MODELLING THE HYDROLOGICAL IMPACTS OF LAND COVER CHANGE IN THE SIRAN BASIN, PAKISTAN

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by

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TO MY LOVING PARENTS & DOODLE
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ABSTRACT

Many forested catchments in northern Pakistan have undergone land cover change during the last few decades. Extreme floods and extended droughts observed in these areas have lead to the question: How do human influences affect the water balance of a montane catchment? The underlying socio-political factors that have lead to the changes in forest cover and catchment hydrology are well documented, but there have been very few efforts to spatially correlate the cover changes with the catchment water balance. A deterministic model based on high resolution spatial and temporal data offers the ability to simulate the hydrological impacts of changes in land cover in a spatial context. In an attempt to assess the impacts of changing forest covers on individual hydrological processes, a GIS-based model Siran HYDMAPS has been developed for the Siran Basin, Pakistan. This model integrates the spatial databases with the well-known hydrological process algorithms (e.g. Penman-Monteith evapotranspiration and Green-Ampt infiltration models). Spatially distributed static (topographic and soil) parameters for this model are extracted from a regional GIS developed specifically for the project. The dynamic (vegetation-related) parameters are estimated from the land cover maps, derived by digital processing of multi-resolution, multi-temporal Landsat MSS (5.3.1979) and TM (10.7.1989). Relative relief and shadowing in rugged terrain of the Himalayan foothills, that cause major problems in image processing, have been given particular attention. A rule-based approach was adopted to refine land cover maps with the integration of GIS for mapping the level II forest classes. Mapping of forest cover changes was carried out by post-classification change detection techniques. The Siran HYDMAPS predicts a decrease in radiation balance and interception capacity, and an increase in evapotranspiration and catchment response of the Siran Basin, as a result of land cover changes. It was concluded that the water imbalances in this catchment, observed during the last two decades, were caused by the integrated effects of land cover changes and climatic factors.
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This work was continued in Geography Department at Leicester under the supervision of Prof. Millington, where (I must admit) I took full advantage of his Chair. The kind advice of my co-supervisor Dr. Mitchel Langford (Leicester) in computer programming and his impartial assessment of my research seminars are gratefully acknowledged. Dr. Richard Pope and Dr. Jane Wellens carried on their kind assistance in Leicester as well. I wish to pay special thanks to our David Orme, Chief Technician, who signed many 'blank cheques' for me. Bill Hickin, Computer Officer (who, in my opinion, is more kind to first year postgrads), deserves my gratitude for helping me understand from $ to £ of computing. I would also like to appreciate the help of my country fellows Ali Muhammad (Engineering, Reading) and Aamer Iqbal Bhatti (Control Engineering, Leicester) in C. Special thanks are for Ms. Rosemary Gibson, Welfare Officer, LUSU, who made her best efforts to help me survive without any financial constraint towards the completion of my study.
1.1 SCOPE OF THE RESEARCH

Many river basins in the northern Pakistan have undergone severe land use and land cover changes during the last few decades (Haigh, 1991). Extreme floods and extended droughts observed in these areas have led to the question: How do human influences affect the water balance of a montane catchment? The scope of this research is to frame a strategy suited to northern Pakistan’s conditions for the assessment of hydrological impacts of land cover changes in their true spatial context. The approach adopted for this purpose is based on coupling hydrological process models with a high spatial resolution geographical information system at the management unit (catchment) level. A further intention of the study is to develop a new technique for tackling the problem of shadowing on the satellite images of high relief areas. Devising new methods for spatial extrapolation of meteorological data in the rugged terrain of northern Pakistan also comes in the scope of this study. The approach adopted in this study is not site specific as it can be used for meteorological extrapolations (spatial), distributed process simulations and impact assessment in any basin for which GIS databases are available.

1.2 CHOICE AND DESCRIPTION OF THE STUDY AREA

The criteria for the selection of the study area included among others:

*importance of the catchment:* it should be one of the most important catchments in northern Pakistan as far as water, forest and agricultural resources are concerned.

*extent of the problems of deforestation and land cover changes:* ideally one with significant changes in the recent past to study their effects on catchment hydrology.

*diverse geomorphology, soils, hydro-climatology, land uses and vegetation types:* where spatial heterogeneity in natural phenomena and hydrological processes is likely to be at a maximum.

*data availability:* a catchment for which topographic, soil and geology maps and a sufficiently long series of hydro-meteorological data are available.

*size of the catchment:* a medium-sized catchment (≤ 1000 km²) was sought for convenience in geographical data acquisition and handling.
accessibility: the area should be easily accessible for field data collection and verification of the laboratory results.

Keeping in view these criteria, the Siran catchment in northern Pakistan was selected for this study. It lies between 34°:14':16.8" N and 73°:00':07.2" to 73°:22':12.0" E and covers an area of 1040 km² at Phulra gauging station. It comprises the western Himalayan foothills in northern Pakistan which drain into the Siran River; a tributary to the Indus River. The location of the study area is given in Fig. 1.1.

1.2.1 Geomorphology and Soils

The Siran catchment has highly complex terrain; the elevation ranges from 870 m to 4285 m above mean sea level. At lower elevations many level, confined valleys and plateaus are found, while there are slopes as steep as 56° on the upper parts of the mountains. The general aspect of the catchment is southern. The past and ongoing geological activities have resulted in diverse soil parent material which consists of all three types of rocks viz. igneous, sedimentary and metamorphic. Major exposed rocks identified in the catchment include granite, limestone, sandstone, schist and phyllites while the fertile plains are the legacy of alluvium and water-reworked loess. The immense relief and varied lithology coupled with a variety of climatic and biotic influences have yielded a number of soil types. At least seventeen soil complexes have been delineated by the Soil Survey of Pakistan (1988) in this catchment. The soil depth varies from deep in the valleys and along the main river course to very shallow with exposed rocks depending upon the parent material and degree of slope.

1.2.2 Hydro-Climatology

The climate varies from subtropical at lower elevations to moist temperate and alpine at the higher elevations. Therefore catchment's means of temperature and precipitation do not truly present the climatic heterogeneity. Jan (1972) analysed the climate over the Siran Basin and declared that mean annual precipitation increases towards north-east (=1500 mm) and decreases towards south-west (=750 mm). The general climatic pattern is bimodal i.e. both monsoon and Mediterranean systems prevail over
Fig. 1.1: Location of the Siran Basin. Note the main river course and Karakoram Highway passing through the Basin.
the tract encompassing the catchment (Ives, 1990); two thirds of precipitation is received in the summer months (monsoon season) and one third in winter. The upper reaches of the catchment beyond 3000 m elevation mostly receive winter precipitation in the form of snow. Occasionally maximum temperatures exceed 35° C during June at lower elevations while snow receiving peaks sustain a temperature below freezing point for up to eight months. The humidity is lowest from April to June, while July and August are the wettest months.

The catchment is drained by the Siran River which receives its water from two main tributaries namely Jachha Siran (eastern tributary) and Jabbar Siran (western tributary). The former originates from Chakru-Sar (4285 m: the highest peak in the Basin) and covers the longest stretch (=73 km) across the catchment to Phulra gauging station. From Phulra the river flows towards south and merges with the Indus River at Tarbela Dam. The available record of the Siran River (1969-90) shows that the maximum discharge was as high as 385 cumecs observed on 17 July 1977 against the minimum which was as low as 0.6 cumecs on 26 January 1990. The mean discharge of the Siran River at Phulra calculated from this data is 12.4 cumecs. The average annual suspended sediment concentration is 0.3 % (3000 ppm by weight). In addition to supplying irrigation water, this river contributes an appreciable share of water to the huge reservoir behind Tarbela Dam.

1.2.3 Major Land Uses

The Siran Basin has highly honey-combed (inter-mixed) land uses, particularly on the upper mountain slopes. Agriculture is by and large the major land use and covers about 35 % of the total catchment area. The plains, e.g. Pakhly Plain are extensively cultivated by irrigation and double cropping pattern is prevalent. At higher elevations (but limited to 2450 m), and on moderate to steep slopes irrigated and rainfed agriculture is practised on terraces. Wheat, maize and paddy are the crops conventionally grown in this valley but during recent decades large agricultural areas have been brought under tobacco cultivation. Agriculture is usually not practised beyond 2450 m elevation. The growing seasons of the major crops grown in the Siran Basin are given in a crop calendar (Fig. 1.2):

Fig. 1.2: The growing seasons of major agricultural crops in the Siran Basin.
This basin is among the few in Pakistan which are rich in forest resources and it contributes an appreciable part of country's total timber production. About 32% of the area is covered by the conifer forests. This figure, however, does not include small scattered plantations (compact and linear) and individual trees on agricultural areas which are difficult to delineate on small scale maps. The forest lands fall under one of the following three legal categories (Jan, 1972):

Reserved Forests: These are Government owned forests which were originally declared free of public rights and concessions at the time of settlement in 1871. However during the second settlement (1904-05) limited public rights were admitted, in the form of grazing, grass cutting, collection of dry fuelwood and collection of leaves for fodder.

Guzara Forests: The word Guzara means sustenance. These forests are owned by the people individually or jointly and are meant for sustenance of local community primarily by meeting their requirements of timber, fuelwood, grazing and grass cutting.

Protected Forests (Resumed Lands): Originally privately owned forests which were resumed in 1959 and ownership was vested in the Government for the sake of protection.

Grass production for livestock rearing is the third major land use after agriculture and forestry. The pure grasslands and grasslands intermixed with scattered trees in subtropical, temperate and alpine climatic zones altogether occupy approximately 25% of the catchment area.

1.2.4 Ecological Zones

The high variations in relief and climate have produced an altitudinal ecological zonation (Fig. 1.3). The natural vegetation of the catchment includes temperate pine, fir and spruce forests, subtropical pine forests and subtropical and alpine grasses. A brief description of natural vegetation types is given below:

1.2.4.1 Subtropical and Temperate Pine Forests

These pine forests are found from 900-2400 m elevation. Chir pine (Pinus longifolia) forms gregarious stands in the subtropical zone from 900 to 1675 m (Photo. 1.1) and in the transition zone between subtropical and temperate zones (1675 - 2286 m) it associates with
Blue pine (*Pinus wallichiana*). In the moist temperate zone (2286 - 2590 m) blue pine and deodar (*Cedrus deodara*) are found intermixed. Subtropical foothill grasslands exist below 1200 m elevation at all aspects and up to 1675 m on warmer aspects only.

### 1.2.4.2 Moist Temperate Mixed Conifer Forests

Silver fir (*Abies pindrow*) is mostly found in pure stands between 2400 - 3200 m elevation and in places is intermixed with Spruce (*Picea smithiana*) or Blue pine (*Pinus wallichiana*). Small patches of pure deodar (*Cedrus deodara*) are also included in this forest type. Sizeable patches of broad-leaved species including Oak (*Quercus incana*), Walnut (*Juglans regia*), Horse chestnut (*Aesculus indica*), and Maple (*Acer pictum*) are also common in temperate zone. The favourable conditions support a variety of grasses to grow abundantly.

### 1.2.4.3 Alpine Pastures

Above 3200 m elevation, trees usually do not grow and most of the area is occupied by alpine grasses. In places, stunted and mutilated juniper species are found.

![Fig. 1.3: Altitudinal Zonation of Natural Vegetation Types in the Siran Basin.](image-url)
1.3 STATEMENT OF THE PROBLEM

In addition to the general problems of expansion of cultivation, uncontrolled grazing and land mismanagement which are common everywhere in northern Pakistan, there are some problems associated with land cover changes specific to the Siran Basin, these include:

- Development of communication systems has made virgin forests easily accessible resulting in an expansion of legal and illegal felling. The Karakoram Highway and link roads, which opened up the Basin, provided efficient routes of timber extraction and transportation (Sheikh, 1985); the result being that some large slopes well stocked with conifers in early 1970s are now treeless.

- By the early 1970s logging and transportation were carried out by timber merchants and contractors who usually took advantage of over-felling (Bajracharya, 1985). Most of damage was encountered in Guzaras (private forests) which cover almost twice the area under Government-owned Reserved forests (Azhar, 1993).

- Large scale settlement projects in late 1970s further aggravated the situation when hundreds of thousands of war stricken Afghan refugees started camping in forested catchments of NWF Province of Pakistan (Allan, 1987; Archer, 1995) (Photo. 1.2).

- The deforestation, coupled with land mismanagement, has decreased the moisture holding capacity of the soil and accelerated the process of soil erosion. The highest peakflows observed during last two decades have claimed many lives and engulfed large chunks of land, though no official data exists. Increasing concentration of suspended sediment has not only impaired the water quality but is also threatening the economic life of Tarbela reservoir through sediment deposition.

- The 1980s saw much effort being put into reclaiming forest resources in the Siran catchment, with different projects being run by several donor agencies (Allan, 1987; Dixon, 1986). Many forest rehabilitation, soil conservation and environmental conservation projects were initiated during mid 1970s and early 1980s with more or less the same aims, however degrees of success have varied. A trend in the catchment hydrology towards equilibrium in late 1970 onwards (discussed in Chapter 5) was thought to be the immediate impact of these rehabilitation activities. However there exists no literature on any investigation made to correlate the forest cover changes with the catchment hydrology, either spatially or temporally.
Photo 1.1: A view of the high cover chir pine (Pinus longifolia) crop in Tanglai Reserved Forest.

Photo 1.2: A view of deforestation by settlement of refugees at the other corner of the same forest.
1.4 AIM AND OBJECTIVES

The aim of the research is to develop a deterministic distributed model capable of simulating spatial and temporal variations in hydrological processes, and assessing the impacts of land cover changes on these processes.

A hierarchy of objectives were defined to meet this aim which included:

- Development of a digital terrain model, geological and soil data bases from existing maps.

- Land cover mapping and change detection through processing of multi-temporal remotely-sensed data and devising a technique for GPS (global positioning system) based ground verification and accuracy assessment of the land cover maps.

- Development of a new system of meteorological data filing, cataloguing and automated retrieval for computer simulations.

- Integrating spatial data bases and meteorological data sets with the hydrological process models through simulation modules specifically written for this purpose.

- Simulating the water balance components with land cover data from different years, and assessing the impacts of changing land covers on individual components of water balance.

These aim and objectives facilitated the following hypotheses to be tested:

- All spatial and temporal changes in the land use and land cover are likely to impact on the individual hydrological processes and alter the catchment response as a whole.

- Any deviation in the water balance of the Siran Basin, observed during the last two decades, was largely caused by the forest cover changes.

For the sake of simplicity in testing these hypotheses, it is assumed that there has been no significant change in the climate or other spatial characteristics e.g. topography, and soils of the catchment during the last two decades. Nevertheless such assumptions are not valid when studying the hydrological impacts of long-term changes in land covers.
1.5 AN OUTLINE OF THE THESIS STRUCTURE

Chapter 2 of the thesis presents an overview of the general environmental situation of northern Pakistan with particular reference to deforestation in the Siran Basin. A brief review of the wider literature on the hydrological implications of different types and extents of changes in the forest cover is given in section 2.3. Different approaches to modelling the hydrological impacts of land cover change, and the applications of remote sensing and geographical information systems in hydrological modelling are briefly described. The last section of the chapter 2 emphasises the need for a GIS based distributed component model for northern Pakistan's catchments.

Chapter 3 covers different phases of the development of a regional geographical information system for the Siran Basin. These include configuration of the GIS, computing requirements, acquisition of cartographic data, digitisation of various vector coverages, development of the DTM and rasterisation of the soil and geology data.

Chapter 4 addresses the strategy followed for land cover mapping and change detection. The acquisition of Landsat data, geometric rectification and warping and image adjustments to reduce relief effects are given in sections 4.4 and 4.5. The next two sections describe the methods used for image enhancement through the generation of synthetic bands (vegetation indices and tessalled-cap transformations). A series of steps followed in image classification and assessment of classification accuracy are given in detail in sections 4.8 and 4.9. The methods used for post-classification change detection and refinement of classifications in GIS are covered in the last two sections.

Chapter 5 deals with management of meteorological data and analyses of the general climatic pattern and the climatic trends. A new meteorological data filing and retrieval system for computer based simulations has been proposed in section 5.3. General patterns of climate and stream discharge are discussed in section 5.4. The last two sections are concerned with simple precipitation-discharge relationships and lumped modelling of water balance components carried out to compare the results of distributed simulations (cf. Chapter 7).

Chapter 6 outlines the structure and development of the distributed component model for the Siran Basin. The descriptions (e.g. algorithms, module specification etc.) of each process module are given in sections from 6.4 to 6.7. The possible application of the model for soil moisture modelling is briefly described in section 6.8. The last two
sections address the options for measuring the spatial heterogeneity of outputs through various statistical parameters and problems of accuracy assessment of these outputs.

Chapter 7 deals with the field application of the model for real-time simulations and impact assessment analysis. The evaluation of the spatial extrapolation of meteorological data by various statistical parameters is covered by section 7.2. Distributed simulations of hydrological processes and the statistical evaluation of spatio-temporal results of each process are elaborated in section 7.3. The capability of the model for calculating the daily water balance of the Siran Basin has been demonstrated with the observed meteorological data in section 7.4. In the last section the changes in evapotranspiration, infiltration and surface runoff as a result of land cover changes have been quantified spatially and temporally.

Chapter 8 outlines some key issues which have emerged during the course of this study. A synopsis of the results, major conclusions, and the possibilities of future extension are presented in this chapter.
Chapter 2

ENVIRONMENT OF NORTHERN PAKISTAN
2.1 INTRODUCTION

Temporal changes in land use are usually associated with some imbalance in the catchment hydrology at equilibrium. For example, the common notion concerning forests is that the complex of forest soils, roots and litter acts as a sponge soaking up water during rainy spells and releasing it evenly during dry periods; greatly diminished dry season flow is usually ascribed to deforestation (Brujinzeel, 1990). Water engineers and meteorologists are rarely on hand to measure the effects which the changes in land use will have on water resources (Pereira, 1973). However, the impacts of such changes on hydrological processes can be assessed through mathematical models (Anderson and Burt, 1985). These vary in their complexity from 'black box' through 'lumped conceptual' to 'deterministic distributed' models. The scope of this chapter is to present an overview of the general environmental situation prevailing in northern Pakistan with specific relevance to the land husbandry and past land use and land use changes in the Siran Basin. The impacts of various types and extents of land use changes on hydrological processes, as evidenced from the wide literature, have been briefly discussed. The recent efforts to integrate the mathematical models with GIS and remote sensing for the assessment of such impacts have also been reviewed. The last part of this chapter gives a justification for the development and application of a GIS-based process model for the Siran catchment to predict the impacts of land use changes in their real spatial context.

2.2 THE ENVIRONMENT OF NORTHERN PAKISTAN: AN OVERVIEW

The Indus, an antecedent river, arises on the northern slopes of Mount Kailas (6,714 m) in the Gangdise Range of Tibet (Shroder, 1989). It drains about 169,579 km² of catchment by the time it reaches Tarbela Dam in the northern Pakistan. About 26,875 km² (~16 %) of the total drainage area is monsoon-affected, of which 10,356 km² has been reported to fall under active monsoon rains (Khattak, 1977). The natural disasters, associated with the geological processes and tectonic, young landforms e.g. uplift and erosion, landslides, as well as glacier advances, are common in the extreme north of Pakistan beyond the effect of monsoon (Shroder, 1989); whilst a man-made degraded landscape which has evolved as a result of accelerated erosion is clearly seen in the monsoon-affected belt (Pereira, 1981).
2.2.1 Landforms and Geological Hazards

The active geomorphic processes in the Himalayas are driven by an extraordinary rate of mountain uplift produced by ongoing collision of the Indian and Eurasian crustal plates (Molnar, 1986). The general evolution that has produced the spectacular landforms of the western Himalayas (the Indus catchments) is the legacy of floods, landslides and glaciers. The same processes today present the mountain residents with the unique hazardous existence in the midst of great natural beauty (Shroder, 1989).

2.2.1.1 Uplift and Denudation

On average, the rates of Himalayan uplift (~7 to 8 mm/year) are about eight times greater than average maximum denudation. This results in some of the highest peaks in the world (e.g. 8,125 m high Nanga Parbat in the Karakoram Himalayas). The highest rates of erosion occur in glacial regions i.e. 0.6 mm/year, whereas mountain rivers have rates of about 0.4 mm/year (Shroder, 1989).

2.2.1.2 Landslides

The immense relief, strong fracturing and high seismicity cause major slope failures, even in massive crystalline rocks produced as a result of the collision of crustal plates and consequent intense igneous and metamorphic activity. Large rock-falls are common where steep slopes are undercut by rivers and where pressure release occurs following glacial melt. Many slope failures have been recognised in the middle and upper Indus, Gilgit and Hunza Rivers. The Karakoram Highway is constantly cut and blocked by large and small slides. The foothill regions of northern Pakistan, e.g. the Chhattar Plain in the Siran Basin, experience other kinds of failures where clay-rich residual soil slides slowly downhill. Where thick deposits of gravel are undercut by rivers and fault scarps, large and small debris falls and slides occur in valleys. Talus slopes, formed by rock falls, dry grain flows and wet debris flows, range from small cones to huge accumulations several kilometres wide. Debris flows are the most hazardous catastrophic mass movements in which surface debris is mobilised by rain and snow melt and rushes down gullies destroying bridges, devastating fields and even blocking some of the larger rivers (Shroder, 1989).
2.2.1.3 Glacier Advances

More than 160 glaciers of western Himalayas have been analysed, of which those in the valleys of Shimshul, Hispar and Braldu have convoluted moraines indicative of surge behaviour, causing river damming and consequent flooding. The glacial regions are contributing the highest rates of erosion in Himalayas (Shroder, 1959).

2.2.2 Human-Induced Environmental Degradation

Ironically the Himalayan mountain ecosystem is almost as fragile as it looks massive. The impacts of the humans and animals add to the ongoing natural disasters through soil erosion, landslides and slips, annual floods and droughts (Bajracharya, 1985). The activities which still threaten this ecosystem include upland cultivation on steep slopes, over-grazing, over-exploitation of forests, nomadism and urbanisation (Ahmad, 1993). Ellis et al. (1993) concluded that the cumulative impact of these activities was an increased silting and flooding in the adjacent low-lying areas. The following paragraphs describe the major human-induced factors which contribute to current environment of northern Pakistan.

2.2.2.1 Demographic Pressures

The current population density of the monsoon-affected foothill zone of northern Pakistan (including Siran Basin) is 300-500 people/km² (AKRSP, 1992) with a growth rate of over 3% corresponding to a doubling of population in 20-25 years (Hudson, 1992). The Himalayan catchments are having to accommodate ever increasing human populations. With an increase in the human populations in this fragile environment deforestation, over-grazing, expansion of cultivation, constructional activities and overall mismanagement have contributed to the imbalance of natural phenomena and intensified environmental hazards (Shroder, 1989). The beginning of land mismanagement is coincident with the wave of invasions by Central Asians along with their flocks. Gradually they developed paths and roads through the forest areas for their dwellings, agriculture and pastures (Sheikh, 1985). Another big mass migration and settlement across the Indo-Pakistan border took place at the time of independence in 1947. Recently, the flow of millions of refugees from Afghanistan into northern Pakistan constituted one of the largest migration in modern times. Ives and Messerli (1989) critically analysed the situation and pointed out that many of the
tentage villages, which were established in the forested catchments of North West Frontier Province in northern Pakistan, have caused the most extensive environmental damage. Allan (1987) realised that human costs are great but that much of this damage could have been avoided by locating refugee camps further south.

2.2.2.2 Pastoral Systems

Like many other developing countries the data on livestock in this area is not often reliable. However, it is apparent that the livestock population is rising at least as fast as the human population (Hudson, 1992). Livestock rearing has seldom been practised on modern lines and the majority of pastoral communities are just ignorant of the concept of livestock farming. Uncontrolled grazing is considered to be one of the most important factor causing an over-exploitation of rangelands, destruction of many forest areas and failure of many regeneration projects (Sheikh, 1985). Joekes (1995) has warned that the agro-pastoral system in northern Pakistan is under severe pressure. Nomadism, a traditional way of herding prevalent in northern Pakistan over centuries has been found to bear more serious impacts on environment than shifting cultivation. There is a significant burden on the existing forests and range lands exerted by nomadic pastoral tribes who are migrating between the high mountains, foothills and plains along with millions of goats, sheep and cattle in search of forage (Sheikh, 1985).

2.2.2.3 Deforestation and Forest Conservation

Following the passing of the Indian Forest Act (1865), large areas of forests were reserved for commercial purposes. At the time of the first Land Settlement (1887) of the areas now in northern Pakistan, three classes of forests were defined: Reserved, Protected and Guzara (common holdings of village) forests and rights of their use were clearly stated. Mather (1990) stated that nearly all of the forests in the last category have suffered disproportionately in the face of growing population and most of them have now either been converted to agricultural land or have been totally degraded. The management of the Himalayan forests was interrupted during the two World Wars when these forests were exploited to meet the war requirements (Sheikh, 1985). At the time of independence in 1947, the proportion of the forest resources falling to Pakistan had already been exhausted.

Out of Pakistan's total land area of 87.8 m ha, the area under the control of provincial
forest departments is 10.6 m ha (6.1 m ha of rangeland plus 4.5 m ha of forest land).
Actual production forests constitute only 1.3 m ha and are distributed throughout the
country. The provincial distribution of the national forest area is given in Table 2.1:

<table>
<thead>
<tr>
<th>Province</th>
<th>Coniferous Forests</th>
<th>Riverain Forests</th>
<th>Scrub Forests</th>
<th>Coastal Forests</th>
<th>Irrigated Plantations</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWFP</td>
<td>1,022,000</td>
<td>300</td>
<td>115,000</td>
<td>-</td>
<td>300</td>
</tr>
<tr>
<td>Punjab</td>
<td>68,000</td>
<td>56,000</td>
<td>283,000</td>
<td>-</td>
<td>127,000</td>
</tr>
<tr>
<td>Sind</td>
<td>-</td>
<td>232,000</td>
<td>6,000</td>
<td>281,000</td>
<td>70,000</td>
</tr>
<tr>
<td>Baluchistan</td>
<td>116,000</td>
<td>2,000</td>
<td>595,000</td>
<td>2,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Northern Territory</td>
<td>285,000</td>
<td>-</td>
<td>658,000</td>
<td>-</td>
<td>2,000</td>
</tr>
<tr>
<td>Azad Kashmir</td>
<td>379,000</td>
<td>-</td>
<td>26,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,870,000</strong></td>
<td><strong>290,300</strong></td>
<td><strong>1,683,000</strong></td>
<td><strong>283,000</strong></td>
<td><strong>200,300</strong></td>
</tr>
</tbody>
</table>

*Table 2.1: The provincial distribution of forest area by forest types in Pakistan. (Source: Amjad and Khan, 1984.)*

Most of the natural forests in the Siran Basin fall in first category i.e. coniferous
forests. The production forests in Pakistan yield far less than 'international standards'
due to poor site quality and conventional silviculture. For example, coniferous forests
produce 0.7 m³/ha of wood (timber and firewood) annually against their potential of
1.5 m³/ha (Sheikh, 1985). Pressure on the existing forests for fuelwood and timber
has intensified over the past 25 years with consequent large scale deforestation (Ives
and Messerli, 1989) and hacking and lopping of trees. However, the extent and pace of
deforestation in northern Pakistan is difficult to assess due to fact that it is the cover
density rather than total area which is being reduced. Annual growth accounts for only
62% of the annual wood harvest, hence the forest resource is being depleted.

The needs of the people and requirements of forest conservancy plans have always
clashed in northern Pakistan (Sheikh, 1985). For many decades, during the British
period, the policy was to isolate the forest wealth by reserving them as crown forests.
After independence both the government and the people started realising that the forest
resource is a public asset. Bajracharya (1985) analysed the situation and stated that in
recent times the bureaucratic approach to conserve this asset has been proved totally
unsuccessful and the perceptions of forestry in the hills of Pakistan is changing. He
observed that the new premise 'the people are the real owners of the forests and the
forests should be used and managed in the best interests of the owners and the nation
as a whole' is taking a firm root in the mind of forest communities. Ellis et al. (1993)
pointed out that success in most afforestation programmes in Pakistan is still hampered
by a lack of basic data and poor co-ordination between the departments involved.
2.2.4 Marginal Agriculture

Expansion of cultivation to meet the ever increasing demands for food and fodder has been another major cause of destruction of natural forests (Bajracharya, 1985), particularly in the densely populated monsoon belt. The cultivated areas are heavily fragmented consisting of scattered, individually-owned small fields. These fields generally are outward sloping patches of freshly broken-up steep slopes without much terracing or safe methods of disposing surplus runoff (Khan, 1985). Besides steep-slope farming, the use of low grade land for agriculture has intensified during recent decades. Such low potential land is continuously being ploughed for cereal production although it is best suited to grass or forestry (Hudson, 1992). The general pattern of agriculture involves single cropping leaving the land fallow during monsoon months, thus exposing the soil to torrential rains making it prone to sheet wash. The primitive methods of harvesting, still prevalent in this belt, leave no stubble or crop residue on the ground after the crop has been removed (Khan, 1985).

2.2.5 Socio-economic and Political Factors

The subsistence mountain farmers have frequently been perceived as a large part of the environmental problem, but rarely as a part of the solution. Undoubtedly the socio-economic conditions prevailing in northern Pakistan have played a very significant part in the deterioration of the forests (Sheikh, 1985). People in these areas are mostly illiterate and prefer to stick to age-old conventions and convictions. Division of agricultural land from generation to generation has resulted in very small holdings for each farm family. At present meagre agricultural and pastoral activities are probably incapable of supporting subsistence farming.

Conventionally the forests adjoining the habitations have met the fuelwood, fodder and timber demands, but as mentioned earlier, the village forests are over-exhausted and can not serve these purposes any longer. Under the changing circumstances governed by the high population pressures, no energy alternatives for the mountain communities are available in hand to halt the pace of forest decline for fuel. The development of modern communication systems coupled with high price of timber and fuelwood has further enhanced the process of deforestation (Sheikh, 1985). Recently some projects in the social forestry sector have been launched with the prime objective of developing renewable energy source with the intimate involvement of people, though the projects will not have any immediate effect on these forest resources.
Forest ownership has been described by Azhar (1989) and Azhar (1993) as one of the chief factors contributing to forest decline in northern Pakistan. He argued that since most of the natural productive forests are in the hands of local inhabitants, the causes of their rapid deterioration are to be found not only in an extensive admission of open ended communal property rights but also an inadequate specification of those rights. Most of the rights, he traced back, had evolved as a result of a continual struggle for possession between the State and local inhabitants.

The politico-military situation consistently prevailing in northern Pakistan and Kashmir has also resulted in severe environmental and socio-economic repercussions. Ives and Messerli (1989) referred some reports showing that hundreds of thousands of Indian and Pakistan troops are deployed in the general region of Karakoram and Kashmir. The impacts of such a human concentration, coupled with movement of armour, have led to the loss of forests and wildlife, and increased water pollution.

2.3 EVIDENCE OF WATER IMBALANCES

Megahan (1977) reported the results of a catchment condition survey conducted during 1960's covering ~ 90,000 km² in the upper Indus which revealed that 84 % of the survey area was experiencing impaired hydrology. Low forest cover density, range land depletion and severe erosion of the agricultural lands were named as major causes of the hydrologic disorders. Myers (1989) noticed that decreased forest cover in Pakistan was the major cause of increased erosion and severe flooding. As a result of incessant erosion, the topsoil has become thinner, eventually disappearing in many areas leaving only subsoil or bare rock. Soil erosion rates of 2000-4000 tons/km²/yr are reported from the upper Indus catchments (Khattak, 1977). A survey on the sediment load of major rivers indicated that the Indus carries one of the highest sediment load per unit drainage area in the world (Ives and Messerli, 1989). A 13-year annual sediment record, collected by the WAPDA, for the Siran River is presented in Figs. 2.1 a and 2.1 b.

It is evident from Fig. 2.1 that there was an increase in sediment yield and suspended sediment concentration in 1976-1977. This was the time when deforestation activities were intensified in northern Pakistan (Allan, 1987; Haigh, 1991). The decline after 1977 might be the result of forest and catchment conservation campaigns, most of which were initiated in mid 1970's, although no data exists to support this argument. There is a need to investigate the effects of all types of land use changes on catchment
hydrology and to frame a strategy to return the land use in these headwaters to hydrological stability by exploiting their natural ecological role (Pereira, 1981). However, little literature exists on such studies in northern Pakistan's catchments.

Hanif and Shah (1989) studied the effect of different land uses (forest, agriculture and range) on physical properties of soil and hydrological response various regions of northern Pakistan. They concluded that the forest soils had the highest permeability, infiltration capacity and baseflow. Raeder-Roitzch and Masrur (1989) studied the effect of different covers (e.g. bare soil, depleted grass, regeneration and pole crop) on water balance components in Murree area of northern Pakistan. They found that regenerations do not significantly alter the water balance (i.e. evapotranspiration and percolation) of a grassland. A dense chir pine stand at pole stage has been found to
have the highest evapotranspiration and lower total discharge as compared with grassland or bare soil, but tends to stabilise the dry-season baseflow. These studies carried out in northern Pakistan, however, were not aimed at assessing the hydrological impacts of temporal changes in land cover. The following paragraphs review the results of field studies which have been conducted, elsewhere in the world, with the prime aim of hydrological impact assessment of changing land cover.

### 2.3.1 Forest Cover Changes and Deforestation

Forests play an extremely important role in protecting the natural flow of the rivers, besides providing timber and fuelwood. In the areas where forests are exploited solely for watershed management, land is used at a very low level of intensity (Russell, 1981). Interception loss from forest canopies is higher compared to other (non-forest) vegetation types due to their higher LAI. Evapotranspiration, however, depends on the characteristic ability of a forest type to offer a resistance to water loss. For example, evapotranspiration loss from conifer forest canopies is far less than an evergreen broad-leaved forest owing to their maximum resistance to water loss. Oliver and Oliver (1988) suggested the role of trees in intercepting precipitation and evapotranspiration to be thoroughly studied. Infiltration capacities of forest soils are generally higher (Bruinzeel, 1990) and they produce low volumes of runoff with minimum seasonal fluctuations compared to other land uses. Wiersum (1985) argued that the higher infiltration and low runoff are not so much due to the ability of tree canopy to break the power of rain drops but rather in developing a litter layer.

Nevertheless the extent of change in a forest may vary from a low intensity disturbance (e.g. grazing, browsing, pruning, thinning) to clear-felling or deforestation. Consequently the extent of influence, which a forest cover change can have on the catchment hydrology, varies with the extent of that forest change. Hornung and Newson (1986) argued that even the silvicultural practices e.g. site preparation and fertilisation can alter the catchment hydrology, sediment yield and water chemistry. Low and intermediate changes such as continuous grazing for seven grazing seasons in a forest increased stormflow by four times (Bosch and Hewlett, 1982). Bari et al. (1993) reported a decrease in infiltration capacity following livestock grazing in a temperate range of Pakistan. Browsing, in dense forests without grass causes rapid disturbance of the hydrological regime (Pereira, 1973).

Reducing canopy biomass (LAI) by either partial felling (thinning) or pruning decreases interception loss, decreases over-storey transpiration, decreases soil water depletion (Gholz...
et al. 1990), increases under-storey water use; and may increase total streamflow, peakflow and baseflow (Troendle and Kuafmann, 1987). Miller et al. (1988) measured the stormflow and peakflow responses to three treatments: clear felling, selection felling and no disturbance (control) in a small replicated catchment in Quichita Mountain of Alaska. The stormflow yield did not increase significantly due to forest harvest treatments, apparently because permeable soils and subsurface geology allowed deep seepage at the expense of stormflow. Furthermore a cover change in the forests with different species can have widely varied impact on the hydrological regime. For example, Bosch and Hewlett (1982) summarised the results of 94 catchment experiments and concluded that cover changes in pine and eucalyptus forest types have more severe effects on the water yield compared to those in deciduous hardwood and scrub forests.

Deforestation or clear-felling without replenishment is the extreme form of forest cover change. It is such a common practice that globally the area under forests is decreasing by about 20 million hectares a year (Kunkle and Dye, 1981). The most common post-deforestation observation is a deterioration of river regimes (i.e. increased peak flows and decreased low flows). Many hydrologists, e.g. Hasia (1990), are of the opinion that impaired catchment hydrology is the result of deforestation itself; but others, e.g. Bruijnzeel (1990), realise this reflects a lack of good land husbandry during and after clear-felling operations. For example, Rowe and Pearce (1994) measured streamflow after clear-felling in Westland, New Zealand and showed that it increased more in the areas where riparian reserves had been removed compared to the areas where they were left following clear-felling. To Russell (1981), it is not always necessary to use forests for the protection of water gathering areas and the planting of trees is not the panacea for all stream source areas (Pereira, 1981). Certainly the opinions regarding influence of deforestation on water yield and flow regime are contradicting, but scientists are confident to prove that deforestation accelerates on-site erosion and off site (downstream) hazards (Walling, 1983). For example, in Malaysia, Douglas et al. (1992) measured the monthly suspended sediment which increased by 18 times following clear-felling.

2.3.2 Conversion from Forest to Agriculture

The impacts of forest conversion to agriculture are highly varied, as reported by many hydrologists. Russell (1981) argued that it is possible to increase the outflow of water from a forested catchment by replacing the trees with short season arable crops particularly in areas with sufficient rains but a pronounced dry season. He believed that such a change is linked to river flooding and increased sediment load. Pereira (1981), on the other hand, was
of opinion that a commercial agricultural estate with roads, houses, factory, offices and workshop can be developed in a forested catchment without long-term damage to either soil stability or to the amount and regulation of streamflow. He gave the example of Brooke Bond Company which had established such estates by meticulous planning for soil conservation and runoff control, followed by highly competent execution and subsequent management. Cultivation without adequate precautions to prevent surface runoff from reaching erosive velocities results in transport of surface soil, hence producing sheet and gully erosion, subsequent deposition of sediment in channels and storage reservoirs lower in the catchments.

2.3.3 Conversion from Forest to Pasture

Less research has been carried out on the effects of converting forest to pasture. A well-managed pasture generates more runoff than a forest but not necessarily more soil loss (Russell, 1981). Prebble and Stirk (1988) recorded the hydrological effects of a change from forest to pasture at the Narayan Research Institute, Queensland. The evapotranspiration calculated from rainfall, runoff and soil water storage change was similar for both treated (with conversion) and untreated (without conversion) catchments. On the other hand, Shukla et al. (1990) predicted a decrease in evapotranspiration following a conversion of tropical forests to pasture over the Amazon Basin. Bultot et al. (1990) recorded the impacts of basin-wide coverage by pasture and coniferous forests in Belgium. They concluded that annual evapotranspiration was at a maximum for forest-covered catchments and at minimum for pastures. Conversely, the mean annual stream flow was lowest for forests and highest for pastures. Smith (1987), using eight year's of experimental data in eastern Otago, New Zealand, established that the catchment with an introduced pasture yielded more water when compared to exotic forest.

2.3.4 Afforestation and Reforestation

Afforestation is the planting with trees of an area which has never been under a forest cover before; while reforestation means the replenishment of a forest after clear-felling. Sharma (1979) predicted an increase in evapotranspiration after catchment afforestation because of greater canopy cover of forests compared to other vegetation types. Brujinzeel (1990) found that total yield of water from a grassland was usually reduced considerably following afforestation. The catchment restoration (reforestation) through the planting of scrub species, reduced runoff and sediment yield from catchments in Pakistan's subtropical scrub
zone (Hanif et al. 1991). However, the catchment hydrology is highly sensitive to the species planted and their growth stage. For example, Meuser (1990) observed that afforestation with spruce reduced total runoff and ground water replenishment while beech and oak had less severe impact. Many water managers claim that planting fast growing trees e.g. eucalyptus might use more water than the slow growing trees in the natural forest. Borg and Stoneman (1991) concluded that stream flow from a young stand is less than that for a mature one due to the higher removal of moisture from the soil and lower resistance to sap flow from roots to leaves.

2.4 MODELLING THE IMPACTS OF LAND USE CHANGES

Mathematical models have been extensively used in hydrological forecasting to calculate the output data (e.g. runoff hydrograph) from input data (e.g. precipitation). Morris (1981) categorised them as: Black box models, Lumped conceptual models and Distributed Physically-based models. Black box models establish a statistical correspondence between input and output (Anderson and Burt, 1985) but they are not practical means of elucidating the individual components of the hydrologic cycle (Engbuniwe, 1981). Lumped conceptual models, e.g. the Stanford Watershed model and the Institute of Hydrology lumped model, have their use in assessing water resources, provided no major changes in land management occur within the period of interest. They are particularly useful in a ‘before’ or ‘after’ situation, i.e. before and after a vegetational change, in determining the magnitude and trend of changes of streamflow or its time distribution (Blackie and Eeles, 1985). If the parameters of a conceptual model are physically-based, as in TOPMODEL, the model is capable of coping with changes in catchment characteristics, such as urbanisation or afforestation (Anderson and Burt, 1985).

Distributed models, including the Système Hydrologique Européen (SHE) model, USDA Agricultural Research Service Small Watershed Model (SWAM) and the Institute of Hydrology Distributed Model (IHDM), have their utility in forecasting the effect of changes in land use and other spatially variable inputs. Catchment changes such as deforestation rarely take place abruptly over a complete basin. In a distributed model such changes can be treated in their correct spatial context. For example, the deforestation of an area on a watershed divide may have a very different effect from deforestation in a riparian contributing area in a valley bottom hollow (Beven, 1985). Complex distributed model, such as SHE, may not be necessarily more efficient in prediction and forecasting than a lumped-system model, but they are the most efficient means of simulating and understanding the hydrological processes and assessing the spatial heterogeneity of these
processes. The effective use of physically-based distributed models in forecasting has been hampered by problems associated with obtaining and verifying the accuracy of data for large number of model parameters (Abbott et al. 1986). Despite these weaknesses, recently many distributed hydrological process models have been developed with the integration of GIS and successfully applied in United States (e.g. Groves et al. 1983; Johnson, 1989), Europe (Abrahart, 1994; Ott et al. 1989) and Japan (Hoshi et al. 1989). The distributed hydrological modelling in developing countries including Pakistan is still in infancy due limitations of geographical and meteorological data and computing resources.

2.4.1 The Use of Remote Sensing and GIS in Hydrological Modelling

With the growing concerns of environmental conservation, the requirement to model the impacts of land use changes, such as deforestation, on the water resources (in terms of quantity and quality) has intensified. The earliest attempts to deterministic modelling for impact assessment were solely dependent upon data available as published maps and soil surveys. Hydrologists had recognised the power inherent in digital satellite data but existing models were not structured to take full advantage of potential value of such data (Engman and Gurney, 1991). But in the early 1980's developments in GIS technology enabled spatially distributed data to be interfaced with simulation models. The model developed by Groves et al. (1983) for Marshall county, Iowa was among the pioneering efforts towards utilising RS and GIS data in hydrological modelling.

2.4.1.1 Hydrological Applications of Remote Sensing Data

Engman and Gurney (1991) identified two areas where Landsat (MSS and TM) data can be used in catchment modelling. Firstly, in evaluating geomorphic characteristics such as basin area and meander length for a class of empirical equations, and secondly in delineating land use classes for models based on land use components. Many hydrologists, e.g. Allord and Scarpace (1979) and Chandra and Sharma (1978) have developed empirical, and regression-based relationships between annual discharge and Landsat (MSS and TM) derived catchment characteristics. The parameters potentially available from multispectral remote sensing data for a completely distributed model include land use, impervious area, drainage network, ice and snow cover, albedo, vegetation (species, extent, characteristics), groundwater recharge and discharge areas (Groves et al. 1983). Some other parameters such as LAI can be estimated from Landsat data in conjunction with field data (Curran et al. 1992; Schultz, 1993).
2.4.1.2 Geographical Information System and Hydrological Modelling

The GIS is required, on the one hand, to interface the remote sensing data and its products to distributed hydrological models and, on the other hand, to develop and interface other spatial data bases of catchment characteristics e.g. topography, geology and soils. Brilly et al. (1993) have identified three possible linkages between GIS and hydrological models which include: (i) using GIS functions for parameter estimation to run existing lumped-models; (ii) linking GIS databases with models to obtain spatial outputs; and (iii) embedding models within a GIS using the computing language of the host GIS. Many current distributed models belong to the second category i.e. the combination of databases with hydrological process algorithms through computer programmes (Maidment, 1991). This type of distributed parameter models is growing rapidly. High resolution models developed in 1980's had limited experimental (small catchment) applications. But recent developments in computer technology, to handle and manipulate the high resolution geographical data of large areas, enabled the application of distributed models at regional and catchment levels. However most currently available GIS-based hydrological models have not got an ability to effectively handle the time dimension (Brilly et al. 1993).

2.4.2 Hydrological Applications of RS and GIS in Pakistan.

The earliest use of remote sensing data in hydrology in Pakistan was in the estimation of the extent of snow cover through NOAA AVHRR, primarily for forecasting discharge of the Indus River. The Landsat MSS was applied to monitor the areas affected by floods in the Indus Basin in 1973 and, later, to monitor sedimentation and siltation in the Tarbela and Mangla reservoirs (Alizai and Mirza, 1986). Further Landsat (MSS and TM) applications have been confined to land use mapping, change detection, biomass estimation, land cover dynamics and urban management. For example, a nationwide land use mapping was carried out through the manual interpretation of Landsat TM data in 1992 (Whiteman et al. 1992). Recently GIS has been used to integrate multi-resolution remotely sensed data (SPOT, MSS and aerial photographs) to quantify land use changes (Siddiqui and Jami, 1993; Dennis et al. 1991). Millington et al. (1994) modelled moisture availability and land cover dynamics using NOAA-NDVI in drylands of Pakistan. Lang (1992) used integrated RS and GIS in the field of urban development analysis. No literature exists on RS and GIS applications for a completely distributed hydrological process modelling in Pakistan. Nevertheless the development and application of a GIS-based model in Pakistan are constrained by unavailability of source data and restriction of data use besides limitations of computing resources.
2.5 A NEED FOR GIS-BASED MODELLING IN NORTHERN PAKISTAN

The essence of the previous sections of this chapter has been to argue that GIS-based hydrological modelling is required in northern Pakistan because:

i) in the Himalayan foothill catchments, topography, geology, soil, climate and land use are spatially variable even over the small area;

ii) in most catchments, the process of land use change (e.g. deforestation) has intensified during last two decades;

iii) these changes have significant hydrological effects, which are evident from altered hydrology regime (e.g. high peakflows, extended droughts and high sediment yield) of most catchments;

iv) no operational model exists to assess such impacts in northern Pakistan's catchments; and

v) GIS-based process modelling offers an approach with the ability to simulate individual hydrological processes and to quantify the effects of changing land uses on these processes.

To be fully operational such a model ideally should:

i) be based on universally accepted process algorithms so that it can be applied to other catchments for which databases are available;

ii) have minimum reliance on commercial GIS software, the unavailability of which may restrict its application;

iii) be verified with the GIS databases of a catchment for which ample hydro-meteorological data is also available for measuring accuracy of model outputs.

2.6 SUMMARY

- a review of literature on the environmental conditions prevailing in northern Pakistan, with particular reference to past land use changes, has been presented.
the underlying social, economic and political factors contributing to deforestation and land use changes in northern Pakistan have been outlined.

the hydrological consequences of the major land use changes in the forested catchments, such as Siran, have been described.

a brief review of the approaches and current trends to model the impacts of temporal changes in the spatial catchment characteristics has been presented.

a justification for the development of a GIS-based deterministic distributed model for the simulation of hydrological processes and impact assessment analysis has been emphasised.
Chapter 3

DEVELOPMENT OF A
GEOGRAPHICAL INFORMATION SYSTEM
FOR HYDROLOGICAL MODELLING
IN THE SIRAN BASIN
3.1 INTRODUCTION

A pre-requisite to estimation of the parameters for distributed modelling is the availability of spatial data at the desired resolution and in the format which can be retrieved and manipulated by the processing unit. For deterministic hydrological modelling in the Siran Basin, it was necessary to build a regional GIS to a specific configuration. The configuration of the GIS is a combination of a management subsystem, a computer hardware subsystem and a computer software subsystem (Burrough, 1986). It consists of modules such as data input and verification, data storage and database management, data output and presentation, visualised processing and analyses of data and interaction with the user. The data structure is built using an 'overlay' concept i.e. the real world is portrayed by a series of overlays. The topography is represented by the DEM and its derivatives, land use by classified satellite imagery, vegetation by various indices and soils by digitised soil maps. This chapter addresses the configuration and the data structure of the Siran GIS, followed by the procedures adopted to build spatial data layers from the cartographic maps. The image processing for land use mapping, change detection and derivation of vegetation related parameters has been discussed in the Chapter 4. The following is the list of tasks which were defined before commencing work on this phase the study:

- acquisition of existing topographic, geology and soil maps at the largest available scale.

- digitising cartographic data e.g. elevation contours, geology and soil class boundaries, the catchment boundary, and the forests boundaries.

- building the DEM and extracting topographic parameters e.g. slope, aspect, upslope area, and delineating the drainage network and sub-catchment boundaries.

- rasterising digitised categorical data e.g. geology and soil association coverages, and deriving the soil texture map.

- organising the GIS layers to a common resolution and co-ordinate system.
3.2 CONFIGURATION OF THE SIRAN GIS

In building the Siran GIS data base, the most important step was to decide which variables should be represented and how to evaluate and co-ordinate information from different source maps (Schaller, 1994). The spatial resolution and co-ordinate systems for the GIS were also given due consideration. A brief description of the procedures followed to accomplish this task is given in the following sub-sections 3.2.1 to 3.2.3.

3.2.1 Defining Data Requirements

The algorithms chosen to model the hydrological processes dictated the parameters to be included in the GIS and specific data requirement for setting it up. Mounsey and Briggs (1988) recommended that the decision about the data must not depend only upon the objectives of the information system and needs of its users, but several more practical factors must be taken into account. The factors which constrained the data choice for this study among others included time available for data acquisition, availability and restriction of use, consistency, data volumes and limitations of financial resources.

Like many other GIS developed for the analysis of water resources problems, topographic information formed an integral part of the Siran GIS data base. The existing topographic maps of the study area are the only source of relief information, hence acquisition of these maps was given the top priority. In modelling hydrological processes, another basic requirement is the information on geology and soils. The need for soil and geology maps was ranked second in the data priority list. There was also a need for the land cover information to be used during image processing and in the evaluation of simulation results. Such information for the Siran Basin exists as small scale land use maps in the past survey reports and land cover information contained on topographic maps.

3.2.2 Grid Resolution Criteria

In making the decision about the cell size of spatial data, prime importance is often given to the resolution of available raster data e.g. satellite imagery or derived products. A general trend in building the GIS structures, as with the remotely sensed data, has been from coarse to finer resolution. For example, Groves et al. (1983)
developed a remote sensing-based runoff prediction model at a cell size of $120 \times 160$ m$^2$. However in a recent version of TOPMODEL Robson et al. (1991) used a DTM generated at $50 \times 50$ m$^2$ scale to calculate $ln(A/tanB)$ index; and Ott et al. (1991) built a GIS structure of the Mosel River Basin at the resolution of TM ($30 \times 30$ m$^2$) for their hydrological impact assessment model. Even finer resolution ($20 \times 20$ m$^2$) has been employed by Goossens et al. (1990) for integrated soil and water balance mapping in Messinia, Greece. For this project the spatial data layers of the Siran catchment have been produced and maintained at $80 \times 80$ m$^2$ resolution because of catchment area, nature of the problem, scale and quality of source maps and resolution of remote sensing data.

3.2.2.1 Catchment Area

To date, GIS-based hydrological simulation models have been developed and tested on small areas. The storage, retrieval, analysis and display of high resolution (< 80 m) spatial data of a large catchment such as the Siran Basin (1040 km$^2$) can be constrained for technical reasons. Reducing the cell size of any raster layer from 80 to 40 m will increase its volume by four times. Consequently there is a four-fold increase in data storage, memory and processing requirements. For example, the aspect map will occupy 6.8 MB instead of 1.7 MB of hard disk space if the cell size is halved.

3.2.2.2 Nature of the Problem

The resolution and level of precision required in a GIS data depends on its purpose. For example, an 80 m grid is inappropriate for urban planning and management, but arguably acceptable for meteorological extrapolations and hydrological simulations. A very high resolution GIS data may not necessarily yield more accurate results when used for modelling environmental phenomena, as the results may be misleading or even meaningless and untestable (Heywood et al. 1994).

3.2.2.3 Scale and Quality of Source Maps

Most spatial data layers have been derived from one inch scale topographic maps on which the contours are drawn at 50 and 100 ft. interval on gentle and steep slopes respectively (cf. sections 3.3.1.1 and 3.3.1.2). Actual digitisation was restricted to
every fifth contour (250 and 500 ft.) due to poor quality maps (all contours not traceable), digitising time and data volume. The accuracy of the DEM built by interpolation from these contour data could not be increased significantly by reducing the cell size.

3.2.2.4 Resolution of Remote Sensing Data

The image processing products cannot be produced at a resolution finer than the that of the original imagery. One of the satellite imagery used in this study for mapping the land covers of 1970's was Landsat MSS (pixel size ~ 56 x 79 m²). Further justification of processing Landsat MSS for land cover mapping and change detection is given in Chapter 4 (cf. section 4.2.2). In order to interface with the GIS, the image processing product i.e. the land cover map had to be warped to a regular (squared-cell) grid. It was not possible to generate a land cover map at a resolution finer than 80 m which was one of the reasons of using this resolution for the Siran GIS.

3.2.3 The Co-ordinate System

The available topographic, geology and soil maps, although drawn at different scales, are referenced to a longitude / latitude system. After digitisation of these maps, the vector coverages were transformed from digitiser co-ordinates to real world (longitude / latitude) co-ordinates. However these geo-referenced coverages could not be rastersed directly to produce regular (squared) grids at 80 m resolution, unless transformed to distance (metres) co-ordinates. Therefore prior to rasterisation, another transformation had to be carried out from real world co-ordinates to distance co-ordinates. The co-ordinates of the geo-referenced and transformed GIS data are graphically shown in Fig. 3.1.

3.2.4 Computing Requirements

3.2.4.1 Hardware

The computer hardware that supports geographical analysis and mapping includes the central processing unit and peripheral devices. The latter category consists of auxiliary storage units; devices used to enter, analyse and display information and generate hard
Fig. 3.1: The co-ordinates of the Siran GIS data layers: (a) digitised vector coverage geo-referenced to geodetic system, (b) the same coverage transformed to RAW (distance) co-ordinates, (c) geo-referenced rasterised (772 rows × 421 columns) layer, and (d) grid and cell size (metres) of the same raster layer.
copy (Antenucci et al. 1991). A generalised assembly of machines used for the building the Siran GIS, data analysis and mapping is shown in Fig. 3.2.

The digitisation of the cartographic data was implemented manually on a PC connected to a digitising table with a twelve button puck. Later on all coverages were exported to a local Sun workstation for editing and further processing. Part of the work was accomplished on the Leicester University’s main frame computer, operating on IRIX 5.0, to take the advantage of the high speed processing system. As with most spatial data, voluminous raw coverages and processed grids of the Siran GIS structure demanded bulk hard disk space to be available. The grid volume ranged from 400 - 2000 KB depending on the type (integer or float) and value units; each intermediate output occupied same space. The minimum disk space requirement to accomplish the processing of GIS data (excluding remotely sensed data), as estimated before working on the project, was 50 MB. Storage, retrieval and manipulation of grids (772 rows × 421 columns) were not constrained by the RAM (and swap memory) and processing power of the workstation. The hard copy output devices used for this project were postscript A-4 color and thermal calcomp printers.

3.2.4.2 Software

Conceptually the hardware is surrounded by three layers of software i.e. operating system, special system support programs and application software (Antenucci et al. 1991). An illustration of the software used for the GIS data processing in this study is given in Fig. 3.3. Two operating systems namely UNIX 5.0 (on the local workstations) and IRIX 5.0 (on main frame computer) were used. Special system utilities perform certain routine functions and among others they include text editors, language compilers, file managers, format converters, file transfer programmes and special drivers for communication with peripheral devices. An X-window based format conversion programme 'xv' was used in this study, while data transfers between the local Sun workstation and the IRIX file server were carried out using 'ftp'.

The spatial data available as cartographic maps have been entered, processed and maintained using PC and workstation versions of ARCINFO. Except for the digitisation, which was implemented on pc-ARCINFO 3.4, all operations involved in data editing and management were carried out using ARCINFO 6.1, surface analysis module TIN 6.0 and raster modelling system GRID 6.0.
Fig. 3.2: An illustration of the hardware used for building the GIS.

Fig. 3.3: An illustration of three-layered model of software used for building the GIS.
3.3 TERRAIN MODELLING

A Digital Terrain Model (DTM) can be perceived as ordered arrays of numbers that represent the spatial distribution of topographic attributes such as elevation, slope, aspect and upslope area. A subset of DTM which represents the elevation above some arbitrary datum in a landscape is termed as Digital Elevation Model (DEM). Often a DEM is derived by digitising topographic maps and other terrain attributes which describe the land form are extracted from it. There are three alternative methods of structuring elevation data which are commonly used namely; (i) square-grid, (ii) triangular irregular network (TIN) and (iii) contour-based networks. Of these, the most widely used data structures consist of square-grid networks because of ease of computer implementation and computational efficiency (Collins and Moon, 1981).

The DEM and its two physiographic derivatives i.e. degree of slope and aspect have formed essential parts of most GISs developed for process simulations in the mountainous areas (Moore et al. 1991). In addition to these three layers, the Siran GIS data base includes some other parameters directly extractable from the DEM e.g. upslope area for overland flow modelling. This section briefly describes the procedures followed to develop the Siran DTM and to assess its quality.

3.3.1 Acquisition of Topographic Maps

3.3.1.1 Significance, Source and Scale

Since digital data as such is not available, existing topographic maps were the only source of elevation information. In addition they carry information on drainage network, land cover, communication network and location of villages and towns. Due to severe restrictions on the international availability of large scale maps of South Asia since 1950 (British Library, no date), only those published before 1947 could be acquired to meet the research needs. Seven reprographs of contiguous map sheets of one inch series (Sheet Ref: F-43/1 to F-43/3 and F-43/5 to F-43/8) published in 1941 were supplied by the British Library, London. These maps are referenced on a geodetic (longitude / latitude) system and contain elevation contours drawn at 50 feet and 100 feet intervals on gentle and steep slopes respectively. The prominent peaks and depressions are represented by the spot heights.
3.3.2 Quality Assessment

The most common measure for the quality of a map feature is its relative and absolute positional accuracy. Some other quality characteristics include lineage, attribute accuracy, logical consistency, completeness and timeliness (Antenucci et al. 1991). The topographic maps available for this study were originally produced to conform to the British map accuracy standards and it was not possible to measure absolute accuracy because no other information was available. However, minor positional inconsistencies were found during edge matching contour coverages digitised from individual sheets. As Robson et al. (1992) have noted, small scale maps, such as these, fail to identify some of very steep slopes which are represented by toothed contours. Since for this study only the black and white reprographs (photocopies) of the original maps were available, many contours appeared to be fading away and losing continuity.

3.3.2 Digitisation of Topographic Maps

Since the maps were unsuitable for digital scanning, the contour lines and spot heights were digitised manually. The sequence of steps followed to enter the elevation data has been given here;

a. A manuscript was prepared before data entry by tracing every fifth contour (drawn as bold lines) from each of seven topographic maps.

b. The digitisation was accomplished using pc-ARCINFO ADS 3.4 in 'stream' mode, to ensure capture of maximum information, and individual lines were labelled with the height values.

c. The seven contour coverages (digitised from seven maps) were appended into a single coverage representing the whole catchment and transformed from digitiser co-ordinates to real world co-ordinates.

d. Similarly the spot heights were digitised, labelled, appended, transformed and saved as a single point coverage.

e. Both these layers were exported to a Sun workstation for displaying the errors and interactively editing them. The edge matching and editing of contour labels was carried out using ARCEDIT.
f. A triangulated irregular network (TIN) was generated from contour coverage using ARCTIN for viewing the surface and identifying possible errors.

g. Unfortunately the digitised contour coverages failed to represent some of the prominent peaks and depressions shown on the source maps as spot heights. In order to incorporate the missing information, the contour and point coverages were merged together.

h. The step (f) was repeated after each edit until all known errors were removed.

3.3.3 Construction of the Digital Elevation Model

Three types of the DEM structures (contour-based structure, TIN and grid-based structure) have been widely used in hydrological modelling. The most efficient DEM for the estimation of topographic attributes and distributed hydrological simulations consists of a grid-based network because of its ease of computer implementation and computational efficiency (Collins and Moon, 1981). These DEMs are constructed by interpolation of elevation data from digitised contours or irregularly spaced spot heights.

3.3.3.1 Interpolation of the Elevation Data

Interpolation is the process whereby a value is derived for a new point based on the known value of points around it (ESRI, 1989). The digitised contours usually contain far more elevation points than required for interpolation, however their number can be significantly reduced by converting the contours to a TIN. In this study, the TIN generated using ARCTIN contained 52,068 nodes compared to 161,812 segments contained in the input contour coverage. The regular DEM of the Siran Basin at 80 m resolution was generated by linear interpolation from the TIN. In order to build the value attribute table (VAT), the DEM was converted to an integral type grid with one meter class interval. The DEM was clipped with a vector coverage representing the catchment boundary to exclude all data outside the object area. Out of the 325,012 cells the Siran DEM (Fig. 3.4) contains, 162,415 (~ 50 %) lie outside the catchment boundary (NODATA cells) and virtually do not take part in further grid processing.
3.3.3.2 The DEM Quality Assessment

The major drawback of a grid-based DEM is that it fails to capture vital information describing abrupt changes in relief pattern (Stocks and Heywood, 1994). Some other disadvantages of this structure include (Moore et al. 1991):

- the size of grid mesh affects the computational efficiency and simulation results.
- the computed upslope paths are unrealistic as they tend to zigzag.
- precision is lacking in definition of specific catchment area and true curvature of catchment’s boundary line.

Since the Siran DEM was derived from the topographic maps, its accuracy could never be greater than the source data which themselves contained errors. The distortion, introduced after transforming the data from geodetic (latitude / longitude) to distance (RAW) co-ordinates, was a source of geometrical inaccuracy of the DEM. There was no reference data available to measure the global and relative vertical accuracy of the DEM, except for the source maps. Some of the very high peaks (e.g. Chakru-Sar top at 4285 m) along the catchment boundary could not be truly represented. In order to measure the relative vertical accuracy, the DEM values at 95 selected locations were compared with those on the topographic maps and the calculated mean RMS error was 18.7 m.

3.3.3.3 Conditioning of the DEM

The DEM constructed for the Siran Basin can be conveniently processed through traditional algorithms to derive many topographic attributes including slope, aspect and shaded relief. However, the extraction of topographic structure for overland flow modelling is hindered by the depressions (sinks) contained in the DEM. Automated calculation of the upslope area and overland flow path delineation necessitate the conditioning of the DEM i.e. filling the depressions prior to further processing. The algorithms for ordering grid cells and creating a depressionless DEM for hydrological modelling have been developed by Jenson and Domíngue (1988) and are presented by Smith and Brilly (1992). The identification and filling of depressions in the DEM is an iterative process (ESRI, 1993). Three depressions were identified in the Siran DEM which were filled in three iterations.
Digital Elevation Model of the Siran Basin

Class Interval 1 m Resolution 80 m

Scale 1:400,000

Fig. 3.4: The digital elevation model of the Siran Basin (1:400,000) generated by interpolation from the digitised contours.
3.3.4 Derivation of Topographic Attributes

A DEM is a primary source of topographic information for computer-based distributed modelling (Moore et al. 1991). Speight (1980) has described over 20 parameters which are geomorphologically and hydrologically important and can be extracted from a DEM. The parameters which were derived from the Siran DEM included slope, aspect and the upslope area (area draining through a unit length of contour).

3.3.4.1 Slope and Aspect

The slope or slope steepness is one of the most widely used primary topographic attribute. It plays a key role in several hydrological processes including overland and subsurface flow routing. The aspect (or slope azimuth) is the most important attribute for the calculation of solar irradiation and surface energy balance. These two attributes were automatically derived from the Siran DEM using ARCINFO utilities. The slope and aspect maps of the Siran Basin, produced at 1:400,000 scale are given in Figs. 3.5 and 3.6. Another view of the Siran geomorphology is given in Fig. 3.7: this image was generated by draping a shaded relief image and digitised drainage network over the surface.

3.3.4.2 Upslope Area and Drainage Network

The upslope area, \( A_u \), is a measure of surface or shallow subsurface runoff at a given point on the landscape (Moore et al. 1991). This attribute is also used to calculate the wetness index, \( w = \ln (A/\tan \beta) \), which is an indicator of spatial distribution of soil moisture content (Beven and Kirkby, 1979). The algorithms given by Jenson and Domingue (1988) and Smith and Brilly (1992), for GIS-based routing models, were used to calculate upslope area from the Siran DEM. The cells with a high accumulated flow (given a threshold value of 100) were used to identify the stream channels and those with zero accumulation were identified as ridges. This automatically derived drainage network provides general information about the drainage pattern of the catchment and can be used in raster analysis but lacks information about the curvature and length of the streams.
Fig. 3.5: A slope classification map derived from the Siran DEM. Note the slope ranges from 0 (in the plains) to as steep as 59° (in the upper mountains).
Aspect Classification of the Siran Basin

Class Interval 1 Deg. Resolution 80 m

Scale 1:400,000

Fig. 3.6: An aspect classification map derived from the Siran DEM. The degree of aspect increases from North clockwise. Note many valleys (light pink) are inclined slightly towards North.
Fig. 3.7: A three dimensional view of the Siran Basin at 10:00 hours on 5 March 1979. This image was generated by draping a shaded relief grid and digitised drainage network over the 3D surface.
3.4 GEOL OGY AND SOIL DATA BASES

To apply a theory-based method to infiltration modelling, several soil parameters need to be measured or estimated. For example, the Green-Ampt Model cannot be applied unless some information about effective hydraulic conductivity, the wetting front suction and the initial moisture content is available. These soil parameters of the hydrological significance are closely related to soil physical properties (Rawls et al. 1993) and to large extent can be estimated from soil textural information (Chu, 1978). A soil texture map of the Siran Basin, as such, is not available but can be derived from the geology and soil association maps using topographic parameters of elevation, slope and aspect.

3.4.1 Acquisition of the Geology and Soil Maps

3.4.1.1 Source and Contents of Maps

The geology and soil association maps were published by the Soil Survey of Pakistan in 1988 at 1:250,000 scale. The photocopies of portions of these maps covering the Siran Basin were taken from the National Agricultural Research Centre Library, Islamabad for the purpose of this research. The geology map provides information about the major geological formations and soil parent materials found in the area. The soil map represents the types of soil complexes and soil associations formed from the underlying parent materials. Within each soil association the physical properties of the soils e.g. texture and depth depend largely on the topographic parameters i.e. elevation, slope and aspect. A descriptive document accompanying the soil maps provides ample information on the spatial variation in soil texture and depth depending upon these parameters.

3.4.1.2 Quality Assessment

The information contained in the maps is based on a reconnaissance survey hence the class boundaries are arbitrary. This problem was exaggerated by the small scale (1:250,000) of the maps which fail to identify the local spatial variability in geology and soils; a characteristic of this high relief catchment. However for raster GIS processing at 80 m resolution, in the absence of any other source of data, this scale was considered appropriate. Some positional inaccuracies were found in overlaying the
digitised geology and soil maps with other vector coverages digitised from topographic maps due to the differences in their projection and scale. The maximum positional error was of the magnitude 132 m on the ground. This inaccuracy was reduced to a 90 m (maximum) by using rubber sheeting operation.

3.4.2 Digitisation and Rasterisation

A manuscript of each map was prepared before entering the data. The identification and tracing of class boundaries were obstructed occasionally by overlapping and coinciding drainage channels. Actual digitisation was carried out in 'point' mode to avoid unnecessary information being entered. The arcs outside the object area were clipped, united with the catchment boundary coverage and the polygon topology of the coverages built. Each polygon was assigned the same code as on the source maps to ease the evaluation and processing of digitised data. The digitised vector coverages were converted to raster geology and soil association maps before processing for soil texture. The rasterised geology and soil association maps the Siran Basin are given in Figs. 3.8 and 3.9.

3.4.3 Extraction of Soil Texture and Depth

3.4.3.1 The Approach

A multi-layer rule-based method was followed to extracting and mapping the soil texture. The information given in the Soil Survey of Pakistan report (accompanying the maps) was incorporated with the GIS data through a routine 'texture' coded in C. The GIS inputs to this routine include: (i) the DEM, (ii) slope (percent) map, (iii) aspect map, (iv) soil association map, and (v) geology map. The soil textural classes are automatically delineated based on the rule-based conditional statements (given in the report). An example of this procedure is given here:

For soil association 9,

if elevation > 900 m,
slope 25 -50 %,
aspect 270 - 359 and 0 - 90 degree,
then surface soil textural class is silt loam.
Geology of the Siran Basin

Fig. 3.8: A raster geological map of the Siran Basin. This map was obtained by digitisation of existing maps (1:250,000) produced by the Soil Survey of Pakistan (1988).
Fig. 3.9: A raster soil association map. This map was obtained by digitisation of an existing soil association map (1:250,000) produced by the Soil Survey of Pakistan.
This statement implies that at the particular point, within the area occupied by the soil association 9 (Makhnial-Rockland Complex), the textural class will be silt loam provided all conditions given in the statement are met. A total of eleven soil textural classes were identified within the Siran Basin on the basis of information given in the survey report which are shown in Fig. 3.10. The derived information on the soil texture was used to estimate the parameters of Green-Ampt infiltration model such as hydraulic conductivity, suction and effective porosity. The depth of the soil which is another important physical parameter for estimating the moisture storage capacity, is highly variable from place to place in the catchment. For the sake of convenience four soil depth classes were defined i.e. 'exposed rock to shallow' (0-15 cm), 'shallow to moderately deep' (16-30 cm), moderately deep to deep (31-100 cm) and 'deep to very deep' (>101 cm). Each soil textural unit with a soil association delineated as above was assigned a typical depth class according to the information given in the survey report (Fig. 3.11).

3.4.3.2 Accuracy of Extracted Maps

The spatial variation of the dynamic medium like soil is not as straightforward as presented by these maps. In the complex Himalayan terrain this problem is an important issue as high rates of erosion and deposition cause localised changes in the soil properties. The assumption of homogeneity of soils within an area of 6400 m² (represented by one grid cell) of the catchment will rarely hold true. The extracted maps contain inherent inaccuracies of the constituent data (soil association and geology maps) and some level of bias involved in generating them. The accuracy of the soil texture map was assessed against an independent set of field data, which was collected as part of ground truthing of the land cover maps (cf. section 4.9.1). A total of 127 sites were visited during December 1994 and January 1995 and five secondary samples were drawn randomly from within each site. The texture of each soil sample was determined by 'feel method' and the depth was measured with the help of an auger.

Except for the Pakhly and Chattar plains, the texture the soils was highly variable even within a primary sampling site (240 x 240 m²). The problems in the collection of field data had arisen in the sites with very gravelly soils, boulders and rock outcrops. Each primary site was assigned a textural class to which most of the secondary samples (at least 3 out of 5) belonged. On the basis of this information, the calculated mathematical overall accuracy of the soil texture map was 57.4 %. It emerged that
Fig. 3.10: The textural classification derived from the geology and soil association maps. The approach adopted for the derivation of this map is described in section 3.4.4.1.
Soil Depth Classification
Derived from Soil Association Maps
Scale 1:400,000

Fig. 3.11: The soil depth classification derived from the soil association map. Note the soil in plains along the main river course is very deep while some very steep slopes lack any soil cover.
the textural class 'sandy loam' was under-estimated on this map which occupies most of the area (except for the plains) along the channels. The spatial variations in soil depth were even higher particularly on slopes steeper than 25%. It was realised that five secondary samples do not truly represent the variations within each site and a high degree of bias is likely to be introduced by assigning a typical value (average of five secondary samples) to each sample. Therefore the accuracy of the soil depth map could not be assessed.

3.5 VECTOR AND POINT GIS COVERAGES

In addition to the raster layers described in the preceding sections, the Siran GIS contains several vector coverages. Although these coverages, although do not take part in the raster processing to modelling hydrological processes, but are extremely important in the development of raster GIS layers, image processing and evaluation of simulation results.

3.5.1 Catchment Boundary and Drainage Network

Other than the contour coverage, two important coverages drawn from the topographic maps were the catchment boundary and the drainage network. The catchment boundary coverage was created by digitising the catchment divide - an arbitrary line joining the highest ridges around the Siran catchment separating it from surrounding catchments. A manuscript was prepared and digitisation was carried out in 'stream' mode to capture true curvature of the catchment boundary. It served as a 'cookie cutter' for other GIS data (including satellite imagery) to give them the shape of the Siran catchment. The catchment boundary coverage was also used to calculated the actual area of the catchment.

The drainage network which has been delineated automatically (cf. section 3.3.4.2) is useful in raster analysis, but fails to represent the actual curvature and length of streams as it tends to zigzag and appears loosing continuity. For this purpose, a vector drainage network coverage was generated by digitising the main streams (up to third order) from the topographic maps. The digitised catchment boundary and drainage network coverages are shown in Fig. 3.12.
3.5.2 Forest (1941) and Forest Ownership Maps

The topographic maps (published in 1941) also carry some information about the land cover of the Siran Basin. The area under different forest types (e.g. conifers, scrub) has been represented on the maps with some details on the cover density (e.g. high cover compact forests, linear plantations, scattered trees). It was not possible to capture all information through manual digitisation, therefore only the boundaries of the compact forests (> 10 hectares or 25 acres) were digitised and maintained as a polygon coverage. This coverage has been used to calculate the total area of the Siran Basin which was covered by the forests in 1941, and to quantify the extent of change in the forest cover over time.

The ownership of the forests is the key factor in forest management. Such information is helpful in the evaluation of the change detection results in the light of legal status of the forests. A Forest Map (Legal) reproduced by the Siran Forest Development Project, NWFP Forest Department, drawn at 1:50,000 scale, was available for this study. Three legal categories of the Siran forests have been presented on the map namely Reserved, Protected and Guzara Forests. This categorisation of forests is based on the Land Settlement (1872-73), Indian Forest Act (1927), Hazara Forest Act (1936) and Land Reforms Act (1959). An area represented as forest on this map (Fig. 3.13) may not be necessarily a woodland, but has been declared as forest land by the Government.

3.5.3 Town / Village Location Map

The point coverage representing the location of prominent towns and villages within the Siran Basin (Fig. 3.14) helps in the evaluation of simulation results. It also contains the locations of meteorological stations which are important for the extrapolation of meteorological data.

3.6 SUMMARY

- A regional GIS of a specific configuration for the Siran Basin, Pakistan has been built at 80 m resolution from the maps of widely different sources and scale. This GIS contains all types of spatial data viz. raster and vector (line, polygon and point).
Fig. 3.12: The digitised surface drainage network of the Siran catchment. Note the main Siran river which flows from North to South and covers a distance of 73 km up to the Phulra gauge.
Fig. 3.13: The forest ownership map. The map shows three legal categories of the forests in the Siran Basin; the description of each category is given in section 1.2.3.
Fig. 3.14: The location of main towns within and around the Siran Basin. The meteorological stations situate at Balakot, Oghi, Phulra and Shinkiari.
The DEM was built by interpolation from contours digitised from the topographic maps (scale 1:63360) and its positional and vertical accuracy was assessed. Two primary topographic layers slope and aspect were derived automatically from the DEM and formed integral part of the Siran GIS.

The geology and soil association maps (scale 1:250,000) were digitised and rasterised primarily to derive a soil texture map through a multi-layer rule-based approach. The derived soil textural classification has formed the basis of parameter estimation for the infiltration model.

In order to exclude any data representing the area outside the Siran catchment, the catchment boundary coverage (digitised from the topographic maps) was used as a 'cookie cutter'. The drainage network (up to third order streams) was also digitised from these maps.

The boundaries of the areas covered by the forests in 1941 were digitised from the topographic maps and maintained as a vector coverage. A forest ownership map (scale 1:50,000) was also digitised with an intention to evaluate the forest cover changes in relation to legal status of the forests.

Although the quality control measures could not be adhered to in the development of the Siran because of non-availability of field measured or standard data, all effort has been made to minimise the detected errors.

All constituent layers of the Siran GIS have a common resolution and reference system for perfect overlaying and exist in ARCINFO GRID 6.0 format. These spatial layers can be scanned conveniently by a hydrological model either as binary or ASCII files.
Chapter 4

IMAGE PROCESSING FOR
LAND COVER MAPPING &
CHANGE DETECTION
4.1 INTRODUCTION

Any process of the land phase of the hydrological cycle is highly influenced by the land cover characteristics. Several empirical runoff and erosion models demand land cover parameters as inputs e.g. Parachini and Folving (1994). The deterministic modelling of the processes like evapotranspiration, interception, infiltration and surface/sub-surface flows is possible only if the necessary information on land cover is available for parameterisation. For a distributed modelling system, such information can be effectively derived or estimated from multi-spectral remotely sensed data (Groves et al. 1983; Johnson, 1989; Goossens et al. 1990; Engman and Gurney, 1991; Su and Shultz, 1993). Engman and Gurney (1991) referring to the work of Salomanson (1975) studied the input requirements of the Kentucky watershed model and found that out of 26 input parameters, six could be determined by remote sensing.

Two of the most important parameters i.e. albedo and leaf area index (LAI) are often required to run hydrological process simulations. Of these two parameters the albedo (or brightness index) can be directly derived from the digital remote sensing data (Harris, 1987; Johnson, 1989). However the LAI can be estimated indirectly from remote-sensing based vegetation indices such as Normalised Difference Vegetation Index (NDVI), which characterise vegetation dynamics and intensity, in conjunction with the field data. Temporal (or seasonal) variations in these parameters can be assessed through multi-temporal image processing. Often high frequency remote sensing data is lacking in hydrological modelling, hence to a large extent, a land use or land cover map of the catchment generated from that data is exploited to estimate the albedo and LAI. Each land cover type is assigned a typical value of albedo and LAI and temporal variations in these parameters (which are dependent on the growth stage) are assessed using a crop calendar. Some other vegetation related parameters which can be indirectly estimated from a land cover map include surface heat flux (Hoshi et al. 1989), available water capacity (Goossens et al. 1990) and surface roughness. The long-term changes in the hydrological parameters caused by changes in land covers can be quantified in their spatial context from remotely sensed data of different years.

Two land cover maps, generated from Landsat MSS (5 March 1979) and TM (10 July 1989) images, have formed the most important layers in the Siran GIS. Although the ultimate products of the remotely sensed data have been interfaced with other GIS layers, the image processing has been dealt with separately from the development of GIS (cf. Chapter 3) due to very different source data type and data processing environment.
Following steps were involved in this part of the study:

- Acquisition of at least two Landsat scenes captured at a 10-12 years interval.
- Geometric rectification and registration.
- Defining the Siran land use classification scheme.
- Classification of the imagery through the most efficient classifier and assessment of classification accuracy.
- Mapping the land cover changes through post-classification change detection.
- Mapping the albedo across the catchment and estimating mean albedo of each land cover type.

4.2 DATA ACQUISITION

4.2.1 Issue of Resolution

The decision about the selection of imagery was made after considering several factors. Above all, the main aim of the image processing was to quantify the land cover changes which have taken place in the catchment over the last two decades. For mapping the land covers in the 1970's, Landsat Multi-spectral Scanner (MSS) data (56 × 79 m²) were available. However land cover mapping for late 1980's was carried out through the processing of finer resolution Landsat Thematic Mapper (TM) data (30 × 30 m²).

4.2.2 Date of Overpass, Source and Format of data

Unfortunately the oldest Landsat MSS scene covering the Siran River Basin, which currently exists in the digital format, was for the date 1979. Since the analogue data was dis-regarded for this study, the imagery acquired on 5.3.1979 was chosen. The TM scene used in this study was acquired on 10.7.1989, about 10 years later than first one. Some other factors which were considered while choosing these particular scenes were crop calendar and cloud cover as discussed below:
Crop Calendar: The discrimination between different seasonal crops i.e. agricultural crops can be made more effectively during the active growing season (before senescence). Most winter crops attain maturity in March in the Siran Basin, hence the mapping of these crops (owing to their characteristic reflectance spectra) could be done only from an image acquired during this month. The MSS image acquired on 5.3.1979 was, therefore, specifically chosen for this purpose. One of the reason of choosing the specific TM image (acquired on 10.7.1989) was the mapping of summer crops which generally attain maturity during July. The crop calendar is given in Fig. 1.2.

Cloud Cover: The imagery with the minimum cloud cover ground details were preferred. The MSS imagery was virtually cloud free. However the TM sub-scene of the Siran catchment contained clouds (and cloud shadow) which in total covered 1.96% of the area.

The CCT of the Landsat MSS was supplied by the EROS Data Centre, South Dakota, USA while the Landsat TM data was acquired and supplied by the SUPARCO, Pakistan. All Landsat data were available as binary band sequential (BSQ) formats.

4.2.3 Data Quality

The imagery available for this study were pre-processed at the USGS EROS Data Centre and SUPARCO, Pakistan, for system errors e.g. systematic geometric errors which arise due to scan skew, mirror scan velocity, platform velocity, earth rotation etc. (Bernstein and Ferneyhough, 1975; Bernstein, 1983). For the TM image, the data of band 1 (0.45-0.52 μm) was damaged and could not be used in image processing. However this was not a problem as the remaining optical and near/middle infrared wavebands could supply all the spectral information needed (Parachini and Folving, 1994). The TM imagery had varying number of scan lines in bands 2-5 and 7 which needed to be cropped at the top or bottom for further image processing.

4.3 COMPUTING REQUIREMENTS

The image processing has been carried out on a Sun Sparcstation 10 operating on Solaris 2.4. The estimated data storage requirement of the original Landsat MSS and
TM bands, intermediate and final products was 400 MB. Other hardware requirements included a ½ inch CCT drive for scanning the original data, a ¼ inch cartridge drive for data backing-up and a Postscript A-4 printer for producing the output maps. The image processing software used for this study was ERMAPPER 4.0, although part of the work, which concerned with interfacing the remote sensing data with the GIS, was accomplished on ARCINFO GRID 6.1.

Initially four bands of the entire MSS scene were loaded for the purpose of viewing and identifying the area of interest (AOI). The storage requirement of 8 bit integer raw data of four bands (2983 x 3596 pixels each) was 41 MB. Six bands of entire 16 bit TM scene (5568 x 7020 pixels each) occupied 240 MB of hard disk space. Because of these immense data storage and processing requirements, the geometric rectification (warping) and further processing was restricted to the AOI which covered the Siran Basin and surrounding catchments (Fig. 4.1).

4.4 GEOMETRIC RECTIFICATION AND REGISTRATION

Non-systematic errors which are caused by the attitude (roll, pitch and yaw) and altitude are needed to be rectified before processing the imagery for meaningful results (Bernstein and Ferneyhough, 1975; Bernstein, 1983). Rectification is the process by which the geometry of the area is made planimetric, which may not remove distortion induced by topographic relief displacement in the image. One method of geometric rectification is the polynomial warping, which is accomplished by matching control points on image and reference maps with known co-ordinates in a specific projection system (ERMAPPER, 1993).

The procedure used to warp the Landsat data through the use of ground control points (GCPs) is summarised below:

- The reference data (topographic maps), which had to be used for rectifying the remote sensing data, was available for only a small portion of the area covered by the whole scenes. It was, therefore, decided to confine the rectification to that portion representing the Siran Basin and its immediate surrounds.

- Location of GCPs for digital image processing in developing countries like Pakistan was not an easy task (Batz and Durstein, 1989). Since built structures e.g.
Fig. 4.1: A false colour composite (RGB 421) of Landsat MSS sub-scene before geometric rectification. Note the zigzag course of the Indus River in left half of the image which broadens towards the Tarbela reservoir in the south. The Siran Basin lies in the centre of this image and the Siran River flows towards south-west and merges with the Indus at Tarbela.
road crossings, bridges, buildings etc. were not clearly identifiable on the images, most GCPs were sharp bends or confluences of the narrow sections of streams (Cibula and Nyquist, 1987). Initially twenty nine points were identified on the image and matched with those picked up from 1 inch scale topographic maps.

- The real world co-ordinates (Latitude/Longitude) of all of these points (up to four decimal points of a degree) were entered against their respective positions on the images.

- The inaccuracy of the geometric rectification is generally measured by the root mean square error (RMSE) which is a measure of distortion not corrected by the geometric transformation of the image. Ideally the total RMSE should not exceed 1 pixel for more precise applications (Cibula and Nyquist, 1987). During the process of warping Landsat data, a maximum RMSE of 7.0 was initially obtained which, after the deletion of some erroneous GCPs, was reduced significantly. The maximum and mean RSME of MSS and TM warping are given in Table 4.1 while detailed statistics of this warping are given in Appendix 4-i.

<table>
<thead>
<tr>
<th></th>
<th>Maximum RSME</th>
<th>Mean RSME</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pixels</td>
<td>metres</td>
</tr>
<tr>
<td>MSS</td>
<td>1.6</td>
<td>89.6</td>
</tr>
<tr>
<td>TM</td>
<td>2.49</td>
<td>74.7</td>
</tr>
</tbody>
</table>

*Table 4.1: The maximum and mean RMSE of Landsat MSS and TM warping.*

- After defining the GCPs, the transformation of the image to a geodetic (Longitude/Latitude) projection was performed using a cubic convolution algorithm (Su and Schützle, 1993). The image extent and pixel dimensions of rectified, geo-referenced MSS and TM sub-scene are given in Table 4.2. Fig. 4.2 shows the geo-referenced MSS sub-scene.

<table>
<thead>
<tr>
<th>Image Size</th>
<th>Image Extent</th>
<th>Pixel Size (10^6 rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rows x columns</td>
<td>Longitude (E)</td>
<td>Latitude (N)</td>
</tr>
<tr>
<td>MSS 1191 x 719</td>
<td>From 72°59'14.79&quot; To 73°31'13.47&quot;</td>
<td>From 34°12'21.37&quot; To 34°54'2.2&quot;</td>
</tr>
<tr>
<td>TM 2715 x 1926</td>
<td>From 72°52'59.39&quot; To 73°38'59.79&quot;</td>
<td>From 34°06'16.96&quot; To 34°55'16.69&quot;</td>
</tr>
</tbody>
</table>

*Table 4.2: The image size, extent and pixel size of rectified, geo-referenced Landsat sub-scenes.*
Fig. 4.2: A false colour composite (RGB 421) of Landsat MSS sub-scene after geometric warping. This image (1191 x 719) covers the Siran Basin and its immediate surroundings. Bright red areas on this image represent the lush green seasonal vegetation (e.g. agricultural crops) and brownish red areas are those covered by the forests.
Since the products of image processing had to be interfaced with other GIS layers (cf. Chapter 3), it was necessary to warp the Landsat data to regular (squared pixel) grids and register it within the GIS. The data for each of four MSS bands and five TM wavebands were resampled to regular grids through the nearest neighbour resampling using ERMAPPER map-to-map warping utility (Cibula and Nyquist, 1987). Thereafter the images were exported to ARCINFO, clipped with the Siran catchment boundary (cf. section 3.5.1) and co-registered with the other GIS layers. All subsequent processing of Landsat data were confined to areas within the Siran catchment boundary.

The clipped MSS and TM images contained $772 \times 421$ and $1410 \times 924$ pixels respectively (Figs. 4.3 and 4.4).

4.5 IMAGE ADJUSTMENTS FOR TOPOGRAPHIC RELIEF

The Landsat data of Siran Valley carries serious radiometric inaccuracies caused by relief. Shadowing is the cause of major spectral inaccuracy when mapping land covers in the mountainous areas (Howard, 1991). Topographic influences on the spectral response of satellite data have been discussed by Walsh et al. (1987). One stage land cover classification derived from the Landsat data of the Siran Basin (particularly MSS data acquired on 5 March 1979) has been found to yield misleading results on all north-facing steep slopes. When clustering the data, all land cover types on north-facing slopes of the catchment tended to form a single cluster due to the little difference between pixel values and their low standard deviation. Supervised classification was hindered by the difficulties encountered in locating training sites on shadowed slopes.

An objective method to reduce the topographic effects involves adjusting the pixel values for aspect and gradient prior to classifying the image (Howard, 1991). The spectral transformation can be performed to eliminate/reduce inaccuracies caused by either sun angle or topographic relief. The registration of Landsat data for accurate superimposition on a DTM is a prerequisite to this method of spectral transformation (Nguyen and Ho, 1988). Civco (1989), Yang and Vidal (1990) and Walsh et al. (1994) corrected Landsat data for topographic redistribution of solar radiation. The approach used in this project is also based on solar radiation modelling across the catchment. The spatial distribution of the total incoming solar radiation (or global insulation) across the catchment can be mapped at a particular time (e.g. at the time of satellite overpass) or for a particular day (Iqbal, 1983).
Fig. 4.3: The geo-referenced clipped MSS image. The clipping of the Landsat image was carried out with the Siran catchment boundary to exclude any data outside the catchment. It also economises the computing resource in image processing and hydrol. simulations.
Fig. 4.4: A false color composite (RGB 742) of the warped, clipped Landsat TM image. Note the clouds (and cloud shadows) which obscure about 2% of the catchment area. However, the land covers obscured by the snow cover in MSS image can be mapped from this TM image.
Many recent studies in remote sensing have emphasised the importance of integration a DTM with Landsat data to meet one or more objectives e.g. removal of parallax or geometric correction of the Landsat data (Paracchini and Folving, 1994). The effect of relief on spectral response of a surface also can be modestly reduced by incorporating terrain data through one of the several methods (Howard, 1991). Combining topographic data layers with satellite data to minimise the effects of relief takes several forms; most concern post-classification enhancement (Cibula and Nyquist, 1987) but a few are based on pre-processing spectral transformation. Hoffer (1979) used three topographic data layers i.e. elevation, slope and aspect with a layer of spectrally-distinct cover classes to enhance classification results. Walsh et al. (1990) superimposed several topographic layers with the Landsat TM data for characterising the hydrological structure of a catchment. A classical photo interpretation route i.e. the analysis of tone, texture and terrain, was adopted by Strahler (1981) after discriminating between shadowed and non-shadowed regions through the integration of terrain data. A false colour composite (FCC) can be draped over a 3D surface generated from DTM for enhanced manual interpretation (Nguyen and Ho, 1988). However, it is note-worthy that none of these methods addresses the spectral transformation of the original bands.

The detailed algorithms of modelling solar radiation over the Siran Basin are given in Chapter 6. For the spectral transformation of the Landsat data, it was assumed that the reflectance of a window of the optical and near infrared part of EM spectrum from any surface is proportional to the incoming total solar radiation. It implies that factor ($F$), which projects the total radiation received on the horizontal surface to any sloping surface (Duffie and Beckman, 1974), can be used to reduce the reflectance from that sloping surface to the horizontal surface. Although a particular land cover on different gradients and aspects has widely different spectral reflectance, it must have the same reflectance after being reduced to its horizontal equivalent. Therefore after removing the shadowing effects, caused by topographic relief, the pixel value must represent land cover and not the topography. Following four steps were involved in the spectral transformation procedure:

- shadow matching
- generation of adjustment factor grid
- masking of snow and ice
- multiplication of image bands by the adjustment factor grid
4.5.1 Shadow Matching

Before integrating the DTM (through radiation modelling) with the remotely sensed data, the shadows identified on FCC were matched visually with those identified on a synthetic reflectance image; so called a shaded relief image (Howard, 1991). According to Lambertian law of reflectance and a vertical observer’s angle, the reflectance ($R$) at a point on an image is given by:

$$ R = \max(0, k \cos \alpha) $$

where $k$ is a coding coefficient (255 on 16 bit display) and $\alpha$ is the angle between the normal to the surface and the sun direction (Nguyen and Ho, 1988). The sun azimuth and elevation information contained in the image headers were used to generate a shaded relief image for matching shadows with those identified on Landsat FCCs (Fig. 4.5).

4.5.2 Relief Adjustment Factor

The relief factor to adjust the pixel value for gradient and aspect is the reciprocal of the total solar radiation ratio ($F$) at a particular point over the catchment at the time of overpass. The total radiation on an arbitrarily oriented surface has three components namely beam, diffuse and reflected (Duffie and Beckman, 1974; Whitemen, 1987; Iqbal, 1983; Moore et al. 1991) and is given by:

$$ R_s = R_i F + R_d (1 + \cos \beta) / 2 + (R_d + R_f ) (1 - \cos \beta) \rho / 2 $$

where

- $R_i$ = total radiation received on the sloping surface
- $R_d$ = direct (beam) radiation on a horizontal surface
- $F$ = the ratio between the potential radiation on the sloping surface and a horizontal surface
- $R_f$ = diffuse radiation on the horizontal surface
- $\beta$ = slope angle (percent)
- $\rho$ = albedo of the surface

The total radiation ratio ($F$) between the sloping surface and a horizontal surface is:
Fig. 4.5: A visual comparison of the shadows identified on the MSS FCC (RGB 421) with those identified on a shaded relief image (generated from the DTM using the sun angle information contained in the image header).
\[ F_i = (R_i F / R_0) + (R_i (1 + \cos \beta) / 2R_0) + (1 - \cos \beta) \rho / 2 \] 4.3

where \( R_0 \) = total radiation received on the horizontal surface

(A more detailed description of solar radiation algorithm is given in Chapter 6). The albedo of snow free surface was assumed to be equal to 0.2 (Duffie and Beckman, 1975). However, the effects of shading from direct sunlight by surrounding terrain at enclaved sites (Dozier and Bruno, 1981; Moore et al. 1991) could not be taken into account.

4.5.3 Masking of Snow, Ice and Clouds

Contrary to other land cover types snow has a maximum reflectance in all optical and near infra-red wavelengths (Harris, 1987), although the reflectance decreases with an increase in the age of snow (Smith, 1983). Snow-covered parts of the Siran Basin have been found to have maximum reflectance in all four MSS bands (pixel value of 127 on 8 bit data) irrespective of gradient and aspect. The ice had maximum reflectance in the optical wavelengths but zero in near infra-red wavelengths on all sides of the mountains. Obviously the portion of image representing the snow and ice, if corrected for relief effects would yield misleading interpretations. The problem was tackled by masking the snow and ice covered areas for all bands prior to multiplying the remaining data by the relief factor. The iso-classification (clustering) of the original MSS data into twenty five classes yielded up to six classes representing snow and ice, which were masked during the spectral transformation. Similarly clouds and cloud shadows were masked prior to adjusting the TM image for relief effects.

4.5.4 Image Multiplication by Relief Factor

The final step involved in image adjustment was to multiply each of the four original MSS and TM bands by the relief factor grid, except for the parts occupied by snow and ice (in MSS) and clouds (in TM). The statistics of the image before and after the spectral transformation for relief are given in Table 4.3. The FCC (RGB) of the original and the spectrally transformed MSS data are given in Fig. 4.6. After this operation, the spectrally transformed images were exported from ARCINFO to ERMAPPER for subsequent processing.
Fig. 4.6: The Landsat image before and after topographic adjustments. Note that relief effects are reduced after reducing the pixel value from a slope to its horizontal equivalent through solar radiation modelling.
4.6 IMAGE ENHANCEMENT

Specific users of remote sensing often require the features of special interest to be enhanced at the expense of other background features (Barrett and Curtis, 1976). The image enhancement can be achieved through density slicing, contrast stretching, band ratioing, addition, subtraction and averaging, vegetation indexing and principal component analysis (PCA). The FCC (RGB) displays of the image enhancements, instead of original Landsat wavebands, offer more spectral discrimination among different land cover types. In this study, several vegetation indices and first three principal components of the Landsat data were generated as image enhancements, which helped in characterising the land cover types and in training for supervised classification.

4.6.1 Vegetation Indices

One of the most widely used vegetation index derived from multi-spectral remote sensing data is the Normalised Difference Vegetation Index (NDVI). The NDVI, which was originally developed by Rouse et al. in 1973 (Jensen, 1986), indicates the vegetation amount (Curran, 1980) and the state of vegetation maturity (Su et al. 1993). This index is calculated as (Tucker, 1979):

\[
NDVI = \frac{NIR - RED}{NIR + RED}
\]

where NIR denotes near infrared waveband. The MSS waveband 5 (0.5-0.6 μm) and waveband 7 (0.7-1.1 μm) were used to calculate the NDVI as:

Table 4.3: The comparison between the Landsat MSS data before and after spectral transformation for relief effects.
\[
NDVI = \frac{MSS7 - MSS5}{MSS7 + MSS5}
\]

For the TM, waveband 3 (0.63-0.69 μm) and waveband 4 (0.76-0.90 μm) were used:

\[
NDVI = \frac{TM4 - TM3}{TM4 + TM3}
\]

The NDVI is highly correlated with the vegetation amount and LAI. In many recent studies the NDVI has been used to estimate the LAI in conjunction with the field measured LAI data (Curran et al. 1992; Running, 1986; Su et al. 1993). Since NDVI depends on reflectance characteristics of upper canopy, in strict sense it does not give any idea of the actual biomass or LAI particularly in multistoried forests. In this study, the role of NDVI was restricted to as an image enhancement to help distinguishing the vegetation types. The NDVI map derived from Landsat MSS data is given in Fig. 4.7.

Another important vegetation index is the Perpendicular Vegetation Index (PVI) which defines the distance between each pixel and the plain of soil in the feature space defined by the near infrared and visible wavebands. The PVI developed by Wardley and Curran (1984), makes a clear distinction between major cover types such as bare soil, grass and forests. It can be calculated as:

\[
PVI = \sqrt{(R_s - R_v)^2 + (NIR_s - NIR_v)^2}
\]

where \(R\) and \(NIR\) denote red and near infrared reflectance and the subscripts \(s\) and \(v\) denote soil background and the vegetation respectively. The PVI map was generated using ERMAPPER 4.0 default formula. Some other vegetation indices were also generated by different combinations of the TM wavebands such as \(TM7-TM3\) and \(TM5-TM3\).

4.6.2 Principal Component Analysis

The original Landsat MSS and TM images were transformed through the principle component analysis (PCA) to reduce the dimensionality (data volume) and to enable a best FCC (RGB) display of the image for further analysis. Another objective of the PCA was to map the albedo across the catchment and to calculate mean albedo of each land cover class as discussed in section 4.10. The PCA transforms the highly correlated Landsat data into statistically independent orthogonal axes on which the original data
Fig. 4.7: An NDVI map (left) helps discriminating vegetation. Note the white areas along the main Siran River represent lush green alfalfa crops. Snow has an NDVI value of 0. Such indices can also be derived from tessellated cap transformations (PCs) instead of original Landsat bands. An index map (right) derived using PCs 1 and 2 was used as an enhancement in training.
are projected (Walsh et al. 1990; Townshend, 1984; Harris, 1987; Jensen, 1986). Many image analysts have found that nearly all image information is contained in the first three PCs, thus reducing the TM bands from 6 to 3.

The first PC, which normally shows the brightness or albedo of the surface, accounts for the largest proportion of the variance in the original data followed by the second PC which indicates greenness (Jensen, 1986). The third PC derived from MSS data indicates yellow stuff (Jensen, 1986) while that derived from TM data indicates wetness (Su and Schultz, 1993). The statistics of PCA of the Landsat data of the Siran Basin is given below:

<table>
<thead>
<tr>
<th></th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSS</td>
<td>91.60</td>
<td>5.50</td>
<td>2.60</td>
<td>0.30</td>
</tr>
<tr>
<td>TM</td>
<td>84.60</td>
<td>9.10</td>
<td>5.73</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 4.4: The proportion of variance in the original Landsat data explained by 4 PCs.

These results implied that more than 91.60 % of the variance in the original MSS data could be explained by the first PC. In other words, the first PC derived from MSS data contained more than 90 % of all information contained in four MSS wavebands and first PC derived from TM data contained more than 84 % information contained in six original wavebands. Unlike the original bands, the transformed bands (PCs) are independent of each other and a FCC (RGB) display of first three PCs, instead of original bands, was found extremely helpful in delineating spectrally distinguishable land cover classes (Walsh et al. 1990) and to identify the training sites. The first two PCs derived from MSS data are given in Fig. 4.8.
Fig. 4.8: The PCI (also called brightness index or albedo) contains more than 90% of the spectral information in MSS (left) and the PC2 (greenness index) carries up to 5.5% information (right). Note the brightest areas lie on the snow covered parts of the catchment while greenness index is maximum in the agrigutural areas.
4.7 LAND COVER MAPPING

Land cover mapping in the Siran basin was carried out using a carefully defined classification scheme. The training sites were selected, using the colour displays of various combination of bands, vegetation indices and PCs, with the help of topographic maps (1" scale), land use survey reports and field observations. The training data statistics were used to classify the Landsat MSS and TM data to a level I classification, employing the *maximum likelihood* algorithm. After measuring the accuracy of level I classes, the classification were refined by integrating the topographic data using multi-layer rule-based classification approach. To accomplish this task, a link between the ERMAPPER and ARCINFO was established, through which the remote sensing data had to be routed more than once. *Fig. 4.9* gives a simplified illustration of the image processing strategy for land cover mapping adopted for this study.

![Image of image processing strategy for land cover mapping](image)

*Fig. 4.9: A simplified illustration of the image processing for land cover mapping.*

4.7.1 Classification Scheme

The number of classes to be represented on the land cover maps were defined bearing in mind the implications of dominant land cover types found in the region on the hydrological processes (Ott *et al.* 1989). The main features of the classification scheme used in this study were:
i. Major land uses in the Siran Basin, that can be identified on topographic maps and available land use maps or reported in literature, include agriculture, forests and grasslands. An appreciable proportion of the total area of the basin lacks any soil and vegetation cover e.g. exposed rocks and stream beds. Upper reaches of the Basin beyond 3500 m elevation remain covered with snow for most part of the year. The information on the land cover types were used in image processing as a starting point for the land cover classification. The first digit of a class code in Table 4.5 represents this broad category e.g. class 1 represents arable land covers, 2 represents forests and so on.

ii. 'Level I' includes all those classes which are spectrally distinguishable and training is possible for supervised classification. Initially three classes of conifer forests were defined (on the basis of crown cover density) i.e. 'High Cover Conifers (> 50 % cover)', 'Medium Cover Conifers (25-50 % cover)' and 'Low Cover Conifers (< 25 % cover)'. Due to fact that very open forests and regenerations do not significantly alter the spectral response of the grass-covered surface (Lo and Fung, 1986), and that grasslands rarely exist without scattered trees, the last of the three forest classes (Low Cover Conifers) was merged with 'Grasslands' to constitute a single mixed class 'Grass and scattered trees'. Up to four agricultural cover classes could be delineated on the MSS and TM images for training. This stratification within each class is represented by a second digit of a class code e.g. classes 11 to 17.

<table>
<thead>
<tr>
<th>Major Land Cover</th>
<th>Code</th>
<th>Level I Class</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arable</td>
<td>1</td>
<td>Wheat</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alfalfa</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Winter non-cereals</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paddy</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tobacco</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maize</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bare Soil</td>
<td>17</td>
</tr>
<tr>
<td>Conifer Forests</td>
<td>2</td>
<td>High Cover Conifers (&gt; 50 % cover)</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium Cover Conifers (25-50 % cover)</td>
<td>22</td>
</tr>
<tr>
<td>Grassland</td>
<td>3</td>
<td>Grass and scattered trees</td>
<td>31</td>
</tr>
<tr>
<td>Exposed Rock</td>
<td>4</td>
<td>Exposed Rock</td>
<td>41</td>
</tr>
<tr>
<td>Stream Beds</td>
<td>5</td>
<td>Stream Beds</td>
<td>51</td>
</tr>
<tr>
<td>Snow</td>
<td>6</td>
<td>Snow</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 4.5: The land cover classes (level I) and their codes.
are all arable land cover classes on the basis of crop types.

iii. 'level I' classes, particularly forest classes, were found poorly defined for the estimation of hydrological parameters. For example, forest class '21' represents a high cover (> 50% cover) conifer forest, but fails to offer any information on the forest species and composition of the ground flora (which control most of the processes of surface hydrology). However the 'level I' classification can be refined to 'level II' classification (to incorporate information on forest types) through multilayer rule-based classification in GIS (cf. section 4.9).

The codes assigned to each land cover class type are given in Table 4.5 and some examples of the cover types to be interpreted from Landsat data are given in Photos 4.1-4.6.

4.7.2 Training

The training for supervised classification was carried out with the help of topographic maps (1" : 1 mile) and small scale land use maps (reduced copies of 1:50,000 scale maps). Since the maps and images had the same co-ordinate system, the training regions delineated on the maps were interactively transferred onto the colour displays of various combination of PCs and vegetation indices (NDVI and PVI) after histogram equalisation / Gaussian normalisation (Parachini and Folving, 1994). The training region data were saved as a separate vector polygon coverage which, later on, was copied onto the original MSS and TM images. The minimum number of samples (pixels) belonging to each class was fifty to have a meaningful statistics as suggested by Su and Shultz (1993). Thereafter the training statistics were calculated for supervised classification.

4.7.3 Image Classification

The comparative studies of different classification algorithms e.g. unsupervised cluster analysis, minimum distance and maximum likelihood have revealed that the maximum likelihood algorithm is the most accurate for land cover classification and offers the best results (Curran, 1985; Estes et al. 1982; Conese and Maselli, 1992). Some image analysts, for example Jensen (1986), argued that this method requires many more computations per pixel than other methods but does not necessarily produce superior
results, particularly when histogram of a class is not normal (Su and Shultz, 1993). Since the computing resource was not a limiting factor in this study, the classification of Landsat data for land cover mapping was carried out using maximum likelihood algorithm. The description of this algorithm is given elsewhere (Curran, 1985; Jensen, 1986; Harris, 1987).

For the supervised classification of Landsat MSS data of the Siran Basin, all of the four bands were input with equal probability of all classes and zero threshold of rejection so that the output should not contain unclassified pixels. Likewise five wavebands (2-5 and 7) were used to classify the TM image with equal probability of all classes. However, the pixels representing cloud shadows were left unclassified due to NULL values in band 3 and 4. The area estimates of each of level I classes obtained initially by supervised classification are given in the Table 4.6.

On the upper reaches of the Basin, winter snow completely obscured the underlying ground features (Fig. 4.3) on the MSS image. Below this limit, the ground snow on the forest floor has been found to alter the spectral response of the overlying forest cover. To map the actual land cover types of summer (after snow melts), it was assumed that areas fully or partly covered by snow in 1979 were the same as in 1989. The justification of this assumption is that the snow receiving areas in upper reaches of the Basin are generally inaccessible and presumably they have undergone minimum land cover changes over the ten years time. The areas obscured by clouds (and cloud shadow) in TM image were compared with the corresponding area on the topographic maps. Since on the topographic maps those areas were represented as mixed agriculture-forest-grass cover type, the cloud and cloud shadow on the TM classification were subjectively replaced by the cover class '31' (grass and scattered trees). The land cover map derived from TM data was warped to 80 m resolution (772 × 421) to interface with the GIS and for change detection. The area estimates for each land cover class after making these changes are given in Table 4.7.

The reflectance characteristics of the level I land covers are shown graphically in Figs. 4.10 a and 4.10 b. Land cover (level I) maps of 1979 and 1989 produced at 1:400,000 scale are shown in Figs. 4.11 a and 4.11 b. Some field sites which may help to describe each land cover type represented on these maps are shown in Photos 4.1-4.6.
<table>
<thead>
<tr>
<th>Class</th>
<th>Code</th>
<th>MSS (5.3.1979) (772 x 421)</th>
<th>TM (10.7.89) (1410 x 924)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>11</td>
<td>9688 km²</td>
<td>-</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>12</td>
<td>9917 km²</td>
<td>-</td>
</tr>
<tr>
<td>Winter Non-Cereals</td>
<td>13</td>
<td>11307 km²</td>
<td>-</td>
</tr>
<tr>
<td>Paddy</td>
<td>14</td>
<td>-</td>
<td>11426 km² 18.24</td>
</tr>
<tr>
<td>Tobacco</td>
<td>15</td>
<td>-</td>
<td>39707 km² 63.39</td>
</tr>
<tr>
<td>Maize</td>
<td>16</td>
<td>-</td>
<td>95765 km² 152.89</td>
</tr>
<tr>
<td>Soil</td>
<td>17</td>
<td>18599 km² 19.03</td>
<td>85718 km² 136.85</td>
</tr>
<tr>
<td>Hi Cov Conifers (≥ 50 %)</td>
<td>21</td>
<td>17184 km² 109.97</td>
<td>40822 km² 65.17</td>
</tr>
<tr>
<td>Med Cov Conifers (25-50 %)</td>
<td>22</td>
<td>24354 km² 155.86</td>
<td>201333 km² 321.44</td>
</tr>
<tr>
<td>Grass and scattered trees</td>
<td>31</td>
<td>28847 km² 184.62</td>
<td>104980 km² 167.60</td>
</tr>
<tr>
<td>Exposed Rock</td>
<td>41</td>
<td>5851 km² 37.44</td>
<td>11906 km² 19.00</td>
</tr>
<tr>
<td>Gravel Beds</td>
<td>51</td>
<td>3994 km² 25.56</td>
<td>47534 km² 75.89</td>
</tr>
<tr>
<td>Full Snow / Ice cover</td>
<td>61</td>
<td>11075 km² 70.88</td>
<td>-</td>
</tr>
<tr>
<td>Part Snow cover</td>
<td>62</td>
<td>21815 km² 139.61</td>
<td>-</td>
</tr>
<tr>
<td>Clouds</td>
<td>71</td>
<td>-</td>
<td>10459 km² 16.69</td>
</tr>
<tr>
<td>Unclassified (cloud shadow)</td>
<td>-</td>
<td>-</td>
<td>2321 km² 3.76</td>
</tr>
<tr>
<td>ALL</td>
<td>162,631</td>
<td>1040.83</td>
<td>651920 km² 1040.83</td>
</tr>
</tbody>
</table>

Table 4.6: Initial results of supervised classification of Landsat MSS and TM
<table>
<thead>
<tr>
<th>Class</th>
<th>Code</th>
<th>Pixels 1979</th>
<th>km²</th>
<th>Pixels 1989</th>
<th>km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>11</td>
<td>10118</td>
<td>64.75</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>12</td>
<td>10223</td>
<td>65.42</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Winter Non-Cereals</td>
<td>13</td>
<td>12250</td>
<td>78.40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Paddy</td>
<td>14</td>
<td>-</td>
<td>-</td>
<td>2733</td>
<td>17.49</td>
</tr>
<tr>
<td>Tobacco</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>8833</td>
<td>56.53</td>
</tr>
<tr>
<td>Maize</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>23827</td>
<td>152.49</td>
</tr>
<tr>
<td>Bare Soil</td>
<td>17</td>
<td>24354</td>
<td>155.86</td>
<td>21149</td>
<td>135.35</td>
</tr>
<tr>
<td>High Cover Conifers (≥ 50 %)</td>
<td>21</td>
<td>22903</td>
<td>146.57</td>
<td>10233</td>
<td>65.49</td>
</tr>
<tr>
<td>Med Cover Conifers (25-50 %)</td>
<td>22</td>
<td>28826</td>
<td>184.48</td>
<td>43025</td>
<td>275.36</td>
</tr>
<tr>
<td>Grass and scattered trees</td>
<td>31</td>
<td>41438</td>
<td>265.20</td>
<td>40146</td>
<td>256.93</td>
</tr>
<tr>
<td>Exposed Rock</td>
<td>41</td>
<td>7286</td>
<td>46.63</td>
<td>2493</td>
<td>15.95</td>
</tr>
<tr>
<td>Stream (gravel) Beds</td>
<td>51</td>
<td>5233</td>
<td>33.49</td>
<td>10192</td>
<td>65.22</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td></td>
<td><strong>162,631</strong></td>
<td><strong>1040.83</strong></td>
<td><strong>162,631</strong></td>
<td><strong>1040.83</strong></td>
</tr>
</tbody>
</table>

*Table 4.7: Area estimates of level 1 classes for 1979 and 1989*
Fig. 4.10 a: Spectral response of land cover types derived from Landsat MSS (0-127 scale).
Fig. 4.10 b: Spectral response of land cover types derived from Landsat TM data (0-255 scale).
Fig. 4.11 (a): The land cover map for 1979. This map was derived by the supervised classification of Landsat MSS. Note the forest classes have been defined on the basis of canopy cover density, because different forest types are not spectrally distinguishable.
Land Cover Classification (1989)
Processed from Landsat TM acquired on 10.7.89
Scale 1:400,000

Fig. 4.11 (b): The land cover map for 1989 derived from Landsat TM. Note the changes which have taken place over ten years time e.g. the areas where high and medium cover conifers have been replaced by very low cover conifers and/or grass. Also note the expansion of stream beds.
Photo 4.1: Wheat cultivation with irrigation in the plains. A representative site of cover class 'II'.

Photo 4.2: In the upper mountains and valleys rainfed agriculture is practised on terraces. This site represents the winter fallow lands which belong to cover class 'Bare soil (17)'. 
Photo 4.3: The area covered by chirpine forest has 25-50% crown cover and represents the land cover class 'med cov conifers (22)'.

Photo 4.4: Very low cover conifers (<25% cover) on the mountains are difficult to be distinguished from the surrounding grass on Landsat images, hence they belong to a mixed class 'grass & scat. trees (31)'. 
Photo 4.5: The stream beds occupy an appreciable proportion of the total area in the Siran Basin. A representative site of cover class 'stream beds (51)'.

Photo 4.6: The habitation such as this could not be classified separately, since they have a spectral response very similar to stream beds. This was one of the reasons for over-estimation of the class 'stream beds (51)'.

4.8 CLASSIFICATION ACCURACY ASSESSMENT

A ground feature does not necessarily have a characteristic reflectance in all topographic conditions and more than one feature are likely to have the same spectral response. For example, the spectral response of a particular vegetation type will differ on different aspects and slopes and more than one vegetation type may have the same reflectance in optical and near infrared wavebands. Therefore all land cover classification maps must be assessed for accuracy (Curran, 1985; Harris, 1987; Buckland and Elston, 1994; Walsh et al. 1982) prior to using for a specific purpose. Dozier and Strahler (1983) have identified three sources of errors in land cover maps: (i) boundary line errors, (ii) geometric errors (control point location errors), and (iii) classification errors. The first of these three categories does not apply to raster land cover maps while the second one has already been quantified (cf. section 4.4). The classification interpretation errors remain to be checked before the land cover map can be exploited for hydrological simulation modelling.

To check the classification accuracy, it is usual for some test points to be sampled in each class using a statistical sampling method and the comparisons are made with some form of reference data such as ground checking, existing maps, aerial photographs or other sensor data. The ground truth checking is the most widely used means by which the accuracy of a classification can be measured (Walsh et al. 1982). This is particularly important in the Himalayan region where other sources of data are notoriously unreliable (Thompson and Warburton, 1985). The collection of adequate ground truth is essential to ensure accurate classification of Landsat data (Walsh et al. 1982). The number of sampling sites, size of each sampling site and sampling design are few of many critical issues in ground truth checking.

Van Genderen et al. (1978) noted that many researchers have adopted a particular sampling strategy without fully describing the methods for selecting the sample number, size of sampling unit and location of sampling sites. Harrison and Dunn (1993) pointed out a number of problems relating to the application of traditional sampling theory to a two dimensional natural population such as landscape. They argued that the sampling theory assumes either a population of discrete elements or a continuously varying function, however, for the studies of land use the nature of population (landscape) is much more complex. In sampling the landscape a number of attributes (land cover categories) are usually measured within the sample site, hence the multivariate nature of data makes defining an optimal sampling scheme difficult. A
sampling scheme which is appropriate for one cover type e.g. forests may not be appropriate for other cover types e.g. agricultural crops or grass.

The assessment of classification accuracy of the Siran land cover map was accomplished in two main phases: (i) collection of ground data, and (ii) statistical analysis of ground truth data. Time of data collection, appropriate number of samples, size of sampling site and which variables to record were the most important considerations of the first phase. Likewise the selection of the most appropriate statistical method to compile and analyse the ground truth data was the major consideration of the second phase.

4.8.1 Ground Data Collection

The main feature of the ground data collection scheme was to visit maximum number of sampling sites and to record only those properties which were essential to describe the land cover characteristics.

4.8.1.1 Time of ground data collection

Curran (1985) observed that the ground truthing of remote sensing based maps often takes place years after image is acquired when the properties are static e.g. geology. Justice and Townshend (1981) recommended the collection of ground data synchronous with the imaging when the observed properties are dynamic. However the estimation of variable ground properties can be possible after imaging. Nevertheless the time of ground data collection for land cover accuracy assessment is influenced by several external factors. Bearing in mind several factors including (i) climate, (ii) logistics and (iii) crop calendar, the collection of ground truth data for this study was carried out in December 1994 and January 1995.

4.8.1.2 Sample Number

The decision about the number of sites to visit is a crucial issue in the ground truthing (Conese and Maselli, 1978), since it needs a compromise to be made between the statistical reliability of ground data and time and cost involved. Many image analysts have not elaborated on the methods they have used to determine the appropriate
number of samples for ground truthing. Cibula and Nyquist (1987) generated 200 random samples for field verification of land cover map of the Olympic National Park, WA, USA. Harrison and Dunn (1993), after experimenting with different number and size of samples, suggested that most efficient sampling approach is to take many small samples. Jordon (1994) selected 49 samples for the validation of a GIS-based deforestation risk model. Hay (1979) recommended that at least 50 samples per class are required for ground truthing. Curran and Williamson (1985) gave a statistical method of calculating the number of samples by:

\[ SN = 100(CV)^2 \]

where \( SN \) = sample number and \( CV \) = coefficient of variation. Since this method necessitates undertaking a pilot study, it could not be applied for this study. Van Genderen et al. (1978) employed binomial expansion theorem to calculate the minimum number of samples required for the statistically reliable ground data collection. This method which is based on the probability theory has been used to calculate the number of samples required for measuring the accuracy of the Siran land cover map.

In order to calculate the optimum (minimum) number of samples, we consider a sample 'x' from a stratum (class), of which 'f' have been found in error. The probability of making interpretation accuracy 'q' when the probability of real errors in 'x' is 'p' can be calculated by the binomial expansion of \((p+q)^x\) as:

\[(p+q)^x = \sum_{f=0}^{x} \binom{x}{f} p^f q^{x-f} \]

The probability of errors 'f' in the sample 'x' is given by:

\[ P[f \text{ errors in } x \text{ sample}] = \binom{x}{f} p^f q^{x-f} \]

If the errors in the sample 'x' are zero i.e. \( f = 0 \), then the last term of the binomial expansion can be used to calculate this probability that is:

\[ P[f \text{ errors in } x \text{ sample}] = q^x \]

The achievement of perfect results i.e. \( f = 0 \) does not imply that the image interpretation is error free, as these results may occur by chance in a situation where a
substantial proportion of the land cover classification was in fact, erroneous. For \( f = 0 \), the probability of scoring interpretation errors in the samples of varying size taken from a population with real error proportion \( p \) is given in Appendix 4-ii.

By using the table the minimum sample size for checking any interpretation accuracy can be determined. For example, taking the specified accuracy of the image interpretation of 90% \( (q = 0.90) \) as suggested by Anderson et al. (1972) and the conventional probability of scoring errors in the sample \( (p = 0.05) \), the minimum size of the sample from each stratum \( x \) using \( p = q \) is 30. It is the minimum number of sample since \( f = 0 \) from a small sample signifies very little. Obviously the sample size must increase with the increasing probability of \( f \).

For the collection of ground truth data to measure the accuracy of the Siran land cover map, the minimum (optimum) number of samples sites to visit for each of the five strata viz. arable, forests, grasslands, exposed rock and stream beds was 30. Hence the total number of sampling sites, calculated on the basis of probability theory, was \( 5 \times 30 = 150 \). In fact more emphasis was given to the vegetation classes and a few non-vegetation sample sites were actually visited as can be inferred from the confusion matrices (Tables 4.8 a and 4.8 b).

4.8.1.3 Size of field checking sites

For checking the accuracy of a land cover map derived from remotely sensed data, the area of sampling site should be related to spatial resolution and geometric accuracy of the map (Justice and Townshend, 1981). Generally the size of a site equals the area represented by one pixel plus the margin for geometric inaccuracy. The dimension of the sampling site are calculated as:

\[
A = P[1 + 2L]
\]

where \( P \) = pixel dimension (i.e. 80 m)
\( L \) = the accuracy of location in terms of pixels

Hence each of the squared sampling site measured 240 m length on either side (assuming \( L = mean \ RMSE = 1 \)). The area of each sampling site calculated by \( A^2 = (P[1 + 2L])^2 \) measured 57,600 m². Total area of 150 samples to be visited measured 8.64 km² or \( = 0.83 \) percent of the total study area.
4.8.1.4 Sampling Design

Probability sampling, which involves objective selection of sampling sites, was used for the collection of ground truth data. Of the several methods of probability sampling, stratified random sampling with an equal number of samples from each stratum is the most efficient method and preferred by Rudd, (1971); Van Genderen, (1978); Congalton, (1988); Rosenfield et al. (1982); Jordan, (1994) and Card, (1982). The five level I classes derived through the supervised classification were treated as the strata within which the samples were allocated as described in the previous sections.

The row and column co-ordinates of each pixel belonging to a certain interpreted class and their respective real-world co-ordinates were generated through a routine COORDINATE which has been specifically written (in C) for this purpose. This routine assigns an identity number to each pixel belonging to a class. A sample output of this programme is given in Appendix 4-iii. Separate co-ordinate files for each of five classes were produced from which the required number of samples were drawn randomly by another routine RANDOM. Having known the map co-ordinates the sample sites were marked on the topographic maps with the help of a transparent grid.

4.8.1.5 Locating the Sites in the Field

After having marked the position of each sampling site on the topographic maps, the Global Positioning System (GPS) was used to locate these sites in the field. The instrument (Magellan Navigator 3000) was first initialised by collecting the ALMANAC within the study area. The central Latitude/Longitude of all those sites or WAYPOINTS which could be visited in one day were entered as ROUTES. After reaching the central point of each sampling site, its POSITION was re-confirmed before collecting any data. The dimensions of each site were measured with the help of a 100 metre tape, although the step-count method was used to delineate those sites for which stretching of tape was not possible.

4.8.1.6 Recording of Sampling Variables

The decision about what variables to observe or measure in the field is highly subjective and depends on the surveyor's objectives. For example, Jordan et al. (1994) recorded following variables at each sampling site pertaining to deforestation in Nepal:
aspect, slope, altitude and ground cover. The last category included percent of bare soil, stone, shrub, grass and leaf litter, tree height and canopy cover. For the ground truthing of the Siran land cover maps, it was endeavoured to keep the number of variables to the minimum for convenient evaluation of the data.

A ground data form was designed so that the required information could be collected systematically at each site (Justice and Townshend, 1981). Section 'A' of this form gives the sample location description. General topographic and soil observations were entered in the section 'B'. Section 'C' contains a space for the sketch of land covers at each site to be drawn. Additional information on the vegetation e.g. species and growth stage were entered in section 'D'. A specimen data collection form is given in Appendix 4-iv.

Most of the present land cover data was gathered from within the sampling sites. However, those sites which were not accessible or those to which the access was restricted (e.g. private premises), were assessed from a distance using a binocular (Green et al. 1993). Out of a total of 135 sites, 9 could not be approached due to shortage of time and were assessed using this method. However the observation and recording of 'present' land covers types could not meet the objective of ground truthing; the accuracy assessment of land cover maps of 1979 and 1989. For this purpose, the information on the past land uses (i.e. 1979 and 1989) were gathered by interviews with the local people (Jordan, 1994).

4.8.2 Measures of Classification Accuracy

The accuracy of classification (level I) was calculated by two methods i.e. (i) simple mathematical and (ii) statistical based on probability analysis through binomial expansion. Two confusion matrices (Tables 4.8 a and 4.8 b) were prepared from the interpreted and observed land cover data of 1979 and 1989.

Mathematical Accuracy: Mathematical class accuracy (100 × correct sample / total interpreted samples) are given in the last column of the confusion matrices. The overall accuracy of the land cover classifications for 1979 and 1989 were 82.98% and 76.29% respectively. High cover conifer forests (21) had maximum accuracy in both classifications, 95.00 % and 91.66 % respectively. Least accurate of nine classes in both classifications was 'stream beds (51)' with accuracy of 50 % and 11.11 %. The possible reasons for mis-interpretation of this class are developed in the following
### Table 4.8a: Confusion matrix for land covers of 1979.

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>21</th>
<th>22</th>
<th>31</th>
<th>41</th>
<th>51</th>
<th>Total</th>
<th>Accuracy%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddy</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>11</td>
<td>76.00</td>
</tr>
<tr>
<td>Tobacco</td>
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<td>15</td>
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<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>17</td>
<td>78.54</td>
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<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>21</td>
<td>76.19</td>
</tr>
<tr>
<td>Soil</td>
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<td>1</td>
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<td>2</td>
<td>1</td>
<td>2</td>
<td>15</td>
<td>80.00</td>
</tr>
<tr>
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<td>91.66</td>
</tr>
<tr>
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<td>3</td>
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<td>1</td>
<td>25</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>30</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Stream Beds</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>11.11</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>17</td>
<td>18</td>
<td>12</td>
<td>15</td>
<td>29</td>
<td>25</td>
<td>2</td>
<td>3</td>
<td>135</td>
<td>76.29</td>
</tr>
</tbody>
</table>

### Table 4.8b: Confusion matrix for land covers of 1989.

<table>
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<th>Land Cover</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>21</th>
<th>22</th>
<th>31</th>
<th>41</th>
<th>51</th>
<th>Total</th>
<th>Accuracy%</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
<td>1</td>
<td>2</td>
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<td>2</td>
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<td>2</td>
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<td>76.00</td>
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<td>1</td>
<td>2</td>
<td>1</td>
<td>17</td>
<td>78.54</td>
</tr>
<tr>
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<td>16</td>
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<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>21</td>
<td>76.19</td>
</tr>
<tr>
<td>Soil</td>
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<td>1</td>
<td>12</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
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<td>91.66</td>
</tr>
<tr>
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<td>25</td>
<td>2</td>
<td>3</td>
<td>135</td>
<td>76.29</td>
</tr>
</tbody>
</table>

Table 4.8c: Classification accuracy of three main vegetation cover types.
paragraphs (section 4.9.3). The overall accuracy of vegetation cover types are given in Table 4.8 c.

Statistical Accuracy: The probability of a pixel being correctly classified in 95% confidence limits was calculated using the binomial expansion technique given by Thomas et al. (1987). The results of these statistical analyses are given in Appendix 4-v. Although for accuracy assessment based on probability theory, samples larger than 30 are recommended (Thomas et al. 1987; Van Genderen, 1978), smaller samples were used to calculate the class level accuracy. The overall accuracy of nine class land cover maps of 1979 and 1989 were 77.70% and 71.15% respectively. Except for the mixed class 'Grass and scattered trees (31)', all classes in land cover map for 1979 had higher levels of accuracy than those calculated for 1989.

4.8.3 Evaluation of Accuracy Testing

To a large extent, the actual land covers of the Siran Basin are honey-combed (inter-mixtures of two or more land covers) (Photo 4.7) and a classification based on a discrete algorithm (maximum likelihood) can not effectively accommodate this diversity (Parachini and Folving, 1994). The mixture modelling technique, instead of discrete algorithms, can yield superior area estimates in such conditions, but makes difficult the estimation of hydrological parameters. Since the main aim of land cover mapping in the Siran Basin was the estimation of hydrological parameters, the land cover maps were based on discrete classification algorithm, hence their class accuracy must not be over-estimated. In fact, the cover classes shown on these maps (Figs. 4.11a and 4.11b) represent only the dominant land covers occupying the corresponding area in the Basin. For example, the cover class 'high cover conifers (21)' corresponds to an area occupied more than 50% the forest crown cover, irrespective of its associated land covers on the rest of the total area of that class. Moreover the ground truthing of these maps was based on discrete sampling technique by which each sample site had to be assigned one of the cover class represented on the maps. Practically it was not possible to measure actual proportions of different land covers within each sample site, hence a judgement had to be made at some sites. For example, a distinction between two sample sites, one having 51% crown cover and other having 49% cover, was made subjectively in order to put them in two different classes i.e. 21 and 22 respectively.
Photo 4.7: The mixed land covers found in the large part of the Siran Basin could not be effectively mapped from Landsat data using a discrete classification method (maximum likelihood). A method based on mixture modelling may yield better land cover estimates but makes hydrological parameter estimation (for distributed process simulation) very difficult.
Among vegetation classes 'high cover conifers (21)' have been found to have maximum accuracy. The accurate interpretation of this class was due to its characteristics spectral response. The minimum reflectance in all MSS and TM wavebands (Figs. 4.10 a and 4.10 b) made this class spectrally distinguishable from all other classes. The interpreted class 'grass and scattered trees (31)' was the least accurate, since the most of the sample sites corresponding to this class were found to have mixed land covers e.g. very low cover conifers, grass, abandoned agriculture etc. in varying proportions (e.g. Photo 4.7). Many sample sites interpreted from the Landsat data as 'grass and scattered trees (31)' were having higher proportion of fallow agricultural lands (covered by seasonal grass), hence they belonged to one of the arable cover classes (11 - 17).

The accuracy assessment of two non-vegetation classes i.e. exposed rock (41) and stream beds (51) was constrained by limited number ground samples for which statistical probability could not be measured. The worst accuracy of the class 'stream beds (51)' in both maps was due to the fact that the stream beds and habitations with galvanised iron roofed houses had similar spectral response in all MSS and TM wavebands (Photos 4.5 and 4.6). Many sample sites interpreted as 'stream beds (51)' on the land cover maps were actually habitations with built structures such as roads. It can be inferred from Table 4.4 that the area under cover class 'stream beds (51)' has been doubled over ten years time (1979 to 1989). An increase in the area of this class was brought about partly by the lateral expansion of gravel beds due to cutting of river banks by flash floods and partly by the expansion of habitations.

One of the underlying reasons which resulted in mis-interpretation of land covers from MSS data was the ground snow in the mixed conifer and fir forests which altered the characteristic spectral response of these forests (Photo 4.8). Another reason was the hill shading (particularly on MSS image) (Photo 4.9) which could not be corrected by solar radiation redistribution modelling during image adjustments for relief effects (cf. section 4.5). It is note-worthy that the accuracy analysis revealed a lower accuracy of the land cover map for 1989 derived TM (30 x 30 m²) data compared with that for 1979 derived from MSS (56 x 79 m²) data. Since accuracy increases with map resolution (Curran, 1985), the map for 1989 presumably must have had higher accuracy. The underlying reason of the lower accuracy of the map, derived from TM data, was the warping from 30 m to 80 m resolution by neighbourhood algorithm. Changing of map resolution was inevitable to interface the land cover map with the GIS and change detection. This warping resulted in reduction of noise and consequently in the map accuracy.
Photo 4.8: The snow on the forest floor alters the spectral response of the overlying canopy. About 13% of the MSS image could not be classified due to this problem (cf. Table 4.6).

Photo 4.9: Another problem in image processing was the effect of hill shading on MSS image. The method used to adjust the images for topographic relief does not take into account hill shading effects.
4.9 MULTI-LAYER RULE-BASED CLASSIFICATION (LEVEL II)

The processes of forest hydrology e.g. interception, evapotranspiration, infiltration and runoff are highly influenced not only by the crown cover percentage but also by the dominant forest species and composition of the ground flora. Two high cover conifer stands with different tree and ground flora species, although appearing as a single class 'high cover conifers (21)', may have widely different hydrological response. For example, a chirpine stand (lacking any ground flora) will respond to rainfall very differently from a fir stand (having abundant ground flora) of the same crown cover density. The level I classes of conifer forests listed in Table 4.7 were derived on the basis of their characteristic spectral response and do not contain any information about the forest species and composition. Therefore these forest classes (21 and 22) seem to be poorly defined for the purpose of hydrological parameter estimation. This fact necessitates the refinement of the land cover maps generated through the supervised classification.

The integration of topographic data within the land cover classification map is one of the three techniques described by Curran (1985) for refining the classification. Justice and Townshend (1981) referring to the work of Flouzat (1978) suggested that a priori data can be used to aid the mapping of forest distribution. The technique of integrating the topographic data can be advantageously used in the regions where the vegetation zonation is controlled by the altitude e.g. in the Mediterranean region. For example, Cibula and Nyquist (1987) derived nine land cover classes of the Olympic National Park, WA, through the unsupervised classification of the Landsat MSS data, with more than 90 percent overall accuracy. The classification was enhanced through the rule based integration of topographic data to obtain up to 21 land cover classes maintaining the same level of accuracy. Su and Shultze (1993) have used the rule-based method for the correction of classification errors.

The altitudinal control of vegetation zonation in the Siran Basin (cf. section 1.2.4) makes the DTM a potential discriminant for classification refinement. There exist five major forest types within the Basin (Jan, 1972); the composition of each of these forest types is given in Appendix 1-i. The two forest classes interpreted from the Landsat data i.e. 21 and 22 were further stratified, with the integration of the DTM, into level II classes. A total of ten theoretically possible combinations (Fig. 4.12) were obtained, all of which were present in the Basin.
Level II Classification was performed within ARCINFO GRID 6.1, inputting level I land cover maps, the DEM and aspect maps (cf. Chapter 3). The results of level II classification are summarised in the Table 4.9. Having known the vegetation composition of different forests types, Level II classifications could supply much more information for the estimation of hydrological parameters. However, the class level accuracy of level II classifications could not be measured due to lack of ground truth data.

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>300</th>
<th>914</th>
<th>1675</th>
<th>1980</th>
<th>2286</th>
<th>2590</th>
<th>3200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect</td>
<td>A</td>
<td>A</td>
<td>S</td>
<td>N</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Forest Type</td>
<td>Scrub</td>
<td>Chirpine</td>
<td>Bluepine</td>
<td>Bluepine &amp; Deodar</td>
<td>Firs &amp; Spruce</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level I Classes Code</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HighDensity Forest</td>
<td>21</td>
<td>211</td>
<td>212</td>
<td>213</td>
<td>214</td>
<td>215</td>
<td></td>
</tr>
<tr>
<td>MediumDensity Forest</td>
<td>22</td>
<td>221</td>
<td>222</td>
<td>223</td>
<td>224</td>
<td>225</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4.12: The multi-layer rule based classification scheme for level II classes.**

<table>
<thead>
<tr>
<th>Level I Class</th>
<th>Code</th>
<th>Level II Class</th>
<th>Code</th>
<th>Land Cover 1979</th>
<th>Land Cover 1989</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi Cov Conifers (&gt;50%)</td>
<td>21</td>
<td>Scrub</td>
<td>211</td>
<td>236 1.51</td>
<td>14 0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chirpine</td>
<td>212</td>
<td>13658 87.41</td>
<td>1601 10.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bluepine</td>
<td>213</td>
<td>4527 28.97</td>
<td>3367 21.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mixed Bluepine / Deodar</td>
<td>214</td>
<td>2597 16.62</td>
<td>3239 20.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Firs / Spruce</td>
<td>215</td>
<td>1885 12.06</td>
<td>2012 12.87</td>
</tr>
<tr>
<td>Hi Cov Conifers Total</td>
<td>22903</td>
<td>146.87</td>
<td>10233</td>
<td>65.49</td>
<td></td>
</tr>
<tr>
<td>Med Cov Conifers (25-50 %)</td>
<td>22</td>
<td>Scrub</td>
<td>221</td>
<td>3242 20.74</td>
<td>965 6.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chirpine</td>
<td>222</td>
<td>18623 119.18</td>
<td>30340 194.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bluepine</td>
<td>223</td>
<td>3438 22.00</td>
<td>7485 47.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Firs / Spruce</td>
<td>225</td>
<td>2077 13.29</td>
<td>2185 13.98</td>
</tr>
<tr>
<td>Med Cov Conifers Total</td>
<td>28826</td>
<td>184.48</td>
<td>43025</td>
<td>275.36</td>
<td></td>
</tr>
<tr>
<td>Forest Total</td>
<td>51720</td>
<td>331.06</td>
<td>53258</td>
<td>340.85</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.9: Area estimates Level II classes generated through Rule-Based Classification in GIS**
4.10 LAND COVER CHANGE DETECTION

The area estimates for the land cover classes (Table 4.7) represented on the two maps (Figs. 4.11a and 4.11b) revealed that there had been no major changes in the main land cover types (Arable, Forests and Grass) in Total Area. Changes in these three classes were -2.7, +9.7 and -8.2 km² respectively. However, there have been extensive changes in the spatial distribution of the forests and crown cover density. Such temporal changes can be monitored in their true spatial context using multi-temporal satellite data. Howard (1991) reviews the past efforts to detect and monitor forest cover changes using Landsat data. Several techniques of change detection including image differencing, PCA differencing and post-classification differencing are in use. Singh (1983) employed these differencing techniques in an attempt to map the forest cover changes in Manipur, India from multi-temporal Landsat MSS data. Estes et al. (1982) referring to the work of Weismiller et al. (no date) considered the post-classification change detection technique to be optimum and results as a standard for evaluating the results from other techniques. However, this method requires extremely accurate classifications to be made before changes could be quantified. The post-classification change detection technique can be applied to multi-resolution remote sensing data or their products, after they are resampled to the same resolution. For example, Siddiqui and Jamil (1993) used multi-resolution (MSS, TM and SPOT) data for post-classification forest change detection over last 14 years on the part of Margalla Hills, Pakistan. The accuracy of a 'Change Map' must not be expected greater than the product of individual classification accuracy.

Although for land cover mapping in the Siran Basin multi-resolution (MSS and TM) data were used, the final land cover maps had the same resolution (80 m). The changes in the forest area and crown cover percentage were mapped from these two level I classifications (1979 and 1989) through post-classification change detection method. The spatial changes which occurred in the forest area and crown cover density over ten years time (1979 to 1989) are shown in Fig. 4.13. The results of change detection are given in Table 4.10. The area shown in white represents parts of the basin where no or very little (not detectable) change in forest cover has occurred during this period. Pink shade shows those areas where forests have been thinned and cover class '21' (> 50% cover) has been replaced by '22' (25-50% cover). Complete loss of forest through clear-felling (shown in green) largely appeared on the plains and gentle slopes near villages. These results support Haigh's (1991) statement that deforestation is a matter of recent historical record. Deforestation has occurred as a result of bringing more land
Forest Cover Changes (1979–89)

Accuracy 89.63% (1979) x 84.44% (1989) = 75.77% (change)

Scale 1:400,000

Fig. 4.13: Changes in the forest cover from 1979 to 1989. Note most deforestation has occurred in the plains while forests in the upper mountains were relatively unchanged due to inaccessibility. New plantations are appearing mostly in the eastern parts of the Basin.
under cultivation (Allan, 1986), rapid accessibility and settlement of Afghan refugees (Allan, 1987; Archer, 1995). One of the several sites where complete deforestation has occurred during 1970's and 1980's is shown in Photo 1.2 (cf. Chapter 1)

Fortunately, the process of forest cover changes is not one-way as new plantations and regenerations are also making their appearance (shown in brown). These young forests are the results of efforts in 1970's under massive tree planting programmes (Wani, no date), watershed restoration projects and several other projects to assist villagers intensify food, fuel and fibre production on low quality, dry upland soils (Dixon, 1986). Khattak (1987) discussed the Mansehra Project which was initiated in 1977 and aimed at re-afforestation of 203,000 ha of barren hills. Photo 4.10 shows one of such sites where new conifer (chirpine) plantation have made their appearance in 1980's. Another conspicuous change has taken place in the area under stream beds, which has been doubled from 1979 to 1989. Photo 4.11 represents the extent of the problem of lateral migration of the main Siran River caused by flash floods.

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>Code</th>
<th>1979 Pixels</th>
<th>1989 Pixels</th>
<th>Change Pixels</th>
<th>km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>11</td>
<td>10118</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>12</td>
<td>10223</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Winter Non-Cereals</td>
<td>13</td>
<td>12250</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Paddy</td>
<td>14</td>
<td></td>
<td>2733</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tobacco</td>
<td>15</td>
<td></td>
<td>8833</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>16</td>
<td></td>
<td>23827</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fallow</td>
<td>17</td>
<td>24354</td>
<td>21149</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Arable</td>
<td>56945</td>
<td>56542</td>
<td>-403</td>
<td>-2.57</td>
<td></td>
</tr>
<tr>
<td>Hi Cov Conifers (&gt; 50 % cover)</td>
<td>21</td>
<td>22903</td>
<td>10233</td>
<td>-12670</td>
<td>-81.08</td>
</tr>
<tr>
<td>Med Cov Conifers (25-50 % cover)</td>
<td>22</td>
<td>28826</td>
<td>43025</td>
<td>+14199</td>
<td>+90.87</td>
</tr>
<tr>
<td>Total Forest</td>
<td>51729</td>
<td>53258</td>
<td>+1529</td>
<td>+9.78</td>
<td></td>
</tr>
<tr>
<td>Grass + scattered trees</td>
<td>31</td>
<td>41438</td>
<td>40146</td>
<td>-1292</td>
<td>-8.26</td>
</tr>
<tr>
<td>Bare Rock</td>
<td>41</td>
<td>7286</td>
<td>2493</td>
<td>-4793</td>
<td>-30.67</td>
</tr>
<tr>
<td>Stream Beds</td>
<td>51</td>
<td>5233</td>
<td>10192</td>
<td>+4959</td>
<td>+31.73</td>
</tr>
<tr>
<td>Total ALL</td>
<td>162631</td>
<td>162631</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10: Area estimates of land cover changes.
Many new plantations had appeared in the Siran Basin during the last two decades. A 14 year old chirpine plantation shown here is a representative site of areas recently brought under forests.

An example of a deteriorating land cover change. The bed of the Siran River has migrated laterally during the last two decades by floods and any vegetation cover from the banks has washed away.
Forest cover change results have also been evaluated in the light of forest ownership which is considered the most important factor in forest management (Azhar, 1989). The changes that occurred in Reserved, Protected and Guzara Forests (cf. section 1.2.3) are shown graphically in Fig 4.14.

These results revealed that most deforestation from 1979-1989 occurred on the privately owned lands. Since the focus of past afforestation and planting campaigns were also private waste lands (Dixon, 1986; Khattak, 1987), almost the same area appeared to have new forest cover. However, a comparison between cover changes in Reserved and Protected (Government owned forests) and Guzara (communal forests) does not support Azhar's (1993) arguments that Guzaras were the forests worst affected by recent deforestation in the Siran Basin.

4.11 HYDROLOGICAL PARAMETER ESTIMATION

The ultimate use of land cover maps in deterministic hydrological modelling is the estimation of vegetation-related parameters. The level II classifications for 1979 and 1989 can be exploited to estimate the hydrological parameters to input to the simulation models. The parameter input requirements of different process models vary
depending upon the algorithms used. Most hydrological parameters can be measured physically in the field, but for the distributed modelling in the large basins, this is not a practical approach. In the absence of field measured data, the typical values (given in the literature) can be assigned to each of the vegetation class. For example, the parameters of crop height and LAI which are input to Penman-Monteith evapotranspiration model can be estimated for each vegetation type, represented on land cover maps of the Siran Basin, using the typical values given by Meteorological Office (1981) and Kirkby (1987). Nevertheless the vegetation-related hydrological parameters e.g. albedo and LAI are highly dynamic and are dependent upon the growth stage of the seasonal vegetation. The temporal variations in these parameters can be assessed using the crop calendar (cf. section 1.2.3).

The albedo can be directly derived from the Landsat data (Harris, 1987). The brightness index map generated through the PCA (cf. section 4.6.2) was used to estimate the mean albedo of each land cover class represented on the land cover maps. On a 16 bit display (i.e. 0-255 scale) the albedo ranged from 25 to 190 (i.e. 0.09 - 0.74); the maximum albedo corresponds to an area occupied by snow on Landsat MSS image while the minimum albedo corresponds to a high cover conifer forest represented on the land cover maps. The mean albedo of an individual land cover type was estimated by taking the mean of all areas under that particular cover type. The albedoes estimated for each land cover class are given in Table 6.1. The temporal variations in albedo were ignored due to non-availability of multi-temporal Landsat data.

The LAI of each vegetation cover type was estimated from the literature values gathered from different sources. The daily variations in LAI of seasonal crops were estimated using a linear equation (Eqn. 6.33) developed by Meteorological Office (1981). The estimated LAI values used in this study for all vegetation cover classes are given in Table 6.4.

4.12 SUMMARY

- The information about the land cover characteristics is vital to most hydrological process simulations. For the distributed hydrological modelling in the Siran Basin, land cover mapping was carried out using multi-resolution, multi-temporal Landsat data.
• The multispectral Landsat data were geometrically corrected and co-registered with the Siran GIS (cf. Chapter 3).

• The shadowing caused by topographic relief hindered the accurate classification (unsupervised and supervised) of Landsat data. A method was developed to reduce the relief effects on Landsat data through solar radiation redistribution modelling.

• Several vegetation indices were derived from Landsat data primarily to enhance the spectral response of different vegetation types to aid in the training for supervised classification. The PCA was performed to reduce the dimensionality of the data and to produce mutually independent data sets to delineate spectrally distinguishable cover classes.

• Image classification was carried out using maximum likelihood algorithm with equal probability of all cover classes. The land cover maps were warped to 80 m resolution and interfaced with the GIS.

• The accuracy of each of two level I maps was tested using the ground data collected in December 1994 and January 1995. The cover class 'high cover conifers (21)' was found to have the maximum accuracy.

• The land cover maps were refined for level II classes, with the integration of the DTM, using a multi-layer rule-based approach. Although the accuracy of level II classes were not tested, they were found more informative for the estimation of hydrological parameters than the level I maps.

• Changes in the forest cover which had occurred over ten years (1979 to 1989) were mapped and quantified using post-classification change detection technique. These changes were also evaluated in the light of forest ownership.

• Albedo was mapped across the catchment and mean albedo of each land cover type was estimated. Other hydrological parameters e.g. LAI can be estimated from these land cover maps using the literature values to input to simulation models (cf. Chapter 6).
Chapter 5

HYDRO-METEOROLOGICAL DATA MANAGEMENT
CLIMATIC ANALYSES & LUMPED WATER BALANCE MODELLING
5.1 INTRODUCTION

As well as the physical parameters that characterise the catchment, a deterministic process model requires sufficiently long series of computer compatible meteorological data (Fleming, 1979). Important variables to calibrate or run a theory-based hydrological simulation model include precipitation, temperature, evaporation, solar radiation, wind velocity and relative humidity. Stream discharge data are also required to calibrate and verify simulation models where the ultimate outputs are hydrographs. The decisions about the number of meteorological stations and length and interval of records are dependent not only on the research objectives but on several practical problems such as availability and reliability of data, available data formats and time and cost involved in data acquisition. As is the case in many other countries, such data are recorded by more than one agency (Fleming, 1975) in Pakistan. The most important agencies are the Water & Power Development Authority (WAPDA) and the Meteorological Department. The data acquired from different sources, after formatting to computer readable formats, can be either analysed for catchment level lumped simulations or extrapolated and input to distributed models. This chapter focuses on the acquisition and management of meteorological data recorded at stations within and around the Siran Basin. These data have been analysed to assess the general climatic pattern, catchment response and past trends in the climate and the catchment response. They were also used to calculate the components of the water balance equation on a catchment scale with the prime objective of comparing the results of distributed simulations (cf. Chapter 7). The following is a list of tasks undertaken to accomplish this part of the study:

- acquisition of available meteorological data from at least four stations and the Siran River discharge records.
- entry, editing, augmentation and filing of data and developing a data retrieval system for computer simulations.
- analyses of each of meteorological variable for assessing climatic pattern and recent past trends.
- analyses of hydrographs and past trends in catchment response.
- calculation of components of a simple water balance model.
5.2 DATA: SOURCES, FORMAT AND QUALITY

To meet the WMO (Fleming, 1979; Shaw, 1983) and USWB (Tennyson, 1986) standards of meteorological station density (1 station per 250 km²), the data from at least four stations were required for hydrological simulations. Since only two stations, Shinkiari and Phulra, lie within the Siran catchment, it was decided to include data from two more stations, Oghi and Balakot, situated just outside it. Unfortunately no station (except for Oghi where limited solar radiation data was available) record solar radiation or sunshine data. The sunshine data recorded at Kakul were therefore used for this study. Of these five stations those at Oghi, Phulra and Shinkiari are run by the WAPDA under their Surface Water Hydrology Project. The published data for these stations were supplied by the project office at Lahore with the prior permission of the WAPDA head office. The Siran River discharge data recorded at the catchment outlet (Phulra) were also supplied by the WAPDA. The data for Balakot and Kakul were recorded and supplied with permission by the Meteorological Office, Lahore. A location map of these and other meteorological stations in the northern Pakistan is given in Fig. 5.1. It is noteworthy that all of these stations lie in the valleys and their records do not represent the climate of the steep slopes and upper reaches of the Basin (Heywood, 1994), unless projected using a standard technique. The description of instruments and methods used for recording the climatic variables and river discharge is given in Table 5.1.

Most of the data were supplied in the form of published reports and in hand-written raw format. Several inconsistencies were found in the duration, interval and units of available records as is evident from the Table 5.2. For example, 14 years hourly precipitation records were available for Oghi and Phulra against 11 year monthly totals for Balakot. This table gives the duration and interval of hydro-meteorological data available for this study.

5.3 DATA MANAGEMENT

All available data were entered, edited, augmented for gaps and maintained as daily and monthly data files. For distributed hydrological simulations, a data retrieval system was devised. The various steps involved in the data management are explained in the following sub-sections:
Fig. 5.1: The location map of meteorological stations in northern Pakistan. The data recorded at Balakot, Kakul, Oghi, Phulra and Shinkiari were used in this study.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Instrument, Method and Measuring Interval</th>
</tr>
</thead>
</table>
| Precipitation | Universal Weighing type recording gauge  
Records hourly precipitation. Daily precipitation depth for 24 hours read at 0800 hrs.                                                                                     |
| Pan Evaporation| US Weather Bureau Class 'A' Evaporation Pan (45" diameter)  
Daily evaporation for 24 hours is measured at 0800 hrs daily, either volumetrically or by use of an adjustable hook gauge. A rain gauge is read at each evaporation pan site to determine appropriate correction for rainfall. |
| Temperature   | Max-Min Thermometer (housed in standard shelter)  
Maximum and minimum air temperatures are read daily in °F or °C at 0800 hrs.                                                                                       |
| Humidity      | Wet and Dry Bulb Thermometer (with hydrometric tables)  
Wet and dry temperatures are measured daily at 0800 and 1700 hrs in °F. Corresponding relative humidity is read from hydrometric table.                                          |
| Wind Velocity | Recording Anemometer  
Wind intensity (miles / day) is recorded daily at 0800.                                                                                                               |
| Solar Radiation| USWB Pyrheliometer  
Records hourly sunshine. Total daily sunshine duration (hours), read at 0000 hrs.                                                                                      |
| Discharge     | Enamelled Plates (fixed in steps)  
Depth is read at one hour interval for the whole day throughout the year. Mean daily discharge (cusecs) is estimated using rating tables.                                  |

Table 5.1: Measuring Standards of the Climatic Data.
<table>
<thead>
<tr>
<th>Met. Variable</th>
<th>Balakot Duration</th>
<th>Balakot Interval</th>
<th>Oghi Duration</th>
<th>Oghi Interval</th>
<th>Phulra Duration</th>
<th>Phulra Interval</th>
<th>Shinkiari Duration</th>
<th>Shinkiari Interval</th>
<th>Kakul Duration</th>
<th>Kakul Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunshine Hours</td>
<td>-</td>
<td>- - - - - - - -</td>
<td>- - - D</td>
<td>- - - - - -</td>
<td>1989-90 D</td>
<td>D D D D</td>
<td>1985-87 D</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stream Discharge</td>
<td>-</td>
<td>- - - - - - - -</td>
<td>1969-87 D</td>
<td>1989-90 D</td>
<td>D D D D</td>
<td>D D D D</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Description of available hydro-meteorological data.

N.B: M, D and H denote monthly, daily and hourly data.
5.3.1 Data: Entry, Editing and Augmentation

All available daily precipitation and discharge data were entered onto spreadsheets as annual data files. Daily values of other variables such as temperatures (minimum, maximum and daily mean), wind and humidity data were entered as single variable files, only for selected years to run daily simulations. Monthly totals and monthly averaged daily values of each of these variables were calculated and saved as monthly data files.

These data were edited for errors introduced during data entry and converted to S. I. units. Like most hydro-meteorological data, they had periods during which there were errors (e.g. printing errors) or the data was absent altogether (Fleming, 1979). All gaps in the model input data were filled and corrected. For example, missing daily precipitation $P$ for any station $x$ was approximated with data from other three stations $a$, $b$ and $c$ using this equation (Sharp and Sawden, 1983; Bras, 1990):

$$
P_x = \frac{1}{3} \left( \frac{P_a}{P_x} + P_b \frac{P_a}{P_x} + P_c \frac{P_a}{P_x} \right)
$$

where $P_a$, $P_b$, $P_c$, $P_x$ denote normal annual precipitation of these stations. Gaps in the daily discharge series were filled by calculating the recession constant $K$ through the equation:

$$
Q_t = KQ_{t-1}
$$

where $Q_a$ and $Q_t$ denote initial discharge and discharge after time $t$.

5.3.2 Data: Filing and Retrieval System

Daily hydrological simulations require the meteorological data from all stations to be entered every time the model is run. To avoid the cumbersome task of data entry (and errors in data entry), a data filing and retrieval system was devised. For this purpose yearly data files (in ASCII format) were created which contained daily values of all variables recorded at all stations. An example of this format from the 1979 data file (beginning from first day of the year) is given in Table 5.3.
Since these meteorological variables are required to simulate daily evapotranspiration, these files have been linked to evapotranspiration model through a sub-routine Metread. This sub-routine, which has been coded in C, scans meteorological data from data files for the day of interest and inputs to the evapotranspiration model (cf. section 6.3). For example, if the simulations are to be run for the day of Landsat MSS capture (5 March 1979), the output of Metread will look like one given in Fig. 5.2.

<table>
<thead>
<tr>
<th>Temperature (deg Celsius)</th>
<th>Relative humidity (%)</th>
<th>Wind (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oghi 944 1250 804</td>
<td>Oghi 7200 7000 5200</td>
<td>Oghi 24</td>
</tr>
<tr>
<td>Phul 1028 1222 808</td>
<td>Phul 7200 7100 4750</td>
<td>Phul 19</td>
</tr>
<tr>
<td>Shin 917 1056 812</td>
<td>Shin 7800 7000 5050</td>
<td>Shin 19</td>
</tr>
<tr>
<td>Bala 861 806 1139</td>
<td>Bala 7500 6600 4950</td>
<td>Bala 17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3: The format of daily meteorological data files for computer retrieval.

5.4 PRELIMINARY ANALYSIS OF THE CLIMATE

Each of the meteorological variables i.e. precipitation, temperature, relative humidity, wind velocity and solar radiation was analysed individually to assess the general pattern of the climate prevailing in the Siran Basin. Recent past trends in the climatic pattern have also been assessed using simple mathematical methods.

5.4.1 Precipitation

The precipitation is received either as liquid or solid form; the former comprises drizzle, rain and dew whereas the latter comprises snow, glaze, hail and frost. The precipitation data available for this study represents the sum of all of these forms. The precipitation is the major input to the catchment, hence is the most important meteorological variable in catchment hydrology. The frequency of the precipitation data depends on its use; for example, monthly water balance can be calculated from...
This programme scans daily meteorological data sets organized in yearly files. METREAD needs to know the year, month and date of simulation.

ENTER DATASET NAME (e.g. met1979.txt) : met1979.txt

1: ENTER YEAR OF SIMULATION : 1979
2: MONTH NUMBER OF YEAR 1979 (1 - 12) : 3
3: DAY OF MONTH 3 OF YEAR 1979 (1-31) : 5

* WARNING : Before initialising simulation please confirm that meteorological data for 5:3:1979 is absolutely correct.

Press any key to see the data

METEOROLOGICAL DATA RECORDED AT FOUR STATIONS ON 5:3:1979

<table>
<thead>
<tr>
<th>Oghi</th>
<th>Phulra</th>
<th>Shinkiari</th>
<th>Balakot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°C)</td>
<td>8.06</td>
<td>9.72</td>
<td>7.78</td>
</tr>
<tr>
<td>RH (%)</td>
<td>96.00</td>
<td>85.00</td>
<td>88.50</td>
</tr>
<tr>
<td>Wind Vel (m/s)</td>
<td>0.45</td>
<td>0.82</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Any error/omission must be corrected by editing relevant data file.

Press any key to continue

Fig. 5.2: An example output of Metread. This sub-routine scans daily meteorological data from daily files and inputs to the evapotranspiration model.
monthly precipitation data while the simulation of infiltration process may require hourly (or even more frequent) data.

The actual annual precipitation data has revealed that during the period 1969 to 1982, 1974 and 1977 were the driest and the wettest years respectively. Most of the annual precipitation is received as monsoon showers which is evident from monthly distribution of total annual precipitation (Fig. 5.3). It shows that nearly half of the annual precipitation at Balakot, Phulra and Shinkiari is received during monsoon months i.e. July, August and September. The heavy rains during these months are the result of favourable environment generated by westerlies. Oghi seems to have been least affected by the monsoon and a bimodal precipitation pattern tends to predominate. The underlying reason is that westerly troughs usually travel along the southern edge of the Himalayas, giving more rains on the mountain slopes but little elsewhere and they fail to cross high mountain barriers. A detailed description of the development of monsoon weather system in south-western Asia and western Himalayas of northern Pakistan is given by Barry and Chorley (1982).

Since all stations lie in the valleys, their precipitation records are not representative of the whole Basin. For lumped analysis of climate, precipitation-runoff relationship and water balance modelling, an areally-averaged precipitation was calculated using the Theissen method (Fleming, 1975; Bras, 1990). Theissen coefficients using four station data to estimate average precipitation \( P_{\text{avg}} \) over the Basin were:

\[
P_{\text{avg}} = 0.31 P_b + 0.42 P_s + 0.12 P_o + 0.15 P_p
\]

For the years during which the data for Balakot were not available, the average was estimated as:

\[
P_{\text{avg}} = 0.67 P_b + 0.18 P_s + 0.15 P_p
\]

where \( P_b, P_s, P_o \) and \( P_p \) denote precipitation at Balakot, Shinkiari, Oghi and Phulra respectively. The Theissen method, however, ignores the effect of topography (Fleming, 1979). In fact, the precipitation in northern Pakistan depends not only on its physical location and topography but also the structure of both surface and upper atmosphere (Gauhar, 1980). In general, amount of precipitation increases with rising elevation. For example, Tennyson (1986) calculated for the Rocky Mountains in the US that the increase in annual precipitation was 83 mm per 100 m rise in elevation. Jan (1972) analysed the climate of the Siran Basin and concluded that the precipitation
Fig. 5.3: Mean monthly and accumulated precipitation of four stations.
increases from south-western low-lands to north-eastern high mountains. Such correlations between location, topography and precipitation are valuable when extrapolating the data for distributed modelling from a low-density meteorological network to the whole basin (Goossens et al. 1990). A multivariate regression analysis for the Siran Basin was carried out using annual precipitation data from 13 stations lying within and around the Basin and following equation was obtained with an $R^2 = 81.6\%$:

$$P_s = (27.0 \text{ Long} + 7.583 \text{ Lat} + 0.0047 \text{ Elev} - 2195.4) \times 25.4$$

where $P_s$ is the estimated annual precipitation (mm) at any point $X$ and $\text{Long}$, $\text{Lat}$ and $\text{Elev}$ represent the longitude, latitude and elevation (m) of that point. Detailed results of regression analysis are given in Appendix 5-i. This equation, in conjunction with the inverse distance-squared equation will be used to extrapolate spatially the daily precipitation in Chapter 6. The real trends in annual precipitation were obtained and plotted as three-year moving-means (Sharp and Sawden, 1983) and are shown in Fig. 5.4:

![Fig. 5.4: Three-year moving-mean trends in annual precipitation of four stations and the catchment mean (Theissen Average).](image)

It is evident from these curves that during mid 1970's, there was a positive trend in total annual precipitation. The daily records of these stations revealed that the Basin received more torrential monsoon showers during mid 1970's. Again Oghi seems to be least affected by such annual trends.
5.4.2 Temperature

Temperature is the only meteorological input to Thomthwaite evapotranspiration model and one of the important inputs to Penman type models. The monthly maximum and minimum air temperatures for four stations are given in Fig. 5.5. Again these values do not truly represent the temperature of slopes and high mountains. For example, there were few nights with minimum temperatures below freezing between 1969 and 1983 according to the daily temperature records. Whereas upper reaches of the catchment sustain minimum temperatures below 0°C over many months.

However the data recorded by the sparse, low-altitude dominated meteorological network can be extrapolated using the ambient lapse rate (i.e. 6.5°C fall in temperature per 1000 m rise in elevation) from ground to tropopause (Barry and Chorley, 1982). The major shortcoming of the lapse rate approach is that it fails to take into account the effects of slope, aspect and ground albedo on the spatial variation in the temperature. Logically, these effects can be incorporated in the spatial distribution of temperature through the modelling of incoming short-wave radiation (cf. section 6.4.3).

To input to the evapotranspiration model, the mean daily values were calculated from minimum and maximum air temperatures using the equation (Bras, 1990):

\[ T_{\text{mean}} = \frac{T_{\text{max}} + T_{\text{min}}}{2} \]

where \( T_{\text{mean}} \), \( T_{\text{max}} \), and \( T_{\text{min}} \) denote mean, maximum and minimum temperatures respectively.

5.4.3 Solar Radiation and Sunshine Hours

These data are required to estimate the net radiation, the most important input to theory-based (e.g. Penman type) evapotranspiration models (Saxton, 1982; Shiau, 1973). A very limited daily solar radiation record (1971 only) was available for Oghi. However, solar radiation on horizontal surface can be estimated from the sunshine hour data using Angstrom type (Sopian, 1992; Canada, 1992). Raja and Twidell (1990) have given the coefficients of this equation for non-dimensional calculation of solar
Fig. 5.5: Mean monthly maximum and minimum temperatures recorded at four stations.
radiation from sunshine data in Pakistan. Three year actual daily sunshine data (1985-87) recorded at Kakul was available to run daily simulations. Monthly averaged daily normal of sunshine and solar radiation (1961-90) on horizontal surface are shown in Fig. 5.6. In the absence of other data these were used to run the model for rest of the years (for which daily data was not available).

The sunshine duration or total radiation on a horizontal surface can be used to empirically estimate the net radiation for lumped modelling of energy dependent processes (Saxton, 1982). But for distributed hydrological simulations in a complex terrain, such estimates for a horizontal surface are inadequate. The spatial extrapolation of total incoming radiation and net radiation can be carried out by first fractioning total radiation received on the horizontal surface into its components (beam and diffuse radiation) and then projecting them independently to all facets of the catchment (cf. section 6.4.2).

![Figure 5.6: Monthly averaged daily day length, sunshine hours and total radiation (Global Insulation).](image)

**5.4.4 Wind Velocity**

Unlike the influence of net radiation, the influence of wind on evapotranspiration is conflicting. But it has been established that the influence of wind velocity is secondary compared with that of net radiation in energy dependent processes (Ward, 1974 p.99). The wind velocity is a measure of turbulence in the atmosphere which controls the aerodynamic resistance (the resistance to movement of water from surface of the plant into the air).
The monthly averaged daily wind velocity (recorded at 2 meters from the ground) are given in Fig. 5.7. It is evident from this figure that Oghi experiences highest wind movements throughout the year compared with other stations. Furthermore, the wind velocities at Oghi are at the maximum during winter months; another evidence of a different weather system (Mediterranean) pre-dominating this area (cf. section 5.4.1).

![Fig. 5.7: Monthly averaged daily wind velocity recorded at Oghi, Phulra and Shinkiari.](image)

### 5.4.5 Relative Humidity

The relative humidity data is used to estimate saturation deficit (difference between saturated vapour pressure and actual vapour pressure) which indicates the dryness of the air. The monthly averaged relative humidity at 0800 am and 1700 hours are given in Fig. 5.8. It reveals that during June relative humidity is at its minimum whereas August is the most humid month. In general, the humidity remains higher in the morning hours (0800 hrs) compared to the evening (1700 hrs) throughout the year. To input to evapotranspiration model, the mean daily relative humidity was calculated by taking mathematical mean of these two values.

### 5.4.6 Pan Evaporation

The rate of evaporation from a water surface closely represents the lake evaporation or potential evapotranspiration rate after making adjustment for the pan factor (Fleming, 1975). In the absence of field measured evapotranspiration data, pan evaporation data
Fig. 5.8: Mean monthly relative humidity recorded at Oghi, Phulra and Shinkiari.
is the only source of information to compare the results of distributed simulations of evapotranspiration. Like all other meteorological variables, pan evaporation data does not represent the slopes and higher mountains. The averaged monthly depths of the water evaporated from the open pans for the period of available records are given in Fig. 5.9.

5.4.7 River Discharge

The river discharge data are required to calculate catchment response and catchment level water balance and to assess the accuracy of simulated hydrographs. The total discharge of the river includes direct runoff, interflow (delayed runoff) and sub-surface flow. The discharge hydrographs can be theoretically separated into these three components using typical or measured recession constants (Schulze, 1978; Bras, 1990). The direct runoff, thus obtained can be used to assess the accuracy of infiltration simulations (cf. section 7.3.5).

The temporal statistics (on logarithmic scale) of twenty one years (1969-87, 1989-90) daily discharge records of the Siran River at Phulra are given in Fig. 5.10. During this period the maximum mean daily discharge (13600 cusecs) was observed on 17 July 1977 whereas the minimum discharge (21 cusecs) was observed on 26 January 1990. The maximum discharge values are also required to calculate the return period of floods of certain magnitudes. The mean and median of these records were 662 and 441 cusecs respectively. The extended low flows during 1971 and 1990 indicate drought conditions while high peaks during 1976, 1977, 1987 and 1989 are indicative of flash floods.

These values however do not supply any information on how many days the discharge was equalled or exceeded a certain limit. For this purpose, a histogram analysis of the data was carried out with the classes defined on logarithmic scale. Appendix 5-ii contains the details of days the discharge was within a certain discharge class. The accumulated frequencies from this table were used to calculate the percentage of time the discharge did not exceed the upper limit of a class (Smith and Stopp, 1983). This summation curve (Fig. 5.11 a) implies that the Siran discharge did not exceed 100 cusecs for 1.39 % of time for which the data was available. In other words, the discharge was below 1000 cusecs for 81.51 % and below 10000 cusecs for 99.98 % of the time. This information was plotted as a discharge-frequency curve (Fig. 5.11 b) on
Fig. 5.9: Monthly and accumulated pan evaporation recorded at four stations.
Fig. 5.10: Temporal statistics of twenty one years daily discharge records.
Fig. 5.11 (a): Summation curve of the daily discharge of the Siran River at Phulra.

Fig. 5.11 (b): Mean daily discharge-frequency curve.

Fig. 5.11 (c): Return period curve.
a logarithmic paper. From this probability curve it can be predicted now that the probability of a discharge equalled or exceeded than 1000 cusecs is only 7.00 % (seven days out of 100). The maximum daily discharge values of individual years (Fig. 5.10) were used to create maximum flow probability curve (Fig. 5.11 c). The return period or the recurrence interval of a particular flow can be evaluated from this curve.

5.5 CATCHMENT RESPONSE

For calculating the components of the water balance equation and determining precipitation-discharge relationships, the mean daily discharge was converted to equivalent depths of water. One of the simplest and the most important relationship between precipitation and discharge is known as the catchment response. It indicates the efficiency of the catchment to yield runoff (or discharge) as a response to incident precipitation and can be calculated as total annual runoff as percent of precipitation (Smith and Stopp, 1973; Tennyson, 1986). For the Siran, the catchment response is shown in Fig. 5.12, for the period of available record.

The catchment response, in addition to the climatic factors, is highly influenced by changes in physical characteristics of the catchment e.g. land cover. Nevertheless the catchment response varies from year to year and can also be modified according to the aims of catchment management through manipulation of the land covers (Hanif et al. 1990). The trend in the annual catchment response, which can be plotted using three-year moving-mean method (Fig. 5.13), indicates the combined effects of changes in climate and land cover. As it is evident from this curve, there was a positive trend during the first half of 1970's. This was the era during which most land cover changes such as deforestation had occurred in the Basin and highest floods and sediment yield were reported in the literature (cf. section 1.3). Nevertheless the altered catchment response was the result of combined influences of climatic factor and land cover changes rather than deforestation alone which is often held responsible for it. However there exists no data and such hypotheses remain to be tested.
Fig. 5.12: The catchment response - annual discharge as a fraction of annual precipitation.

Fig. 5.13: Annual trends in the catchment response.
5.6 LUMPED MODELLING OF WATER BALANCE COMPONENTS

The continuous, dynamic water balance of a river basin obeys the fundamental equation of hydrology (Schaake and Chunzen, 1989) i.e.

\[ I - O = \frac{\Delta s}{\Delta t} \]

where \( I \) = inputs, \( O \) = outputs and \( \Delta t \) denotes change in the system. For a catchment where precipitation is the input and evapotranspiration and runoff are the outputs (neglecting transfer of ground water across the basin boundaries) the equation takes the form:

\[ P - E - Q = \frac{\Delta s}{\Delta t} \]

or the difference between the precipitation and runoff equals evapotranspiration plus change in the catchment water store i.e.

\[ P - Q = \frac{\Delta s}{\Delta t} + E \]

Assuming that annual changes in the water store are negligible, any difference between annual precipitation and runoff accounts for actual evapotranspiration. This annual water balance for the Siran Basin is shown in Fig. 5.14.

![Fig. 5.14: Partitioning of annual precipitation into discharge and actual evapotranspiration.](image)
The estimates of annual actual evapotranspiration obtained through this method will be used to compare the results of distributed simulations of evapotranspiration based on Penman-Monteith approach (cf. section 7.3.1).

Obviously, changes in the soil water store cannot be ignored when calculating monthly water balance. In this case, the right hand side of equation 5.9 accounts for the combined effects of evapotranspiration and changes in soil water store. Fig. 5.15 shows precipitation, runoff and balance (evapotranspiration and changes in soil water store) on monthly basis from June 1969 to October 1983. However, the two components of balance i.e. evapotranspiration and changes in soil water store can be separated though estimating the monthly evapotranspiration using the Thornthwaite model.

Fig. 5.16 gives the monthly $E_t$ estimated for all stations. Since the Thornthwaite $E_t$ is a function of temperature alone, these figures should not be taken as the representatives of the whole catchment. To calculate the catchment's mean $E_t$, the temperature from all stations was first reduced to 1000 m elevation and then projected to different elevation zones (Fig. 5.17) using ambient lapse rate. The $E_t$ was calculated separately for each zone (Fig. 5.18) and a weighted areal average was calculated. Fig. 5.19 gives a graphical comparison between the estimates of $E_t$ for individual stations and an areal average.

It is worth mentioning that the estimated potential evapotranspiration through Thornthwaite approach maintains a unique relationship with the open pan evaporation. The ratios between them for individual stations are given in Fig. 5.20. These results have revealed that observed pan evaporation data can be advantageously used to compare the results of distributed simulations of evapotranspiration (cf. section 7.3.2).

The $E_t$ or the actual evapotranspiration in equation 5.8 was estimated using the method given by Schaalke and Chunzen (1989) i.e.

$$E_t = E_0 \left( \frac{D_{\text{max}} - D_i}{D_{\text{max}}} \right)$$

5.10

where $D_{\text{max}}$ represent the maximum soil moisture deficit and $D_i$ is the soil moisture deficit for the month of interest. As a first approximation, the monthly soil moisture deficit was calculated as:
Fig. 5.15: Monthly precipitation, runoff and the balance (evapotranspiration + soil water changes) from January 1969 to December 1983.
Fig. 5.16: Mean monthly precipitation and estimated potential evapotranspiration for four stations.
Fig. 5.17: Elevation zones of the Siran Basin.

Fig. 5.18: Variation in the Thorthwaite $E_p$ with changing elevation.
Fig. 5.19: Monthly estimates of $E_p$ for four stations and an areal average.

Fig. 5.20: Relationship between potential evapotranspiration and open pan evaporation.
\[ D_t = P - (Q + E_p) \]

The \( D_{\text{ext}} \) was taken as the maximum deficit (1969-1983) when \( E_p \) was supposed to be zero. Figure 5.21 shows the deviation of actual evapotranspiration from potential evapotranspiration using this simple relationship. After having estimated the actual evapotranspiration, the monthly water balance of the catchment was plotted (Fig. 5.22). In addition, the changes in the soil water store were estimated for the period of available record (Fig. 5.23). These results will be of extreme help in comparing and evaluating the results of distributed modelling of the water balance components in Chapter 7.

5.7 SUMMARY

- To run distributed hydrological process simulations and to assess the accuracy of outputs, the meteorological and discharge data recorded at all stations within and around the Siran Basin were acquired. The daily meteorological data (sunshine, temperature, relative humidity and wind velocity) were entered, edited and formatted to computer-readable multi-variable yearly files.

- A data retrieval system was devised by which the data files were linked with the process simulation models. A sub-routine Metread coded in C, for this purpose, scans daily data from these files and inputs to the simulation models.

- Each of meteorological variable has been analysed individually to assess the general climate of the Siran Basin. It was established that these data, particularly temperature and radiation, recorded at all stations do not represent the whole catchment and some reliable methods are required to extrapolate these data to slopes and high mountain summits.

- The past trends in the climatic variables such as precipitation have been worked out using simple mathematical methods. It was emerged that there generally there was a tendency towards increasing precipitation during 1970's.

- The statistical analysis of daily discharge record (1969-90) of the Siran River has been carried out, primarily to assess the temporal variation in the river discharge. The discharge-frequency and maximum flow probability (return period) curves were derived and evaluated.
Fig. 5.21: Monthly actual evapotranspiration estimated from potential evapotranspiration and soil moisture deficit
Fig. 5.22: Monthly precipitation, runoff and estimated actual evapotranspiration from January 1969 to December 1983.
Fig. 5.23: Monthly changes in soil moisture store from January 1969 to December 1983.
The catchment response during the period from 1969 to 1990 varied from 0.33 (1974) to 0.55 (1976). For a particular year, the catchment response seems to be highly influenced by the amount of precipitation. The trend analysis revealed that there was a positive trend in the catchment response during the decade of 1970's. The changes in the land covers e.g. deforestation which occurred during this period may be one of the underlying reasons of this trend.

The components of a monthly water balance equation were calculated for the period of available records, with an intention to compare the results of distributed process simulations (cf. Chapter 7). The evapotranspiration component of this equation was estimated using Thornthwaite model and a simple soil moisture deficit approach.
Chapter 6

DEVELOPMENT OF A GIS-BASED HYDROLOGICAL MODEL FOR PROCESS SIMULATIONS & IMPACT ASSESSMENT
6.1 INTRODUCTION

A lumped-systems modelling approach fails to assess the hydrological impacts of changing spatial characteristics of a catchment e.g. land cover (Beven, 1985). When the aim of modelling is impact assessment, a distributed-systems approach is potentially more realistic, since it incorporates the variability in the catchment characteristics that control hydrological processes (Steyaert and Goodchild, 1994). The spatially distributed parameters that can be input to such models are effectively provided by integrating deterministic models with a geographical information system (Johnson, 1989). Major forms of linkages between GIS and hydrological models include: (i) using GIS functions for parameter estimation to run existing lumped-models; (ii) linking GIS data bases with models to obtain spatial outputs; and (iii) embedding models within a GIS using the computing language of the host GIS (Brilly et al. 1993). Most existing GIS-based models fall in the second category (Abrahart et al. 1994; Brilly, 1993). For example, Hoshi and Uchida (1989) modelled evapotranspiration using such an approach. Goa et al. (1993) developed a model which comprised coupled modules for the simulation of separate processes and used GRASS to extract the model input parameters and to visualise the model results. Grayson et al. (1993) realised that most GIS-based models have been developed for research catchments that are orders of the magnitude smaller than management areas. A good example of large-scale distributed hydrological modelling with integrated GIS is MEDRUSH, developed by Abrahart et al. (1994), which uses GRASS to store, examine and manipulate the geographical inputs and outputs.

In this research a catchment-level model Siran_HYDMAPS has been developed for the Siran River Basin, Pakistan. It integrates the GIS databases with the detailed algorithms for climatic extrapolation (developed for this study) and the simulation of individual hydrological processes. The model can be either run to simulate these processes for a particular day or to simulate the impacts of varying spatial characteristics of the catchment on these processes over time. This chapter describes the model structure, process algorithms, encoding, compilation and execution of individual modules and their linkages. The options available for viewing, plotting and statistical analyses of model outputs have also been discussed.
6.2 MODEL STRUCTURE

The model Siran_HYDMAPS comprises several interlinked process modules encoded in C. They can be run independently or all in a sequence from the main menu. Main inputs to these modules are the GIS layers generated by ARCINFO GRID 6.1 in ASCII format (Van Deursen, 1993); each layer containing 772 rows by 421 columns (cf. section 3.2.2). Other spatial inputs include the outputs from the previous process e.g. infiltration process cannot be simulated unless the output from interception module is available. A simplified illustration of the modelling approach is given in Fig. 6.1. As a module is executed, the appropriate spatial data layers are scanned from the GIS to extract model parameters at each grid cell. All of these layers, except for land cover, are supposed to be static while land cover is input as a dynamic (replaceable) layer. To run a simulation the meteorological inputs are either taken from the daily or monthly data files for a particular year (cf. section 5.3.2) or entered manually. The impacts of changing land covers are assessed by inputting the mean monthly data. The meteorological data (precipitation, net radiation and temperature) are first extrapolated to the whole catchment using the methods (developed for this study) before starting a simulation. The outputs of these modules, except for the routing module, are saved as spatial data files of the same format as that of input GIS data which can be displayed and plotted using ARCINFO GRID 6.1 or a later version. The statistical analyses of any spatial input or output data layer can be performed within Siran_HYDMAPS. Fig. 6.2 shows a series of steps involved in the execution of a typical module 'Evap_map' on a Sun workstation.

Fig. 6.1: An illustration of the Siran_HYDMAPS: a distributed model for the Siran Basin, Pakistan.
Fig. 6.2: A demonstration of a typical module Evap_map on a Sun workstation (from top left clockwise). (i) the module needs the names of land cover and meteorological data files (other GIS layers have default names) and the particular day for which simulations are to be carried out, (ii) before starting simulation, the meteorological records are scanned and confirmed, (iii) the module scans all GIS data, and (iv) finally the module asks to specify the output option and output file name. The output file can be converted to ARCINFO grid and plotted using ARCPLOT or GRID 6.1 (and later versions).
6.3 COMPUTING REQUIREMENTS

Most of the programming was carried out using IRIX version of C compiler installed on the Leicester University Central Computer; although some sub-routines were written using Turbo C++ on a PC. The codes provided in the disk (Appendix 6-i) are compatible with UNIX and IRIX versions of C (the compilation procedure is given in Appendix 6-ii). The compiled modules could be invoked either within or outside the ARCINFO environment. Since each module is associated with multiple GIS layers (772 x 421) as inputs, the computing requirements in terms of hard disk space, swap memory and processing time must be specified before initialising simulations. For example, the potential evapotranspiration simulation module (Evap_map) scans at least five GIS layers, each occupying approximately 2 MB of space, which implies that at least 12 MB (= 2 MB for output) must be made available before running it. To run all modules in a sequence 20-25 MB of hard disk space is required. The minimum RAM requirement of an individual module depends upon its GIS inputs and number of variables involved in an algorithm. Total RAM (and swap memory) of the system must be larger than the size (in MB) of the input GIS plus four times the number of variables involved in an algorithm (i.e. 4 bytes per variable). The processing time depends on the number of computations in an algorithm and the specification of the computer. For example, it takes 10-15 seconds to produce an evapotranspiration outputs on IRIX against 45-60 seconds on a local Sun Sparkstation 10 operating on UNIX. All model outputs are compatible with ARCINFO 6.1, hence they can be visualised and plotted using ARCPLLOT or raster GIS ARCINFO GRID 6.1. Since most commercial GIS software has an option to import the spatial data in ASCII format, the outputs of this model are not solely dependent on ARCINFO as they can be imported using any GIS (e.g. GRASS and IDRISI) with minor alterations in the header information.

6.4 EXTRAPOLATION OF METEOROLOGICAL DATA

One of the major problems encountered in hydrological modelling over hilly terrain concerns the lack of meteorological data from a dense network of observatories for interpolation. Heywood et al. (1994) noted that such data are available in the valleys, close to settlements rather than on mountain sides or summits. The problem lies in the fact that precipitation and temperature have to be extrapolated for distributed modelling hydrological processes over a large area. Net radiation which is the most important input to theory-based evapotranspiration models (Saxton, 1982), also needs to be extrapolated accurately to ensure the accuracy of the simulation itself. Although
energy-dependent processes are less sensitive to other variables such as wind velocity and relative humidity, the extrapolation of these variables are also required for reliable results. The accuracy of quantitative results of meteorological extrapolation depends on the authenticity of theory and reliability of data (Halpin, 1994).

For this study, an objective method of extrapolating hourly and daily precipitation, recorded at four meteorological stations (cf. section 5.2), has been developed. This method is a combination of multivariate regression and an inverse-distance squared method. It takes into account the locational and topographic effects, in addition to the relative distance of all stations, on the spatial distribution of precipitation. Net radiation is mapped from sunshine data and ground albedo using detailed sun-earth astronomical relationships. The method developed for the extrapolation of temperature considers several factors affecting spatial variation in the air temperature e.g. elevation, slope, aspect and ground albedo. The mean daily temperature is first extrapolated using the ambient lapse rate; further variation on the same elevation (but on different slopes and aspects) are approximated by short wave radiation modelling. Other, comparatively less important, meteorological variables such as wind velocity and relative humidity are extrapolated using inverse-distance squared method. However the results of extrapolation could not be assessed for their statistical accuracy due to the lack of field data.

6.4.1 Precipitation

Several methods of precipitation extrapolation for computer-based hydrological simulations are available. To model urban storm-runoff, the proximal distance method, e.g. Theissen polygon method (Johnson, 1989), can yield satisfactory results. Smith (1992) recommends for computer simulations, a grid-based extrapolation using the inverse-distance squared method using the following equation, where the estimate for jth point at a distant d apart from the station i is:

$$ P_j = a \sum_{i=1}^{n} \frac{1}{d_i^2} P_i $$  \hspace{1cm} 6.1

where a is calculated from:

$$ a = \left( \sum_{i=1}^{n} \frac{1}{d_i^2} \right)^{-1} $$  \hspace{1cm} 6.2
This method estimates, for any point within the study area, the distance-weighted precipitation from the precipitation data recorded at all stations. However over large mountainous areas such simplified methods are inappropriate, since they overlook the local variation in total amount and intensity of precipitation introduced by geographical location and topography (Tennyson, 1986).

In fact, the precipitation in northern Pakistan is highly influenced by the physical location and topography (Jan, 1972; Gauhar, 1980; Tennyson, 1986). A multivariate regression analysis, such as one carried out by Goossens et al. (1990), which relates precipitation to latitude, longitude and elevation can be used if precipitation data from a sufficiently large number of stations is available. A multivariate regression analysis of annual precipitation data recorded at twelve stations, lying in the monsoon belt of northern Pakistan (within and around the Siran Basin) was carried out. Eqn. 6.3 is the resultant of this analysis ($R^2 = 0.82$):

$$P_j = (27.0 \text{ Long.} + 7.583 \text{ Lat.} + 0.0047 \text{ Elev.} - 2195.4) \times 25.4$$  \hspace{1cm} 6.3

where $P_j$ denotes estimated annual precipitation (mm) at any point within the study area and Long., Lat. and Elev. denote longitude, latitude (decimal degrees) and elevation (m) respectively. Although the multivariate regression method (Eqn. 6.3) considers the effects of location and topography on the spatial distribution of precipitation, fails to extrapolate high frequency (daily or hourly) precipitation. The extrapolation of daily and hourly data needs the relative distances of all stations to be considered for which data is recorded.

The method of precipitation extrapolation developed for this study combines the multivariate regression and inverse-distance squared methods. This method estimates daily or hourly precipitation for any point $j$ within the Siran Basin considering not only the location and topography, but also the relative distances of all
stations from that point. Fig. 6.3 helps understanding this method. According to this combination method the annual precipitation at point \( j \) estimated from Eqn. 6.3 maintains a unique ratio with the precipitation \((P_j, P_z, \ldots)\) of individual stations i.e. \( \frac{P_j}{P_i}, \frac{P_j}{P_z}, \ldots \) etc. If the daily precipitation \((p_j)\) for any station \( l \) is available, the estimate for \( j \) can be obtained using this ratio as:

\[
p_j = \frac{P_j}{P_i}
\]

where \( P \) and \( p \) denote annual and daily precipitation respectively. Since the daily and hourly precipitation is highly variable spatially, such a simplified relationship is inadequate. When the daily data from the four stations is used in the extrapolation, four different estimates for the same point \( j \) may be obtained (using the regression method) with reference to each station i.e. stations 1, 2, 3, and 4. The relative distances \( d_1, d_2, d_3 \), and \( d_4 \) are then considered to calculate a distance-weighted mean of these four estimates using inverse-distance squared methods.

A comparative study was conducted to compare the extrapolation results obtained using different methods i.e. a multivariate regression, inverse-distance squared and combination methods. The results revealed that there was no significant difference between the catchment's mean (areal average) precipitation (Fig. 6.4) and any method can be used for lumped hydrological modelling in the Siran Basin. However there was a significant difference between the extent of spatial variations (measured by standard deviation) which are more important in distributed modelling than the mean precipitation. The combination method, developed for this study, predicts maximum spatial variation in precipitation as it can be visualised from Figs. 6.5 and 6.6.

Fig. 6.4: Comparison between precipitation extrapolation using three methods. All methods gave same areal mean (left) but different spatial distribution as measured by standard deviation (right).
Fig. 6.5: The extrapolation of precipitation using the inverse-distance squared method. Note the effects of topography on the precipitation distribution are ignored.

Fig. 6.6: The extrapolation of precip. using the combination method which considers the effects of location, topography and relative distances to all meteorological stations.
The extrapolation results obtained using this method supported the results Jan (1972) who analysed the climate of the Siran Basin and predicted the maximum precipitation in the north-east and the minimum in the south-west (cf. section 1.2.2). A sub-routine *Isohyte*, which was written in C based on the combination approach for the extrapolation of daily and hourly precipitation data, formed the integral part of the interception and infiltration modules.

### 6.4.2 Net Radiation

The accurate estimation and mapping of net radiation over the catchment is the key to accurate simulation of energy-dependent processes such as evapotranspiration. Most meteorological stations do not record this variable as such, rather it is estimated from total incoming radiation (global insulation), received on a horizontal surface, using an empirical relationship (Saxton, 1982). For distributed process modelling over complex terrain it must be estimated taking into account the spatial variability of the catchment characteristics. The net radiation \( R_n \) is taken as the difference of the net short wave radiation flux and the effective long wave radiation flux (de Jong, 1973):

\[
R_n = R_i - R_l \tag{6.5}
\]

where \( R_n \) = net radiation

- \( R_i \) = the net short wave radiation that has been absorbed, and
- \( R_l \) = the effective long wave radiation emitted by the surface.

The effective long wave radiation flux \( (R_l) \) is the function of surface and air temperatures and, in most cases, can be estimated empirically using one of the several equations (de Jong, 1973). In this study the empirical equation developed by Monteith was used.

\[
R_l = e_s \sigma T_s^4 + (1-e_s)e_a \sigma T_a^4 \tag{6.6}
\]

where

- \( T \) = temperature (°C)
- \( e \) = atmospheric emissivity
- \( \sigma \) = Stefen-Boltzman constant (4.903x10\(^{-6}\)).

subscripts \( s \) and \( a \) denote saturated and actual respectively.
The estimation of $R_s$, therefore, depends on the extrapolation of temperature which is discussed in the following section. The net short wave radiation flux ($R_s$) is the proportion of total short wave radiation flux ($R$) that is actually absorbed by the earth surface and is given by:

$$R_s = R_s (1 - \rho)$$

where $\rho$ denotes surface albedo (de Jong, 1973).

For this study total radiation ($R$) on horizontal surface was calculated from sunshine duration data using an Angstrom type (Sopian and Othman, 1992; Canada, 1992). The coefficients of this equation for Pakistan were previously calculated by Raja and Twidell (1990). The extrapolation of total radiation received on horizontal to sloping surfaces can be performed by multiplying it with the potential solar radiation ratio ($F$).

This is the ratio of the potential radiation on a sloping surface to that on a horizontal surface and has been widely used in hydrological and ecological contexts as an approximate method of examining the spatial distribution of radiation across a catchment (Moore et al. 1991). The major shortcoming of the above approach to mapping solar radiation across complex terrain is that it ignores all atmospheric effects which tend to reduce the contrast between sloping and horizontal sites.

To get over this problem, total radiation ($R_{tot}$) received on a sloping surface should preferably be estimated by summing up its components which have been extrapolated independently. Duffie and Beckman (1974) and Whiteman (1990) have identified three components of total radiation on the tilted surface i.e. beam, diffuse and reflected. The beam component ($R_b$) is affected by the slope and aspect more than the diffuse component ($R_d$), hence separate estimates of direct and diffuse components are required (Bristow, 1985). Diffuse radiation ($R_d$) is generally small compared to the beam ($R_b$) fraction (as Whiteman (1990) has measured at different locations) and can be thought of as uniform over a horizontal surface. The factor which projects the diffuse radiation from horizontal to sloping surfaces represents the portion of sky dome in view of the sloping surface i.e. $(1+\cos\beta)/2$. The estimation of reflected component on a sloping surface also depends upon the albedo ($\rho$) of the surrounding areas.

Total radiation received on a horizontal surface can theoretically be fractioned into beam and diffuse radiation using the approach developed by Liu and Jordan (1960) and presented by Duffie and Beckman (1974). They have shown for horizontal surfaces that the ratio of daily diffuse radiation ($R_d$) to daily total radiation ($R_{tot}$) for individual
days is nearly a unique function of the cloudiness index, that is the ratio of daily total radiation to potential radiation \(\frac{R_d}{R_{th}}\):

\[
\frac{R_d}{R_{th}} = 1 - \frac{R_{th}}{R_{ab}}
\]

6.8

In the absence of an atmosphere all radiation received on a surface is short wave (beam) radiation, therefore the ratio \(F\) can be used for the catchment-wide projection of the beam fraction only. By summing up three components viz. beam \([R_bF]\), diffuse \([R_d(1+\cos\beta)/2]\) and reflected \([(R_b + R_d)(1-\cos\beta)/2]\), total radiation received on an oriented surface approximates:

\[
R_{tot} = R_bF + R_d(1+\cos\beta)/2 + (R_b + R_d)(1-\cos\beta)/2
\]

6.9

where

- \(R_{tot}\) = projected total radiation on sloping surface
- \(R_b\) = beam radiation on horizontal surface
- \(R_d\) = diffuse radiation on horizontal surface
- \(\beta\) = slope of the surface
- \(\rho\) = albedo of the surrounding surface

The ratio \(F\) in equation (6.8) is calculated by independently estimating the potential radiation on horizontal surface \(R_{ab}\) and on an arbitrarily oriented surface \(R_{ab}\) i.e:

\[
F = \frac{R_{ab}}{R_{ah}}
\]

6.10

where \(R_{ah}\) is calculated from:

\[
R_{ah} = \frac{(12/\pi)}{I_sE_o[\pi/180 \omega_s (\sin\delta \sin\phi) + (\cos\phi \cos\delta \sin\omega_s)]}
\]

6.11

where

- \(I_s\) = solar constant = 4921 kJm\(^{-2}\)hr\(^{-1}\) (Iqbal, 1983)
- \(E_o\) = eccentricity correction factor
- \(\delta\) = declination
- \(\phi\) = latitude
- \(\omega_s\) = sunrise hour angle = \(\cos^{-1}(-\tan\phi \tan\delta)\)

The variation in potential solar radiation over complex terrain is a function of slope, aspect and time of year (Moore et al. 1991). On an arbitrarily oriented surface daily potential radiation equation (Iqbal, 1983) takes the form:
\[ R_{\rho \delta} = \left( \frac{12}{\pi} \right) J_{3E_d} \cos \beta \sin \delta \sin \phi \left( \omega - \omega_\mu \right) \frac{\pi}{180} \]
\[ - \sin \delta \cos \phi \sin \beta \cos \gamma \left( \omega - \omega_\mu \right) \frac{\pi}{180} \]
\[ + \cos \phi \cos \delta \cos \beta \sin \omega_\mu - \sin \omega_\mu \]
\[ + \cos \delta \cos \gamma \sin \phi \sin \beta \sin \omega_\mu - \sin \omega_\mu \]
\[ + \cos \delta \sin \beta \sin \omega_\mu \cos \omega_\mu \mu \]

where \( \beta \) = slope of the surface
\( \gamma = \) azimuth \([+180^\circ(\text{eastwards}) > 0^\circ(\text{South}) > -180^\circ(\text{westwards})]\)
\( \omega_r = \) sunrise hour angle, and
\( \omega_s = \) sunset hour angle on an oriented surface.

For a surface oriented towards the east \((\gamma > 0)\):

\[
\omega_r = \cos^{-1} (-x y - (x^2 - y^2 + 1)^2 / x^2 + 1) \]
\[
\omega_s = \cos^{-1} (-x y + (x^2 - y^2 + 1)^2 / x^2 + 1) \]

Since the sunrise and sunset hour angle for a tilted surface can never be greater than that for a horizontal surface, the minimum of these two is taken as \( \omega_r \) or \( \omega_s \).

\[
\omega_r = \min[\omega_r \cos^{-1} (-x y - (x^2 - y^2 + 1)^2 / x^2 + 1)] \]
\[
\omega_s = -\min[\omega_s \cos^{-1} (-x y + (x^2 - y^2 + 1)^2 / x^2 + 1)] \]

And for westerly oriented surface \((\gamma < 0)\):

\[
\omega_r = \min[\omega_r \cos^{-1} (-x y + (x^2 - y^2 + 1)^2 / x^2 + 1)] \]
\[
\omega_s = -\min[\omega_s \cos^{-1} (-x y - (x^2 - y^2 + 1)^2 / x^2 + 1)] \]

Above equations (Eqns. 6.15 to 6.18) use \( x \) and \( y \) calculated from:

\[
x = (\cos \phi / \sin \gamma \tan \beta) + (\sin \phi / \tan \gamma) \]
\[
y = \tan \delta [(\sin \phi / \sin \gamma \tan \beta) - (\cos \phi / \tan \gamma)] \]

However Eqn. 6.9 fails to take into account the effect of shading from direct sunlight by the surrounding terrain at enclaved sites (Moore et al. 1991). This is an horizon.
problem, the solution of which is computationally intensive and cannot be estimated by simple neighbourhood algorithms (Dozier and Bruno, 1981).

An important surface parameter for the estimation of net short wave radiation (Eqn. 6.7) is the albedo which is spatially as well as temporally variable (de Jong, 1973). The mean (spatial) albedo values of each land cover class, which were estimated from Landsat data using the method described in section 4.11, are listed in Table 6.1. Seasonal pattern of albedo variation can also be assessed if more images of different dates are available. For this study the temporal variation is ignored due to unavailability of such data.

The solar radiation mapping module (Sun_map) based on these algorithms (Eqns. 6.5 - 6.20) simulates actual daily or monthly averaged daily potential radiation, total incoming radiation and net radiation over the Siran Basin. The GIS inputs to this module are the DTM (to extract elevation, slope and aspect parameters), a snow cover map and a land cover map (to extract surface albedo). The spatial variation of potential radiation and total incoming radiation can be visualised in Figs. 6.7 and 6.8. A visual output of simulated net radiation is given in Fig. 6.9.

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>Code</th>
<th>Albedo</th>
<th>Land Cover</th>
<th>Code</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>11</td>
<td>0.260</td>
<td>Hi Cov Conifers (&gt; 50 %)</td>
<td>21</td>
<td>0.127</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>12</td>
<td>0.199</td>
<td>Med Cov Conifer (25-50 %)</td>
<td>22</td>
<td>0.175</td>
</tr>
<tr>
<td>Winter Non-Cereals</td>
<td>13</td>
<td>0.232</td>
<td>Grass + scattered trees</td>
<td>31</td>
<td>0.198</td>
</tr>
<tr>
<td>Paddy</td>
<td>14</td>
<td>0.189</td>
<td>Bare Rock</td>
<td>41</td>
<td>0.198</td>
</tr>
<tr>
<td>Tobacco</td>
<td>15</td>
<td>0.200</td>
<td>Stream Beds</td>
<td>51</td>
<td>0.216</td>
</tr>
<tr>
<td>Maize</td>
<td>16</td>
<td>0.201</td>
<td>Snow</td>
<td>61</td>
<td>0.740</td>
</tr>
<tr>
<td>Fallow</td>
<td>17</td>
<td>0.213</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1. Albedo values of land cover class derived from Landsat MSS and TM data. The method used to estimate mean albedo of each land cover class is described in section 4.11.

6.4.3 Temperature

Air temperature can be projected to higher elevations from the recording station using the ambient lapse rate i.e. 0.6°C fall in temperature with every 100 m rise in elevation (Meteorological Office, 1981). However, the variation introduced by slope and aspect on the same elevation cannot be taken into account using this approach. Obviously well illuminated surfaces will be warmer than those in shade or facing away from sun. Moore et al. (1993) referred the extrapolation technique proposed by Running et al.
Fig. 6.7: The spatial distribution of potential radiation on 5 March. The potential radiation is a function of slope, aspect and time of the year and ignores the effects of atmosphere.

Fig. 6.8: The spatial distribution of total radiation (global insulation). Since the total radiation takes into account the effects of atmosphere, the spatial contrasts are reduced.
Fig. 6.9: Simulated net radiation on 5 March 1979. Note that spatial distribution of net radiation is affected not only by the topography but also by the ground albedo. Snow covered areas of the catchment have the minimum net radiation (owing to their highest albedo) while high cover conifer forests have the maximum net radiation (owing to their minimum albedo).
(1987) which corrects for elevation using the lapse rate and slope-aspect using the ratio of short wave radiation on a sloping surface to that on an unobstructed horizontal surface.

The method devised for this study reduces the mean daily temperature data recorded at four stations to a common elevation (i.e. 1000 m) and projects it to other elevations using the ambient lapse rate. At a certain elevation, the mean daily temperature on a horizontal surface can be estimated from:

\[ T_h = T_{\text{red}} 	imes \left( \frac{H - 1000}{1000} \right) \times 0.006 \]  \hspace{1cm} (6.21)

where \( H \) = elevation (m), 
\( T_h \) = estimated mean daily temperature (°C) on a horizontal surface, and 
\( T_{\text{red}} \) = mean of temperatures reduced to 1000 m elevation from all stations (°C).

Further variations on the same elevation \( H \) are approximated by \( F_i \), the ratio of total incoming radiation received on sloping surface to that on a horizontal surface i.e.: 

\[ T_{\text{ad}} = T_v \times F_i \]  \hspace{1cm} (6.22)

where \( T_{\text{ad}} \) = estimated mean daily air (°C) on a sloping surface at an elevation \( H \), and 
\( F_i = \frac{R_{\text{ad}}}{R_i} \) \hspace{1cm} (6.23)

where \( R_i \) is the total radiation on a horizontal surface (cf. paragraph following Eqn. 6.7) and \( R_{\text{ad}} \) is the total radiation on a sloping surface (Eqn. 6.9). Comparative visual outputs of temperature extrapolation using ambient lapse rate (Eqn. 6.21) and the combination method (Eqn. 6.22) are given in Figs. 6.10 and 6.11.

### 6.4.4 Wind Velocity and Relative Humidity

The sensitivity analyses of meteorological input variables to the evapotranspiration carried out by many hydrologists, for example Ward (1974) have revealed that this process is less sensitive to wind than net radiation and temperature. In the absence of an appropriate model, the wind data were extrapolated using the inverse-distance squared method.
Fig. 6.10: The extrapolation of mean daily temperature using ambient lapse rate. Since this method depends on elevation only, it follows the pattern of the DEM (Fig. 3.4).

Fig. 6.11: The extrapolation of mean daily temperature using the combination method. The effects of topography and surface albedo are considered by lapse rate and radiation modelling.
The extrapolation of relative humidity data was required to estimate the vapour pressure deficit; the difference between saturated and actual vapour pressures. The saturated vapour pressure is a function of air temperature only (Schütz, 1978), hence it is influenced by the extrapolation of temperature itself. The actual vapour pressure is estimated from the relative humidity data, which in this study, was extrapolated using inverse-distance squared method.

For the extrapolation of wind velocity and relative humidity data, Eqn. 6.1 can be re-written as:

\[ X_j = a \sum_{i=1}^{n} \frac{1}{d_{ij}^2} X_i \]

where \( X_j \) = extrapolated value of the variable \( X \) at a point \( j \).
\( X_i \) = the observed values of \( X \) at stations \( i \) (\( i = 1,2,3.. \))
\( d_{ij} \) = distance between the station \( i \) and the point \( j \), and
\( a \) is calculated from:

\[ a = \left( \sum_{i=1}^{n} \frac{1}{d_{ij}^2} \right)^{-1} \]

6.5 HYDROLOGICAL PROCESS SIMULATIONS

At a regional (catchment) or local scale, the hydrological cycle is a physical, sequential and dynamic system which operates within a set of physical laws that control the movement, storage and disposition of water within the system (Ward, 1975). This system will normally have a single input, precipitation, and two major outputs, evapotranspiration and runoff. The main storages and processes (which transfer water from one storage to another) involved in this system are shown in Fig. 6.12.

The distributed physical and vegetation characteristics of the Siran Basin (which can be derived from the GIS; cf. Chapters 3 and 4) enabled the simulation of three of the most important processes of the surface phase of the hydrological cycle i.e interception, evapotranspiration and infiltration. The processes of interception is largely dependent upon the land cover characteristics and dictates the proportion of precipitation which may reach the surface directly or as stem flow and throughfall. In this study the interception process has been simulated using the model developed by the
Meteorological Office (1981) which solely depends on the vegetation characteristic i.e. LAI. The water which is intercepted by the vegetation canopy is lost from the system as evaporation. The evaporation from the intercepted water contributes an appreciable proportion of the total evapotranspiration loss and the rest of the evapotranspiration demand is met from the soil moisture store. For the simulation of evapotranspiration process and the estimation of total evapotranspiration demand (potential evapotranspiration), the Penman-Monteith model was used. The net precipitation which reaches the soil surface is either entered into the soil by infiltration or flows down to the channels as overland flow. The process of infiltration was simulated employing the Green-Ampt model for pre-ponded and ponded stages. Various sub-surface processes such as interflow, percolation and base flow need thorough investigation into the water storage and release characteristics of the soil profile. Since for this study, such information was not available, these sub-surface processes could not be simulated.

Fig. 6.12: Systems diagram of the hydrological cycle at a local or regional scale. (From an original diagram by Dr. J. Lewin, UCW, Aberystwyth, reproduced in Ward (1975)).
6.5.1 Evapotranspiration

Accurate spatial and temporal estimation of actual evapotranspiration is the key to success of many hydrological models. Although evapotranspiration varies continually throughout the day, for a lumped-systems hydrological modelling a spatially averaged daily quantity is often adequate for general applications (Haan, 1982). Where the impact of spatial characteristics of a catchment (e.g. land use) on this process are to be assessed, precision in simulating spatial pattern of evapotranspiration is inevitable. Distributed process models offer an efficient means to account such spatial variations in evapotranspiration. Actual evapotranspiration is usually estimated from the potential evapotranspiration given the moisture storage and release characteristics of the soil.

6.5.1.1 Potential Evapotranspiration ($E_p$)

Jensen (1973) recommended the combination equation of evapotranspiration e.g. Penman equation or its modification to be used for periods of five days or less. Penman's approach has the advantage that the standard climatic data with some empirical coefficients can be used in a physically meaningful equation (Shiau, 1973). The original equation to calculate evaporation $E_p$ takes the form:

$$ E_p = \frac{\Delta \left( H + E_u \right)}{\gamma (\Delta + 1)} $$

6.26

where $H$ = heat budget (or net radiation)
$\Delta$ = slope of saturation vapour pressure curve at mean air temperature
$\gamma$ = constant in wet and dry bulb hygrometer equation, and
$E_u$ is an empirical expression for the drying power of air calculated as:

$$ E_u = 0.35(0.5 + 0.01 U_2)(e_s - e_a) $$

6.27

where $U_2$ = mean wind speed at 2 m above the ground
$e_s$ = saturated vapour pressure
$e_a$ = actual vapour pressure

The method is however, data and computation intensive. The original equation needs four meteorological variables i.e. duration of bright sunshine, mean air temperature,
mean relative humidity and, mean wind speed (Shiau, 1972) which are not recorded at most of the meteorological stations particularly those in developing countries. Despite this Jensen (1973) emphasised that data availability should not be the sole criterion in selecting a method, since some of the data needed can be estimated with sufficient accuracy to permit the using a better method such as Penman's equation. Haan (1982) concluded that in general, energy balance or energy balance aerodynamics equations will provide the most accurate results of various meteorological methods because they are based on physical laws and relationships.

Several modifications and simplifications have been made to Penman's combination method since its introduction in 1948. Kirkby (1987) pointed out that the work by Monteith has refined the analysis of evapotranspiration in two ways - first by increasing our understanding of the heat transfers involved in evaporating moisture from leaf to air and secondly, by considering the process by which moisture moves from a plant onto the leaf surface via the stomata. Electrical resistance forms the best analogy for the process involved. Resistance to movement of water on to the plant surface is controlled by soil moisture and plant growth and is expressed by the bulk surface resistance. Resistance to the movement of water from a plant surface into the air is given by aerodynamic resistance which is dependent on turbulence in the atmosphere. The equation used in Penman-Monteith model (Kirkby, 1987) takes the form:

\[
E_p = \frac{D(R_n - G) + \rho c_p (e_s - e_a)}{L[D + g(1 + \frac{r_s}{r_a})]}
\]

where

- \( E_p \) = rate of water loss (kg/m²/sec)
- \( D \) = rate of change of saturated vapour pressure with temperature (mb°C)
- \( R_n \) = net radiation (W/m²)
- \( G \) = soil heat flux (W/m²)
- \( \rho \) = air density (kg/m³)
- \( c_p \) = specific heat of air at constant pressure (1005 J/kg)
- \( e_s \) = saturation vapour pressure at screen temperature (mb)
- \( e_a \) = screen vapour pressure (mb)
- \( L \) = latent heat of vaporisation (2465000 J/kg)
- \( g \) = psychrometric constant
- \( r_s \) = bulk surface resistance (s/m)
- \( r_a \) = bulk aerodynamic resistance (s/m)
Aerodynamic resistance \( (r_a) \) used in the mode is given by:

\[
 r_a = \frac{\ln \left( \frac{y}{2} \right)}{k^2 u}
\]

where \( z_0 = 0.1 \times \text{crop height} \) (h)

\( k = \text{von Karman constant} \) (0.41)

\( u = \text{wind speed} \) (2 m above crop)

The height of a seasonal crop varies from \( h_1 \) to \( h_2 \) during the growing season i.e. between day of emergence \( (d_e) \) and day of full cover \( (d_f) \) according to the assumed relationship:

\[
 h = h_1 + (h_2 - h_1)(d - d_e)/(d_f - d_e)
\]

Bulk surface resistance \( (r_s) \) varies widely with type and age of crop, and with external factors such as soil moisture deficit. A realistic scheme for surface resistance estimation includes seasonal variation in leaf area index \((LAI)\). For most of the surfaces it is necessary to calculate \( (r_s) \) on daily basis for both day and night time. For seasonal crops e.g. agricultural crops surface varies from bare soil to densely foliated and water may be extracted directly from the soil or soil and crop both at a time. To account for these simultaneous processes, MORECS (Meteorological Office, 1981) used the expression:

\[
 1/r_s = (1-A)/r_w + A/r_w (\text{day time})
\]

where \( r_w = \text{surface resistance of the crop freely supplied with water and dense enough to make soil evaporation negligible} \), \( A = (0.7)^{AV} \)

\( r_m = \text{surface resistance of bare soil (assumed to be 100 s/m for wet soil)} \).

A typical leaf resistance when stomata (at night for instance) are closed is several thousand times greater than during the day time and estimated as:

\[
 1/r_l = LAI/2500 + 1/r_w (\text{night time})
\]

Since MORECS was evaluated under different conditions in Britain than those prevailing in Siran Basin, \( r_w \) for different crops should preferably be measured physically to improve the \( E_p \) estimates based on Penman-Monteith method.
Seasonal variation in LAI in cereals and deciduous trees is assumed to be linear and is given by the equation:

\[
\text{LAI} = (\text{LAI}_{\text{max}} - 0.1)(d - d_{j})/d_{p} - d_{j}) + 0.1
\]

for \((d_{p} < d < d_{j})\)  

6.33

When LAI remains unchanged between full cover and harvest \(r_{j}\) is calculated as:

\[
r_{j} = r_{c}(\text{min}) + 50\left(\frac{d - d_{j}}{d_{h} - d_{j}}\right) + 50\left(\frac{d - d_{j}}{d_{h} - d_{j}}\right)^{2}
\]

for \(d_{p} < d < d_{j}\)  

6.34

The \(r_{c}\) in conifers is dependent on temperature and vapour pressure and estimated as:

\[
r_{c} = 25r_{c}(\text{min})/(T_{sr} + 5)
\]

for \((-5 < T_{sr} < 20)\)  

6.35

\[
r_{c} = 25r_{c}(\text{min})
\]

for \((T_{sr} > 20)\)  

6.36

\[
r_{c} = 10000
\]

for \((T_{sr} < -5)\)  

6.37

The screen temperature \(T_{sr}\) is assumed equal to air temperature. However this model does not incorporate the calculation of night time loss, interception loss and feedback with soil moisture (Kirkby, 1987).

6.5.7.2 Actual Evapotranspiration (\(E_{a}\))

The \(E_{a}\) falls increasingly below the \(E_{p}\) as the amount of water available in the soil decreases (Haan, 1982; Beven and Kirkby, 1978). The stage at which \(E_{p}\) and \(E_{a}\) start departing is dependent on the magnitude of evaporative demand and the hydraulic properties of the moist soil. Many researchers have shown that \(E_{a}\) remains close to \(E_{p}\) until most of the water is exhausted for crops with low evaporative demands. Where the evaporative demands of vegetation are very high, \(E_{a}\) drops far below \(E_{p}\) at even relatively high soil moisture levels. To calculate \(E_{a}\) from \(E_{p}\), plant available water and hydraulic conductivity of the soils are required to be estimated. Shaake and Chunzen, (1989) have used simple relationship of the form:
where \( S_a \) and \( S_{\text{max}} \) denote actual and maximum soil moisture. Although monthly soil moisture modelling has been carried out for the Siran Basin (cf. section 6.6) actual evapotranspiration was not estimated using Eqn. 6.38 and \( E_a \) was assumed to be equal to modelled \( E^\text{cal} \) calculated by Penman-Monteith equation. The facts which support this assumption are:

- The transpiration from deep-rooted vegetation types (e.g. conifers) is least affected by the surface soil moisture conditions as much of the water is drawn from lower depths of soil, which are more likely to be saturated.

- Most agricultural crops e.g. paddy, tobacco and maize (which have high evaporative demands) are grown in the valley under irrigation, hence soil moisture rarely constrains the evapotranspiration until the stage of vegetation senescence is reached.

- Modelling a decrease in rate of \( E^\text{cal} \) with an increase in soil moisture deficit, without field verification, may yield dubious results (Goossens et al. 1990).

### 6.5.1.3 Estimation of Penman-Monteith Model Parameters

Penman-Monteith model requires four meteorological inputs i.e. temperature, relative humidity, wind velocity and net radiation. Of these net radiation is not available as such rather it is estimated from the sunshine data using the algorithms described in section 6.4.2. For the mapping of net radiation in the Siran Basin the topographic parameters are derived from the Siran GIS and the ground albedo for each land cover class is taken from Table 6.1. The mapping of potential evaporation (Eqn. 6.28) also needs some vegetation related parameters to be estimated. For example the bulk aerodynamic resistance \( r_n \) is calculated from the effective height of the crop (Eqn. 6.29) and bulk surface resistance \( r_s \) is calculated from the maximum surface resistance \( r_{n}\text{max} \) (Eqn. 6.31). The typical values of the effective height and daytime \( r_n \) for each vegetation type are given by Kirkby (1987) and Meteorological Office (1981). The values of these two parameters (effective height and \( r_n \)) corresponding to different vegetation classes found in the Siran Basin are listed in Table 6.2.
Another parameter i.e. LAI (used in Eqn. 6.31) is also required to be estimated for each vegetation type. The maximum LAI values of each vegetation class used in this study are listed in Table 6.4; the temporal variations in LAI are assessed from Eqn. 6.33 using a crop calendar (Fig. 1.x).

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>Codes</th>
<th>( h ) (m)</th>
<th>daytime ( r_m ) (w/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural crops</td>
<td>11-16</td>
<td>0.08 - 0.8</td>
<td>40</td>
</tr>
<tr>
<td>Grassland</td>
<td>31</td>
<td>0.15</td>
<td>80 (Jan), 80, 60, 50, 40, 60, 70, 70, 70, 80 (Dec)</td>
</tr>
<tr>
<td>Coniferous trees</td>
<td>21, 22</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>Bare Soil</td>
<td>17</td>
<td>0.05</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 6.2: Typical effective heights and minimum surface resistance \( r_m \) of different vegetation types found in the Siran Basin. For description of classes and class codes cf. section 4.8.1

6.5.1.4 Evap_map: Evapo-transpiration Module

The algorithms described in the previous paragraphs were encoded as the Evap_map module to simulate daily evapotranspiration over the Siran Basin. This module works in two modes. Firstly, meteorological data are scanned automatically from yearly data files (cf. section 5.3.2). Secondly, these data are entered manually for each station. The second mode (inputting the monthly normal meteorological data), enables the spatial changes in the evapotranspiration as a result of changes in the catchment characteristics e.g. land cover to be simulated. Table 6.3 summarises the spatial and meteorological inputs required to run Evap_map, the spatial outputs which can be generated and the computing requirements. A potential evapotranspiration map generated by this module is given in Fig. 6.13.

<table>
<thead>
<tr>
<th>GIS Inputs</th>
<th>Meteorological Inputs</th>
<th>Spatial Output Options</th>
<th>Computing Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) DEM</td>
<td>Yearly meteorological data file (containing daily values of temperature, wind velocity, relative humidity and sunshine) in appropriate format (cf. section 5.3.2) or actual daily data.</td>
<td>(1) Potential Radiation</td>
<td>Disk Space: 12-13 MB</td>
</tr>
<tr>
<td>(2) Slope Map</td>
<td></td>
<td>(2) Total Radiation</td>
<td>RAM: 10 MB</td>
</tr>
<tr>
<td>(3) Aspect Map</td>
<td></td>
<td>(3) Net Radiation</td>
<td>Processing Time: 10-20 secs (on irix)</td>
</tr>
<tr>
<td>(4) Snow Map</td>
<td></td>
<td>(4) Temperature</td>
<td></td>
</tr>
<tr>
<td>(5) Land Cover Map</td>
<td></td>
<td>(5) Potential Evapotranspiration (mm/hr)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6) Total Daily Potential Evapotranspiration (mm).</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Specifications of Evap_map module in terms of data inputs, outputs and computing requirements.
Potential Evapo-transpiration (mm)

Fig. 6.13: An evapotranspiration map generated by Evap_map module. Spatial distribution of evapotranspiration is highly dependent on the net radiation, temperature and other meteorological variables. A significant variation is introduced by the vegetation characteristics such as aerodynamic resistance and surface resistance. Note that the conifer forests have the minimum evapotranspiration despite of the maximum net radiation (cf. Fig. 6.9), because of their highest resistance to water loss.
6.5.2 Interception

Interception is the detention of precipitation above the soil surface by the vegetation canopy elements or surface litter. Interception capacity is controlled by the compounded effects of atmospheric and surface characteristics. Vast experimentation has revealed that there are no significant correlation of meteorological variables such as wind, humidity and temperature with interception (Blake, 1975). In many interception models of practical use the character of the interception store has been based solely on the assessment of surface area index or leaf area index (LAI). In this research, a simple interception model that was adopted by the Meteorological Office (1981) in MORECS and is based on an assessment of LAI has been used. This model has been applied for water balance mapping under different vegetation and climatic conditions throughout the UK, hence it not site specific. In this study detailed information about the specific surface characteristics (canopy elements and surface litter) of each land cover class were not available. Since this interception model needs minimum vegetation parameters to be estimated, it was preferred over other methods.

According to this model, the interception capacity is estimated as:

\[ I_c = \alpha \text{LAI} \]  

where \( \alpha \) is the capacity per unit LAI and is assumed to be 0.2 mm, hence \( I_c = 0.2 \text{LAI} \).

Actual daily interception is calculated using the equation:

\[ I = R_p \]  

for \( (I \leq I_c) \)

where \( p \) denotes the proportion of precipitation \( (R) \) intercepted by the vegetation overlying the soil is calculated as:

\[ p = I \cdot (0.5)^{\text{LAI}} \]  

for \( (p \leq p_{\text{max}}) \)

where \( p_{\text{max}} \) is the portion of precipitation which produces full wetting. To take into account the evaporation loss from the interception store between rainfall events (particularly during summer months) a seasonal factor is introduced. The daily interception \( I_g \) in summer is taken as twice that calculated for winter using Eqn. 6.36.
i.e. \( I_p \leq 2I \leq R \). For this study this factor varies evenly throughout the year i.e. starting from 1 on the first day of the year, approaching 2 towards the end of June and declining to 1 on the last day of year.

6.5.2.1 Estimation of Interception Model Parameters

The leaf area index is the only surface parameter required to estimate interception. Blake (1975) realised that the measurement of the LAI is time consuming because it varies throughout the year. It is not a usual practice to measure LAI for hydrological modelling on a large scale. There exist several prospects for estimating the LAI from Landsat data for land cover classes in conjunction with field measurements. For example, Curran et al. (1992) estimated seasonal LAI in slash pine using NDVI derived from Landsat TM data with an \( R^2 \) as high as 0.86. However such regression relationships are time and site specific. In the absence of field data this parameter has to be estimated from typical values for different vegetation types (Meteorological Office, 1981). Since natural vegetation of the Siran Basin is mostly composed of evergreen species (Malik, 1963; Saeed, 1964; Khalid, 1966), the temporal variation in the LAI of forest classes has been ignored.

Maximum LAI of each vegetation class has been assigned according to its growth pattern and composition. For example, the sub-tropical chirpine forest which forms even-aged gregarious stands with little or no ground flora has smaller LAI than a

<table>
<thead>
<tr>
<th>Cover Class</th>
<th>Code</th>
<th>Maximum LAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural crops</td>
<td>11 - 16</td>
<td>4.0</td>
</tr>
<tr>
<td>Grass and scattered trees</td>
<td>31</td>
<td>2.5</td>
</tr>
<tr>
<td>High cover scrub</td>
<td>211</td>
<td>6.0</td>
</tr>
<tr>
<td>High cover chirpine</td>
<td>212</td>
<td>5.0</td>
</tr>
<tr>
<td>High cover bluepine + chirpine</td>
<td>213</td>
<td>6.0</td>
</tr>
<tr>
<td>High cover bluepine</td>
<td>214</td>
<td>7.0</td>
</tr>
<tr>
<td>High cover firs and spruce</td>
<td>215</td>
<td>8.0</td>
</tr>
<tr>
<td>Med cover scrub</td>
<td>221</td>
<td>4.0</td>
</tr>
<tr>
<td>Med cover chirpine</td>
<td>222</td>
<td>3.0</td>
</tr>
<tr>
<td>Med cover bluepine + chirpine</td>
<td>223</td>
<td>4.0</td>
</tr>
<tr>
<td>Med cover bluepine</td>
<td>224</td>
<td>4.5</td>
</tr>
<tr>
<td>Med cover firs and spruce</td>
<td>225</td>
<td>5.0</td>
</tr>
</tbody>
</table>

*Table 6.4: Maximum LAI (estimated) for different vegetation types used in this study. For the description of these Level II vegetation classes cf. section 4.10.*
multi-storied temperate fir and spruce forest type with an abundant ground flora. The daily variation in the seasonal (agricultural) crops is approximated by Eqn. 6.33, while the LAI of grass varies between 1.0 and 2.5 during the growing season. The maximum LAI value adopted from multiple sources e.g. Curran. et al. 1992; Kirkby, 1987; Meteorological Office, 1981; Loustau et al. 1992 and used in this study for the land cover classes are given in Table 6.4. As more relevant data on LAI becomes available through other sources, these values can be updated.

6.5.2.2 Inter_map: Interception Module

The Inter_map extrapolates the daily and hourly precipitation recorded at four stations and calculates accumulated daily interception over the Siran Basin, based on the algorithm discussed earlier, for any day of the year. The output of this module are prerequisites to the infiltration simulation module Infilt_map. The specifications of this module in terms of inputs, outputs and computing requirements are summarised in Table 6.5.

<table>
<thead>
<tr>
<th>GIS Inputs</th>
<th>Meteorological Inputs</th>
<th>Spatial Output Options</th>
<th>Computing Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) DEM</td>
<td>Daily precipitation data to be entered manually.</td>
<td>(1) Extrapolated Precipitation Map (2) Estimated LAI Map (3) Daily Interception Map (4) Net Precipitation Map</td>
<td>Disk Space: 5-6 MB RAM: 4 MB Processing Time: 2-4 secs (on irix)</td>
</tr>
</tbody>
</table>

Table 6.5: Specifications of Inter_map module in terms of data inputs, outputs and computing requirements.

6.5.3 Infiltration

Infiltration is the movement of surface waters into the soil matrix (Bras, 1992). Nevertheless the flow of water into the soil is three-dimensional, but it commonly assumed that one-dimensional vertical flow dominates. There are several empirical and theory-based models which simulate the process of infiltration. One of the most commonly used infiltration model is Green-Ampt model which is based on a Darcy-type water flux (Rawls et al. 1993). It is a simplified representation of the infiltration process and Hortonian surface runoff in the field (Chu, 1978) and is recommended by...
many hydrologists, for example Schluze (1978), for computer-based hydrological modelling.

In this study the process of infiltration has been simulated using the Green-Ampt Model. The infiltration rate for steady rainfall is calculated in two stages i.e. pre-ponding and post-ponding (Chu, 1978; Mein and Larson, 1973; Rawls et al. 1993). The pre-ponding infiltration rate \( f \) prior to ponding time \( t_p \) equals the precipitation intensity \( R \) given by:

\[
f = R \quad \text{for} \, (t \leq t_p)
\]

6.42

The infiltration rate after ponding \( (t > t_p) \) is controlled by the effective hydraulic conductivity \( K \), average suction at wetting front \( S_j \) and initial moisture condition \( \theta_i \) of the soil and is estimated from:

\[
f = K + \frac{KS_j(\phi - \theta_i)}{F}
\]

6.43

where \( \phi \) = total porosity of the soil

\( F \) = accumulated infiltrated volume respectively.

The ponding time is calculated from the accumulated infiltration \( F_p \) from time 0 to ponding and precipitation intensity \( R \) by:

\[
t_p = \frac{F_p}{R}
\]

6.44

and \( F_p \) is estimated from:

\[
F_p = \frac{S_j(\phi - \theta_i)}{R} \frac{K}{K - 1}
\]

6.45

6.5.3.1 Estimation of Green-Ampt Model Parameters

The three soil parameters \( K, S_j \) and \( \theta_i \) required for use in the Green-Ampt Model can be physically measured in the field (Rawls et al. 1993). However for large-scale
distributed simulation of infiltration on heterogeneous soils this is not a practicable approach. These parameters to a large extent are estimated from the typical values given in literature for various soil textural classes. The soil texture map (Fig. 3.10) which has formed an important spatial layer in the Siran GIS was used to estimate the Green-Ampt parameters. The scheme adopted to estimate these three parameters for simulating infiltration in the Siran Basin is as follows:

**Initial Moisture Content ($\theta_i$):** The term ($\phi - \theta_i$) used in Green-Ampt equation (Eqn. 6.43) represents the difference between total porosity and initial moisture content. Total porosity ($\phi$) for each soil textural class is a unique value and it can be adopted from the literature. However initial moisture content ($\theta_i$) remains to be measured or estimated from moisture-tension relationships (Rawls et al. 1993). For this study the average moisture content (moisture held at -33 kPa tension) for each soil textural class has been taken as initial moisture content ($\theta_i$). The difference between total porosity and moisture held at -33kPa is termed as effective porosity (Rawls et al. 1993). The estimated values of effective porosity ($\phi - \theta_i$) for each soil textural class are listed in Table 6.6.

**Suction at wetting front ($S_f$):** The suction at wetting front varies widely for each soil textural class. In this study the average suction was taken as typical of each soil class (Table 6.6).

**Effective Hydraulic Conductivity ($K$):** This is estimated from saturated hydraulic conductivity ($K_s$) for each soil textural class (Table 6.6). For bare areas outside the canopy (e.g. bare soil), $K$ is taken as $0.5K_s$. For bare areas under a canopy (no ground cover under chirpine), $K$ equals $K_s$. Areas with a ground cover have macroporosity

<table>
<thead>
<tr>
<th>Soil Textural Class</th>
<th>Average Effective Porosity ($\phi - \theta_i$)</th>
<th>Average Suction at wetting front (cm) ($S_f$)</th>
<th>Sat. Hyd. Cond. (cm/hr) ($K_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.417</td>
<td>4.95</td>
<td>23.56</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.401</td>
<td>6.13</td>
<td>5.98</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.412</td>
<td>11.01</td>
<td>2.18</td>
</tr>
<tr>
<td>Loam</td>
<td>0.434</td>
<td>8.89</td>
<td>1.32</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.486</td>
<td>16.68</td>
<td>0.68</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>0.330</td>
<td>21.85</td>
<td>0.30</td>
</tr>
<tr>
<td>Clay loam</td>
<td>0.390</td>
<td>20.88</td>
<td>0.20</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.432</td>
<td>27.30</td>
<td>0.20</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>0.321</td>
<td>23.90</td>
<td>0.12</td>
</tr>
<tr>
<td>Silty clay</td>
<td>0.423</td>
<td>29.22</td>
<td>0.10</td>
</tr>
<tr>
<td>Clay</td>
<td>0.385</td>
<td>31.63</td>
<td>0.06</td>
</tr>
</tbody>
</table>

*Table 6.6: Typical values of Green-Ampt soil and moisture parameters of each soil textural class.*
and therefore \( K \) is calculated as \( AK^* \), where \( A \) denotes the macroporosity factor. This factor is calculated individually for agricultural areas and areas with undisturbed natural vegetation. For agricultural areas it is calculated as:

\[
A = \exp(2.82 - 0.099 S + 1.94 BD)
\]

and for grasslands and forests with ground cover this factor is calculated as:

\[
A = \exp(0.96 - 0.032 S + 0.04 C - 0.032 BD)
\]

where \( S, C \) and \( BD \) represent percent sand, percent clay and bulk density of the soil. These equations consider the effects of possible factors such as particle size and bulk density (or organic matter) on macroporosity of soil and were used in this study. The typical percentages of sand and clay for each textural class were taken from the USDA soil textural triangle. The values of \( BD \) of surface soil under different land uses were adopted from Hanif (1989) who measured \( BD \) in all forest soils of northern Pakistan.

6.5.3.2 Infilt_map: Infiltration Module

This module is based on the Green-Ampt Model discussed above and simulates the infiltration with hourly precipitation data. However it is not capable of generating temporal outputs i.e. it produces a single spatial layer of accumulated infiltration or surface runoff for a rainfall event irrespective of its duration. Short duration events (< 6 hours) can be easily dealt with using this module due to large the catchment area and consequently high time of concentration \( t_c \) (for the Siran is 7.6 hours). However long duration (> 6 hours) events need to be splitted into < 6 hours sections. The inputs, outputs and computing requirements of Infilt_map are given in Table 6.7:

<table>
<thead>
<tr>
<th>GIS Inputs</th>
<th>Meteorological Inputs</th>
<th>Spatial Output Options</th>
<th>Computing Requirements</th>
</tr>
</thead>
</table>
| (1) Soil Texture Map 
(2) Land Cover Map 
(3) Daily Interception Map (output of Inter_map) | Hourly precipitation data to be entered manually. | (1) Extrapolated Precipitation Map 
(2) Net Precipitation Map 
(3) Accumulated Infiltration Map 
(4) Accumulated Surface Runoff Map | Disk Space: 7-8 MB 
RAM: 6 MB 
Processing Time: 2-4 secs (on irix) |

Table 6.7: Specifications of Infilt_map module in terms of data inputs, outputs and computing requirements.
6.6 SOIL MOISTURE MODELLING

Soil moisture store occupies a pivotal position in catchment hydrology (Fig. 6.12) and it controls directly or indirectly most of the surface and sub-surface hydrological processes e.g. evapotranspiration, infiltration and percolation. The spatial modelling of soil moisture can be carried out using a simple water balance approach. According to this approach the input to the catchment is the precipitation and potential evapotranspiration is taken as the only output. Any difference between the precipitation and potential evapotranspiration is assumed to be a change in the soil moisture store (Goossens et al. 1990; Van Deursen and Kwadijk, 1993).

The annual climatic pattern prevailing in the Siran Basin is bimodal i.e. precipitation distribution forms two prominent peaks (cf. section 5.4.1). During winter (December and January) and the monsoon (July and August) precipitation exceeds total potential evapotranspiration (Fig. 5.16). The soil moisture modelling approach adopted for this study depends on the simplified assumption that soil moisture is at field capacity in January and in July. Soil moisture at field capacity $S_{M(PC)}$ was mapped across the catchment by assigning typical moisture values (Rawls and Brakensiek, 1993; Schulze, 1978) to each soil textural class (Fig. 3.10) depending upon the depth (Fig. 3.11). For months other than January and July, the difference between precipitation and potential evapotranspiration of the month of interest was added to previous month’s soil moisture file using the equation (Van Deursen and Kwadijk, 1993):

$$SM_{(mn)} = SM_{(mn-1)} + (P_{(mn)} - E_{p(mn)})$$

where $SM_{(mn)} = \text{soil moisture (mm) for the month of interest}$
$$SM_{(mn-1)} = \text{soil moisture (mm) for previous month}$$
$$P_{(mn)} = \text{total precipitation (mm) for the month of interest}$$
$$E_{p(mn)} = \text{potential evapotranspiration (mm) for previous month, and}$$
$$SM_{(PC)} = \text{soil moisture (mm) at field capacity.}$$

Monthly precipitation for each month $P_{(mn)}$ was mapped using combination method of extrapolation (cf. section 6.4.1) through the sub-routine Isohyte, while potential evapotranspiration ($E_{p(mn)}$) was mapped by running Evap_map (Mode 2). The monthly...
fluctuations in soil moisture store of the Siran Basin have been mapped (Fig. 7.20) and described in section 7.5.

6.7 STATISTICAL ANALYSES OF Siran_HYDMAPS OUTPUTS

The graphical display of spatial outputs of Siran_HYDMAPS are usually not required every time the model is run, but the calculation of the statistics is. In order to avoid the cumbersome task of importing all model outputs into a GIS, such as ARCINFO, for statistical analyses, a statistical module Map_stat, which is capable of doing this task more efficiently, has been written and interlinked with other modules. The statistical parameters which describe any spatial outputs of Siran_HYDMAPS include maximum, minimum, range, mean, standard deviation, skewness and kurtosis. Map_stat calculates these six parameters for any spatial output and also generates a frequency distribution table for a histogram analysis.

6.8 ACCURACY OF Siran_HYDMAPS OUTPUTS

The risks of inaccurate or improbable extrapolation of any phenomenon increases with the number of variables and the complexity of the environment (Heywood, et al. 1994). Halpin (1994) realised that the extrapolation can be very risky without a deep understanding of the inter-relationships of all variables involved. The results of meteorological extrapolations for distributed hydrological modelling in spatially complex environment can be highly questionable without testing them for accuracy against observed data. To check the accuracy of a high resolution GIS-based extrapolation, the data from a dense network of meteorological stations is required (Heywood et al. 1994). In most cases, ample field measured data are not available, hence the statistical reliability of climatic extrapolations can not be measured.

The spatial extrapolations of precipitation and temperature, for the distributed modelling in the Siran Basin, were based on new methods developed in this study (cf. sections 6.4.1 and 6.4.3). Unfortunately these methods could not be tested for their reliability, due to the lack of field data. Despite of this weakness, they were preferred over other methods (area or distance weighted areal averaging methods e.g. Theissen polygon, isohyetal method) because they take into account all factors which may possibly affect the spatial distribution meteorological variables in the complex terrain of the Siran Basin.
Many hydrologists e.g. Moore et al. (1993) have developed and applied GIS-based hydrological models without addressing the measures they have used to check the accuracy of their models. In fact the accuracy of hydrological process simulations depends not only on the theories and spatial data used, but also the extrapolation of input meteorological data. Heywood et al. (1994) concluded that at present the GIS-based simulations and predictions are hindered by the fact that neither the theories nor the data are adequate. The accuracy testing of a high resolution hydrological process simulation in a large catchment is even more harder in the face of high degree of spatial variability of the processes and time and cost involved in field data collection. In most GIS-based distributed process models the accuracy of independent processes (e.g. infiltration, interception) is usually not measured rather a final output (i.e. a hydrograph) is measured for its accuracy by comparing it with the observed hydrograph.

In this study the results of distributed evapotranspiration simulation were compared with the observed pan evaporation data recorded at four meteorological stations (cf. section 7.3.2). The accuracy of infiltration simulation was tested against the surface runoff data which was generated from observed discharge data using a hydrograph separation technique. However the results of interception simulation could not be tested due to unavailability of any field data.

6.9 SUMMARY

- A distributed hydrological model Siran_HYDMAPS, which integrates the GIS databases with the well-known theories of hydrological processes, has been developed for the Siran Basin, Pakistan. It comprises several interlinked process modules encoded in C, which simulate the evapotranspiration, interception and infiltration in spatial context. The model structure and computing requirements for developing and running the model have been discussed.

- New objective methods of precipitation and temperature extrapolation have been devised. The precipitation extrapolation method developed in this study combines the multivariate regression and the inverse-distance squared method. It takes into account the factors such as location and topography for the spatial distribution of daily and hourly precipitation. Temperature extrapolation method, which is a modification of ambient lapse rate method, considers all topographic and land cover factors through solar radiation distribution modelling.
Net radiation, which is driving force for all energy-dependent processes such as evapotranspiration, has been extrapolated from sunshine data using detailed algorithms of estimating net radiation on sloping surfaces.

The procedures to estimate the soil and vegetation related parameters to run individual modules have been elaborated.

The process modules e.g. Evap_map, Inter_map, and Infilt_map were demonstrated for their capability to simulate the processes of evapotranspiration, interception and infiltration by producing example spatial outputs.

Monthly soil moisture fluctuations has been mapped through modelling the potential evapotranspiration.

The statistical analyses of spatial model outputs can be performed using a module Map_stat which has been specifically encoded for this purpose.

All process modules have been interlinked through a main programme allowing the user to run the process simulations as intended.
Chapter 7

APPLICATIONS OF Siran_HYDMAPS
FOR THE HYDROLOGICAL PROCESS
SIMULATIONS & IMPACT ASSESSMENT
OF LAND COVER CHANGES
7.1 INTRODUCTION

The development of the distributed hydrological model (Siran_HYDMAPS) for the Siran catchment, Pakistan has been discussed in Chapter 6 and the working of its independent modules has been demonstrated using assumed or sample meteorological data. The scope of this chapter is to evaluate the model's capability to extrapolate observed meteorological data and to simulate the processes of evapotranspiration, interception, infiltration and surface runoff at a catchment scale. The spatial heterogeneity of each model output has been measured by various statistical parameters viz. maximum, minimum, mean, standard deviation, skewness and kurtosis. The daily and monthly variations in the spatial statistics of meteorological extrapolations and hydrological processes have also been assessed by producing mult-temporal outputs of Siran_HYDMAPS. The model has also been evaluated for its ability to calculate the spatial daily water balance of catchment. Soil moisture has been mapped for each month and the monthly fluctuations in soil moisture have been evaluated in the light of catchment's water balance. Lastly the impacts of changes in land cover (1979 to 1989) on the individual hydrological processes e.g. evapotranspiration, interception and infiltration have been quantified both in spatial and temporal contexts. The alteration in the catchment response brought about by the changes in land cover was quantified independently for low and high intensity precipitation.

7.2 EVALUATION OF METEOROLOGICAL EXTRAPOLATIONS

Nevertheless each facet in the catchment is composed of a unique combination of topography, soil, geology and vegetation cover. The compounded effect of these characteristics strongly influences the spatial distribution of precipitation, net radiation and temperature. The spatial extrapolation of these meteorological variables (cf. section 6.4) revealed that in complex terrain, like that of the Siran Basin, simplified averaging techniques (arithmetic mean, area weighted mean or distance weighted mean) are inadequate for distributed hydrological modelling. These results have strongly supported Barry (1992) and Heywood et al. (1994) who reported high degree of climatic variability at all spatial scales. The main model Siran_HYDMAPS does not have independent extrapolation modules, rather some options have been attached with the process modules for the extrapolation of input meteorological variables (cf. sections 6.5.1.4, 6.5.2.2 and 6.5.3.2). For example Evap_map can be run to produce temperature and net radiation maps in addition to generating its ultimate output i.e. an
evapotranspiration map. Some intermediate products e.g. potential radiation and total incoming radiation (global insulation) maps can also be produced by executing Evap_map. Similarly the module Inter_map extrapolates daily precipitation data as a pre-requisite to interception mapping while simulation of infiltration and surface runoff by Infilt_map necessitates extrapolation of hourly precipitation data. The statistics calculated for each spatial output when plotted on the time scale helps assessing the temporal (e.g. daily, monthly) pattern of variation of extrapolated meteorological variables.

7.2.1 Precipitation

The spatial extrapolation of precipitation is a pre-requisite to the simulation of interception and infiltration processes. The method used in this study takes into account factors such as location (latitude and longitude), elevation and relative distance to the meteorological stations which record precipitation (cf. section 6.4.1). A daily precipitation map based on this method may look like Fig. 6.6, which was generated with the assumed precipitation data for four stations. Extreme spatial variations are seen when producing such maps using observed precipitation data. Another example of spatial extrapolation is the accumulated precipitation map of July 1979 (Fig. 7.14) which was prepared by summing up of 13 daily precipitation maps which were themselves produced from hourly data recorded at four stations (cf. section 5.2). The spatial statistics of this map calculated by Map_stat (cf. section 6.7) shows that accumulated monthly precipitation varied from 130 mm in the south-west to 268 mm in the north-east, with a catchment mean of 195 mm. It is evident from this visual output that the spatial mean value only applies to a small portion of the whole catchment (shown in yellow) while most of the area has value more or less than the mean (shown in blue and red). The extent of spatial variation is assessed from the standard deviation which is as high as 27.7.

The results of spatial extrapolations conform to those obtained by Jan (1972) and Tennyson (1986), on the basis of climatic analyses in the Siran Basin, as far as total precipitation is concerned. However the method used in this study cannot predict the form of precipitation (e.g. rain, snow). This problem is more pronounced during winter months when most of the catchment area above 3000 m elevation receives precipitation as sleet or snow. Obviously spatial extrapolation without the consideration of this fact is likely to overestimate surface runoff and underestimate
infiltration into the soil, particularly during snowfall season. Such seasonal effects on infiltration process will be discussed later in this chapter (cf. section 7.3.5).

7.2.2 Net Radiation

The extrapolation of net radiation involves simulation of potential radiation and total incoming radiation which can also be mapped (optionally) as intermediate outputs of Evap_map. The spatial distribution of simulated potential radiation, total incoming radiation and net radiation for 5 March 1979 is shown in Figs. 6.7, 6.8 and 6.9 respectively. From the spatial statistics (maximum, minimum, mean and standard deviation) of these maps it is apparent that the most contrasting pattern is seen in potential radiation (incoming short-wave radiation in the absence of atmosphere). Some illuminated parts of the catchment receive as much as 39 MJ/m²/day, while some other parts of the catchment in shadow receive none (Fig. 6.7). However the distribution of potential evapotranspiration represent a hypothetical condition where the effects of an atmosphere are ignored.

Nevertheless the presence of an atmosphere in natural conditions reduces this contrast between illuminated and shadowed parts of the catchment. Fig. 6.8 (total incoming radiation map) that no part of the catchment is completely in the dark since some part of diffuse or reflected radiation may be reaching. The reduction in spatial contrasts due to the presence of an atmosphere are quantified by the differences in the standard deviation of potential and total incoming radiation distributions (which dropped from 6.0 to 1.5). These spatial results strongly supported Fleming's (1987) findings, as referred by Moore et al. (1991), who predicted a lower spatial variation in total incoming radiation than in potential radiation.

As discussed earlier (cf. section 6.4.2), the net radiation in addition to topography (which affects the distribution of incoming radiation) is highly influenced by surface albedo (Gray, 1992) and air temperature and this added spatial variation can be visualised (Fig. 6.9). A prominent feature of this map is the negative radiation balance in the extreme northern parts of the catchment. It emerged by the spatial analyses of the net radiation (Fig. 6.9) and the land cover for March 1979, that the areas having negative net radiation correspond to the snow-covered areas. This results from the very high albedo of and consequently very low levels of absorption of incoming short-wave radiation. Contrarily the high cover conifer forests were found to be having
Fig. 7.1: Monthly variations in daily potential radiation distribution over the Siran Basin. These temporal curves were obtained from spatial statistics of the twelve monthly potential radiation maps.

Fig. 7.2: Monthly variations in daily total radiation (global insulation) distribution over the Siran Basin. These temporal curves were obtained from spatial statistics of the twelve monthly total radiation maps.
maximum radiation balance, primarily due to their lowest albedo compared to other land covers (Table 6.1).

Monthly variations in potential radiation, total radiation and net radiation have been assessed by generating multi-temporal radiation outputs and calculating their statistics. For example, the twelve maps of monthly averaged daily potential radiation were generated and their spatial statistics (maximum, minimum, mean and standard deviation) were plotted (Fig. 7.1). It is evident from this figure that some north-facing parts of the catchment remain almost completely in the dark throughout the year as shown by the very low value of the minimum curve. The maximum curve shows monthly variation in daily potential radiation received by the most illuminated parts of the catchment. During winter months most of the catchment receives far less or more than the catchment mean due to the low sun angle resulting in a standard deviation as high as 6.7 in December and January. Contrary to this during summer months most of the area receives potential radiation very close to the mean and standard deviation drops to 4.0 in May and June.

The monthly statistics of the twelve total radiation (global insulation) maps (Fig. 7.2) revealed that no part of the catchment remains completely in dark having received some diffuse and/or reflected radiation. However the pattern of monthly variation is not regular (which can be seen in Fig. 7.1) and these are fluctuations due to presence of an atmosphere and cloudiness. The effects of cloudiness are more pronounced during the monsoon months when diffuse radiation (which is more or less uniformly distributed over the catchment) constitutes the major proportion of total radiation (Whiteman, 1992). The reduced spatial heterogeneity during July, August and September compared to other months can be seen from these curves (Fig. 7.2) which show that most of the catchment area receives radiation very close to the catchment maximum resulting in a standard deviation as low as 1.0.

Temporal curves of net radiation are also affected by seasonal variations in ground albedo. It can be inferred from the curves of daily net radiation (Fig. 7.3 a and 7.3 b) that some parts of the catchment (snow-covered parts of the extreme north) have a negative radiation balance for at least nine months of a year. This situation arises from the albedo being very high (causing most of incident radiation to be immediately reflected back into the atmosphere) causing long-wave emittance to exceed the incoming short-wave radiation absorption. The maximum net radiation curve corresponds to the south-facing slopes of the catchment covered by high cover conifers. Since the albedo of these evergreen forests is supposed to be unchanged
throughout the year (cf. section 4.11 and Table 6.1), it is not surprising that the maximum net radiation curve follows the general pattern of maximum curve of total incoming radiation (Fig. 7.2). The minimum curve corresponds to sheltered snow-covered parts of the catchment (north-facing slopes) where there is an abrupt decline in the spatial variation (standard deviation) in May due to snow melt (Saeed, 1968) and, consequently, an increase in the net radiation. Changes in the albedo brought about by the changes in land cover and/or land use tend to alter the spatial distribution of net radiation and its seasonal variations. Therefore net radiation has been mapped separately for each of two years (1979 and 1989). The changes in radiation balance which have taken place over ten years in the Siran catchment will be discussed later in this chapter (cf. section 7.5).

7.2.3 Temperature

The extrapolation of temperature is a pre-requisite to the estimation of long-wave emittance, net radiation and evapotranspiration. The method devised for this study takes into account the effects of elevation through ambient lapse rate and of slope, aspect and ground albedo through solar radiation distribution (cf. section 6.4.3). The results of spatial extrapolation of mean daily temperature (e.g. Fig. 6.11) are logically acceptable since they show south-facing slopes being warmer than north-facing ones at the same elevation due to greater total incoming radiation. For a particular day, e.g. 5 March 1979, the difference between the coolest (spatial maximum) and warmest (spatial minimum) parts of the catchment was as high as 27 °C with a catchment mean of 10 °C.

The monthly variation in the catchment maximum, minimum, mean and standard deviation of daily temperature are shown in Fig. 7.4. It can be seen from these curves that the difference between spatial maximum and minimum of the catchment is not a constant value (contrary to the ambient lapse rate method which extrapolates temperature on the basis of elevation only and maintains this range throughout the year). A noticeable feature of these curves is that north-facing slopes in the upper catchment have a daily temperature below freezing point for most the year, as seen from the minimum curve in Fig. 7.4. The maximum curve corresponds to the hottest areas which lie in the low-lying plains where monthly variations in temperature follow the pattern of total radiation (Fig. 7.2).
Fig. 7.3 a: Monthly variations in daily net radiation distribution over the Siran Basin in 1979. These temporal curves were obtained from spatial statistics of the twelve monthly net radiation maps for 1979.

Fig. 7.3 b: Monthly variations in daily net radiation distribution over the Siran Basin in 1989. These temporal curves were obtained from spatial statistics of the twelve monthly net radiation maps for 1989.
Fig. 7.4: Monthly variation in mean daily temperature. Some areas have <0°C for at least 8 months.

7.3 EVALUATION OF PROCESS SIMULATIONS

The processes of evapotranspiration, interception and infiltration were simulated by running the *Evap_map*, *Inter_map* and *Infilt_map* modules of the model *Siran_HYDMAPS* using observed meteorological data. The spatial statistics of each output were calculated using *Map_stat* module and the temporal variations were assessed by plotting the spatial statistics over different time scales.

7.3.1 Evapotranspiration

Since the amount of evapotranspiration is directly proportional to the net radiation for a uniform vegetation cover (Gray, 1992), the spatial distribution of simulated evapotranspiration presumably should follow the spatial pattern of net radiation. The Penman-Monteith Model which formed the basis of evapotranspiration mapping in this study takes into account the two major vegetation characteristics, viz. *bulk aerodynamic resistance* and *bulk surface resistance*, which strongly influence the spatial distribution of evapotranspiration. For example, conifers offer maximum surface resistance to water loss compared to other vegetation types and consequently transpire less than broad-leaved vegetation types (Kirkby, 1987). The spatial distribution of evapotranspiration, therefore, results from the compounding effects of the distribution of net radiation and vegetation type. It can be inferred from the evapotranspiration map...
of 5 March 1979 (Fig. 6.13) that the simulated minimum evapotranspiration is for the areas covered by snow (having negative net radiation) and for those occupied by conifers (which have maximum resistance to water loss). The maximum evapotranspiration has been predicted for the agricultural crops grown in low-lying areas. The results conform to the Meteocological Office (1981) and Kirkby (1987) who predicted maximum evapotranspiration for agricultural crops and minimum for conifers. However these are contrary to the findings of Raeder-Roitizch and Masrur (1989) who estimated maximum evapotranspiration for conifers in the chirpine zone of northern Pakistan. This contradiction has arisen due to the fact that they used a different approach for the estimation of evapotranspiration (through soil moisture accounting) without considering the effects of slope and aspect and ignoring deep percolation and lateral transfer of ground water.

Daily and monthly variations in evapotranspiration were assessed by producing multi-temporal outputs of Evap_map module. For example, a total of 365 daily maps for 1979 were produced from observed meteorological data by running Mode 1 (cf. section 6.5.1.4) of this module for the purpose of model evaluation for daily simulations. The statistics of these maps were plotted on a daily time scale (Fig. 7.5). These results revealed an evapotranspiration rate as high 13 mm in some low-lying parts of the catchment was on 20 June 1979. In fact, the highest rate of evapotranspiration was the result of the very high temperature (34°C; the highest in 1979) recorded at Phulra station. The catchment’s mean evapotranspiration reached its peak on 21 June (7.86 mm) which resulted from the combined effects of high temperature and very low humidity recorded at all stations. Local variations in the meteorological variables (e.g. temperature and relative humidity) have been found to affect the spatial variation (standard deviation) of the evapotranspiration rate. For example, the highest difference in relative humidity recorded at Shinkiari (83 %) and Balakot (40 %) on 27 June have yielded the spatial variation (standard deviation) in evapotranspiration as high as 3.95. The results of daily evapotranspiration simulation were used to calculate daily water balance of the catchment as discussed later in this chapter.

The general pattern of monthly variation can be inferred from the spatial statistics of 1979 (Fig. 7.6). It is evident that during winter the spatial minimum, maximum and mean tend to converge. This represents a spatial distribution of very high skewness and kurtosis where most map cells have values equal to or very close to the mean. Furthermore, winter distributions are positively skewed meaning majority of cells have values greater than the mean. In the summer spatial distributions are leptokurtic i.e.
Fig. 7.5: Temporal (daily) pattern of variation of simulated daily evapotranspiration in 1979. The spatial statistics was calculated from 365 daily evapotranspiration maps produced by Evap_Map (Mode 1) using observed meteorological data.
the maximum number of cells have value far less or more than mean and are negatively skewed i.e. majority of cells have value less than mean. The spatial statistics for a particular month have revealed that in the complex terrain of the Siran Basin, the catchment’s mean evapotranspiration value signifies very little. Therefore the results of spatial distribution of evapotranspiration must be evaluated statistically using different spatial parameters such as maximum, minimum, standard deviation, skewness and kurtosis.

![Graph showing monthly variation in simulated daily evapotranspiration for 1979.](image)

**Fig. 7.6: Monthly variation in simulated daily evapotranspiration for 1979.**

### 7.3.2 Accuracy Assessment of Evap_map Outputs

In this study, the measured evapotranspiration data were not available to test the accuracy of Evap_map outputs. However the results of monthly simulations for 1979 (Fig. 7.6) have been compared with those obtained by lumped simulations using Thorthwaite method (Fig. 5.16). This comparison (Fig. 7.7) revealed that the distributed modelling using Evap_map (based on Penman-Monteith approach) tends to overestimate the evapotranspiration rate for most part of the year. It was established by regression analysis (Table 7.1) that the Evap_map estimates are higher upto 50 % than the lumped estimates obtained using Thorthwaite model. These results do not favour Hoshi and Uchida (1989) who predicted a lower rate of evapotranspiration using a distributed Penman-type model than that obtained using a lumped Thorthwaite model.
Fig. 7.7: A comparison between the results of distributed and lumped evapotranspiration simulations for 1979.

Fig. 7.8: A comparison between the simulated evapotranspiration estimates (lumped and distributed) and pan evaporation recorded at Phulra (Ph), Oghi (Og) and Shinkiari (Sh).
In order to check whether the \textit{Evap\_map} estimates could be used safely for calculating catchment water balance, the results (Fig. 7.6) were also compared with the pan evaporation data for 1979. The pan evaporation is measured in the valleys (cf. section 5.4.5) where evaporation rate is usually higher than upper mountains. Since the evapotranspiration from all vegetated surfaces is always less than pan evaporation, logically the \textit{Evap\_map} estimates should not exceed pan evaporation. The regression analysis revealed a high correlation between the \textit{Evap\_map} estimates and observed pan evaporation recorded at all meteorological stations. The ratio of catchment's mean simulated evapotranspiration and pan evaporation ranges from 0.66 to 0.93, i.e. evapotranspiration simulated by \textit{Evap\_map} is 66 to 93% of the observed pan evaporation. Although the \textit{Evap\_map} estimates obtained in this study are higher than lumped estimates, they do not exceed pan evaporation recorded at any station at any time of the year (Fig. 7.8). Despite the fact that the accuracy of distributed simulations can not be assessed due to unavailability of measured evapotranspiration data, it was felt that \textit{Evap\_map} can be used for calculating catchment's distributed water balance without introducing serious errors.

<table>
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<th>(Y): Distributed Evapotranspiration (Penman Monteith)</th>
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<tr>
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<td>(x) (a)</td>
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<td>Lumped ET (Thorthwaite)</td>
<td>1.50</td>
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<tr>
<td>Pan (Phulra) Evaporation</td>
<td>0.75</td>
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<tr>
<td>Pan (Oghi) Evaporation</td>
<td>0.79</td>
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<td>Pan (Shinkiari) Evaporation</td>
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*Fig. 7.1: The relationship of Thorthwaite evapotranspiration estimates and pan evaporation with \textit{Evap\_map} estimates.*

### 7.3.3 Interception

The module \textit{Inter\_map} simulates interception process on the basis of LAI assessment (cf. section 6.5.2). Hence the spatial distribution of interception is likely to follow the pattern of LAI distribution. An interception map may look like the one given in Fig. 7.15 which was produced by adding up 16 daily interception maps for July 1979 (there were 16 rain days in that month). This map shows that the area in the catchment occupied by fir and spruce forests (which have a maximum LAI owing to their canopy structure as well as an abundant ground flora) has the maximum interception while the area occupied by exposed rock, bare soil and stream beds has lowest total interception.
For assessing the temporal pattern of variation, twelve LAI maps (for LAI estimation cf. section 4.11, Fig. 6.4) and twelve interception capacity maps were produced and their statistics were calculated. The maximum LAI curve (Fig. 7.9), which corresponds to evergreen fir and spruce forests remains unchanged throughout the year. The seasonal variation in the mean LAI are due to LAI changes in agricultural crops and grass (Eqn. 6.33). Presumably the interception capacity curves (Fig. 7.10) should have followed the same pattern, whereby maximum interception capacity should remain unchanged throughout the year. A gradual change in the interception capacity from winter to summer is due to a seasonal factor in the interception model (cf. section 6.5.2) which accounts for evaporation loss from interception store between low-intensity multiple showers.

7.3.4 Infiltration and Surface Runoff

The module Infilt_map has four output options: (i) extrapolated precipitation, (ii) net precipitation (total precipitation - interception), (iii) infiltration and (iv) infiltration-excess surface runoff. All of these outputs are important in the calculation of the daily water balance of the catchment. The evaluation of the module was carried out using observed hourly precipitation data for January and July 1979. These months were specifically chosen for the assessment of catchment response to winter and monsoon rains separately. The mapped outputs of Infilt_map for July 1979 are given in Figs. 7.14, 7.15, 7.16 and 7.17. It is evident from these maps that the breakdown of precipitation into infiltration and surface runoff depends largely on the soil texture as they follow the general spatial pattern of soil textural classification (Fig. 3.10). To a lesser degree than soil texture, vegetation type affects the spatial distribution of infiltration and surface runoff mainly due to the spatial variations in the soil bulk density and macroporosity that differ with vegetation types and agricultural practices (Rawls et al. 1992).

The difference between the spatial maximum and minimum infiltration in July 1979 was 186 mm, with a mean of 139 mm (Fig. 7.16). In some parts of the catchment (red in Fig. 7.16) which have sandy soils all the precipitation was infiltrated and no surface runoff occurred. The area which yielded the maximum surface runoff (151 mm) in response to precipitation lies in the extreme east of the catchment and is clearly shown
**Fig. 7.9:** Monthly variation in LAI in the Siran Basin for 1979. The maximum curve represents the LAI of high cover conifer forests which remains unchanged throughout the year.

**Fig. 7.10:** Monthly variation in interception capacity in 1979. Note the mean curve follows the pattern of mean LAI (Fig. 7.9). A gradual increase towards summer months is due to a seasonal factor in the interception algorithm.
in Fig. 7.17 (deep blue) and corresponds to an area of very steep exposed rock under forest cover (see Figs. 3.5, 3.10 and 4.11 for description of this area).

The response of each facet (composed of a unique set of topography, soil and vegetation type), and consequently the whole catchment, to incident precipitation is not a constant since it is largely modified by precipitation intensity (Mein and Larson, 1973). This fact is evident from the daily figures of precipitation breakdown into infiltration and surface runoff for January and July 1979 (Fig. 7.11a and 7.11b). In this figure the total height of a bar represents catchment's mean precipitation which is devided into interception, infiltration and surface runoff. Some low intensity showers in January (Fig. 7.11a) produced very low surface runoff (5.3 % on 25 Jan) while an appreciable proportion of a high intensity event was converted to surface runoff (30 % on 14 Jan). The changes in catchment response with the precipitation intensity can be further assessed from Infilt_map outputs for July 1979 (Fig. 7.11b) when two events (17 and 21 July) with the same amount of precipitation yielded widely different proportions of infiltration and surface runoff.

7.3.5 Accuracy Assessment of Infilt_map Outputs

Certainly the spatio-temporal variation in Infilt_map outputs (i.e. infiltration and surface runoff) are largely influenced by the combined effects of soil and vegetation characteristics and precipitation intensity. The accuracy of most models which simulate surface runoff is assessed by comparing the model outputs with the observed hydrograph data (e.g. Ott et al. 1989). Such data are usually recorded at the catchment outlet and represent total discharge of the catchment. This includes baseflow, interflow (lateral flow) and surface runoff (Schulz, 1978). The only observed data available, in this study, to assess the accuracy of Infilt_map outputs (particularly surface runoff) was the daily discharge data for the Siran River recorded at Phulra gauge (Table 5.2). The total discharge data was split theoretically (after Bras, 1990; Schulz, 1978) into baseflow and total runoff (surface runoff and interflow) using a recession constant of 0.95 (Fig. 7.12a and 7.12b). A further split into interflow and surface runoff was not carried out due to the uncertainty over the recession constant. The curve shown by a dashed line, which represents a total of interflow and surface runoff, was assumed to be the observed surface runoff to test the accuracy of Infilt_map outputs.
Fig. 7.11a: Simulated interception, infiltration and surface runoff as fractions of daily precipitation in January 1979.

Fig. 7.11b: Simulated interception, infiltration and surface runoff as fractions of total precipitation in July 1979.
Fig. 7.12a: Hydrograph separation into baseflow and interflow+surface runoff using recession constant (January 1979).

Fig. 7.12b: Hydrograph separation into baseflow and interflow+surface runoff using recession constant (July 1979).
Fig. 7.13a: A comparison between simulated and observed surface runoff (January 1979).

Fig. 7.13b: A comparison between simulated and observed surface runoff (July 1979).
It can be inferred from Fig. 7.13 that Infilt_map simulates surface runoff only on the
days of precipitation and is not capable of coping with the delayed response of the
catchment (lag time and time of concentration). Therefore the module tends to
overestimate the surface runoff for rainy days and underestimates for dry days. The
actual response of the catchment is usually gradual (as it is evidenced from observed
runoff data in Fig. 7.13) and most runoff peaks occur one day later than the day of
precipitation occurrence. To confirm the presumption that such large errors in daily
simulations were only due to a time shift, the observed and simulated daily surface
runoff were accumulated for another mutual comparison. The results revealed that the
difference between accumulated observed and simulated surface runoff, particularly for
July, were actually not as high as inferred from the daily results, since the accumulated
curves closely coincide (Fig. 13 b). However it was established that Infilt_map
overestimates surface runoff for winter months e.g. January (Fig. 13 a). The most
probable reason of this deviation of the simulated runoff from the observed runoff is
that northern and north-eastern parts of the upper catchment (above 3000 m elevation)
receive winter precipitation mostly in the form of snow, instead of rain. As discussed
earlier, the precipitation extrapolation method used in this study cannot discriminate
between the forms of precipitation (cf. section 7.2.1) and all precipitation is treated as
rain, hence it tends to overestimate the surface runoff.

7.4 DAILY WATER BALANCE

It can be inferred from the system diagram of a regional water balance (Fig. 6.12) that
a part the precipitation is intercepted by vegetation surface and/or surface litter. The
net precipitation which reaches the soil surface after subtracting this loss is further
divided into infiltration and overland flow (surface runoff) depending on the soil and
vegetation characteristics of that part of the catchment. The division of the
precipitation into interception, infiltration and surface runoff can be written in the form
of an equation:

\[ P = I_r + I_i + R_{suf} \]  

7.1

where \( P \), \( I_r \), \( I_i \) and \( R_{suf} \) denote incident precipitation, interception, infiltration and
surface runoff (all in mm).
The intercepted water \( (I_i) \) is evaporated as a part of total evapotranspiration \( (ET) \) of a particular day and rest of the demand is met from soil moisture store. This equation takes the form:

\[
ET = I_i + ET_{\text{soil}}
\]

where \( ET_{\text{soil}} \) denotes evapotranspiration loss from soil moisture store.

The infiltrated volume \( (I_p) \) adds to soil moisture store from which it flows in all the three dimensions. The movement of water from soil moisture store is dictated by the soil properties (e.g. moisture holding capacity and hydraulic conductivity) and available moisture content. When the moisture holding capacity of the soil is reached, the excess soil moisture either is seeped down to ground water or reaches the channel store as inter flow (delayed). The modelling of these sub-surface processes needs thorough investigation of moisture holding and releasing characteristics of each of soil horizon down the profile to saturated zone (Bras, 1992). Since in this study such information was not available, the infiltrated proportion of daily precipitation will be treated as total volume of water contributing to soil moisture store, evapotranspiration from soil, ground water and inter flow i.e.:

\[
I_p = +\Delta SM + +\Delta GW + R_{\text{sub}} + ET_{\text{soil}}
\]

where \( +\Delta \) denotes an increase in soil moisture \( (SM) \) and ground water \( (GW) \) and \( R_{\text{sub}} \) is inter flow (sub-surface lateral flow).

Based on these concepts, the components of daily water balance for January and July 1979 were simulated running Evap\_map (Mode 1), Inter\_map and Infiltr\_map modules with the observed daily sunshine, temperature, relative humidity and wind data and hourly precipitation data. The results are graphically shown in Fig. 7.18 a and 7.18 b. In these figures the occurrence of interception (or evaporation from interception store), infiltration and surface runoff have been shown as discrete values (since they are available for rain days only) against evapotranspiration loss from soil moisture which is represented as a continuous process through the month.

It is evident from these figures that the interception is least affected by the precipitation intensity and remains more or less constant through a particular month. A lower evapotranspiration from a soil moisture store \( (ET_{\text{soil}}) \) on rain days is the result of low
Fig. 7.14: Total precipitation (mm) for July 1979. This map was generated by Infil_map using observed hourly precipitation data recorded at Balakot, Phulra, Oghi and Shinkiari.

7.15: Total simulated interception (mm) for July 1979. This map was generated by Inter_map using daily precipitation data and land cover map for 1979.
Fig. 7.16: Total simulated infiltration for July 1979. Note the spatial distribution of infiltration generally follows the pattern of soil textural classification (Fig. 3.10).

7.17: The simulated surface runoff for July 1979. The spatial distribution of surface runoff is opposite to that of infiltration. A runoff map is required the catchment response mapping.
Daily Water Balance (January 1979)

Fig. 7.18 a: Simulated components of daily water balance (evapotranspiration from interception store, evapotranspiration from soil moisture store, infiltration and surface runoff) for January 1979.

Daily Water Balance (July 1979)

Fig. 7.18 b: Simulated components of daily water balance (evapotranspiration from interception store, evapotranspiration from soil moisture store, infiltration and surface runoff) for July 1979.
temperature, cloudiness and consequently less simulated evapotranspiration (ET) and the interception which makes up an appreciable share total loss. Since ET\textsubscript{ani} is the major loss from the soil moisture store, its simulation is of extreme importance for the spatial and temporal soil moisture assessment. The daily fluctuation in the catchment's soil moisture store were estimated taking infiltration (I\textsubscript{T}) as the input and evapotranspiration from soil moisture store (ET\textsubscript{ani}) as the output. Ignoring the ground water recharge and interflow in Eqn. 7.3, the equation for the estimation changes in soil moisture can be written as:

\[ \pm \Delta SM = I_T - ET_{ani} \]  \hspace{1cm} 7.4

The catchment's mean (spatial mean) daily soil moisture fluctuations were estimated using Eqn. 7.4 and the results are given in Fig. 7.19a and 7.19b for January and July 1979 respectively.

The soil moisture changes estimated through distributed modelling, using Siran\_HYDMAPS modules (Eqn. 7.4), were compared with those obtained by lumped modelling (cf. section 5.6). This comparison revealed very closely coinciding soil moisture estimates obtained by the two methods for January 1979, but widely different estimates for July 1979. Fig. 5.25 which was based on lumped modelling shows that the total change in soil moisture of the catchment in January and July 1979 were +55 mm and +100 mm respectively. The simulated soil moisture change using Siran\_HYDMAPS (Fig. 7.19) was +53 mm for January and -36 mm for July 1979. The greater difference between the estimates of soil moisture changes for July were most probably due to an overestimation of evapotranspiration by Evap\_map module (cf. section 7.3.4).

7.5 MONTHLY SOIL MOISTURE FLUCTUATIONS

Although daily water balance of the catchment can predict changes in the soil moisture store, it does not supply any information about the total volume of this store. In order to estimate the maximum capacity of this store (moisture held at field capacity) and its monthly fluctuations, the approach describe in section 6.6 was adopted. For this purpose, a short algorithm was written in C. The depth of moisture held at field capacity was mapped using the soil texture (Fig. 3.10) and soil depth (Fig. 3.11) maps and assigning a typical field capacity value to each soil textural class (after Schulze, 1978; Rawls et al. 1993). The estimated field capacity varies from 0 to 40 cm.
Soil Moisture Changes (January 1979)

![Graph showing soil moisture changes in January 1979](image)

*Fig. 7.19 a: Simulated daily soil moisture fluctuations (spatial mean) in January 1979.*

Soil Moisture Changes (July 1979)

![Graph showing soil moisture changes in July 1979](image)

*Fig. 7.19 b: Simulated daily soil moisture fluctuations (spatial mean) in July 1979.*
depending upon the soil texture and depth (up to a maximum depth of 100 cm). For example, deep clayey soils found in the Pahull plain have a maximum field capacity (40 cm), while the exposed rock on very steep slopes has the minimum (0 cm). As mentioned in section 6.6, in January and July, the precipitation exceeds potential evapotranspiration (Fig. 5.16), total depth of water held during these two months was supposed to be equal to the maximum field capacity. The fluctuations in the soil moisture were estimated by taking a difference of monthly precipitation and evapotranspiration. The monthly fluctuations in the depth of soil water store of the Siran catchment are shown in Fig. 7.20.

From January to March, there is no apparent change in the soil moisture store because of very low evapotranspiration rate thought the catchment. In April, May and June evapotranspiration rate increases very rapidly owing to high temperature and net radiation. Furthermore, during this period the agricultural crops attain maturity and as the consumptive use increases, they transpire at very high rates. The extreme monthly changes in the soil moisture store are seen in the areas under agricultural crops, while areas under conifer forest cover are least affected due to their low evaporative demand. However Fig. 7.20 represents soil moisture changes under natural climatic conditions i.e. without irrigation. In practice, most agricultural crops are grown with irrigation and the soil moisture is not allowed to drop to wilting point, unless the stage of vegetation senescence is reached. With the onset of monsoon season in July, the soil returns to its field capacity and the deficit cycle starts again.

7.6 IMPACT ANALYSES OF LAND COVER CHANGES

In addition to determine the spatio-temporal variations in the meteorological variables and hydrological processes, the Siran_HYDMAPS can predict changes in these processes in response to the changes in the spatial characteristics of the catchment e.g. land cover. The impact analyses of the changes in the land cover, on the hydrological processes necessitates the changes in climate, soil and topography to be ignored. Obviously such an assumption is not valid if the impacts are modelled for a long-term land cover change (which have occurred over decades). Since in this study the hydrological impacts are to be assessed for land cover changes which have occurred in a period of ten years (1979 to 1989), this simplified assumption is not likely to introduce serious errors in the impact analysis results. For the purpose of impact analysis, Siran_HYDMAPS was run using the mean monthly meteorological data recorded at all the four stations.
Fig. 7.20: Monthly changes in the soil water store of the Siran catchment. The maximum water holding capacity (water content held at field capacity) was mapped using the soil texture and depth maps (Figs. 3.10 and 3.11). Each soil textural class was assigned a typical value of field capacity and total volume of water held at field capacity was estimated from the depth of soil profile. Monthly fluctuations in the soil water store were estimated by adding the difference of precipitation and potential evapotranspiration to previous months' soil water content.

It can be inferred from these maps that there is a slight change in the soil water store before April. During the first three months, the evapotranspiration rate remains very low due to low temperature and net radiation, and precipitation exceeds or equalises the evapotranspiration. An abrupt change is
seen in April, when most agricultural crops attain maturity and their evaporative demands are very high. Maximum soil water deficit occurs in April, May and June when evapotranspiration exceeds precipitation. Note the areas occupied by the conifer forests are least affected owing to their lowest evaporative demands.

The soil in the catchment returns to its field capacity during monsoon season (July and August). Since evapotranspiration is very high in these summer months, soil water deficit occurs very quickly, particularly in agricultural lands. The winter rains in December and January tend to replenish the soil water store with reaches its field capacity in January.
7.6.1 Changes in Radiation Balance (Net Radiation)

*Evap_map (Mode 2)* was run using the mean monthly sunshine, temperature, wind velocity and relative humidity data for simulating net radiation for each of the two years (1979 and 1989). The spatial and temporal statistics of the net radiation for 1979 and 1989 are given in Fig. 7.3a and 7.3b. Apparently there appears no significant difference between the temporal curves (Fig. 7.3a and 7.3b), although spatial distribution pattern has definitely altered over ten years. The difference between the catchment's mean net radiation of 1989 and 1979 (Fig. 7.21) shows that generally there has been a reduction from 1979 to 1989. The most probable reason of less absorption and more emittance of radiation in 1989 than in 1979 was an increase in ground albedo brought about by the opening of conifer forests (cf. section 4.10). It can be further inferred that the winter months are more affected by the change in net radiation; the maximum predicted decrease in net radiation over ten years was as high as 1.5% in November and December. An overall (annual mean) decrease of 0.76% has been predicted in daily net radiation from 1979 to 1989.

7.6.2 Changes in Evapotranspiration

The changes in evapotranspiration were predicted by executing *Evap_map (Mode 2)* with land cover maps for 1979 and 1989 and monthly averaged daily meteorological data. A total of 24 maps were produced and all the six statistical parameters were calculated primarily for the purpose of quantifying the effects of land cover over ten years on the process of evapotranspiration. Despite a decrease in net radiation in all months, an increase in evapotranspiration from 1979 to 1989 has been predicted for most part of the year (Fig. 7.22). The underlying reason of this increase is a replacement of 'high cover conifers (21)', which have the lowest evaporative demand (cf. section 7.3.1), by other land cover classes such as 'medium cover conifers (22)', 'grass and scattered trees (31)' and 'arable (11-17)' on warmer aspects.

The changes in total annual evapotranspiration were mapped (Fig. 7.26) by summing up monthly evapotranspiration maps of each of two years separately and then subtracting total evapotranspiration for 1979 from the total evapotranspiration for 1989. It can be inferred from this map (Fig. 7.27) that the magnitude of change in total annual evapotranspiration is as high as ±1700 mm per annum. These extreme changes in evapotranspiration were predicted for the sites where a complete change in land cover (e.g. forest to agriculture or vice versa) has occurred in ten years (see forest
Fig. 7.21: Monthly pattern of net radiation changes from 1979 to 1989.

Fig. 7.22: Monthly pattern of potential evapotranspiration changes from 1979 to 1989.
cover change map in Fig. 4.13). There has been an overall increase of 0.57% in the annual total evapotranspiration over ten years (1979 to 1989).

Such results may be misleading if evaluated without calculating the actual proportions of the catchment area undergone such extreme changes. The change-area analysis of this map (Fig. 7.27) revealed that over about 60% of the area, the changes in annual evapotranspiration were negligible or none at all. In 14% of the total area the magnitude of annual change in evapotranspiration was within ±200 mm while 20% of area has undergone severe changes of the magnitude beyond ±1000 mm (Fig. 7.23).

The changes in evapotranspiration of each land cover class (which have been brought about by a shift in their physical location or spatial distribution) have also been quantified. For example, a reduction in the annual evapotranspiration of conifer forests has been predicted, the reason being that most deforestation occurred on warmer aspects and new plantations are making their appearance on cooler aspects (Fig. 4.13). The extreme changes were predicted for ‘bare soil (17)’ with a decline of about 100 mm per annum. This type of analysis (Fig. 7.24) is of great importance in the high relief catchments such as the Siran catchment. It reveals that it is not only the change in total area, but also a change in physical location of a land cover which is important for hydrological impact assessment point of view.

7.6.3 Changes in Interception Capacity

The changes in the interception capacity over ten years were predicted from monthly maps produced for 1979 and 1989 separately. It is evident from the difference between catchment’s mean interception capacity for 1989 and 1979 (Fig. 7.25) that there has been a reduction for all months mainly due to an opening of conifer forests (and consequently reducing the LAI) and a changed agricultural pattern. The reduction in interception capacity as a result of a reduced forest LAI modest and uniform (in the second half of the year). The greater differences between the simulated interception capacity for 1979 and 1989 in the first half of the year have been found to be the result of differences in LAI of seasonal crops of 1989 and 1979. In fact, more area was brought under long-rotation single cropping with tobacco as major crop (which has very low LAI in April and May and attains full cover in July) in 1989 compared to 1979 when the much of this area was occupied by winter crops (which attain full cover and maximum LAI in April and May) (cf. crop calendar in Fig. 1.2). In general, the
Fig. 7.23: The extent of change in annual total evapotranspiration of the Siran Basin resulting from land cover changes from 1979 to 1989.

Fig. 7.24: The changes in annual total evapotranspiration of each land cover class resulting from a shift in their physical location from 1979 to 1989.
mean interception capacity of the catchment has been reduced by 7.28% from 1979 to 1989 due to a reduction in LAI.

7.6.4 Changes in Infiltration & Catchment Response

The process of infiltration responds to the compounding effects of precipitation intensity and hydrological properties of the soil (cf. section 7.3.4). Since each vegetation type has a characteristic ability to influence the hydrological properties of the soil (e.g. macroporosity and hydraulic conductivity), the catchment's potential to generate surface runoff is greatly modified by any change in the vegetation cover type. The impacts of land cover changes on the soil properties and consequently on the infiltration process can be assessed using Infiltr_map with the land cover maps for each of the two years (1979 and 1989).

The changes in the catchment response (surface runoff as percent of total precipitation) from 1979 to 1989 were quantified for an assumed six-hour event in the month of July, (precipitation intensity 5, 10, 20, 20, 10, 5 mm/hr) at all four stations. The spatial variation in the catchment response to this 70 mm event was of the magnitude ±86% with an overall increase of approximately 2% over ten years. The same increase in catchment response (~2%) was estimated for a low-intensity six-hour event (0.5, 0.5, 2, 2, 0.5, 0.5 mm/hr) in July.

The change-area analysis (Fig. 7.26) revealed that the response of about 68% of the catchment area (white in Fig. 7.28) was unaltered over ten years. The spatial distribution of the areas with modified response are shown in Fig. 7.28 which correspond to the areas which have undergone major land cover changes (Fig. 4.13). The severity of change in the catchment response varies with the extent of land cover changes; the most affected being the areas with a complete land cover change. The maximum increase in the catchment response was predicted for the areas where high cover conifer forests have been replaced by grass or very low cover forests.
Fig. 7.25: Monthly pattern of changes in the interception capacity resulting from a reduction in catchment’s LAI from 1979 to 1989.

Fig. 7.26: The extent of changes in the catchment response (100× surface runoff / precipitation) from 1979 to 1989.
Fig. 7.27: The predicted changes in annual evapotranspiration in the Siran Basin, from 1979 to 1989. Note the extreme change has occurred in the areas with a complete land cover change.

Fig. 7.28: The difference between the catchment response for July 1989 and 1979. Note the area where CR has increased roughly equals the area where CR has decreased over ten years.
7.7 SUMMARY

- The model *Siran_HYDMAPS* has been found capable of simulating daily solar radiation components and radiation balance with the limited sunshine data.

- A new method of precipitation extrapolation based on a combined approach of *multivariate regression* and *inverse-distance squared* has been developed. This method gives fairly acceptable estimates of the precipitation amount over complex terrain of the Siran Basin, but fails to take into the account the form of precipitation (e.g. rain, snow).

- A combination method of temperature extrapolation has been devised and successfully applied to extrapolate mean daily temperature across the catchment. This approach which takes into account elevation, slope, aspect and ground albedo has been found capable of generating logically acceptable results, more than any other approach.

- The module *Evap_map* based on Penman-Monteith approach seems to over-estimate evapotranspiration, although these estimates never exceed observed pan evaporation, hence can be safely used for water balance modelling.

- Since little information was available on the LAI of different vegetation types found in the Siran Basin, the interception estimates of *Inter_map* are based on an estimated LAI and are not recommended for more precise applications.

- The module *Infilt_map* simulates the process of infiltration and surface runoff estimated by this module closely coincides with the observed surface runoff data, particularly during summer. However, during winter months *Infilt_map* over-estimates runoff and under-estimates infiltration, primarily owing to its incapability of predicting the form of precipitation (e.g. rain, snow, sleet).

- The model has been found highly efficient in predicting the changes in radiation balance and water balance components, resulting from land cover changes, in their true spatial context.

- It was established that the daily radiation balance (net radiation) of catchment was reduced by 0.76 % (annual average) from 1979 to 1989.
Despite a decrease in net radiation, an increase of 0.57 % (annual average) in daily evapotranspiration has been predicted.

The interception capacity was reduced by 7.28 %; largely because of a changed agricultural pattern.

Generally speaking the catchment response (100 × surface runoff / precipitation) to high intensity precipitation has been increased by approximately 2 % over ten years.
Chapter 8

CONCLUSIONS & SUGGESTIONS
FOR FURTHER RESEARCH
8.1 INTRODUCTION

This research was aimed at assessing the hydrological impacts of land cover changes, particularly deforestation, in the Himalayan foothills of northern Pakistan. The approach adopted in this study is based on developing a hydrological model which integrates the GIS databases with the well-known process simulation algorithms. On one hand, the model performs real-time simulations of the processes of evapotranspiration, interception, and infiltration and, on the other hand, predicts the changes in these processes in response to any spatio-temporal change in land cover. This approach allowed the following hypotheses to be tested:

- All spatial and temporal changes in the land use and land cover are likely to impact on the individual hydrological processes and alter the catchment response as a whole.

- Any deviation in the water balance of the Siran Basin, observed during the last two decades, was largely caused by the forest cover changes.

Several key issues emerged during the development of the GIS, image processing and development and application of the model, which are summarised in this chapter. The results of land cover change detection and their impacts on individual hydrological processes have also been concluded. The prospects for further improvement of this work have been discussed and some suggestions have been made.

8.2 SOME KEY ISSUES

8.2.1 Reviewing the Problem and the Best Solution

Nevertheless in the complex terrain of the Siran Basin, it is not the change in total area under a particular land cover (e.g. conifer forests), but the change in the spatial distribution of that land cover, which is more important for hydrological impact assessment. Therefore an empirical model or a lumped-conceptual model cannot effectively predict the impacts of such land cover changes on the hydrological processes (Beven, 1985). A GIS-based model offers the best opportunity to quantify...
the changes in hydrological processes in response to temporal changes in land cover changes in their spatial context.

8.2.2 The Siran GIS: Experimental or Operational?

A distributed hydrological model necessitates the availability of a GIS, built on a specific configuration, for the estimation of spatial characteristics of a catchment. The GIS for the Siran Basin was developed at 80 m resolution. A question frequently raised during this study was: 'Why not a finer resolution?'. In fact, there were several factors involved in making the decision about this resolution of the GIS. Above all, the GIS databases had to be input to an operational model developed for hydrological simulations in a large catchment (1040 km²). Furthermore, an increase in the resolution may not necessarily increase the accuracy of the meteorological extrapolation and the hydrological process simulation. In addition, the limitations of computing resources should not be overlooked.

8.2.3 Some Site Specific Problems in Image Processing

The Landsat images used in this study, for land cover mapping, carried serious radiometric inaccuracies caused by topographic relief. A particular attention has been given to minimise the effects of topography through solar radiation redistribution. However, this method does not take into account the effects of hill shading (Moore et al. 1991), hence the land cover on slopes with obstructed radiation was misinterpreted. Various forest types could not be delineated because of the similarity of their reflectance spectra, hence a rule-based classification (level II) had to be performed (Cibula and Nyquist, 1987). Another problem encountered in the processing of Landsat MSS (acquired on 5 March 1979) was the snow on the forest floor, which hindered the land cover interpretation in large part of upper catchment.

8.2.4 Model Structure and Algorithms Used

Many modern GIS software (e.g. ARCINFO and GRASS) have their codes accessible to users, so that new modules can be written within the GIS environment. The Siran HYDMAPS was structured not to rely on a particular commercial GIS, the unavailability of which may render the model unusable. The spatial inputs and outputs,
although, compatible with ARCINFO, can be read and processed by any GIS software with minor alterations in the header.

One of the major problems encountered in hydrological modelling in mountainous areas is the extrapolation of meteorological data e.g. precipitation, temperature and net radiation (Heywood et al. 1994). New methods have been devised, in this study, for extrapolations of these meteorological variables across the Siran Basin. Although these methods give logically acceptable results, their accuracy could not be measured due to lack of meteorological data. The algorithms used to simulate the hydrological processes are based on physical laws and they are not site specific. The evapotranspiration is estimated using the Penman-Monteith model, while the process of infiltration is simulated using Green-Ampt model; both of them are globally accepted.

8.3 CONCLUSIONS

- A post-classification change detection of the land cover maps for 1979 and 1989 has shown an increase of ~10 km² (2.9 %) in the total area under conifer forests. However, the forest cover density has been reduced in most forests from 1979 to 1989. It emerged that there was a vast scale change in the spatial distribution of conifer forests during this period.

- Most changes have occurred in the chir pine type where the cover density has been reduced in 88 % of the total area. An overall decrease in the total area, under this forest type, from 1979 to 1989 was only 2 km² (0.97 %). Other forest types i.e. blue pine, fir/spruce remained relatively unchanged mainly due to inaccessibility.

- The climate analysis of the Siran Basin revealed an increasing trend in precipitation, river discharge, sediment yield and catchment response in mid 1970's. This was the era, as reported by many researchers (e.g. Allan, 1987; Bajracharya, 1985), when the process of deforestation was intensified in the Siran Basin. This coincidence lead to the notion that deforestation was the sole factor behind this hydrological disorders and the climatic factors were overlooked. The efforts to correlate changes in land cover with the changes in catchment hydrology were hindered by an extreme heterogeneity of spatial characteristics of the Himalayan foothill catchments.
• The GIS-based hydrological model (Siran_HYDMAPS) has been found capable of not only extrapolating various meteorological variables and simulating the hydrological processes in the Siran Basin, but also predicting the changes in these phenomena in response to changes in land cover in a spatial context.

• The results obtained by running Siran_HYDMAPS have shown a decrease in daily net radiation; a driving force for energy dependent processes, from 1979 to 1989. Most affected were the areas which have undergone a complete land cover change (i.e. deforestation), primarily due to an increase in the ground albedo. The estimated maximum change in daily net radiation of these areas was up to 3 MJ/m²/day (= 27 %). The overall reduction in catchment's daily net radiation from 1979 to 1989 was 0.76%.

• Contrarily, an increase in potential evapotranspiration has been predicted for the same period. The overall increase in annual evapotranspiration was only 0.57 %. However, over 60 % of the catchment area, there was none or non-significant change in evapotranspiration from 1979 to 1989. The maximum increase (up to 1600 mm/annum) was estimated for the areas where conifer forests were completely replaced by agricultural crops. These results should not be misunderstood, since the removal of broad-leaved forests (e.g. rain forests which have a high evaporative demand) has a very different impact on evapotranspiration than the removal of conifers (e.g. pine forests found in the Siran Basin, which offer maximum resistance to water loss) (Kirkby, 1987). For example, Shukla et al. (1990) reported a decrease in evapotranspiration in response to deforestation over the Amazon Basin.

• The physical location of land cover has been found to be one of the most important factor in the catchment hydrology (Beven, 1985). For example, a change in location of conifer forests, from 1979 to 1989, has resulted in a decrease in annual evapotranspiration of high cover conifer forests by 50 mm (11.79 %).

• Interception capacity is a function of LAI. A reduction of LAI due to opening of conifer forests has caused a decrease in interception capacity by 7.28 % over ten years.

• The impacts of changing land cover, on the process of infiltration and the catchment response were quite straightforward. The deforestation has been found to decrease the infiltration capacity, mainly due to a reduced macroporosity and
hydraulic conductivity. A maximum of 68% increase in the catchment response has been predicted for the areas which have undergone complete deforestation. These results favoured Russell (1981) who predicted an increase in the outflow of water from a forested catchment by replacing the trees with short season arable crops. However, 68% of the area was not affected by any change in the catchment response. Only 2% increase in the mean catchment response has been predicted for both high intensity and low intensity showers.

- The results of this research have fully supported the hypotheses, which were defined before commencing this work. However, it is concluded that the land cover changes of the type and extent, which have taken place between 1979 and 1989 in the Siran Basin, cannot cause a devastating effect on the catchment hydrology. Therefore the impact analysis of any change in the spatial characteristic of the catchment such as deforestation must be carried out in conjunction with climatic trend analysis.

8.4 SUGGESTIONS FOR FURTHER WORK

- A major weakness in this model (like many other models of this category) lies with the estimation of soil parameters. The estimation of Green-Ampt infiltration model parameters, in this study, was based on the literature values, typical of each textural class. Though it is not practicable to physically measure these parameters in the large catchments, the estimated values may be tested in the field using an appropriate sampling method. Furthermore, a sensitivity analysis of each Green-Ampt parameter need to be carried out.

- It was realised, during the ground truth checking of land cover maps, that the mixed land covers found in the Siran Basin cannot be adequately mapped using a classification method based on a discrete algorithm. Ideally, the land cover mapping in the Siran Basin may be carried out using a mixture modelling technique. However, great care has to be exercised in estimating the hydrological parameters from a land cover map based on mixture modelling.

- More temporal Landsat images need to be processed in order to assess the temporal pattern of variation in ground albedo.
• One of the most important hydrological parameters i.e. LAI may be estimated from temporal Landsat data in conjunction with the field measured data. The estimates of Siran_HYDMAPS can be made more reliable and accurate with the Landsat derived LAI estimates.

• The results of spatial meteorological extrapolations and process simulations may be tested for their accuracy by a field investigation in the Siran Basin.

• The algorithms used in this model are not site specific. Hence it may be further tested with GIS databases built for other catchments.
References


British Library (no date). *South Asian Map Collection*.


Hoffer, R. M. et al. (1979). Digital processing of Landsat MSS and topographic data to improve capabilities for computerized mapping of forest cover, Technical Report, LARS, Purdue University, Indiana.


Malik, M. A. 1963. *Revised working plan for chir reserved forest of the lower Siran and Agror valleys*, Forest Department, West Pakistan.


Saeeed, S. H. (1964). Revised working plan for the upper Siran reserved forests of the Siran forest division, Forest Department, West Pakistan.


Appendix 4-i (a): The root mean square error (RSME) of all ground control points (GCPs) in Landsat MSS warping. Note the maximum RSME of this warp is 1.7 pixels and a mean RMSE is 1.18 (i.e. = 66 m on the ground).
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</table>

Appendix 4-1 (b): The root mean square error (RSME) of all ground control points (GCPs) in Landsat TM warping. Note the maximum RSME of this warp is 2.7 pixels and a mean RMSE is 1.67 (i.e. 50 m on the ground).
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Appendix 4-ii: This table was created on the probability theory (binomial expansion) and can be used to determine the minimum number of samples for gound truthing (after Van Genderen, 1978). For example, if the specified image interpretation accuracy is 0.9 and the probability of scoring errors is 0.05, the minimum number of samples from each stratum will be 30.
Following list gives the coordinates of all cells belonging to the Class No. 11.

(i) the row and column position from LL corner of the image
(ii) the distance (meters) from LL corner to cell centre
(iii) the longitude / latitude of the cell centre.

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</tbody>
</table>

Appendix 4-iii: An example output of the programme COORDINATE. This programme generates the position of each of the pixel belonging to a particular land cover class, on the map and in the field. The required number of samples can then be picked from this list using another programme RANDOM specifically written for this purpose.
### A: Site Location Information

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</tbody>
</table>

<table>
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<td></td>
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</tbody>
</table>

### B: General Site Description

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</tbody>
</table>

<table>
<thead>
<tr>
<th>Slope (Degrees)</th>
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</thead>
<tbody>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Texture (5 samples)</th>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Depth (m)</th>
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</tr>
</thead>
<tbody>
<tr>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percent Rock Outcrops (5 samples)</th>
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</thead>
<tbody>
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</tbody>
</table>

### C: Sketch of Land cover

![Sketch of Land cover]

### D: Additional Information

### E: Evaluation of field Data

- Actual Land Cover Class (1994)
- Actual Land Cover Class (1989)
- Interpreted Land Cover Class
- Actual Land Cover Class (1979)
- Interpreted Land Cover Class

---

*Appendix 4-iv: A specimen field data collection form. The section 'A' contains the description of site location and section 'B' contains general geomorphological and soil information. The land cover cover information is entered as a sketch map (section D). The percentage of each land cover within each sample site was calculated and finally each site was assigned one of the interpreted land cover classes in section D.*
<table>
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<th>No. Incorrect</th>
<th>Binom. std. dev.</th>
<th>p</th>
<th>em</th>
<th>es</th>
<th>m</th>
<th>Accuracy %</th>
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Appendix 4-v (a): Statistical accuracy assessment of the land cover map for 1979. This method of measuring the accuracy (after Thomas et al., 1987) demands the minimum number of samples to be 30. In this study, much smaller sample i.e. 16 were used. Note 'high cover conifer forests (21)' have the maximum accuracy and the over all accuracy level is 77.7%.
### Accuracy of Land Cover Map 1989

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<th>em</th>
<th>es</th>
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<td>24</td>
<td>20</td>
<td>4</td>
<td>1.83</td>
<td>0.83</td>
<td>0.37</td>
<td>0.26</td>
<td>20</td>
<td>71.21</td>
</tr>
<tr>
<td>Exposed Rock</td>
<td>41</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel Stream Beds</td>
<td>51</td>
<td>9</td>
<td>1</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>135</td>
<td>104</td>
<td>31</td>
<td>4.89</td>
<td>0.77</td>
<td>0.42</td>
<td>0.30</td>
<td>104</td>
<td>71.15</td>
</tr>
</tbody>
</table>

*Appendix 4-v (b): Statistical accuracy assessment of the land cover map for 1989. Note the class level and overall accuracy is lower than that calculated for 1979. The underlying reason is a resampling of land cover map derived from TM data to 80 m resolution which resulted in the loss of noise and consequently the accuracy of all classes. The overall accuracy level is 71.15%.*
Regression Analysis

The regression equation is

\[ \text{rain} = -2195 + 27.0 \text{ long} + 7.58 \text{ lat} + 0.00144 \text{ elev} \]

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-2195.4</td>
<td>704.2</td>
<td>-3.12</td>
<td>0.014</td>
</tr>
<tr>
<td>long</td>
<td>27.00</td>
<td>10.88</td>
<td>2.48</td>
<td>0.038</td>
</tr>
<tr>
<td>lat</td>
<td>7.582</td>
<td>6.978</td>
<td>1.09</td>
<td>0.309</td>
</tr>
<tr>
<td>elev</td>
<td>0.00144411</td>
<td>0.00094111</td>
<td>1.53</td>
<td>0.164</td>
</tr>
</tbody>
</table>

\[ s = 4.827 \quad \text{R-sq} = 81.6\% \quad \text{R-sq(adj)} = 74.6\% \]

Analysis of Variance

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>3</td>
<td>824.49</td>
<td>274.83</td>
<td>11.79</td>
<td>0.003</td>
</tr>
<tr>
<td>Error</td>
<td>8</td>
<td>186.43</td>
<td>23.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>1010.92</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unusual Observations

<table>
<thead>
<tr>
<th>Obs</th>
<th>long</th>
<th>rain</th>
<th>Fit</th>
<th>Stdev</th>
<th>Fit Residual</th>
<th>St.Resid</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>73.2</td>
<td>35.00</td>
<td>47.04</td>
<td>1.49</td>
<td>-12.04</td>
<td>-2.62R</td>
</tr>
</tbody>
</table>

R denotes an obs. with a large st. resid.

MTB >

Appendix 5-i: The results of a multivariate regression analysis. In this analysis, the dependent variable (precipitation [inches]) was regressed over three independent variables [longitude, latitude (decimal degrees), and elevation [feet]].
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>63</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>158</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>251</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>353</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>502</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>654</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>800</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>964</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1134</td>
<td>100</td>
<td>0</td>
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</tr>
<tr>
<td>1328</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1532</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1748</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2077</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2512</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3061</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3640</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4096</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4872</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5688</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6544</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7544</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8704</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10000</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Appendix 5.5: The frequency distribution of the daily Sierra River discharge data (1968-90). The discharge classes were defined on a logarithmic scale. This analysis of daily discharge data is a pre-requisite to discharge-frequency curve preparation.
Siran_HYDMAPS

Readme.txt

Siran_HYDMAPS is a distributed hydrological modelling system for the Siran Basin, Pakistan. This includes five inter-linked modules encoded in C.

Compilation

1. The programmes provided herewith are IRIX 5.0 compatible. They include five analytical modules viz: evap_m1.c, evap_m2.c, interl.c, infiltl.c and stat.c while the sixth one, link.c, is an inter-linkage programme.

2. Transfer these programmes in ASCII mode to IRIX and compile each of them to object files (.o files) using the command line:

   cc -c program.c -lm

3. Inter-link these objects into an executable programme Siran_HYDMAPS using this command line:

   cc -o Siran_HYDMAPS link.o evap_m1.o evap_m2.o interl.o infiltl.o stat.o -lm

4. Execute Siran_HYDMAPS either at $ or ARC prompt.

Data Preparation

Each module in Siran_HYDMAPS needs to scan one or more layers of GIS data. The data provided with the programmes exists in compressed (.Z) format. To make it readable by the model, prepare it following these steps:

1. Transfer compressed (.Z) files to IRIX in binary mode.

2. Uncompress all files. The inflated files will have no extension.

   -continued-
3. Rename these GIS files with .asc extension, e.g. convert dtm to dtm.asc file. This renaming is essential since the default names specified in the programmes end with .asc. The default file names the programme searches for are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>dtm.asc</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>slope.asc</td>
<td>Slope Map</td>
</tr>
<tr>
<td>aspect.asc</td>
<td>Aspect Map</td>
</tr>
<tr>
<td>cover79.asc</td>
<td>Land Cover Map for 1979</td>
</tr>
<tr>
<td>cover89.asc</td>
<td>Land Cover Map for 1989</td>
</tr>
<tr>
<td>snowcov.asc</td>
<td>Snow Cover Map</td>
</tr>
<tr>
<td>texture.asc</td>
<td>Soil Textural Classification</td>
</tr>
</tbody>
</table>

4. The meteorological data files exist in text format, e.g. met1979.txt. They should be transferred to IRIX in ASCII mode and no change is required.

NB: The compiled programme and all data files must be in the same directory.