7	12.8	10.4	nf	nf	9.1	7.7

nf - no flow; ps - permanently sealed; na - sample was not collected

Annex 3 (Continued)

SAR of the surface water monitoring points (refer to Chapter 4, Figure 4.1)

Month/ Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Dec 2009	4.9	1.4	1.3	1.2	ps	0.2	0.7	0.9	63.4	6.7	4.4	4.5	6.5	6.4	7.0	6.3
Jan 2010	5.5	1.0	0.9	nf	ps	0.6	0.5	0.9	nf	nf	4.5	2.5	4.6	4.5	6.0	5.6
Feb 2010	3.3	1.9	1.4	1.5	ps	0.2	0.6	1.4	nf	4.1	1.4	3.7	4.8	5.1	3.5	3.4
Mar 2010	5.7	1.5	1.2	1.4	ps	0.1	2.7	0.9	23.9	3.2	4.4	2.9	4.3	4.9	4.9	3.9
Apr 2010	7.6	2.6	1.6	2.0	ps	0.1	0.2	0.0	51.2	nf	6.0	5.4	nf	nf	nf	5.8
May 2010	6.8	1.7	1.9	1.7	ps	0.2	0.6	7.1	37.2	6.7	5.4	4.9	nf	nf	nf	5.7
Jun 2010	5.3	1.6	1.1	1.2	ps	0.1	0.4	6.1	nf	5.9	4.7	4.8	nf	nf	nf	5.4
Jul 2010	5.5	3.5	3.2	3.1	ps	2.5	2.4	3.0	nf	6.4	6.4	5.9	7.7	5.9	8.2	7.1
Aug 2010	6.3	2.5	2.6	3.0	ps	0.7	1.5	1.9	29.8	3.9	3.3	4.3	2.3	2.5	2.0	6.4
Sep 2010	3.5	2.5	2.0	2.1	ps	0.1	1.6	1.5	19.0	2.7	8.5	3.0	3.3	2.8	3.4	4.5
Oct 2010	5.9	2.4	2.1	2.1	ps	0.2	1.2	1.7	18.5	3.4	3.7	3.0	5.2	5.5	4.3	4.0

nf - no flow; ps - permanently sealed; na - sample was not collected

Annex 4

RSC (meq/L) of the surface water monitoring points

Month/ Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Nov 2007	3.4	5.4	0.0	7.0	4.2	4.4	12.2	6.6	0.0	3.5	5.8	13.8	3.5	3.6	4.0	na
Feb 2008	0.0	0.0	2.4	0.8	0.0	1.4	0.6	0.0	1.0	nf	nf	0.0	0.8	0.8	0.0	0.0
Mar 2008	0.2	0.0	0.0	0.0	0.0	0.0	1.9	1.7	0.8	0.5	0.0	2.4	2.5	7.0	nf	2.0
Jun 2008	3.5	1.0	9.8	1.4	3.0	1.0	4.9	23.4	7.5	23.4	9.8	9.4	1.5	0.0	nf	11.8
Aug 2008	0.0	0.0	0.0	0.0	0.0	1.3	0.2	0.4	5.0	0.4	0.0	0.8	0.3	0.0	1.4	1.4
Oct 2008	2.3	0.0	0.0	0.0	0.0	0.1	1.2	2.6	2.7	0.0	0.0	2.1	2.1	1.5	2.9	2.6
Dec 2008	2.5	0.0	0.4	nf	nf	1.2	2.2	2.1	3.6	3.3	0.0	1.8	2.3	3.0	1.5	1.1
Feb 2009	5.3	3.8	2.4	1.3	1.1	0.0	4.1	5.0	5.2	3.7	2.7	2.1	2.5	4.3	3.4	2.7
Mar 2009	7.6	2.7	0.9	0.0	1.2	0.0	3.1	4.6	4.3	3.1	2.3	3.3	3.3	3.2	2.8	3.1
Apr 2009	4.2	2.7	0.9	0.0	1.2	0.0	3.1	2.3	3.6	3.3	2.3	3.0	2.4	3.2	2.8	3.0
May. 2009	2.4	2.4	2.4	0.0	2.2	1.3	5.1	4.4	5.7	4.0	2.8	3.1	3.0	2.4	2.4	3.1
Jun 2009	8.3	0.0	0.0	nf	1.1	0.9	3.0	0.0	5.2	3.7	3.4	1.6	nf	nf	3.9	3.9
Jul 2009	6.1	1.2	0.5	0.0	0.6	0.9	3.7	3.8	4.8	2.9	2.3	2.6	3.7	2.9	3.0	3.7
Aug 2009	6.3	0.5	1.1	0.2	ps	1.0	3.2	3.4	4.4	2.6	12.2	3.1	1.7	0.0	0.0	2.6
Sep 2009	4.2	0.3	1.2	1.2	ps	2.0	4.4	3.6	8.7	9.4	3.7	3.4	3.3	3.4	3.4	4.2
Oct 2009	1.8	0.0	0.0	0.0	ps	0.0	0.0	1.3	2.7	5.6	0.0	0.0	0.0	nf	nf	0.0
Nov20 09	2.2	0.0	0.0	0.0	ps	0.0	0.5	2.4	1.8	3.8	0.0	0.0	nf	nf	0.0	0.5

nf - no flow; ps - permanently sealed ; na - sample was not collected

Annex 4 (Continued)

RSC (meq/L) of the surface water monitoring points

Month/ Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Dec 2009	1.4	0.0	0.0	0.0	ps	0.0	0.0	0.0	2.3	3.9	0.0	0.0	0.0	0.0	0.4	1.7
Jan 2010	0.2	0.0	0.0	nf	ps	0.0	0.0	0.0	nf	nf	0.0	0.0	0.0	0.0	0.1	0.7
Feb 2010	0.5	0.0	0.0	0.0	ps	0.0	0.0	0.0	nf	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar 2010	3.8	0.0	0.0	0.0	ps	0.0	4.6	0.6	0.0	0.0	0.0	0.0	1.4	1.4	0.9	1.2
Apr 2010	2.7	0.0	0.0	0.0	ps	0.0	0.0	0.0	0.0	nf	0.0	0.0	nf	nf	nf	0.0
May 2010	5.3	0.0	0.0	0.0	ps	0.0	0.0	4.0	0.0	5.5	0.0	0.0	nf	nf	nf	0.7
Jun 2010	6.7	0	0	0	ps	0	1.4	0	nf	7.3	0	0	nf	nf	nf	2.6
Jul 2010	3.3	0	0	0.5	ps	0.3	4.4	3.1	nf	3.4	3.5	2.6	2.8	1.9	3.4	2.9
Aug 2010	3.4	0.2	0.8	0.6	ps	1.8	3.6	2.3	0	2.0	0.2	1.5	1.2	1.9	1.4	3.2
Sep 2010	1.7	0	0.6	1.2	ps	1.4	3.8	2.6	0	1.9	3.8	3.2	2.0	1.6	2.2.	2.3
Oct 2010	5.2	0	1.2	0	ps	0.8	3.5	1.2	0	2.3	0.3	0.7	1.9	2.7	0.6	3.4

nf - no flow; ps - permanently sealed ; na - sample was not collected

Annex 5

EC (dS/m) of the groundwater

Month/Location	1	2	3	4	5	6	7	8	9	10
September 2009	1.7	1.1	0.5	1.0	0.6	1.1	1.0	0.7	0.8	1.3
October 2009	0.7	0.6	1.7	2.5	1.1	0.9	na	na	2.3	1.0
November 2009	1.0	2.2	1.1	2.5	0.6	1.0	0.6	0.9	2.4	2.6
January 2010	1.0	2.2	1.1	2.4	0.6	1.6	0.6	0.9	1.9	2.4
February 2010	1.0	2.2	1.1	2.5	0.7	1.5	0.6	1.5	2.0	1.8
March 2010	1.1	2.4	1.2	na	0.7	0.7	0.7	1.6	1.8	1.8
April 2010	0.9	2.0	1.1	2.5	0.5	na	0.6	0.9	2.4	2.7
May 2010	1.03	2.26	1.16	2.60	0.61	0.71	na	1.06	1.90	3.08
June 2010	1.00	1.34	1.13	2.51	0.59	0.65	0.35	0.96	2.87	3.06
July 2010	1.00	0.89	1.13	1.19	0.59	0.69	1.01	1.02	1.33	2.60
August 2010	0.92	1.25	1.08	2.28	0.58	0.63	0.93	0.96	0.82	2.16
September 2010	0.88	2.22	1.06	2.30	0.59	0.64	1.10	0.95	1.00	1.50
October 2010	0.88	2.21	1.05	2.38	0.55	0.61	1.33	1.02	1.51	1.55
November 2010	0.88	2.17	1.04	2.29	0.54	1.45	0.63	1.37	1.71	1.88

na - sample not available

Annex 6

SAR of the groundwater

Month/Location	1	2	3	4	5	6	7	8	9	10
September 2009	5.4	3.7	0	6	0.7	21.2	25	1.1	1.9	8.8
October 2009	1	0.3	9.9	12.5	10.3	6.9	na	na	6.7	1.4
November 2009	0.6	8.6	8.7	12.2	0.4	6.9	1.3	6.6	4.7	4.76
January 2010	2.1	7.2	8.8	11.2	0.2	6.1	1.4	8.1	3.7	4.5
February 2010	1.2	6	16.3	10.4	0	4.8	0.7	5.3	5.7	2.8
March 2010	1.7	6.31	17.87	na	1.2	4.05	0.78	8.27	6.1	6.1
April 2010	1.7	5.3	10.5	10	0.3	na	0.5	11.6	3.9	4.5
May 2010	1.4	6.2	22.2	12.0	0.2	1.3	na	20.2	7.8	6.1
June 2010	2.3	5.7	17.9	13.3	0.9	1.8	4.3	9.4	7.8	7.9
July 2010	1.9	5.7	21.6	8.2	1.0	1.6	5.0	4.1	5.9	8.7
August 2010	2.2	5.1	17.1	11.3	0.7	1.4	4.2	9.4	1.5	5.2
September 2010	1.3	6.6	15.5	11.4	0.6	1.4	4.5	12.0	2.1	2.8
October 2010	0.6	5.6	7.2	10.7	0.2	0.7	4.7	8.2	2.3	2.4
November 2010	1.1	5.7	9.1	9.4	0	3.6	0.8	5.6	2.1	2.9

na - sample not available

Annex 7

RSC (meq/L) of the groundwater

Month/Location	1	2	3	4	5	6	7	8	9	10
September 2009	0	3.1	0	4.2	0	3.7	2.7	0	0.6	4.9
October 2009	0	0	1.9	2.5	3.4	1.9	na	na	1	0
November 2009	0.1	4.6	3.6	1.9	0	2.4	0.4	0.9	0	0
January 2010	0	3.2	2.2	1	0	0	0.8	1.3	0	0
February 2010	2.3	3.7	7.1	3.3	0.7	1.2	1.4	2.2	3	0
March 2010	2.4	2.8	6.5	na	2	6.2	0.7	3.3	5.1	5.3
April 2010	0	0.3	3.4	0	0	na	0	3.2	0	0
May 2010	1.5	4.8	6.6	4.8	1	3	na	7	5.9	0
June 2010	4.8	7.1	6.6	6.3	4	3.1	4.7	5.9	4.7	3.3
July 2010	2.6	3	6.3	2.6	4.1	4	4.0	3.1	4.0	1.6
August 2010	2.7	5	6.9	5.3	2.9	3	2.4	4.3	2.5	0.2
September 2010	3.4	6.9	6.4	6.1	4.3	3.5	2.1	5.8	2.1	3.9
October 2010	3.2	4.3	6.6	4.7	2.2	2.6	1.2	4.1	1.2	0
November 2010	0.1	4.1	4.9	3.1	0	0	0.5	2.3	0	0

na - sample not available

Annex 8

Scientific and local names of trees, shrubs and grasses

Scientific name	Local name	Life
Acacia modesta	Phulai	Tree
Acacia nilotica	Kikar	Tree
Albezia lebbek	Siris	Tree
Bauhinia variegate	Kachnar	Tree
Capparis decidua	Karir	Shrub
Cenchrus ciliaris	Dhaman	Grass
Chrysopogan aucheri	--------	Grass
Conyza Canadensis	Ghedar buti	Herb
Cynodon dactylon	Khabbal	Grass
Dalbergia sissoo	Shisham	Tree
Desmostachya bipinnata	Dab grass	Grass
Dodonea viscosa	Snatha	Shrub
Eleusine flagellifera	Chimber	Grass
Eriobotrya japonica	Lauqat	Tree
Eulaliopsis binnata	Babbur	Grass
Grewia populifolia	Gangir	Shrub
Gymnosporea royleana	Putakhi	Shrub
Heteropogon contortus	Sariala	Grass
Leucaena leucocephala	Iple Iple	Melia
Meli azadarach	Bakain	Tree
Olea ferruginea	Kaho	Tree
Pennisetum purpureum	Mott grass	Grass
Phragmites karka	Narra	Grass
Pongamia glabra	Sukh Chain	Tree
Prosopis juliflora	Mesquite	Tree
Punica granatum	Anar	Shrub
Pyrus malus Linn	Apple	Tree
Salix spp	Willow	Tree

Annex 8 (Continued)

Scientific and local names of trees, shrubs and grasses

Scientific name	Local name	Life
Saccharum bengalenses	Saroot	Grass
Schoenoplectus litorilis	Large sedge	Sedge
Syzygium cumunii	Jamun	Tree
Terminilia arjuna	Arjan	Tree
Typha domengensis	Kundar	Herb
Zizyphus mauritiana	Ber	Tree
Zizyphous nummularia	Melah/Jangli ber	Shrub