GIS BASED STUDY OF GEOMORPHOLOGY, LANDUSE AND WATER RESOURCE IN SMALL WATERSHEDS

A THESIS

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WATER RESOURCES DEVELOPMENT

by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **GIS BASED STUDY OF GEOMORPHOLOGY, LANDUSE AND WATER RESOURCE IN SMALL WATERSHEDS** in partial fulfilment of the requirement for the award of the Degree of Doctor of Philosophy and submitted in the Department of Water Resources Development and Management of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from January, 2004 to July, 2008 under the supervision of Dr. U. C. Chaube, and Dr. S. K. Tripathi, Professors, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(DESHMUKH DHANANJAY SURESH)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

A proper understanding of morphological parameters, land use and land cover, underlying geology and hydrological behavior of a watershed can be significantly useful in watershed planning particularly in the absence of observed time series data. Literature review has brought out the following observations which motivated the present research work.

(i) Comparative study of different watersheds in terms of several morphological parameters is tedious and lacks clarity. There is need to evolve suitable watershed indices which represent combined effect of several parameters on permeability of geological formation and intensity of erosion.

(ii) Land use and land cover is undergoing significant changes at the level of small watersheds. Such changes can not be ignored in developmental planning.

(iii) Error in flood estimation and hydrologic design of structures may occur if watershed is assumed to be linear (unit hydrograph theory) while in fact its response may be nonlinear.

(iv) Observed hydrological data is usually not available for small watersheds. In such situations regional approach is followed. There is a need to evolve methods for establishing homogeneity among the watersheds.

(v) Potential of Remote Sensing and GIS techniques is considerably greater than the research work has addressed so far.

(vi) Watershed development and management, to be sustainable, has to be based on satisfying the basic needs of the local population. This aspect needs to be integrated in watershed planning process.

In this context, a GIS based study of an area covering geomorphology, geology, dynamic changes in land use caused by human interference and hydrologic behavior has been carried out.

Study Area

The study area covers watersheds of three adjacent rivers namely Barureva (488 km^2), Sher (1635 km^2) and Umar (699 km^2) which conjoin together to form an important southern sub-basin of Narmada basin in its upper reaches in Madhya Pradesh State of India. Umar and Barureva rivers are, in fact, tributaries of Sher River. From the south of the Satpura highlands down to the Narmada in the north, drainage system of the three rivers represents an accretional plain of alluvium deposits. The study area has

been divided into 89 sub watersheds (68 are of the 4^{th} order). Size of these is in the range of 1.77 sq km to 219 sq km.

Morphological Analysis of the Study Area

Morphological parameters of the three watersheds (Barureva, Sher and Umar) and their corresponding fourth order sub watersheds have been calculated with help of data attributes generated from the GIS analysis. A major part of Barureva (77.4%) and Umar (89%) watersheds are within 0 to 3% slope range. Sher watershed is comparatively hillier exhibiting considerable range of slope (nearly flat to very steep slope zone).

Q-Q plots and frequency histograms of 1-4 orders length suggest the normality of the data hence all the 89 sub watersheds have been retained for further analysis.

The fractal dimensions have been computed from power relationship of drainage parameters with area using data of 68 sub watersheds. Along with these fractal dimensions, degree of randomness (Cheng et al., 2001) is determined by combining several fractal dimensions into a single factor with help of principal component analysis. The spatial distributions of chosen fractal dimensions and degree of randomness are depicted for 68 sub watersheds to explain the pattern of drainage evolution and geological control in relation to various geological formations. The evolution of drainage pattern and shape of sub watersheds formed on the alluvium is highly controlled by alluvium formations, where as the evolution of drainage pattern and shape of sub watersheds formed on Deccan trap is found to be least controlled by its formation. The extent of geological control on drainage pattern goes on decreasing as the share of the alluvium formation decreases.

Geomorphological Permeability Index

A Geomorphological Permeability Index (GPI) considering length ratio (R_t), drainage density (D_d), drainage frequency (D_f) and relief ratio (R_h) has been proposed to assess the nature of permeability and ground water recharge potential in eighty nine sub watersheds.

GPI values are in the range of 0.05 to 119. Sub watersheds on alluvium formation have GPI higher than 20 whereas sub watersheds with GPI in the range of 0.05-2.55 are formed on the Deccan trap which is massive compact and impermeable. Field visits have shown that in those watersheds having GPI values less than 1, ground water structures are either very less or nonexistent. Settlements in these watersheds are very scanty.

Sub watersheds with GPI values in the range of 4.8-6.3 have alluvium formation (37-51% of area) in lower part while upper part is dominated by hilly and hard rock formations. This type of situation is suitable for ground water recharge in lower part and rain water harvesting in the upper hilly part.

Sub watersheds comprising of 16-28% alluvium formation show low values of GPI (1.2-1.85). These sub watersheds are in runoff production zone and suitable for surface water harvesting. These watersheds require erosion control measures.

Therefore on the basis of proposed GPI, the sub watersheds may be identified for suitable treatment measures in terms ground water recharge, surface water harvesting and erosion control structures.

Morphological Index of Erodibility

Part of Sher, Barureva and Umar watersheds near the confluence with Narmada river and entire area of small tributaries (Dhamani and Saras rivers) were affected by badland formation in the year 1972. Over the years, these badlands have been mostly reclaimed for agriculture use as discussed in Chapter 7. However an index of erodibility has been proposed and used to identify and compare severity of erosion as existed in the year 1972 in different watersheds.

The MIE index uses morphological parameters such as drainage density (D_d), drainage frequency (D_f), texture ratio (T) and relief ratio (R_h) which have direct relationship with soil erosion while shape parameters(R_c, R_e and R_f) have inverse relation with soil erosion.

The isopach map shows alluvium deposits underneath, in the range of 30 m to more than 150 m in depth. Intensity of badland network is found to be maximum within 1 km distance to major river course. It is also observed that encroachment of badland formation is more intense on alluvium deposits which have the depth 120 m or more.

Morphological index of erodibility (MIE) have been estimated for eight watersheds which are under the badland formation. MIE index values for these watersheds vary from 811 to 9208. A watershed which has alluvial formation and under agricultural use (not affected by badland formation) has the morphological index value of 200. It is recommended that a watershed in this region can be characterized as badland if its MIE is more than or equal to 4 times the MIE of normal watershed under agricultural use having same geological formation (alluvium). MIE index can be used as simple tool to quantify the degradation of watersheds.

Analysis of Land Use and Land Cover Changes

Land use and land cover of the Barureva, Sher and Umar watersheds have been determined for three different years i.e. 1972, 1989 and 2000 using satellite imageries.

Processing of satellite imageries: Band layers of the satellite imagery for the years 1972, 1989, 2000 are based on different sensors. Classification of satellite imageries has been done using visual interpretation technique. The recent satellite imagery pertaining to year 2000 was selected initially. Recent photographs and spatial data base information are used to understand and recognize color, texture and tone of intended land use and land cover in the study area. Classified superimposed polygon layer of year 2000 is used as guide layer to identify the changes in size, colour, texture and tone of patches of land classes in a satellite imagery layer of year 1989. According to changes observed in the size of the land classes, these have been modified in superimposed polygon layer and saved as land use and land cover of 1989. Similar procedure is applied for land use and land cover classification of year 1972. Recognizable changes have taken place in land classes in the three watersheds during period from 1972 to 1989 (17 years) and during period from 1989 to 2000 (11 years). The land use changes are analyzed in terms of magnitude of area, percent change and dynamic rate of change per year for the intended periods. Moreover dynamic transition matrixes for three watersheds have been used to explain the conversion of land classes.

Agricultural area has now become dominant in Barureva (72%) and Umar (77%) watersheds. The expansion in agricultural areas in these watersheds has occurred through reclamation of badland areas. Rate of deforestation in recent time period (1989-2000) has been comparatively higher than for the previous period (1972-1989). The barren land in Barureva and Umar watersheds has decreased in recent period (1989-2000) due to conversion into agriculture land. On the other hand, barren land in Sher watershed has increased by 13.71% due to deforestation in recent period (1989-2000). The expansion of urban settlement has mostly occurred by replacing agricultural area. The upper part of Sher watershed shows higher amount of water body area in comparison to Barureva and Umar watersheds. The appearance of water bodies in the upper part of watersheds areas suggests that surface water storage is necessary for expansion of agricultural area.

Relation of GPI and LULC:

Land use changes have also been studied at sub watershed level and correlated with their GPI values. Following inferences are drawn based on study.

1) Increase in surface water bodies has occurred in those sub watersheds whose GPI values are less than 15. Without further increase in water bodies these sub watersheds (remotely located and scattered settlements) will undergo more deforestation to increase the rainfed agriculture area for meeting food demand.
2) There is no definite relation between increase in settlement size and increase in water bodies suggesting that domestic water supply is not dependant on surface water. On the other hand increase in settlements has occurred in sub watersheds having GPI greater than 15 suggesting groundwater as main source of water supply to the settlements.
3) Barren land existed in sub watersheds having GPI less than 10 but has now been converted into agricultural land.
4) Sub watershed having GPI greater than 15 do not depend on surface water bodies for increase in agriculture and water supply to settlements.

Driving Factors for Change in Land Use and Land Cover

The study area consists of rural watersheds. Driving factors for change in land use and land cover are related to basic human needs (food, fodder and fuel) and economic dependence on agriculture in the study area. Demand of food, fodder has to be met locally in absence of adequate infrastructure facilities and low purchasing power of population in the remotely located sub watersheds. Analysis of land use and land cover shows that the rate of deforestation has accelerated in recent period to expand agricultural area so as to meet demand of food and fodder and to improve economic status. A sample analysis of Umar watershed illustrates the following.

Whereas population has increased by 79.42% during thirty years period of analysis, agriculture area increased by 42.97% only. Umar is an agricultural watershed with 67.02% percent area under alluvium. Pressure of food demand on available agriculture land has tremendously increased necessitating improvement in crop production through use of ground water for irrigation. Falling trends in ground water level are observed in alluvial sub watersheds. On the other hand rising trend is observed in wells located in upper part of study area over Deccan trap formation (19S, 53S, and 55S). Agriculture area in these sub watersheds has remained nearly static. Rise in water table is probably due to creation of water bodies in these sub watersheds. Pressure of fodder demand on forest and barren land has increased by 107.36% over 30 years period. However it is reasonable to believe that part of this pressure might have been eased by crop residue which is also used as fodder.

Runoff Potential under Varying Land Use and Land Cover

Curve number (CN) in the SCS-CN method represents runoff potential which is an important consideration in surface water utilization and for design of hydraulic structures and erosion control measures.

The CN computed from observed rainfall (P) and runoff events (Q) is termed as CN (PQ). The CN computed using land use and land cover is termed as CN (LU). The analysis has been carried out to (1) use observed data sets of rainfall (P) and runoff (Q) events of period greater than 1-day and develop year wise series of Curve Number (CN(PQ)), (2) estimate yearly series of Curve Number using land use and hydrological soil cover data (CN(LU)) and compare with observed CN(PQ), (3) forecast runoff potential i.e. CN(LU) on the basis of change in land use,(4) test the performance efficiency of SCS-CN method on gauged Sher watershed and its application to nearby ungauged Barureva and Umar watersheds and (5) compare the CN values of popular SCS-CN method and slope adjusted SCS-CN method at watershed level and at sub watershed level for assessing effect of slope on runoff potential.

The CN (PQ) values have been computed in Sher watershed for the selected 187 rainfall-runoff events spread over 26 years (1977-2002). Most of the selected events have duration of 4-7 days. Observed events mostly occur in month of July, August and September.

The annual CN (PQ) is defined as average of CN values for rainfall-runoff events in a year. It varies in the range of 69 to 87 over 26 years. The median value of CN (PQ) for observed data period is about 74 and average value is about 75. Values in the range of 70-79 are most significant values and these truly represent the AMC II condition of the Sher watershed.

Estimation of CN from land use and land cover: CN values estimated on the basis of land use and land cover are termed as CN (LU). The classified land use maps of different years are crossed with hydrological soil group map by GIS operation to generate the collective layer. Thereafter the collective layers have been assigned the CN values appropriate for Indian condition. The collective layers with their assigned CN values have been used to generate distributed CN map of years 1972, 1989 and 2000.

The annual CN (LU) values show rising trend with the time. The increase in CN (LU) with time period is attributed to increase in agriculture area in all watersheds. The equations of trend of CN (LU) with time (year) for three watersheds can be used to predict runoff potential with change in land use and land cover in future.

Comparison of CN (LU) and CN (PQ) values shows close agreement. Moreover, derived land use land cover data from satellite imageries from years 1972, 1989 and 2000 also gets validated. The SCS–CN method along with annual CN (LU) values has been used for computation of daily runoff over period of 26 years. The agreement between computed and observed event runoff has been judged on the basis of the NS efficiency and RMSE values. The NS efficiency for entire data set (for all events spread over 26 years) is about 75 % which is quite satisfactory. Model performance is again verified by plotting computed and observed runoff with the line of perfect fit. It is concluded that the SCS method with dynamic annual CN (LU) is capable to predict direct runoff satisfactorily in gauged Sher watershed. Therefore the dynamic CN (LU) estimated for ungauged Barureva and Umar watersheds can be used for runoff prediction being under same hydrometerological zone.

Although the effect of the slope on runoff volume has been established by research studies, few attempts have been made to study effect of topography in the SCS-CN method. The present study shows that slope adjusted CN is less than conventional CN over areas with slope less than 5% and more than conventional CN for areas with slope more than 5%. Higher the deviation from 5% slope more is the difference. Significant difference in CN is observed in the forest lands which are usually located on slopes. For micro watershed planning, SCS-CN method should be modified to incorporate effect of change in land use also in addition to effect of slope. Further research is needed to study effect of morphological parameters on the curve number.

Hydrologic Nonlinearity of Watersheds

Hydrologic linearity is related to the mutual proportionality of hydrograph peaks and runoff depths for storms of same duration. The peak discharge volume relationship ($\log Q_p = b + m\log V$) proposed by Rogers (1980) without consideration of storm duration is empirical in nature. In spite of its criticism, the relation between peak discharge-runoff volume has been subject of research around the world due to its simplicity and potential applications.

Analysis of 1 hour unit hydrographs (V=1 cm) of 18 watersheds in Narmada basin shows strong correlation between peak discharge and catchment area (in log space) as the duration of rainfall excess is same (1 hour). However, in general, basin area alone can not be used to explain variance of b ($b=\log Q_p$ for unit hydrographs) if duration of storm is not same.

Slope of PDVR in log-log space (m) can be used as a measure of non linearity and to identify family of hydrologically similar watersheds. Analysis of 30 flood hydrographs of four watersheds (Umar, Kolar, Teriya and Temur) in upper Narmada basin shows that these watersheds exhibit nonlinear hydrologic character. Regression analysis shows strong correlation between peak discharge and runoff volume (0.872 to 0.983) for these four watersheds. Analysis of relation in logarithm space between V and q_p/V^2 suggests hydrologic similarity between all the four watersheds.

Error in hydrologic design can occur by over estimating or underestimating flood discharge when a watershed is assumed to be linear while in fact it may be nonlinear in terms of catchment's response to rainfall. Case study of Umar watershed shows that UH model is not applicable in this nonlinear watershed and PDVR can be reliably used for prediction of peak discharge. Therefore the popular usage of UH theory necessitates validation of linearity concept in the rainfall-runoff process.

Peak discharge per unit excess rainfall in the 89 sub watersheds have been estimated using relation between b and the geomorphological parameters such as A, S and L. A large part of watershed is found to have flood potential in the range of 0.2 to 5 $m^3/s/km^2$ of the watershed. In a more realistic study, flood potential of different sub watersheds should be compared for unit rainfall and not for unit excess rainfall. However the value of m (degree of non linearity) is required for these ungaged sub watersheds.

Keywords : Morphological analysis, Fractal analysis, Geomorphological Index of Permeability, Morophological Index of Erodibility, Badland formations, Land use land cover change, Driving factors, Runoff potential, SCS-CN method, Hydrologic nonlinearity and similarity.

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A	Watershed area
AMC-I	Antecedent Moisture Condition for dry condition
AMC-II	Antecedent Moisture Condition for normal condition
AMC-III	Antecedent Moisture Condition for wet conditions
b	Intercept of relationship between log Q_p and logV
C_m	Constant of channel maintenance
CN	Curve Number
CN(LU)	Curve Number derived from Land use and soil cover information
CN(PQ)	Curve Number estimated from observed data of P and Q
CN_2	CN for antecedent soil moisture condition II
CN_3	CN for antecedent soil moisture condition III
D	Fractal dimension from power law relationship of sum of total stream length of all order and area
D1	Exponent from power law relationship of sum stream length of first order and area
D2	Exponent from power law relationship of sum stream length of first order and area
D3	Exponent from power law relationship of sum stream length of third order and area
D4	Exponent from power law relationship of sum stream length of fourth order and area
D_d	Drainage density
DEM	Digital Elevation Model
D_f	Drainage frequency
D_{lm}	Fractal dimension from power law relationship of main stream length and area
Dn	Fractal dimension from power law relationship of total number of streams of all order and area
Dp	Fractal dimension from power law relationship of basin length and area
DSRO	Direct Surface Runoff
ETM+	Enhanced Thematic Mapper

GIS	Geographic Information System
GPI	Geomorphological Permeability Index
H	Maximum watershed relief
HSG	Hydrological Soil Group
Ia	Initial abstraction
ILWIS	Integrated Land and Water Information System
IUH	Instantaneous Unit Hydrograph
L_b	Watershed length
L_c	Centroid of catchment
L_g	Length of overland flow
L_{MS}	Main stream length
L_p	Watershed perimeter
L_u	Total stream length
LULC	Land use and land cover
m	Slope of the line of relationship between log Q_p and logV
MIE	Morphological Index of Erodibility
MSS	Multi-spectral Scanner
NS efficiency	Nash-Sutcliffe Efficiency
N_u	Stream number
P	Total rainfall
PCA	Principal Component Analysis
PDA	Fractal dimension from power law relationship of perimeter and area
PDTVR	Peak discharge, time and volume relationship
PDVR	Peak discharge and volume relationship
Q	Direct runoff
Q_{comp}	Computed event runoff depth
Q_{obs}	Observed event runoff depth
Q_p	Peak discharge
R_b	Bifurcation ratio
Rbl	Ratio of bifurcation ratio to length ratio
R_C	Circularity ratio
R_e	Elongation ratio

R_f	Form factor
RGB	Red Green Blue
$R_{h)}$	Relief ratio
RMSE	Root Mean Square Error
R_N	Ruggedness number
R_r	Relative relief
R_t	Length ratio
S	Potential maximum retention
$SACN_2$	Slope adjusted CN for antecedent soil moisture condition II
T	Drainage texture
T_b	Base period of hydrograph
TM	Thematic Mapper
T_p	Time to peak
t_p	Watershed lag time
T_r	Time of excess rainfall
UH	Unit Hydrograph
UTM	Universal Transverse Mercator
V	Runoff volume
α	Soil slope (m/m)
μm	Micro meter

CHAPTER 1
INTRODUCTION

A watershed may be defined as a topographically delineated area which catches the water through precipitation and drains the water through ordered streams to a common outlet. A watershed is a hydrological unit that has also been described as a geomorphologic, physical, biological unit and on many occasions as a socio-economic unit for planning and management of natural resources. Watershed management refers to integrated management of natural resources on watershed basis for sustainable utilization, in which conservation of land and water resources play an important role. A system is considered to be sustainable if it conserves the natural resource base without causing degradation and continues to satisfy the needs of people on long term basis.

Land, water and vegetation are the most important natural resources for providing environmental and livelihood security to the inhabitants. Watershed inhabitants practice multiple uses which involve production of food, fiber, fuel and fodder. In addition, most of the development activities are closely associated to the development of land and water resources. People have often used natural resources indiscriminately for meeting their basic needs.

The basic principle of watershed management is to utilize the land and water resources without causing degradation. A major step in a conservation oriented management process is inventorying and classifying land and then judging its capacity to support certain uses on a sustainable basis. A balanced assessment of geomorphologic, hydrologic, land use and land cover characteristics are basic for making rational use of land and water resources in a watershed.

1.1 BACKGROUND OF THE STUDY

Watershed based activities in India have focus on agriculture development through utilization of land and water resources in small size watersheds. Observed time series data in small watersheds is usually not available. In such situation, integrated analysis of morphological parameters, land use and land cover, underlying geology and hydrological behavior of watershed can be significantly useful. Literature review has brought out the following which motivated the present research work.

(i) Research work has shown that a number of morphological parameters together influence a particular watershed characteristic for example permeability is influenced by drainage density, drainage frequency, length ratio and constant of channel maintenance. Comparative study of different watersheds in terms of several variables and parameters is tedious and lacks clarity. Watershed indices can be used to represent combined effect of several parameters as is done in case of water quality interpretation. Characterization and comparative study of large number of small watersheds then becomes convenient.

(ii) Land use in a watershed is generally considered to be a stationary property. However literature shows that land use and land cover is undergoing significant changes due to increasing human interference.

(iii) Hydrologic and geomorphological characteristics evaluated at watershed level are often assumed to be uniform over the watershed. Changes in properties occurring at sub watershed level (such as increase/decrease in forest cover and agricultural land) may not be reflected at watershed level and the watershed may appear to have uniform properties while in fact spatially distributed non uniform changes may be occurring within the watershed. Such changes should not be ignored in developmental planning and particularly in analyzing hydrologic behavior.

(iv) A watershed is often assumed to be hydrologically linear implying applicability of unit hydrograph theory. Error in flood estimation and hydrologic design of structures may occur if watershed is assumed to be linear while in fact its response may be nonlinear. In small size watersheds non linearity may be significant and unit hydrograph theory may not be applicable.

(v) Observed hydrological data is usually not available for small watersheds. In such situations, regional approach for hydrologic analysis is followed assuming the region to be morphologically and hydrometeorologically homogenous. There is a need to evolve simple methods for establishing homogeneity among the watersheds.

(vi) Per capita availability of agriculture land which is the main source of livelihood in rural India has been decreasing due to population growth. This has necessitated not only control of badland (highly eroded and dissected land) formation but also reclamation of existing badland for productive use. There is a need to evolve an index to characterize the magnitude and severity of badland formation.

(vii) Planners have often adopted segment approach to watershed management. Potential of Remote Sensing and GIS techniques is considerably greater than the research work has addressed so far. It can be useful in synthesis of various aspects of watershed and thus help in adopting integrated approach to watershed management. GIS and Remote Sensing can be useful in analyzing inter-relation between morphological parameters, land use, underlying geology and hydrological behavior of watershed. Such analysis can be significantly useful in watershed planning particularly in the absence of observed field data on surface and ground water resources.

(viii) Watershed development and management, to be sustainable, has to be based on satisfying the basic needs of the population. This aspect needs to be integrated in watershed planning process.

1.2 SCOPE AND OBJECTIVES OF STUDY

Developmental planning and sustainable use of land and water resources should be based on scientific evaluation of various static and dynamic properties pertaining to various physical sciences. Methods, models and modern tools have been used in the past, watershed properties have been analyzed to serve a limited objective, usually pertaining to a particular scientific discipline. This study makes an attempt to integrate some important aspects as shown below in objectives.

Objectives of the Study

1. To carry out GIS based study of an important part of Narmada basin (Sher Barureva and Umar watersheds and its sub watersheds) covering interrelated aspects of geomorphology, geology, land use, human interference, surface and ground water resources. Following are the specific objectives:
2. Analysis of morphological parameters of small watersheds and to study influence of various geological formations on drainage pattern evolution.
3. Development of morphological indices for identification of erosion risk areas, water harvesting areas, ground water recharge areas and bad land characterization.
4. To analyze changes in land use and land cover over a period of time and at macro and micro watershed level using remote sensing data.
5. Analysis of population pressure, food and fodder demand as driving factors for changes in land use land cover and exploitation of ground water resource.
6. To assess runoff potential (SCS-CN method) and the effect of changes in land use land cover and topography on runoff potential of a watershed.
7. To analyze hydrologic nonlinearity and similarity of small watersheds in relation to flood estimation in ungaged watersheds.

1.3 ORGANIZATION OF THESIS

The thesis is arranged in eleven chapters as follows.

Chapter 1: The first chapter provides background for the research problem and the objectives which are proposed to be achieved in this research work.

Chapter 2: This chapter covers literature review in three sections. First section deals with literature on morphological parameters and fractal dimensions in relation to geology.

Second section covers review of Remote Sensing and GIS based studies on land use and land cover changes. Third section covers review of literature on SCS-CN method and linear/nonlinear behavior of watershed.

Chapter 3: This chapter deals with compilation and processing of available data and information pertaining to the study area (topography, drainage pattern, climate, geological setting, ground water condition and aquifer characteristics, land use pattern, soils, human and animal population, irrigation schemes). The data used for various analysis and source of data are mentioned.

Chapter 4: This chapter deals with (i)derivation and inter correlation of morphological parameters of the study area (Barureva, Sher and Umar watersheds and the associated sub watersheds), (ii)study of drainage evolution on various geological formations and (iii) preparation of spatially distributed data base required in subsequent studies on identification of erosion risk areas, surface storage sites, ground water recharge sites(Chapter 5),badland characterization(Chapter 6), runoff potential (Chapter 9) and nonlinearity in hydrological behavior of watersheds(Chapter 10).

Chapter 5: This chapter deals with formulation and estimation of geomorphology based permeability index (GPI). It has been applied for identification of appropriate treatment measures (ground water recharge, rainwater harvesting and erosion control) based on GPI values of various sub watersheds.

Chapter 6: This chapter deals with study of badland formation which once had significant coverage in the study area. The chapter covers analysis of morphological parameters of badland area and geological and river network setting and estimation of morphological based index values for characterizing magnitude and severity of degradation caused by erosion.

Chapter 7: In this chapter land use and land cover of the study area is obtained by visual interpretation of satellite imageries for three different years (1972, 1989, and 2000). The land use pattern of study area has been analyzed though prepared maps, tables and dynamic transition matrices. The land use changes have been analyzed at sub watersheds level also and these changes have been correlated with geomorphological permeability index of the sub watersheds.

Chapter 8: This chapter covers analysis of population pressure, food and fodder demand as driving factors for changes in land use land cover and exploitation of ground water resource.

Chapter 9: This chapter covers analysis of Curve Number (CN) of SCS-CN method which is used as indicator of runoff potential of a watershed. The analysis has been carried out with the purpose (1) to use observed data sets of rainfall (P) and runoff (Q) and develop year wise series of Curve Number (CN (PQ)), (2) to estimate yearly series of Curve Number using land use and hydrological soil cover data (CN (LU)) and compare with observed CN (PQ). (3) to forecast runoff potential on the basis of change in land use. (4) to test the performance of SCS-CN method on gauged Sher watershed and its application to nearby ungauged Barureva and Umar watersheds. (5) to assess effect of slope on runoff potential.

Chapter 10: This chapter deals with the application of peak discharge-volume relation and morphological parameters for identification of hydrologic similarity of watersheds and estimation of flood potential in various sub watersheds using regression equations developed on the basis of drainage basin similarity.

Chapter 11: This chapter presents important conclusions drawn from the study of Sher, Barureva and Umar watersheds.

CHAPTER 2
REVIEW OF LITERATURE

Literature has been reviewed and arranged in following three sections.

First section: covers morphological studies for watershed prioritization and discussion of fractal dimensions in relation to geology of a watershed.

Second section: covers Remote Sensing and GIS based studies on land use and land cover changes. Land use and land cover are significant dynamic properties of a watershed as these are easily and directly influenced by human activities.

Third section: covers two specific aspects of watershed hydrology namely (i) description and application of popular SCS-CN method for estimation of CN which is indicative of runoff potential of a watershed and (ii) nonlinearity in rainfall-runoff response.

The present research work deals with watershed study in GIS environment. Therefore such studies which involved application of GIS have been reviewed.

SECTION-I

2.1 MORPHOLOGICAL BASED STUDIES

2.1.1. Morphological Parameters and Watershed Prioritization

Morphological parameters have been studied by researchers for erosion assessment and for determining relation between different morphological parameters. An important advantage of morphological analyses is that many of its parameters are in the form of ratios or dimensionless numbers thus providing an effective comparison of different watersheds regardless of scale.

In earlier studies, investigations were made to relate single morphological parameter with other watershed characteristics. Bucko (1958), Mikhailov (1972) and Mishra (1980) used drainage density of a watershed for assessing the soil erosion categories. Miller and Charles (1960) and Bhan (1988) used slope units for delineating erosion risk categories. Mishra (1980) reported that an increase in form factor reduces the sedimentation production rate and that drainage density is directly associated with sediment production rate. However in recent time, researchers recognized that various morphological parameters other than drainage density and slope parameters also need to be evaluated and these can be used in combination for the risk assessment and for prioritization of watersheds in absence of observed field information.

Morphological studies in India

Chaudhary and Sharma (1998) carried out morphological analysis for Giri river catchment located in North Western Himalayas. Morphological parameters such as drainage density, relief ratio, and drainage texture and bifurcation ratio were computed for 36 sub catchments of Giri watershed. Sub catchments have been prioritized using mean value of the four morphological parameters as an index. The index is related to the severity of soil erosion. Severest erosive sub catchment is found to have highest value of the index.

Goel (2003) used morphological parameters for prioritization of 32 sub catchments of Soan river situated in lower Shivaliks Hills in Una district of Himachal Pradesh. The ranking of priority have been fixed on the basis of individual values of morphological parameters which are directly associated with the soil erosion. Individual parameters were then used to obtain an averaged priority index which is finally used to rank the sub catchments. The standard deviation of morphological parameters is also used to assess similarity of the sub catchments. Regression analysis among morphological parameters suggested that drainage density has good correlation with the slope and drainage texture.

Singh et al (2003) estimated morphological parameters of sub watersheds of Nana Kosi watershed from Kumaun lesser Himalayas. Various morphological parameters were used to analyze runoff, soil erosion and sediment delivery ratio etc. Morphological parameters along with land use information have been used in the ranking process for resource management.

Pandey et al. (2004) estimated various morphological parameters of sub watersheds of Karso watershed which is situated in Damodar Barakar catchment. Morphometeric parameters were coupled with the land use and soil cover to obtain the integrated map to explain condition of runoff and soil loss in the sub watersheds. Integrated map layers reflecting hydrological and geological conditions were used for delineation of areas for soil and water conservation measures.

Nookaratnam et al. (2005) used morphometric analysis and sediment yield index (SYI) for prioritization of Tarafeni watershed in Midnapur district, West Bengal. Total 82 micro-watersheds from Tarafeni watershed were analyzed for estimation of various morphological parameters. Morphological parameters of micro-watersheds have been ranked on the basis of relationship with soil erosion. A combined parameter of priority has been estimated by averaging the ranks of various morphological parameters of micro-watershed. Low value of index indicates severe erosion and vice versa. SYI values and morphological parameters based ranking together resulted in better prioritization of micro watersheds and to find suitable check dam positioning.

Remote sensing and GIS techniques are being increasingly applied by researchers in India in morphological study of watersheds (Shrivastava, 1997; Nag and Chakraborty, 2003; Shrivastava et al., 2004; Chopra et al., 2005; Suresh et al., 2004; Raju et al., 2002; Tiwari et al., 1997) extracted watershed parameters to develop an empirical model for seasonal runoff estimation using remote sensing and GIS techniques.

2.1.2. Morphological Parameters and Artificial Recharge

Pakhmode et al. (2003) studied Kurzadi watershed in the Deccan volcanic regions in west-central India. Study revealed that drainage density, drainage frequency, length ratio and slope parameters can be effectively used to describe the permeable and impermeable nature of underlying geological formation. Study concluded that a combination of hydrogeological mapping and drainage analysis can form an important tool for identification of artificial ground water recharge sites and surface water storage sites.

Anbazhagan et al. (2005) studied artificial groundwater recharge in Ayyar watershed, Tamil Nadu, India. Thematic map integration was used for demarcation of suitable areas for artificial recharge. Study showed that prioritization of watersheds for artificial recharge planning can be done on the basis of availability of runoff, aquifer dimension, priority areas and water table conditions in different watersheds of a basin.

2.1.3 Morphological Analysis of Badland Formation

Badlands are densely dissected areas, which have been severely eroded and where soil has disappeared or lost most of its fertility. The combined effect of climate and continuous use of erosive land for agriculture prevents the soil from forming or recovering its fertility and erosion continues (Fairbridge, 1968). Formation of badlands gets activated through several processes such as head cutting in gully, scouring, selective erosion transport of sediment (Kirkby and Bull, 2000). The major factors in badland formation and aggravation are excessive human interference, destruction of original protective vegetative cover and accelerated soil erosion. Badland formation exhibits particular land topography and stream morphology, which determine the rate of development of badlands. (Smith and Bretherton, 1972; Howard and Kerby, 1983).

Origin of ravineous channel systems owes to gullying processes which gradually or rapidly grow in dimensions and network. The subject of gully expansion and badland formation has been widely studied in various parts of the world.

Brice (1966) defined a gully as a 'recently extended drainage channel that transmits ephemeral flow, has steep sides, a steeply sloping or vertical head scarp, a width greater than 0.3 m and a depth greater than 0.6 m'. Brice fixed the lowest dimension of a gully, while the ravineous limit of gully development has dimensions of many meters, more than 150 m in width at places between upper edges and in depth up to 50 m or even more, such as in Chambal ravines in north Central India. Tignath et al. (2005) observed that channel system in the badlands of Narmada valley of Central India have average width in the order of 40- 80 m and depth between 5 m and 10 m. Cross-section geometry depends on subsoils and varies from U-shaped in nonresistant to V-shaped in resistant subsoils in the channels.

Brice (1966) and Tuckfield (1964) among many others estimated the rate of gully development, which may not be uniform or continuous. According to Brice (1966), one gully extended 228m in fifteen years, and 107m of this length developed in only one year as result of very high run-off. The channel entrenchment along some of the 2^{nd} and 3^{rd} order tributaries of Sakkar river (near to the present study area) is seen to be of the order of 1000m which occurred in the span of about fifty years (Tignath et al., 2005). In valley-floor gullies, the scarp normally advances up-valley, facilitated by sloughing of material around the margins of plunge pool, and this process leads to increase in height of the head scarp (Blong, 1966). Tuckfield (1964) showed the development of gullies to start from evenly spaced pits on valley floor.

2.1.4 Morphological Parameters and Geological Influence

Agarwal and Chakraborty (1994) carried out morphometric analysis in part of Mussoorie Syncline using remote sensing. Low value of drainage density indicated high permeability of sub soils and low value of bifurcation ratio indicated lack of geological control on the development of drainage pattern.

Lokesh et al. (1996) estimated morphological parameters using planimetric measurements of Pangala river watershed which is situated in Dakshina Kannada district of Karnataka. Study revealed that bifurcation ratio is about 4.0 indicating mature stage of watershed development and geological structures have least influence on the drainage pattern.

Reddy (2004) studied drainage morphometry of basaltic terrain (Deccan traps), Nagpur district, Maharashtra, Central India. Study found that sub watersheds associated with high drainage density, stream frequency and texture ratio show very severe to severe erosion. The analysis revealed that the influence of drainage morphometry is significant in understanding the landform processes, soil physical properties and erosional characteristics.

Sreedevi et al. (2005) anal yzed various aspects of morphometric characteristics of Pageru River watershed. The elongated shape of the watershed is mainly due to the guiding effect of thrusting and faulting. The erosional processes of fluvial origin are predominantly influenced by the subsurface lithology of the watershed. The analysis indicates relationships among various attributes of the morphometric aspects of the watershed and helps to understand their role in sculpturing the surface area of the region. The importance of such analyses is emphasized in the utilization of its results, for locating sites for artificial recharge. It is noticed that stream segments up to 3rd order traverse parts of the high altitudinal zones, which are characterized by steep slopes, while the 4th, 5th and 6th order stream segments occur in comparatively flat lands. These are important locations for constructing check dams.

Hodgkinson et al. (2006) worked on the relationship between geological fabric and drainage patterns in the 81.8 km2 Laceys Creek sub-catchment of the North Pine River catchment, southeast Queensland, Australia. Study revealed the evidence of the evolution of drainage network and the extent to which geological fabric controls the drainage pattern. Large-scale geological structures and palaeo-controls are likely to be the dominant influences on highest order streams; the middle-orders are mainly controlled by the structural grain and lithological fabric; and the lowest orders not yet incised to bedrock may be influenced initially by neotectonism and exogenic controls. Study also concluded that assessment of the influence of rock architecture on drainage patterns is strongly affected by the scale of analysis.

Mesa (2006) carried out morphometric analysis of Lules River watershed and its watersheds using land-sat imageries and topographical maps. Study concluded that the development of stream segments is affected by slope and local relief. The mean bifurcation ratio indicates that the drainage pattern is not much influenced by geological structures. The drainage densities of the sub-watersheds suggest that the general nature of rocks is impermeable.

Jaiswal et al. (2007) carried out morphometric analysis of Gorna and Baghari watershed of Son river of Shahdol district, Madhya Pradesh. Gorna watershed has high drainage density (2.05 km/km^2) due to presence of hills, high percentage of slopes and rock subsurface compared to Baghari watershed which has low drainage density (1.69 km/km^2) due to devoid of hills and presence of gentle slope. It was observed that low constant channel maintenance (0.49 km^2/km) of Gorna watershed characterized by lineaments guided drainage network compared to constant channel maintenance (0.59 km^2/km) of Baghari watershed. Comparatively high values of average stream length, bifurcation ratio and drainage density of Gorna watershed are indicative of more erosion, less stable topography, high runoff potential and poorer ground water occurrence.

2.1.5 Fractal Dimensions and Drainage Evolution

Meaning of fractals: To describe natural entities, Mandelbrot (1983) developed fractal geometry-the so called 'geometry of nature'. Fractal geometry is useful for describing irregular and fragmented patterns found in many disciplines. For example in assessing the length of a coastline, smaller the unit of measurement, longer is the measured length of coastline. Therefore it becomes difficult to measure actual length of a coastline. Similarly length of individual stream is also fractal in nature.

Hydrologists are interested in calculating two fractal dimensions for streams. The fractal dimension (d) of an individual stream is a measure of its irregularity (extent of a stream's meandering). The fractal dimension (D) of a stream network is a measure of ability of the network to fill a plane, and it arises from the branching nature of the network and sinuosity of individual streams. If a stream network is truly space filling, as in the case of topologically random stream network, one could expect a stream network fractal dimension of 2.0 (Schullar et al., 2001).

Fractal dimension for individual stream (d)

Fractal dimension of stream length derived from the relationship of main stream length and area of watershed has been used to prove the self similarity of drainage network.

Hack (1957) demonstrated the applicability of a power function relating main stream length and watershed area for streams of the Shenandoah Valley and adjacent mountains in Virginia (USA). He found the equation

$L = 1.4A^{0.6}$ Where d/2=0.6 therefore, d=1.2 (2.1)

Where, L is the length of the longest stream in miles from the outlet to the divide and A is the corresponding area in square miles. Hack also corroborated his equation through the measurements given in Langbein (1947), who had measured L and A for nearly 400 sites in the northeastern United States.

Many other researchers have corroborated Hack's original study and although the exponent in the power law may slightly vary from region to region, it is generally accepted to be slightly below 0.6. Equation (2.1) rewritten as

$L \alpha A^h$ with h= 0.5 is usually termed "Hack's law."

Mandelbrot (1983) suggested that an exponent larger than 0.5 in $L \alpha A^h$ could arise from the fractal character of river channels which cause the measured length to vary with the spatial scale of the object. Thus equation (1) would be a reflection of a fractal dimension of river channels close to d_l= 2 x 0.6=1.2

Hjelmfelt (1988) examined data from eight watersheds to test Mandelbrot's (1983) hypothesis that the d of the mainstream channel estimated from the Hack law relationship is in the range of 1.1 to 1.2. He found a mean of d= 1.158 and supported the hypothesis that m values greater than 0.5 reflect the fractal nature of river channels or networks.

Fractal dimension for whole stream network (D)

La Barbera and Rosso (1989) found fractal dimension (D) to vary from 1.5 to 2, with typical values of about 1.6 or 1.7. Generally it is recommended that a reliably measured D near to 2 for stream network should be interpreted as an indication of geologically unconstrained pattern, rather than space filling one, recognizing that unconstrained drainage is not necessarily (or even usually) space filling. It follows that interpretation of D between the range of 1 and 2 should be based on the degree of geological constraints at particular range of spatial scales, rather than on the space filling properties of the network (Phillips J.D., 2002).

Hack (1957) suggested that the drainage density is constant throughout a watershed, or alternatively, that the overland flow distance to each stream is same. Based upon this hypothesis, Feder (1988) derived the following relationship to relate the Horton ratios to the fractal dimension of the mainstream length which arises due to a stream's sinuosity.

$$D = 2\frac{\ln R_L}{\ln R_B}, \qquad (2.2)$$

Where R_L and R_B are the length ratio and bifurcation ratio of stream network.

La Barbera and Rosso (1987, 1989) proposed that the network fractal dimension can be computed as the maximum of the ratio of the logarithm of the bifurcation ratio to the logarithm of the length ratio and 1.0.

$$D = \mathrm{Max}\left(\frac{\mathrm{Log}R_B}{\mathrm{Log}R_L}, 1\right) \quad (2.3)$$

They claimed that this equation permits values of *D* between 1.0 and 2.0 with the mean value falling in the range of 1.6–1.7. They also claimed that empirical results demonstrating decreasing drainage densities with increasing area imply that D should not equal to 2.0.

In a published comment, Tarboton et al. (1990) referred to the fact that La Barbera and Rosso (1989) assumed that individual streams, especially first order, were linear measures with a fractal dimension of 1.0. Taking into account the effects of the individual fractal streams, Tarboton et al. derived the following formulation of the network fractal dimension.

$$D = d\,\frac{\log R_B}{\log R_L} \quad (2.4)$$

Tarboton et al. argued that, when using the stream fractal dimension of 1.14, this formulation produces network fractal dimensions closer to 2.0. They contended that the dimension should be 2.0 since, at high resolutions; one could imagine that a network drains every point and thus fills the area it drains. Tarboton et al. suggested that the phenomenon whereby the drainage density decreases with increasing area may be due to the fact that higher resolution maps are typically used when examining smaller catchments.

Cheng Q. (2001) used following relationships for estimation of fractal dimensions of whole drainage network (D).

(i) Using Hack law- $\sum L \propto A^b$,where b=1/2 D

(ii) D= $\frac{\log R_B}{\log R_L}$, where R_B and R_L Bifurcation ratio and length ratio of stream network

(iii) Graphical relationship of area(A) and perimeter(P) of watersheds was used for computation of D

$P \propto A^b$, where b=1/2 D

Application of Fractal Dimension for Identification of Geological Control

Cheng Q. et al. (2001) extracted conventional morphological parameters for approximately 322 drainage watersheds from a DEM of the Oak Ridges Moraine area, southern Ontario, Canada. The distinct patterns identified on the basis of these parameters and on the basis of combined indices were compared with other datasets (geology, bedrock topography, and drift thickness). The stream networks in the area as a whole have statistical space-filling properties i.e. free of geological constraints. Geological and hydrological interpretations suggest that geological structures, bedrock topography, drift thickness, lithology and slope of drainage watersheds are the main geological and morphological factors influencing the evolution of streams in the area. Dombrádi et al. (2007) estimated fractal dimensions for the Transylvanian watershed and the surrounding mountains representing the left side of the Tisza tributary system in Central Europe. Variation in fractal dimensions within the sub regions of study area are tentatively attributed to different vertical motions of topology affecting the morphology of the catchment, while lithological control appeared to be far less dominant.

The surface stream patterns are usually influenced by the underlying geological formations, topography and various hydrological factors. Horton (1945) developed early theories that demonstrated that many hydrologic measurements were available to quantify the description of river networks and drainage watersheds. Subsequently, ''Horton's law'', a series of power-law type of relations, have been extended by others (e.g. Strahler, 1952; Hack, 1957; Gregory and Walling, 1973). The recent development of fractal and multifractal theory has provided new impetus to this field of study with considerable speculation that a wide variety of landforms are fractals and multifractals (e.g. Mandelbrot, 1983; Seiler, 1986; Hjemfelt, 1988; Tarboton et al., 1988; La Barbara and Rosso, 1989; Korvin, 1992; Phillips, 1993; Goodchild, 1982, 1988; Lavalle´ et al., 1993; Robert and Roy, 1990; Cheng, 1995). Geomorphologists have made efforts to interpret the physical processes that might be related to the various power laws (fractals) and their exponent parameters (fractal dimensions) (Phillips, 1993; Goodchild and Klinkenberg, 1993; Nina Siu-Ngan and Lee, 1993). Although there have been observed departures from the random topology model of Shreve (1966, 1967), careful interpretation of the fractal measures (dimensions) estimated from traditional morphometric parameters might provide useful information for understanding the evolution of landforms and the relationship to the underlying geological constraints.

SECTION-II

2.2 LAND USE CHANGE DETECTION STUDIES

Literature review shows that land use land cover in a watershed has often been assumed to be static. However due to increasing human pressure in recent times land use and land cover changes are being significantly influenced by human activities. It is necessary to study changes in land use and land cover in a watershed for its effective management. Satellite remote sensing data have been proven useful in assessing the natural resources and in monitoring the changes. Results that are obtained from integrating remote sensing and geographic information system can be effectively used to plan and monitor land based activities in a watershed.

Bauer et al. (1979) used LANDSAT Multispectral Scanner (MSS) data covering a three-county area in northern Illinois, USA to study the crop areas. Data were classified using computer-aided techniques as corn, soybeans, or "other." County estimates of the area of corn and soybeans agreed closely with those made by the USDA. Recognition of test fields was 80% accurate. Results of the use of priori information about the crop areas in classification, techniques to produce unbiased area estimates, and the use of temporal and spatial features for classification are discussed. The extendibility, variability, and size of training sets, wavelength band selection, and spectral characteristics of crops have also been investigated.

Shrivastava (1992) applied visual interpretation technique for preparation of land use map and geological setting map of Khargone district of Madhya Pradesh, India. The Landsat TM and IRS IA LISS II imageries of false colour composite are used for extraction of land use and geological settings map. Superimposition of drainage map, geological map, land use/cover map and geomorphological map is done for assessment of recharge area, ground water potential zone and location sites for reservoirs at various tributaries of river network.

Panigrahi et al. (1995) used visual interpretation technique for preparation of land use map of Athagarh block of the Cuttack district of Orissa, India from False Colour Composite of IRS IB LISS-II with bands 2, 3 and 4. Classified land use map along with thematic layers of geomorphology and lineaments, drainage were used to prepare a groundwater potential zone map of the study area.

Ratanasermpong et al. (1995) performed the natural resources assessment of Phuket Island (Thailand) using the integration of visual and digital analysis of Landsat-TM data. Using the method of overlaying, change in natural resources during 1987, 1990, 1992 and 1995 were assessed. Analysis revealed that during period of 8 years (1987-1995), 19 % of the mangrove forest land has been deteriorated by urban expansion, on-shore mining, solid waste disposal and particularly coastal aquaculture called shrimp farming. The results of the study were found to be useful for natural resources management focusing on mangrove forest conservation and protection.

Somporn Sangavongse (1995) detected land use changes due to rapid growth of Chiang Mai city in Northern Thailand. Landsat-5 TM imageries of years 1988 and 1991 were employed in this study. For landsat TM scene 1988, band combination of 2, 3, 4, and 3, 4, 5, were chosen for the supervised classification. For Landsat TM scene 1991, Normalized Difference Vegetation Index (NDVI) image was considered on band combination of 2, 3, 4 and 5 for extracting land use and land cover patterns from this scene. Results show that forested areas decreased by about 29% during 1988 to 1991 while agricultural lands and built-up areas increased by about 5% and 26% respectively.

Mendis and Wadigamangawa (1996) observed land use changes using existing land use survey data of year 1983, satellite TM data of year 1992 and aerial photograph of year 1994 for Nilwala River Watershed in the Southern Province of Sri Lanka. TM image of band combination 3, 5, 7 was classified based on maximum likelihood classifier. The major objective of this study was to find out changes of land use/land cover pattern due to implementation of the Nilwala Ganga Flood Protection Scheme. Study revealed that paddy cultivation has been replaced by habitations and other plantations due to social economic development and topographic factors.

Lwin et al. (1998) monitored forest degradation of lower part of Myanmar. Forest degradation have been extracted from Landsat TM data sets of year 1989 and 1995 and annual forest change by using AVHRR time series images (1989 to 1995).The satellite imageries of different sensors and spatial resolution were classified using clustering and supervised classification. Supervised classification uses spectral differences in classified image, topographic features, previous knowledge for identifying land use classes and selecting its training area for the maximum likelihood classifier. Changes in land cover between the two dates (i.e. 1989 and 1995) were detected using post classification comparison algorithm. Based on detected deforestation changes, future deforestation risk area map was prepared. Deforestation risk map provided guidance or regulation against irrational use of forest resources.

Dahal et al. (2002) assessed the land cover change in tropical rain forest of Labanan province of Berau regency, East Kalimantan, Indonesia using Landsat TM images. Two images Landsat-7 ETM+ acquired on 26th August 2000 and Landsat-5 TM acquired on 12th April 1996 were used in this research. The color composites of band 453 in RGB channels show a comparative view of the land cover classes between the two images. Visual interpretation technique was applied on the RGB color composites of bands. The land classes have been identified by observing the colour, texture, tone of patches. Study revealed that clear felling of timber for resettlement and shifting cultivation reduced forest area. According to the indicators of SNPFM, forest cover change is categorized as "fair" on the intensity scale. This study demonstrated that Landsat images can provide timely information required for monitoring forest change.

Weicheng (2002) detected land use changes in an arid and semi-arid region North Ningxia, in Northwest China by utilizing the multi-temporal remotely sensed data (Landsat TM dated 1987, 1989 and ETM 1999). Indicator differencing technique utilizes seven bands information to transform into three indicators such as brightness, greenness and wetness. These three spectral properties of indicators have been used to observe the land use changes by visual comparison. Study revealed that farmland increased so as to increase agricultural output while urban extension was triggered by urban population growth. Rural built-up increase was attributed to agricultural output increase, food product increase, and rural labour force increase. Conversion of land to water-body has relation with agriculture output increase while conversion of water-body to land has relation with sown area increase.

Dontree Suthinee (2003) detected land use changes using remote sensed data and arial photographs of year 1972, 1989 and 2000.Remotely sensed data consisted of Landsat MSS of year 1972, Landsat TM of year 1989 and Landsat ETM+ of year 2000. The visual interpretation technique was used for arial photographs while maximum likelihood classification technique was used for satellite image processing to obtain the land use maps of three different periods. Detailed field surveys, GPS measurements of certain land use samples and land use types as well as semi-structure interview were performed in order to acquire the information needed for analyzing the remotely sensed data. The study concludes that satellite imagery can provide general land use situation at watershed level while aerial photos give more details of land use changes at sub-watershed level.

Alados et al. (2004) proposed a model for study of land cover dynamics. Land cover and landscape patterns were assessed and compared using aerial photographs taken in the years 1957, 1985, and 1994. Changes in land use were found to be triggered by socioeconomic forces. The study explains the extent to which underlying structure of the physical landscape imposes limitations to the vulnerability to human activity of the main vegetation types. According to the data on the probability of vegetation transition over the 37-year period, the shift from tall arid brush to tall grass steppe appeared to be favored by gradual slopes. Steep terrain had a favorable effect on the formation of brushwood and more gradual terrain favored tall grass steppe.

Hietel et al. (2004) described the major spatial-temporal processes of land-cover changes and identified the correlations between environmental attributes and land cover changes in a German marginal rural landscape. The role of potential environmental drivers to cause land-cover changes also has been identified. Land cover dynamics from 1945 to 1998 was correlated with the physical attributes (elevation, slope, aspect, available water capacity and soil texture) of the underlying landscape.

Fox and Vogler (2005) made use of arial photographs, satellite imageries, and topographic maps and GPS data at eight sites in Thailand, Yunnan (China), Vietnam, Cambodia, and Laos over the last 50 years. Results suggest that land use (e.g. swidden cultivation) and land cover (e.g. secondary vegetation) have remained stable and the minor amount of land-use change was due to change from swidden to monocultural cash crops. Results suggest that two forces will increasingly determine land use systems in this region. First, national land tenure policies (the nationalization of forest lands and efforts to increase control over upland resources by central governments) will provide a push factor making it increasingly difficult for farmers to maintain their traditional swidden land-use practices. Second, market pressures (the commercialization of subsistence resources and the substitution of commercial crops for subsistence crops) will provide a pull factor encouraging farmers to engage in new and different forms of commercial agriculture.

Doorn and Correia (2007) derived land cover maps for a study area in southeast Portugal from aerial photographs and satellite image. These are usually categorical maps, in which the land cover is classified into discrete, non overlapping land cover classes. Subsequently, patches are delineated qualitatively according to the land cover classification, assuming homogeneity throughout the whole patch. Land cover map is compared with the mapping undertaken within a national land cover database. Both studies were carried out on the same scale and through visual interpretation of aerial photographs. Differences in land cover classification and allocation are explored using matrix with levels of agreement.

Fan et al. (2007) studied drastic land use land cover (LULC) changes in Guangzhou municipality areas covering five counties over the past 30 years due to economic development, population growth, and urbanization. Author analyzed two Landsat TM and ETM+ images in the dry season to detect LULC patterns in 1998 and 2003, and to examine LULC changes during the period from 1998 to 2003. The type, rate, and pattern of the changes among five counties were analyzed in details by post classification method. LULC conversion matrix was produced for each county in order to explore and explain the urban expansion and cropland loss which were the most significant types of LULC change. Land use conversion matrixes of five counties were discussed respectively in order to explore and explain the process of land use change. The results showed that urban expansion in these five counties has kept an even rate of increase, while substantial amount of cropland vanished during the period. It was also found that the conversion between cropland and orchard land was intensive. Forest land became the main source of new croplands.

Liu et al. (2007) analyzed the eco-environmental changes of the Longdong region of the Chinese Loess Plateau during the period 1986–2004 and identified the controlling factors. Landsat Thematic Mapper (TM) data at a spatial resolution of 30 m were used for analysis. Visual image interactive interpretation based on GIS technique provided information on the direction, rate, and location of eco-environmental changes. The transformation areas and ratios of various eco-environmental types in the region were calculated to obtain the transition matrixes of eco-environmental types. The transition matrix model was used to precisely analyze the variation and rates of the eco-environmental types and their spatial distribution.

SECTION-III

2.3 RUNOFF POTENTIAL AND NONLINEARITY OF WATERSHEDS

A multitude of methods/models are available in hydrologic literature to simulate the complex process of rainfall-runoff in a watershed. In year 1954, the United States Department of Agriculture, Soil Conservation Service (now called the Natural Resources Conservation Service (NRCS)) developed a unique procedure known as Soil Conservation Service Curve Number (SCS-CN) method. Mishra et al. (2005) provides an extensive review of the method and subsequent improvements suggested by various researchers. The method, which is basically empirical, was developed to provide a rational basis for estimating the effects of land treatment/land use changes upon runoff resulting from storm rainfall. According to Garen and Moore (2005) "…the reason for the wide application of curve number method includes its simplicity, ease of use, widespread acceptance, and the significant infrastructure and institutional momentum for this procedure within NRCS. To the date, there has been no alternative that possesses so many advantages, which is why it has been and continues to be commonly used, whether or not it is, in a strict scientific sense, appropriate…"

2.3.1 Theoretical Background

The SCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis equates the ratio of actual amount of direct surface runoff Q to the total rainfall P (or maximum potential surface runoff) to the ratio of actual infiltration (F) to the amount of the potential maximum retention S. The second hypothesis relates the initial abstraction (I_a) to the potential maximum retention (S), also described as the potential post initial abstraction retention (McCuen, 2002). Expressed mathematically,

(a) Water balance equation

$$P = I_a + F + Q \qquad (2.5)$$

(b) Hypothesis of proportional equality

$$\frac{Q}{P - I_a} = \frac{F}{S} \qquad (2.6)$$

(c) Hypothesis of relation between intial abstraction and potential maximum retention

$$I_a = \lambda S \qquad (2.7)$$

The values of P, Q, and S are given in depth dimensions, while the initial abstraction coefficient λ is dimensionless. The first (or fundamental) hypothesis (Eq. 2.6) is primarily a proportionality concept (Mishra and Singh, 2003a). Apparently, as $Q \rightarrow (P-I_a)$, $F \rightarrow S$. The parameter S of the SCS-CN method depends on soil type, land use, hydrologic condition, and antecedent moisture condition (AMC). The initial abstraction coefficient λ is frequently viewed as a regional parameter depending on geologic and climatic factors (Boszany, 1989). The existing SCS-CN method assumes λ to be equal to 0.2 for practical applications. Many other studies carried out in the United States and other countries report λ to vary in the range of (0, 0.3). A study of

Hawkins et al. (2001) suggested that value of $\lambda = 0.05$ gives a better fit to data and would be more appropriate for use in runoff calculations.

The second hypothesis (3) is a linear relationship between initial abstraction I_a and potential maximum retention S. Coupling Eqs. (2.5) and (2.6), the expression for Q can be written as:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{2.8}$$

Eq. (2.8) is the general form of the popular SCS-CN method and is valid for $P \geq I_a$;. For $\lambda = 0.2$, the coupling of Eqs. (2.7) and (2.8) results

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2.9}$$

Eq. (2.9) is the popular form of existing SCS-CN method. Thus, the existing SCS-CN method with $\lambda = 0.2$ is a one-parameter model for computing surface runoff from daily storm rainfall.

Since parameter S can vary in the range of $0 \leq S \leq \infty$, it is mapped onto a dimensionless curve number CN, varying in a more appealing range $0 \leq CN \leq 100$, as:

$$S = \frac{25400}{CN} - 254 \tag{2.10}$$

Where, S is in mm. The difference between S and CN is that the former is a dimensional quantity (L) whereas the later is non-dimensional. CN = 100 represents a condition of zero potential maximum retention (S = 0), that is, an impermeable watershed. Conversely, CN = 0 represents a theoretical upper bound to potential maximum retention ($S = \infty$), that is an infinitely abstracting watershed. However, the practical design values validated by experience lie in the range (40, 98) (Van and Mullem, 1989). CN has no intrinsic meaning; it is only a convenient transformation of S to establish a 0-100 scale (Hawkins, 1978).

2.3.2 CN Estimation and Applications

Reliable estimation of parameter CN has been a topic of discussion among hydrologists and water resources community (McCuen, 2002; Springer et al., 1980; Hjelmfelt, 1991; Simanton et al., 1996; Steenhuis et al., 1995; Bonta, 1997; Ponce and Hawkins, 1996; Sahu et al., 2005; and Mishra and Singh, 2006).

To estimate the average CN values (CN_{II}) mathematically from the rainfall (P)-runoff (Q) data of a gauged watershed, Hawkins (1993) suggested S (or CN) computation using the expression.

$$S = 5\left[P + 2Q - \sqrt{Q(4Q + 5P)}\right] \quad (2.11)$$

Eq. (2.11) can be easily derived from Eq. (2.9).

A considerable amount of literature on the method has been published and the method has undergone through various stages of critical reviews several times (Rallison, 1980; Chen, 1982; Ponce and Hawkins, 1996; and Mishra and Singh, 2003a). Rallison (1980) provided detailed information about the origin and evaluation of the methodology and highlighted major concerns to its application to the hydrology and water resources problems it was designed to solve and suggested future research areas. Chen (1982) evaluated the mathematical and physical significance of methodology for estimating the runoff volume. A sensitivity analysis shows that the errors in CN have more serious consequences on runoff estimates than the errors of similar magnitude in initial abstraction or rainfall.

Though primarily intended for event-based rainfall-runoff modeling of the ungauged watersheds, the SCS-CN method has been applied successfully in the realm of hydrology and watershed management and environmental engineering, such as long-term hydrologic simulation (Knisel, 1980; Woodward and Gburek, 1992; Pandit and Gopalakrishnan, 1996; Choi et al., 2002; and Mishra and Singh, 2004a; and Geetha et al., 2007); prediction of infiltration and rainfall-excess rates (Aron et al., 1977; Mishra and Singh, 2002a, 2004b); metal partitioning (Mishra et al., 2004b,c); sediment yield modeling (Mishra and Singh, 2003a; Mishra et al., 2006a); and determination of sub-surface flow (Yuan et al., 2001). The method has also been successfully applied to distributed watershed modeling (White, 1988; Moglen, 2000; and Mishra and Singh, 2003a).

GIS, which has been designed to restore, manipulate, retrieve and display spatial and non-spatial data, is an important tool in analysis of parameters such as land use/ land cover, soils, topographical and hydrological conditions. Remote sensing along with GIS application aid to collect, analyze and interpret the multidisciplinary data rapidly on large scale and is very much helpful for watershed planning. For ungauged watersheds accurate prediction of the quantity of runoff from land surface into rivers and streams requires much effort and time. Conventional methods of runoff measurements are not easy for inaccessible terrain and not economical for a large number of small watersheds. Remote sensing technology can augment the conventional method to a great extent in rainfall-runoff studies. Researchers (Ragan and Jackson, 1980; Slack and Welch, 1980, Tiwari et al., 1991, Pande and Sahu, 2000) have utilized the satellite data to estimate the USDA soil conservation Services (SCS) Runoff Curve Number (CN).

Recent studies (Sharda et al., 1993, Schumann et al., 2000, Saxena et al., 2000) illustrate that Remote Sensing (RS) and Geographic Information System GIS techniques are of great use in characterization and prioritization of watershed areas. Land use/land cover is the category in which RS has made its largest impact and comes closest to maximizing the capability of this technology (Garbrecht, et al. 2001; Pande et al 2002). One of the options for use of RS and GIS is to improve the estimation of watershed parameters such as Curve Number for a watershed with widely used SCS model from its land use data and digitized soil map (Still and Shih, 1985; Kumar, 1997; Pande et al., 2002). However land use/land cover accuracy is directly related to the spatial resolution of the sensors.

2.3.3 Hydrologic Non-linearity of Watersheds

Linear Hydrologic System: A system is said to be linear if it satisfies the following definition:

Let X_1 and X_2 be two inputs for which the outputs of the system are $Y_1=\Phi(X_1)$ and $Y_2=\Phi(X_2)$ respectively then the system is said to be linear if the following two relations are satisfied:

$Y_1+Y_2= f(X_1+X_2)$ (Superposition) (2.12)

$\Phi\ (CX) = C\ \Phi(X)$ (Homogeneity) (2.13)

Where Φ is linear operator

When the runoff volume (output) from watershed is directly proportional to the precipitation volume (input) for a range of precipitation volumes, the watershed is said to exhibit linear runoff or it is said to be hydrologically linear.

The physical condition occurring on a watershed which results in linear runoff is that the combined effect of hydrologic variables, namely infiltration, interception, depression storage, evaporation and transpiration, must be reasonably uniform throughout the watershed. Such a condition will permit uniform distribution of runoff depth to occur throughout the watershed if the watershed is covered with uniform precipitation.

In an idealized linear watershed, linearity of runoff volume does not depend on rainfall distribution. Any distribution of rainfall can occur on such watershed, and yet the runoff volume will be directly proportional to the precipitation volume.

Nonlinear Hydrologic System: Two definitions of "nonlinearity" appear in literature (Sivapalan et al., 2002). The first definition of nonlinearity is with respect to rainfall-runoff response of a watershed and nonlinearity refers to nonlinear dependence of the storm response on the magnitude of the rainfall inputs. The second definition of nonlinearity (Goodrich et al., 1997) is with respect to dependence of a watershed statistical property such as the annual peak discharge of return period or mean annual runoff on the area of the watershed. Sivapalan et al. (2002) have shown that both type of nonlinearities can exist independently of each other i.e. are unrelated.

Peak Discharge-Volume Relation: Relationship between hydrograph peaks and runoff volume was first proposed by Rogers (1980) who termed it as standardized peak discharge distribution (SPDD). Singh (1994) termed it as peak discharge rating curve because peak discharge runoff volume relation is transformation of the stream gage rating curve. SPDD is defined as the distribution of the logarithm of peak discharge Q_p (m^3/s) plotted against the logarithm of the runoff volume V (cm) of the total hydrograph producing that peak discharge. An equation for this plot can be determined using the least square method and a measure of the fit can be determined. The equation takes the form:

$$Q_p = a V^m$$

or

$$\text{Log } Q_p = b + m \log V \tag{2.14}$$

b (=Log a) is the intercept; Q_p is peak discharge in m^3/s;V is runoff volume under the hydrograph converted to centimeter uniformly distributed over the entire watershed; and m is slope of the line fitting the data.

For hydrologically linear watersheds meeting the UH conditions, slope in equation 1 must be equal to 1.0. Smaller slope indicates hydrologic nonlinearity. Rogers (1980) developed the peak discharge distribution using runoff data of 43 watersheds ranging from 5 to 700 km^2. Mimikou (1983) in his study on catchments in Greece found that equation 1 by itself is sufficient for checking hydrologic linearity and predicting peak discharge. To extend the work of Rogers (1982) and Mimikou (1983), Singh and Aminian (1986) developed relationship between volume and peak discharge on unit area basis by employing a large number (134) of watersheds from the United States, Australia, Italy and Greece.

Intercept b is equal log Q_p when runoff volume V is equal to 1cm.Thus b represents Unit Hydrograph peak. Based on a study in Greece, Mimikou (1983) found that variation in b is significantly explained by the logarithm of any of the two watershed morphological indices AS/L and A/L.

Singh and Aminian (1986) studied 134 watersheds and found that watershed area alone explains variance of b by more than 86% (r^2=0.861). Inclusion of bed slope S and stream length L increased r^2 marginally to 86.9%. Singh and Aminian (1986) therefore concluded that relationship between b and A alone is satisfactory.

The idea that linearity is only meaningful within the concept of storm duration is the thing that is lost in relationship proposed by Rogers(1980). Therefore the relationship is empirical in nature. Still the relationship has been investigated by researchers for its potential applications some of which are listed below. Further investigation of the relationship is given in chapter 10.

Derivation of unit hydrograph: For linear catchments the D-hour unit hydrograph(UH) can be represented by a triangle as proposed by soil Conservation Service (SCS,1972) then knowing Qp (which is equal to log inverse of b) will suffice to specify the UH. The duration of recession from the time to peak is taken as approximately 1.67 times the duration of rise, T_p(Chow 1988).

Flooding potential: Eq. (2.14) can be combined with the SCS hypothesis of representing the flood hydrograph by a triangle in exactly the same way as the UH. This allows determination of not only the flood peak, but also the flood duration and flood volume.

Determination of sediment yield: Singh and Chen (1982) found that relationship between sediment yield and volume of direct runoff is linear in log space. It can be used to estimate sediment yield. Volume of direct runoff can be estimated using SCS-CN method.

2.4 SUMMARY

Integrated watershed planning and management requires inputs from several scientific disciplines (morphology, geology, soil science, land use land cover, forestry, hydrology, agriculture etc). Often determination of watershed properties and watershed analysis has been carried out with a limited objective as is evident from the literature review. Observations based on review of literature are given in Chapter 1 (section 1.1). These observations form the background for this research work.

Literature review shows that GIS and Remote Sensing have become a powerful tool for various multidisciplinary resource explorations. The present research work deals with watershed study in GIS environment.

CHAPTER 3

INTRODUCTION TO THE STUDY AREA AND BASIC ANALYSIS

3.1 LOCATION, TOPOGRAPHY AND DRAINAGE PATTERN

Study area representing Sher, Umar and Barureva watersheds (Figure 3.1) is located between latitudes $22^0 15'00''$N and $23^0 05'00''$N and longitudes $79^0 00'00''$E and 79^0 45'00"E. Survey of India (SOI) toposheets (Scale, 1:50000) numbered 55M4, 55M8, 55M12, 55N1, 55N2, 55N5, 55N6, 55N7, 55N9, 55N10 provide topographic details of the study area. It encompasses area of 2822 km^2. The three adjacent watersheds namely Barureva, Sher and Umar (Figure 3.2) conjoin together to form an important southern sub-basin of Narmada basin in its upper reaches in Madhya Pradesh State of India. The three rivers flow in north-westerly direction from the south. Umar and Barureva meet Sher before the confluence of the latter with Narmada. Thus, Umar and Barureva rivers are in fact, tributaries of Sher river. From the south of the Satapura highlands down to the Narmada in the north, the drainage system of the three rivers represents an accretional plain of alluvium deposits. Sher watershed, having an area of the magnitude of 1635 km^2, is the largest followed by Umar (699 km^2) and Barureva watersheds (488 km^2).

The elevations in study area vary from 300 m to 890 m above mean sea level The Barureva and Umar watersheds have flat topography, however near the confluence of three rivers and along the river course deep gullies and ravines have formed. The upper part of Sher watershed is hilly in the uppermost portion followed by the undulating and plain topography. Middle part of the Sher watershed is identified with hilly terrain while lower part of watershed has flat and depositional topography. However along river course, vertical bank cutting gullies are in active state. Barureva and Umar watersheds have relatively small hilly area, mostly located in upper most part of the watersheds.

Sher river originates from Lakhnadon plateau nearby of Bhaliwara village above mean sea elevation of 640 m. Tributaries like Gurda, Kanera and Machhreva join the Sher river before its confluence with Barureva and Umar rivers. Barurvea river originates from the Bachai reserved forest above mean sea level of 560 m. Barurvea drainage network consist of tributaries like Ketki, Tinsara, Singri and Gahedua rivers.

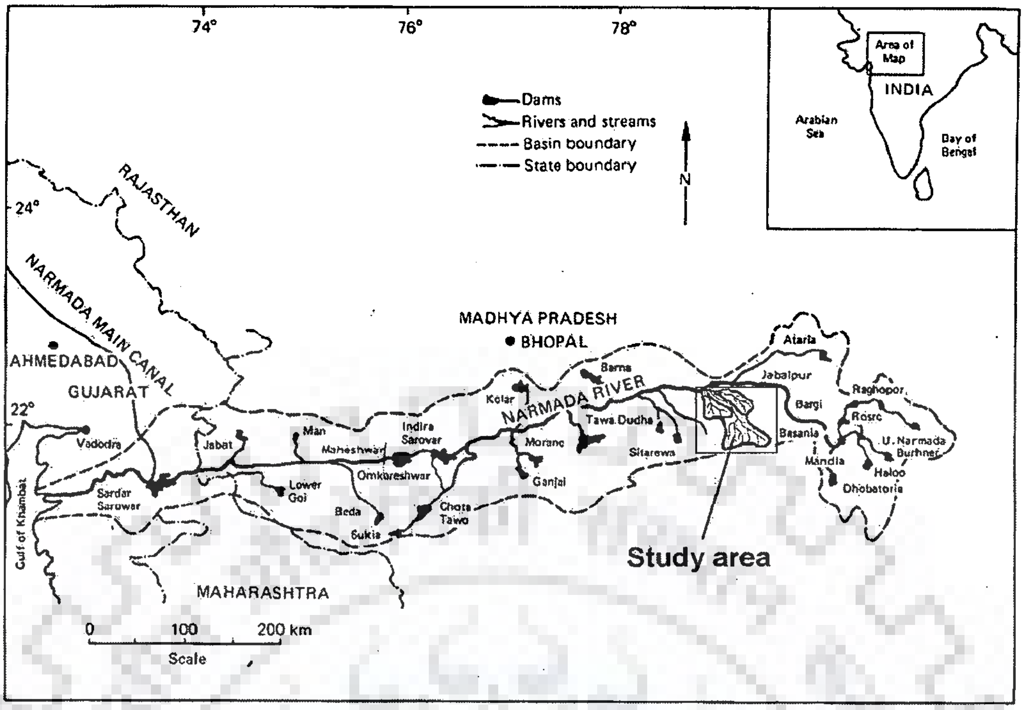


Figure 3.1: Study area location in the Narmada basin

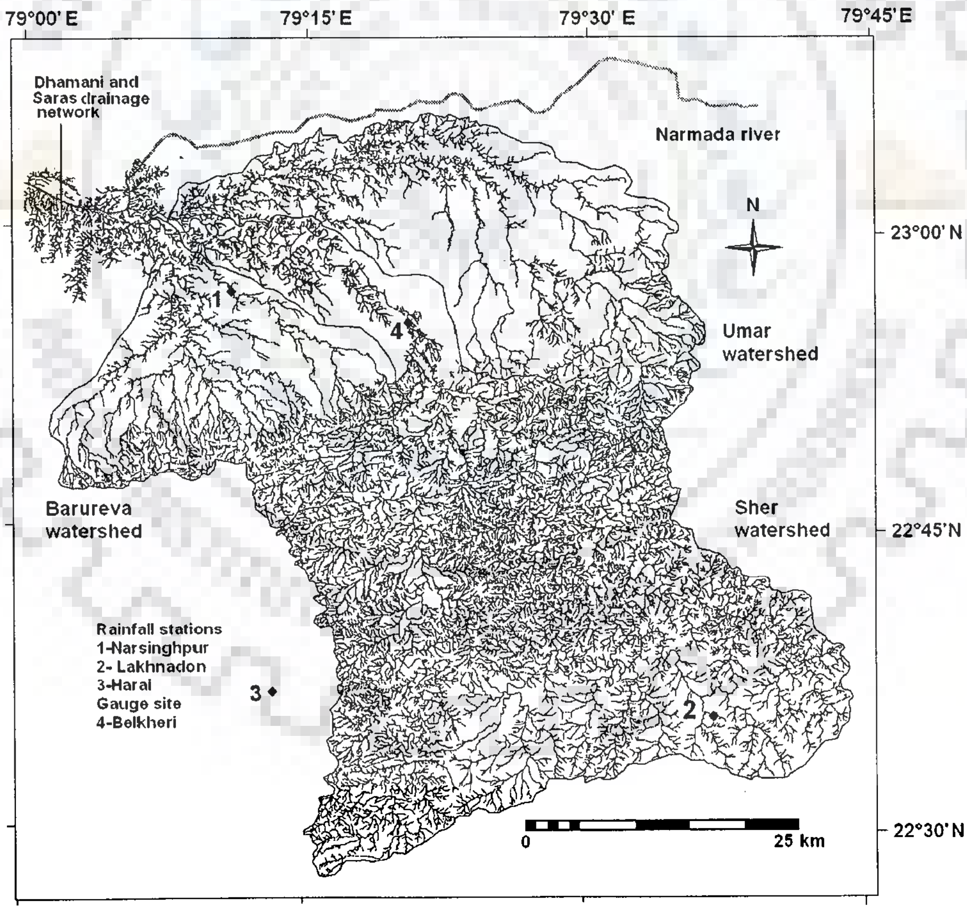


Figure 3.2: The study area, location of rainfall stations and gauge site

Umar originates from the Umargargh Reserved Forest at 610 m above msl. Umar river has tributaries like Datia nala, Jugiya nala, Ghagra nala and Jhamana nala. The confluence of Umar and Barureva with Sher river occurs at 300 m above msl. The drainage patterns of three rivers are mostly dendritic type with medium and coarse drainage network (Figure 3.2).

According to Strahler stream ordering scheme, Sher is seventh order stream while Barureva and Umar rivers are sixth order streams. The Sher river traverses much hilly terrain compared to the Barureva and Umar river. The drainage network of the Sher watershed is relatively dense (D_d=2.68 km/km^2) as compared to Barureva (D_d=2.06 km/km^2) and Umar river's (D_d=1.72 km/km^2) drainage network. The major course length of Sher river is 137 km while Barureva and Umar have 60 km and 86 km major course length respectively. Sher river and its tributaries show meandering due to different geological formations though which it flows while Barureva and Umar river course mostly follow straight path.

3.2 CLIMATE

The study area experiences sub-tropical climate with considerable temporal variations in rainfall, temperature and humidity.

Temperature: The temperature in the study area begins to rise rapidly from about March till May which is generally the hottest month. The mean daily maximum temperature in May falls between 39^0 C and 45^0 C. With the onset of the monsoon in the second week of June, there is an appreciable drop in day temperature. From mid-November on wards, both day and night temperatures decrease rapidly. December and January are the coldest months of the year. Normally, annual temperature varies from the 2^0 C to 45^0 C. On the whole days are warm and nights are cooler.

Relative Humidity: The relative humidity is highest during morning hours in July, August and September months ranging from 83.9 to 89.6%. March, April and May are the months when relative humidity during morning hours is lowest and ranging from 40.3 to 48.6%. The annual mean relative humidity is 60.5% in the morning and 45.6% in the evening hours.

Wind Speed: The mean annual wind velocity in study area (Narsinghpur station) is 4.35 km/hr in the evening and 2.44 km/hr during the morning hours. The wind velocity is highest during the pre-monsoon period, i.e. during May and June. The highest wind velocity of 7.41 km/hr is observed during the month of June and minimum of the 2.98 km/hr magnitude is observed in the month of January. The mean seasonal wind velocity is 3.05 km/hr during morning and 5.96 km/hr during evening. It is observed that mean wind speeds are higher during the evening hours than in the morning hours.

Potential Evapotranspiration: The potential evapotranspiration (PET) is the quantity of water transpirated in unit time by a short crop completely shading the ground of uniform height which is never short of water. It is observed from the previous studies that PET is highest in May (200 mm) and lowest in December (60 mm).

3.3 ANALYSIS OF RAINFALL PATTERN

The area has three distinct seasons in a year, i) rainy season ii) winter season and iii) summer season. The rainy season extends from June to October under the influence of south-west monsoon. The area also receives some rainfall during January and February from north-east monsoon. July and August are the main rainy months. Normally, the rainfall ceases by the end of September. However, some times in recoded years, October also happens to be month of good rainfall. Rainfall records are available for three rainfall stations namely Narsinghpur which is located in lower part of study area and Harai and Lakhnadon which are located in the upper part of study area (Figure 3.2). The daily rainfall data of three stations have been collected from the Indian Meteorological Department (IMD) Pune, India (Table 3.1).

Table 3.1: Rainfall characteristics in the study area

Station Name	Theissen weight	Data available (years)	Inadequate data years	Sample size (year)	Average annual rainfall (mm)	Average monsoon rainfall (mm)
Narsinghpur	0.13	1970-2002	----	33	1187(SD=366) (CV=0.31)	1053 (SD=308) (CV=0.33)
Harai	0.33	1970-2004	1974,1979,1980, 1989 &1996	31	1171 (SD=328) (CV=0.28)	897 (SD=272) (CV=0.30)
Lakhandon	0.54	1973-2004	1989	31	1116 (SD=249) (CV=0.22)	980 (SD=249) (CV=0.25)

Note: Values in brackets indicate standard deviation (SD) and coefficient of variation (CV)

Identification of drought and wet years is explained in Appendix E. The annual variation of rainfall at three stations for the years from 1970 to 2004 is shown in Figure 3.3.

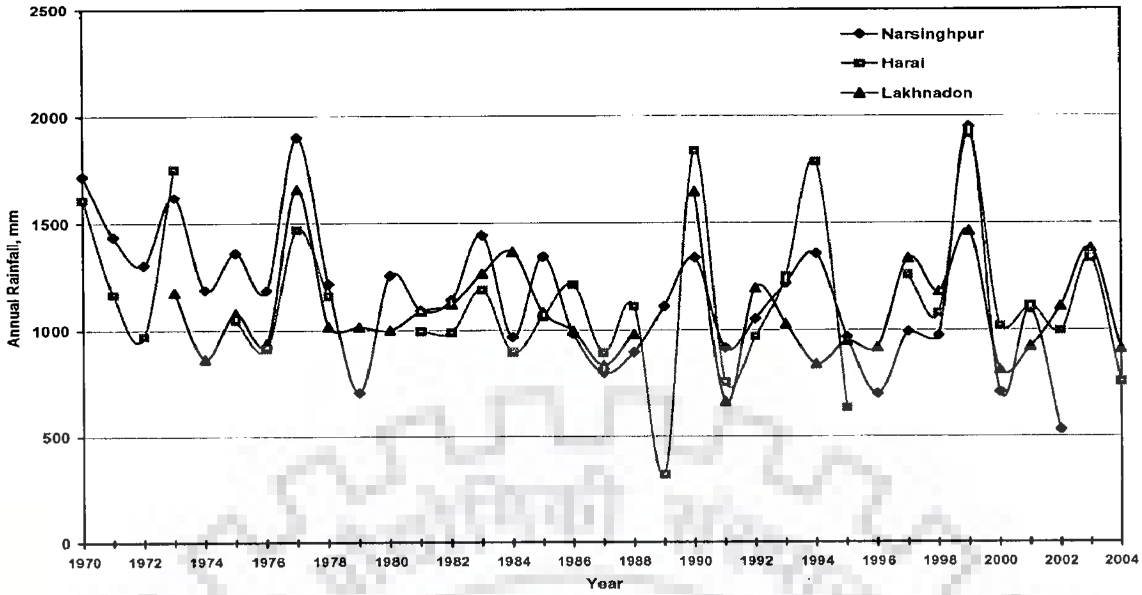


Figure 3.3: Annual variation of rainfall at three stations

The average annual rainfall at Narsinghpur, Harai, Lakhnadon are 1165 mm, 1144 mm and 1092 mm respectively. However, variability of annual rainfall is less at Lakhnadon in comparison with rainfall variability at Narsinghpur and Harai stations. The variations in annual rainfall at three stations indicate that a severe drought occurred in year 2002 at Narsinghpur station, with only 45% of average annual rainfall of the station. Harai experienced severe drought in year 1989, with only 30% of average annual rainfall at the station. Lakhnadon had the severest drought in year 1991 with 61% of average annual rainfall at the station. All the three stations have experienced low magnitude rainfall relative to the average annual rainfall in several years.

The rainfall distribution within a year suggests that about 90% of annual rainfall is received in monsoon period (June-Sept) and the remaining 10% occurs in non-monsoon period. Among all stations, Harai station shows significant difference between average monsoon rainfall and average annual rainfall. About 30-33% of total annual rainfall is received in the month of August. The monthly rainfall distribution pattern is almost similar at the three stations (Figure 3.4).

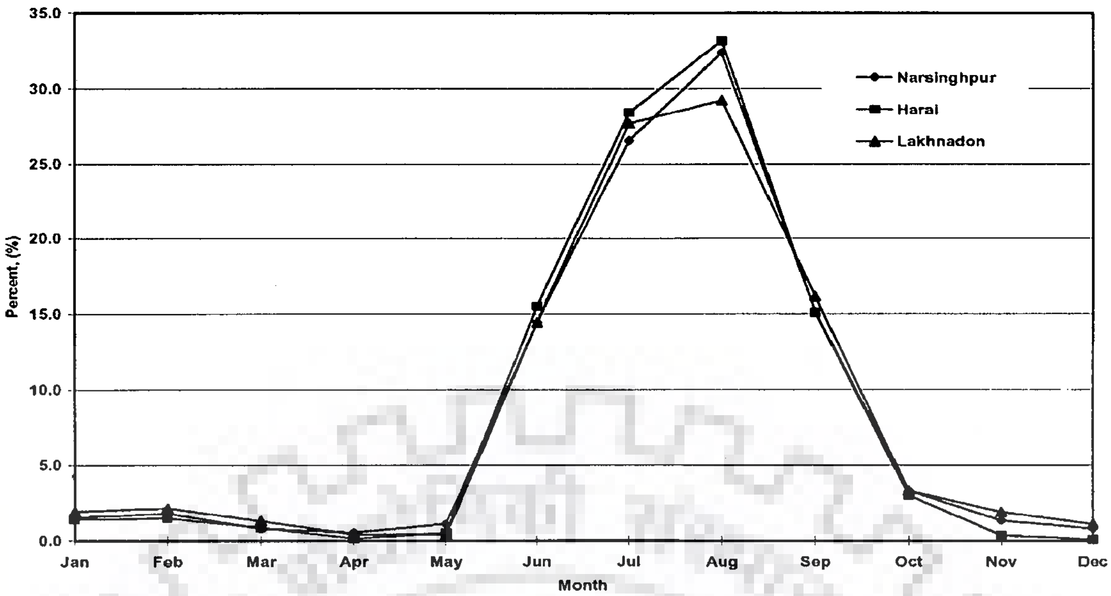


Figure 3.4: Monthly distribution of average annual rainfall at three stations

Rainy Days Analysis

Availability of adequate number of rainy days assures good crop growth development and crop production under rainfed cultivation. A rainy day has rainfall greater than or equal to 2.5 mm. Annual variation in number of rainy days per year is depicted in Figure 3.8. Overall trend of number of rainy days shows gradual decline with over the years and particularly in recent period. Narsinghpur station has highest average number of rainy days (64 days) per year while Harai has lowest average number of rainy days per year (41 days). In general a wet year has higher number of rainy days and a drought year has lowest number of rainy days; however a normal year may sometimes have higher number of rainy days in comparison to wet years.

3.4 GEOLOGICAL SETTING

The geological setting of the study area is shown in Figure 3.5 and summarized in Table 3.2. It is based on the study of the field survey reports and geological maps of administrative blocks (GOI (1998), GOMP (1983, 1988a, 1988b)).

Recent Alluviums, Deccan Traps (basalt) and Gondwana formations are dominant in the upper reaches as compared to quartzite and gneissic-schistose rocks of Archeans complex which are found as limited outcrops along the lower slopes of the Satpura mountains (Figure 3.5) whereas, for larger part, these remain underneath the thick cover of the alluviums. Quartzite formations are, at places, found in Barureva and Umar watersheds, whereas gneissic-schists formation is observed only in the Barureva watershed. Therefore, it may be said that topography of Barureva watershed has all representative rocks of the area and it is complex as compared to Sher and Umar watersheds. Thus, each watershed shows different area proportions and spatial distribution of geological formations, which eventually made them geologically and morphologically different from each other.

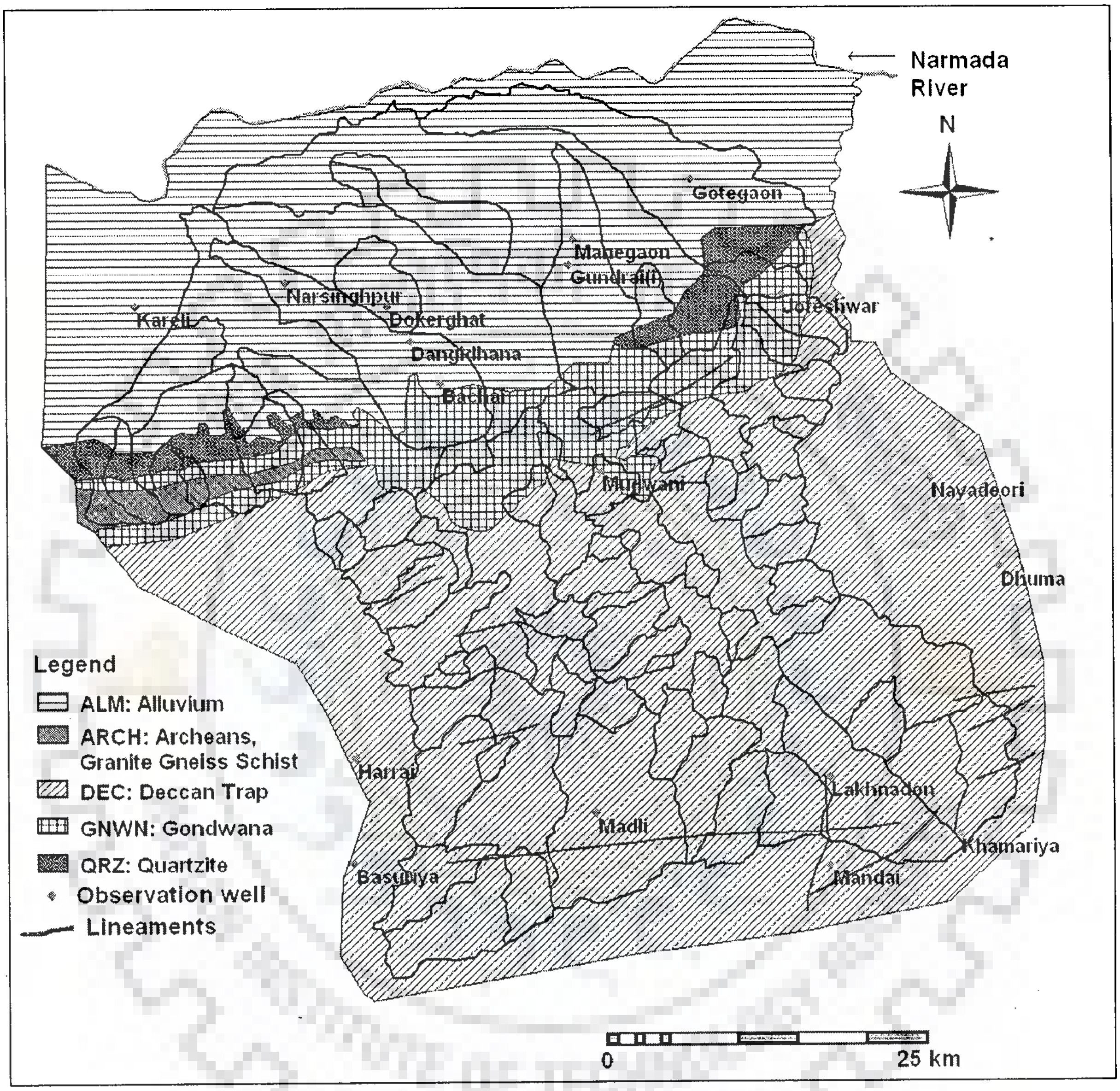


Figure 3.5: Geological formations and observation wells in study area

Table 3.2: Geological formations and its properties in the study area

Age	Geological formation	Nature and water bearing properties
Recent	Alluvium	It consists of soils, sands, gravels, pebbles etc, alluvium shows maximum yielding capacity. Formation associated with clay has minimum permeability and act as aquiclude.
Cretaceoeocene	Deccan trap	Deccan trap are dark coloured, fine to medium grained. The vesicles, joints and fractures are generally filled with the secondary minerals like zeolites etc. Compactness of traps gives rise to low porosity. Ground water occurs in weathered basalts openings.
Jurrassic(upper Gondwana)	Gondwana	The formation comprised of Jabalpur sand-stone. The sand stone is medium to coarse grained, moderately compact and fairly good permeability. The Shale and clayey horizones, intercaletec with sand stone, prevent the movement of water but sandstone itself acts as moderately good aquifer.
Archaean	Quartzites and calcareous crystallines	The rocks are compact, coarse grained and highly weathered. These rocks have low porosity and permeability. The weathered zone and also the intensity of secondary openings provide scope for accumulation of ground water.
Archaean	Archaens group (Granite, Gneiss, schists)	Archaean formations are the oldest and comprise of granite and gneisses. The rocks are hard and compact in nature. The weathered zone and also the intensity of secondary openings provide scope for accumulation of ground water.

3.5 AQUIFER CHARCTERISTICS AND GROUND WATER CONDITION

3.5.1 Aquifer Characteristics

The alluvial aquifer system (Figure 3.5) has layers of fine to medium coarse grained sand and some layers comprising of gravel and kankar(clay aggregates) separated by clay lenses.

The top phreatic aquifer in general ranges in thickness from 2 to 10 m and its top is encountered at depth range of 5 to 20 m below ground level. The yield of dug wells tapping the phreatic aquifer ranges from 7.5 to 12 liters per second. The lower most zone of alluvial has confined aquifer conditions between the clay layers (aquitard). The confined aquifers starting within general depth of 15 to 91 m below ground level constitute the principal aquifer system. It forms a potential source of irrigation water in the area tapped by both shallow and deep tube wells. The yield of these tube wells ranges from 20 to 60 liters per second. The maximum depth of thickness of alluvium aquifer system is found at the place of confluence of three rivers. The depth of thickness decreases from west to east and from north to south away from the confluence point. Alluvium layer is deposited over the Gondwana and Archeans formations in the study area.

The Gondwana formation starts to occur next to the alluvium in south direction. These rocks outcrop as high hills and narrow steep valleys forming the Satpura range. The Gondwana formation comprising of weathered zone of shale and fine to medium sandstones has moderate potential of ground water occurrence and yield of dug wells in this formation ranges from 2 to 3 liters per second.

The Archeans rock formation is the oldest one occurring in the south within the hilly area of Barureva watershed. These are hard, medium to coarse grained rock of granite, gneisses and schists which extend from east to west direction. These rock formations lack pores and fissures which in turn limits supply of ground water. The quartzite formation is seen in upper most part of Barureva and Umar watersheds in the form of narrow strip. These rocks have low porosity and permeability similar to the Archeans complex of granite and schists. The ground water may accumulate in the weathered zone of these rocks with secondary openings.

The Deccan trap formation mostly occurs in upper part of the three watersheds with substantial coverage in the Sher watershed. The ground water occurs under phreatic conditions in weathered zones or joints and fractures extending to shallow depths. These shallow aquifers are tapped by open dug wells near to the confluences of streams or at the intersection of fractures often yielding about 0.57 to 1.16 liter per second. The boreholes which pierce through the various vesicular horizons and its flow contacts yield moderate quantities of water. The yield of boreholes, however, depends upon the thickness of vesicular or jointed horizons and its interconnection with the top recharging zone.

3.5.2 Ground Water Condition

The availability of depth to water level data for 18 observation wells in the study area and vicinity ranges from 10 years for wells in Deccan trap i.e. upper part of the Sher watershed to more than 20 years for alluvium area covering Narsinghpur, Kareli and Gotegaon Blocks in the study area (Chapter 8, Table 8.2). Out of 18 wells; 8 wells are in northern alluvial area and remaining 10 wells are in the Gondwana and deccan trap formation in central and southern part. Observation wells in the vicinity of the study area have been considered for smoothing the interpolation process in the spatial distribution study and also to avoid overestimation of interpolated ground water level data along the boundary of the watersheds. Figure 3.5 shows geological formation in the study area and location of observation wells.

Twelve wells are in the study area and the remaining six observation wells are in the vicinity (Figure 3.5). A point map of observation wells has been generated from the toposheets of Survey of India (Scale: 1:50000) using GIS software, ILWIS 3.0. Historic ground water table depth values of observation wells were filled in the attribute table of the point map. The weighted average point interpolation technique with inverse distance weight function is applied to generate pre and post monsoon water table contour maps and associated water table fluctuation maps over the specific time period.

3.5.3 Spatial Analysis of Depth to Ground Water Table Data

Ground water level variation in the study area has been analyzed for the years 1993 and 1999. For these years, all observation wells in the study area have ground water data. The ground water table contours of pre and post monsoon seasons for year 1993 have been obtained using point interpolation of weighted average method. The ground water table contours (Figures 3.6 and 3.7) show that ground water flow direction is similar to the topographic slope conditions. In alluvium area ground water table fluctuates between 340 m to 380 m above mean sea level. Upper part of Sher watershed shows ground water table depth at 520 to 620 m above mean sea level. The ground water level elevation near the surface water divide of Sher watershed and Godavari basin is about 600 m and shows gradual decrease toward north side.

3.6 LAND USE AND CROP PATTERN

Previous studies (NIH report, CS31) suggest that Sher river watershed has dense to medium type forest cover in the middle part of watershed having hilly terrain. Agriculture is practiced on the plain topography of upper part of watershed as well along the river tracts of Sher river. Alluvial plains of Barureva and Umar watersheds and part of Sher watershed have well developed agriculture. However at places (mostly along the river tracts) badland and gullies are observed which once had substantial coverage in the lower alluvium plain of the three rivers. Forest area in Barureva and Umar watersheds is mostly restricted to upper-most part of hilly terrain although agriculture pockets are also present in the forest area and near to water bodies.

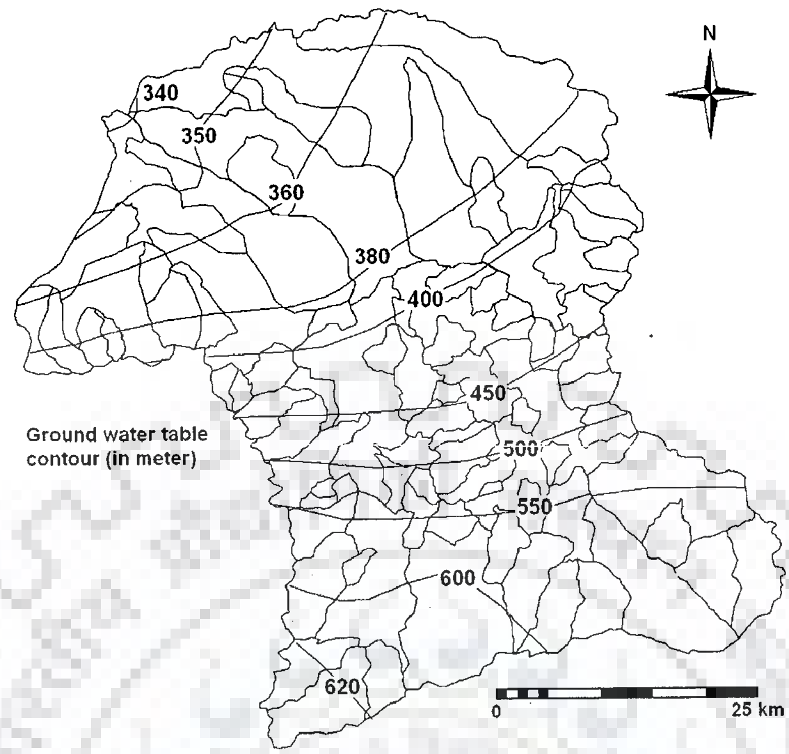


Figure 3.6: Contours of ground water table in pre-monsoon 1993

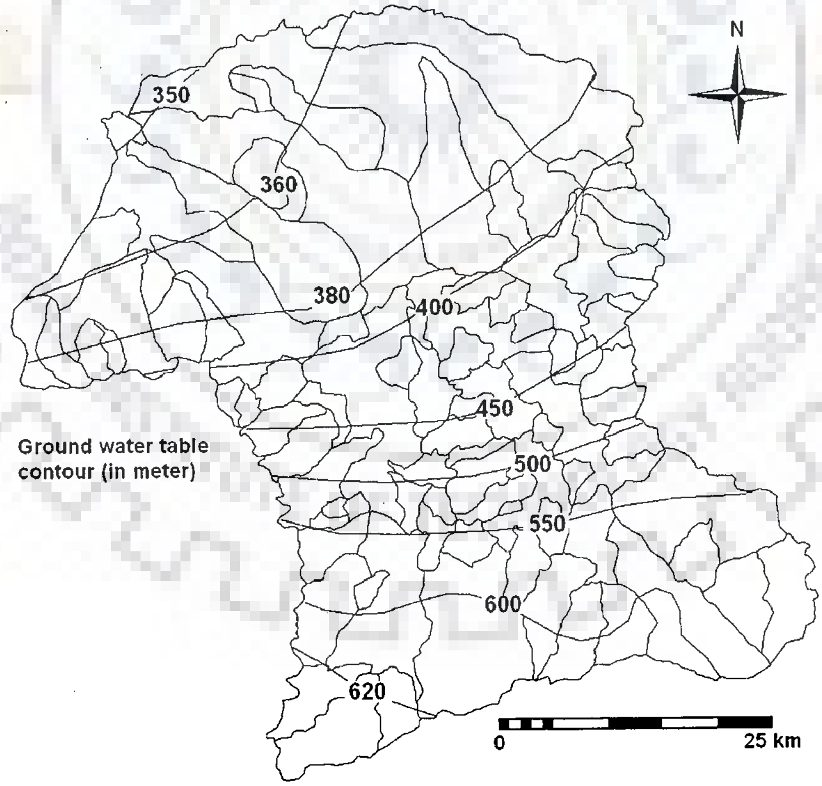


Figure 3.7: Contours of ground water table in post-monsoon 1993

Land use and land cover of study area for years 1972, 1989 and year 2000 have been analyzed and classified using satellite imageries. The dynamics of land cover change are discussed in the Chapter 7.

Main crops grown in Barureva, Sher and Umar watersheds are soyabean, gram, pulses (arhar, moong, masoor), wheat and sugarcane. While in upper part of Sher watershed area covering Lakhnadon block paddy, jawar, ground nut, seasamum are also grown. Over the years, sugarcane and soyabean have replaced other crops in the alluvial plains.

3.7 SOILS

The texture of soil varies from clay, clay loam, sandy clay loam and loam on the basis of location and depth of soil stratum (NIH case studies, 1995 & 1997). The soils of this area are loamy in texture and blended with the clay content (Soils of MP, NBSS Publ. 59). The depth of soil is very shallow and stony with loam texture on the steep sloping hills and it becomes shallow to medium deep clay on medium and gently sloping Deccan platue. The lower part of study area is dominated by medium to deep soil with clay texture. On the basis of available soil properties, lower part of the Sher watershed is classified in hydrological soil group D and upper part of watersheds in hydrological soil group C for hydrological analysis as discussed in Chapter 9.

3.8 GAUGE DISCHARGE DATA

Study area has only one gauge site at Belkheri on Sher river which collects runoff from the area of 1488 km^2. Daily discharge data is available for period of 26 years (1977-2002). The average annual flow is 24.09 m^3/s. The maximum annual flow (52.46 m^3/s) was recorded in the water year of 1994-95 which is 217% of the average annual flow. The lowest annual flow (6.60 m^3/s) was recorded in the water year of 1987-88 which is 27.43 % of the average annual flow. The wet year flows (>30 m^3/s) have been observed in four water years (1977-78, 1984-85, 1990-91, 1994-95 and 1999-2000).

Variation in annual runoff (mm), average annual rainfall (mm) and number of rainy days over the years for gauged Sher watershed is compared in Figure 3.8. Pattern of variation is similar for annual runoff and annual rainfall series.

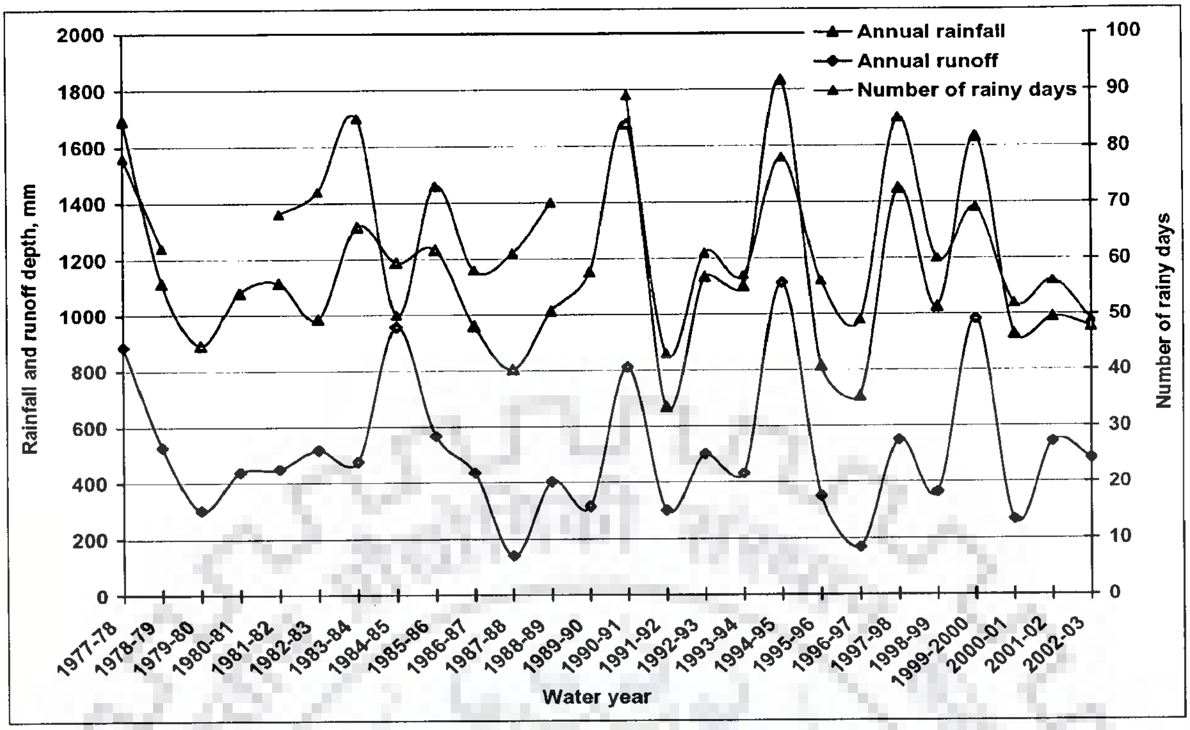


Figure 3.8: Trend of rainy days, annual rainfall, and annual runoff for gauged Sher watershed

3.9 POPULATION

Census data are available on the block basis. A block is an administrative area comprising of several villages. A district consists of several blocks. The study area is spread over the Narsinghpur, Seoni and Chhindwara districts. Within Narsinghpur district, the study area is spread over Narsinghpur, Kareli and Gotegaon blocks whereas in the Seoni district, the study area covers Lakhnadon block. In Chhindwara district, study area covers the Harai block. Parts of study area falling under different block jurisdiction are shown in Figure 3.9 and Table 3.3. The human population scenarios for the past three decades are presented in Table 3.4 as per available information. The part of study area falling in Harrai block of Chhindwara district is comparatively low covering mostly hilly forested area with low population. The block wise animal population data is not available therefore the district level data on animal population (Table 3.5) have been used for estimation of block wise animal population using ratio of livestock per person at district level.

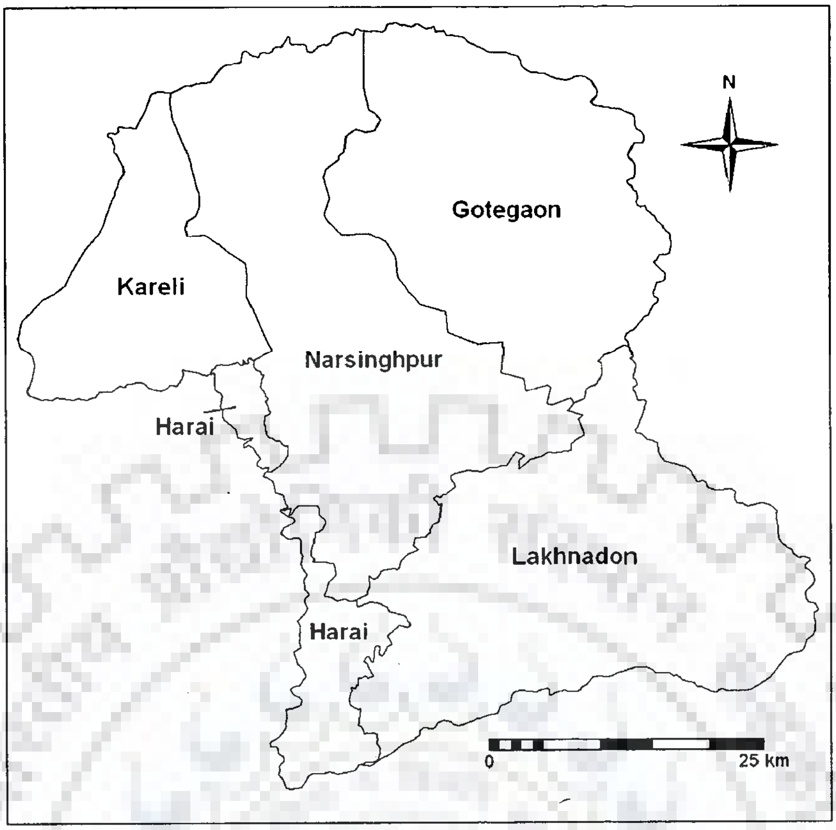


Figure 3.9: Block-area distribution in the study area

Table 3.3: Block area distribution

District	Block Name	Block area km^2	Block area in study area km2	Percent area of block in study area
Narsinghpur	Narsinghpur	1193	818.26	68.59
	Gotegaon	924	690.92	74.77
	Kareli	654	328.75	50.27
Seoni	Lakhnadon	1207	809.27	67.05
Chhindwara	Harai	-	174.49	-
	Sum		2822	100.00

Table 3.4: Human population in different administrative blocks

Year	Administrative Blocks			
	Narsinghpur	Kareli	Gotegaon	Lakhnadon
1971	84784	66339	97000	NA
1991	112140	94469	126576	NA
2001	192076	138471	174041	159330

Table 3.5: Livestock population of Narsinghpur and Seoni districts in year 2003

Livestock	Narsinghpur	Seoni	Average ratio (livestock/person)
Total crossbred cattle	13899	4454	0.00917
Total Indigenous cattle	386903	421468	0.38265
Total cattle	400802	425922	0.39181
Total buffaloes	118310	125752	0.11567
Total sheep	241	393	0.00029
Total goats	96913	158340	0.11846
Total horses and ponies	1072	487	0.00077
Total mules	73	6	0.00004
Total donkeys	681	82	0.00039

3.10 IRRIGATION DEVELOPMENT AND MANAGEMENT IN STUDY AREA

The study area covering four administrative blocks has 15 surface storage tanks and 5 lift irrigation schemes (Figure 3.10). Irrigation potential of these minor irrigation tanks ranges from 20 to 200 hectares while lift irrigation schemes have the potential to irrigate 20 to 45 hectares. These schemes are designed to irrigate agricultural land in rabi (winter) season. The Bargi Multipurpose Project (Rani Avabti Bai Sagar) has been constructed at a distance of 43.2 km from Jabalpur, near village Bijora. The Left Bank Canal (LBC) of the dam has been designed to irrigate 1.57 lakh hectares of land in Jabalpur and Narsingpur districts.

Part of the study area covering alluvium plain will receive irrigation water from this project. Distribution network in the study area covering Gotegaon, Narsinghpur and Kareli blocks is almost complete. Upper part of study area has three minor irrigation projects. At present ground water is the main source of irrigation for agricultural area as shown in Table 3.6.

Table 3.6: Block wise area irrigated by different sources

Block Name	Canal Irrigated Area (ha)	Number of Tube wells			Dug wells		Area Irrigated from other sources (ha)	Area irrigated more than once (ha)	Net area irrigated (ha)	Gross sown Area	Irrigated area as % of gross sown area
		Govt.	Private	Area Irrigated (ha)	Number	Area irrigated (ha)					
Narsinghpur	820	13	489	5924	2327	14241	2002	188	22987	67475	34.07
Kareli	456	24	728	6475	2402	10580	787	155	18298	51794	35.33
Gotegaon	1080	17	874	7528	3217	20523	1420	318	30551	82630	36.97
Lakhnadon	1091	198		372	2823	5224	2641	-	9328	63479	14.69

Figure 3.10: Minor irrigation (MIS) and Lift irrigation (LI) schemes in study area

3.11 DATA USED IN STUDY

The present study deals with spatial and temporal analysis of a large number of small watersheds covering morphological, geological and hydrological aspects and land use land cover dynamics. The basic data as per Table 3.7 have been collected from various sources used in the present study.

Table 3.7: List of data used in the present study

Sl. No	Data used	Source
1	Survey of India toposheets (scale 1:50000)	Survey of India
2	Geological survey studies	Geohydrological reports of Blocks and districts.
3	Soil cover information	NIH study reports and district soil information available on internet websites
4	Land use and land cover information derived using satellite imageries of year 1972, 1989 and 2000.	NIH report, internet downloaded data from Global Land Cover Facility
5	Historical depth to water table data (1977-2002)	Central Ground water Board, Bhopal
6	Daily rainfall data of three stations (1970-2002)	Indian Meteorological Department
8	Daily discharge data of Sher river(1977-2002)	Central Water Commission, Bhopal
9	Animal population (2001)and human population data (1971,1991 and 2001)	Census reports of Govt. of India and data from district web sites.
10	Thirty flood hydrographs of four watersheds and unit hydrographs of eighteen watersheds	Central Water Commission report, NIH study report & Jain et al 1995

3.12 SUMMARY

The chosen area for study exhibits heterogeneity in characteristics providing scope for the intended research work. The study area covers three adjacent watersheds which conjoin together to form an important southern sub-basin of Narmada basin in its upper reaches in Madhya Pradesh State of India. Whereas Barureva and Umar watersheds have nearly flat topography, Sher watershed is relatively hilly and has undulating topography.

Along the river courses vertical bank cutting gullies are in active state. The drainage pattern is dendritic in the three watersheds with higher drainage density in Sher watershed. Analysis of 30 years rainfall data shows that annual rainfall is highly variable causing draught like situation in some years. The three watersheds are geologically and morphologically different with significant spatial variations in availability water resources. Observed discharge data is available only at one site. Most of the area is ungaged. Scrutiny of the available data shows that planning exercises can be greatly improved using GIS and Remote Sensing.

CHAPTER 4
MORPHOLOGICAL ANALYSIS OF THE STUDY AREA

4.1 INTRODUCTION

A watershed is a physically complex system. It consists of a number of Unit Source Areas (having uniform properties), and Partial and Variable Source Areas each exhibiting a different response. The juxtaposition of different source areas of contrasting topography, rock types, and land use and soil characteristics result in areal variations in watershed response and processes. Every hydrologic design is therefore different because the physical properties may vary with site.

Literature review (Chapter 2) shows that morphological properties of a watershed are useful (i) to understand hydrological behavior of small ungauged catchments (ii) for prioritization of a micro-watershed for watershed development and (iii) for selecting site for artificial recharge and groundwater targeting. Computation of morphological parameters in GIS environment has proved to be less tedious, fast and accurate and made best spatial representation of topographic situations as illustrated by various studies (Singh, 1998; Kumar et al., 2001; Singh et al., 2003).

This chapter deals with (i) assessment and comparison of morphological parameters of a large number of small watersheds in the study area using ILWIS 3.0 package, (ii) analysis of inter-correlation among morphological parameters and (iii) fractal analysis and principal component analysis to study influence of various geological formations on drainage pattern evolution.

The spatially distributed data base is used in subsequent studies on identification of erosion risk areas, surface storage sites ,ground water recharge sites (Chapter 5), bad land characterization (Chapter 6), runoff potential (Chapter 9) and nonlinearity in hydrological behavior of small ungaged watersheds (Chapter 10).

4.2. DEFINITIONS

4.2.1 Linear Parameters

a) Watershed area (A): The watershed area reflects volume of water that can be generated from the rainfall. It is a necessary input in various hydrologic models.

b) Watershed perimeter (L_p): It is the length of the watershed boundary.

c) Watershed length (L_b): It is the distance between watershed outlet and farthest point in the watershed.

4.2.2 Shape parameters

a) Form factor (R_f): Form factor is the ratio of the watershed area (A) to the square of the maximum length of the watershed (L_b).

$$R_F = A/L_b^2$$

b) Elongation ratio (R_e): Elongation ratio is the ratio between the diameter of a circle with the same area as that of the watershed to the maximum length of watershed.

$$R_E = \frac{2}{L_b}\sqrt{\frac{A}{\pi}}$$

c) Circularity ratio: Circularity ratio is computed as:

$$R_C = \frac{2}{L_P}\sqrt{\pi * A}$$

4.2.3 Drainage Parameters

Length of overland flow in a watershed is relatively very small than the length of channel flow. The travel time of runoff is an important input in many hydrologic design models. Thus the drainage pattern is indicative of the flow characteristics of storm runoff. A number of parameters have been developed to represent drainage pattern.

a) Stream order

Strahler (1964) suggested the method of stream ordering to analyze the drainage pattern of the area. The basic rules of stream ordering are

i) Streams that originate at a source are defined to be first order streams. ii) When two streams of order u join, a stream of order u+1 is created. iii) When two streams of different order join, the channel immediately downstream has the higher of order of the two joining streams. iv) The order of a watershed is the order of the highest stream.

b) Stream number (N_u): It is the number of stream segments of various orders.

c) Total stream length (L_u): It is the sum of all lengths of all the stream order.

d) Main stream length (L_{MS}): Main stream length is the length of the stream having maximum stream length. This is the length along the principal stream.

e) Bifurcation ratio (R_b): It is the ratio of the number of streams of given order u to the number of streams of next higher order u+1. It reflects the complexity and degree of dissection of a drainage watershed.

$$R_b = N_u / N_{u+1}$$

e) Length ratio (R_t): Horton (1945) proposed length ratio factor as the ratio of the average stream length (L_u) of order u, to average stream length (L_{u-1}) of the previous lower order u-1.

$$R_t = L_u / L_{u-1}$$

High R_t values are associated good permeable formation of the watershed while comparatively low R_t values are associated with impermeable formation of a watershed.

f) Drainage density (D_d): It is the ratio of total length of the streams of all the orders of a watershed to the area of the watershed.

$$D_d = \sum_{u=1}^{n} L_u / A$$

Higher drainage density in a watershed indicates quick disposal of runoff from the watershed. The comparatively low drainage density watersheds provide more opportunity time to infiltrate overland flow which subsequently may have better ground water storage condition under the same rainfall condition. High drainage density is associated with low permeability of underlying geological formation and vice versa.

g) Length of overland flow (L_g): Length of overland flow is equal to one half of the reciprocal of the drainage density.

$$L_g = \frac{1}{2 D_d}$$

h) Drainage frequency (D_f): It is the ratio of the total number of streams in a watershed to the watershed area.

$$D_f = \sum_{u=1}^{n} N_u / A$$

Higher drainage frequency points to a larger surface runoff and steeper ground surface. It mainly depends upon the lithology of the watershed and texture of drainage network. Under the same slope condition, hard geological formations show higher drainage frequency value compared to soft geological formations in a watershed.

i) Constant of channel maintenance (C_m): Schumm (1956) introduced the factor, “constant of channel maintenance”, as the inverse of the drainage density. It is the area required to maintain one linear kilometer of stream channel.

$$C_m = 1 / D_d$$

j) Drainage texture (T): Drainage texture is defined as the ratio of number of streams of first order to the perimeter of the watershed.

$T = N_1 / P$

4.2.4 Slope Parameters

A number of parameters have been developed to reflect variations in watershed relief and to indicate erosion hazard.

a) Maximum watershed relief (H): It is the maximum vertical distance between the lowest and the highest points of a watershed. It is also known as total relief.

b) Relief ratio (R_h)): Relief ratio is the total relief of the watershed (H) divided by the maximum length (L_b) of the watershed. High value of watershed slope shows rich drainage pattern which helps quick disposal of runoff. Low-sloped watersheds provide more time to infiltrate the generated runoff and subsequently build ground water storage.

$R_h = H/L_b$

c) Ruggedness number (R_N): Ruggedness number is defined as the product of the maximum watershed relief (H) and its drainage density (D_d). It provides an idea of overall roughness of a watershed.

$R_N = H*D_d$

d) Relative relief (R_r): Relative relief is the ratio of the maximum watershed relief (H) to the perimeter of the watershed (L_p).

$R_r = H/L_p$

4.3 MORPHOLOGICAL ANALYSIS USING GIS

The map layers of drainage pattern along with stream order, watershed and sub watershed boundaries and contours in the study area have been prepared in GIS environment. The digital elevation model is obtained by linear interpolation of contours layer which is digitized from the toposheets of Survey of India (scale 1: 50000) (Figure 4.1). Various linear measurements such as area, perimeter, watershed length, drainage length and total relief (H) are calculated from the attributes table of map layers such as boundary layer, drainage layer and digital elevation layer. With the help of these linear measurements, formula based morphological parameters are computed for watersheds and sub watersheds of study area.

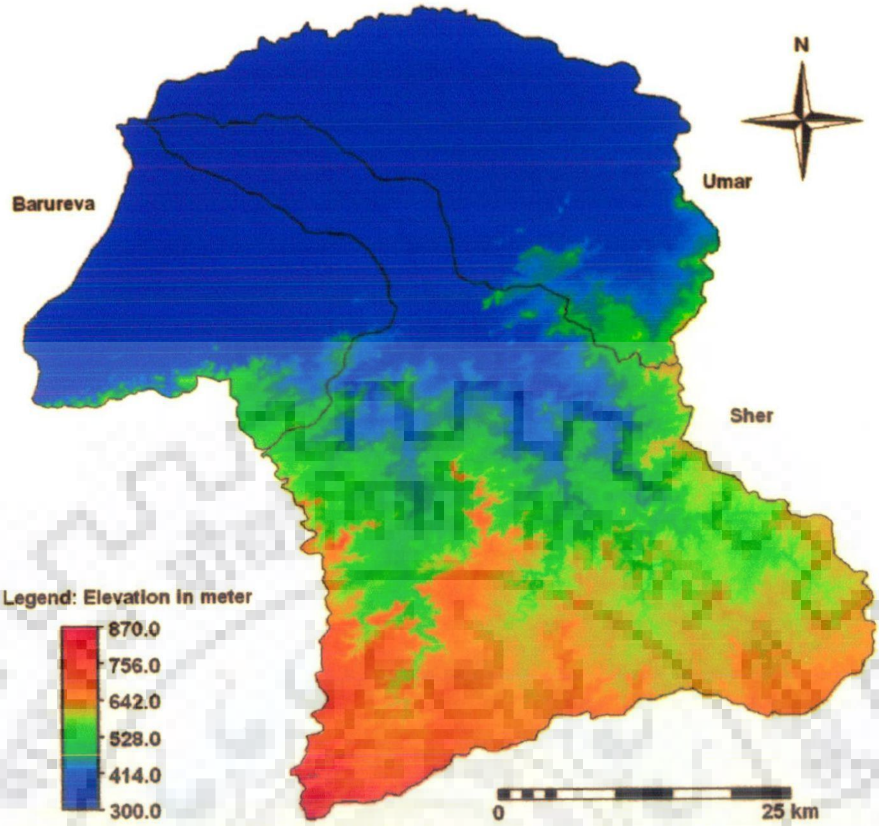


Figure 4.1: Digital Elevation Model (DEM) of the study area

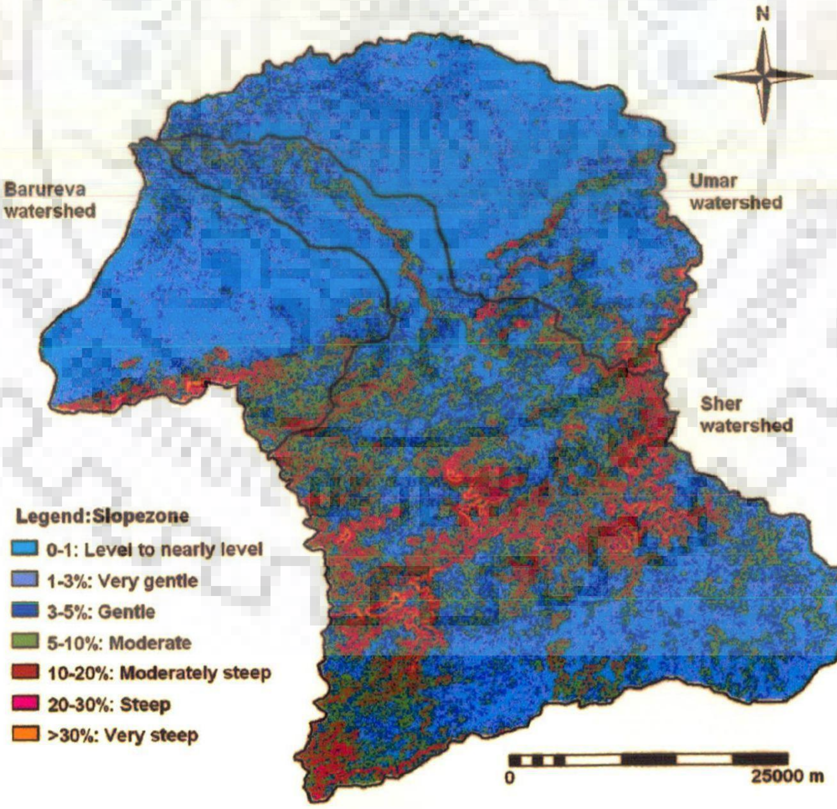


Figure 4.2: Slope zone map of the study area

The slope zone map of watershed is derived (Figure 4.2) from digital elevation model (DEM) using raster map operation with the help of following formula.

$$\text{Slope } (\%) = (\text{HYP } (dx,dy)/\text{PIXEL SIZE}) \times 100 \tag{4.1}$$

The hypotenuse exponential (HYP) function has been used to calculate slope values in percentages, from two input maps (derived from contour layer) which contain height differences of contour values in x-direction (map dx) and in y-direction (map dy). Pixel size of the generated map is 100 m^2.

4.4 ANALYSIS ON WATERSHED BASIS

4.4.1 Morphological Parameters of Three Watersheds

The objective is to describe the formation, orientation and quantitative comparison of watersheds. Morphological parameters are shown in Table 4.1. The Sher river watershed is largest in size (1635 km^2) in comparison to Umar (699 km^2) and Barureva (488 km^2) watersheds. In broader perspective, these watersheds show coarse sub dendritic to dendritic drainage pattern.

Table 4.1: Morphological parameters of three watersheds

Morphological Parameters	Unit	Watershed Name		
		Barureva	Sher	Umar
Area A	km^2	488	1635	699
Perimeter L_p	km	107.33	253.32	150.96
Basin length L_b	Km	30.93	77.56	50.34
Form factor R_f	km^2/km	0.51	0.27	0.28
Elongation ratio R_e		0.81	0.59	0.59
Circularity ratio R_c		0.73	0.57	0.62
Total number of all stream order $\sum N_u$		1087	5918	1489
Total length of all stream order $\sum L_u$	km	1006.69	4373.58	1200.20
Main stream length L_{MS}	km	59.66	137.61	86.35
Bifurcation ratio R_b		3.94	4.15	4.16
Length ratio R_l		2.14	2.07	4.06
Drainage density D_d	km/km^2	2.06	2.68	1.72
Length of overland flow L_g	km	0.24	0.19	0.29
Drainage frequency D_f	No/km^2	2.23	3.62	2.13
Constant of channel maintenanance C_m	km^2/km	0.48	0.37	0.58
Texture ratio T	No./km	7.91	17.62	7.58
Total relief H	m	280.00	550.00	270.80
Relief ratio R_h	m/km	9.05	7.09	5.38
Ruggedness number R_N		0.58	1.47	0.47
Relative relief (R_r)	m/km	2.61	2.17	1.79

A bifurcation ratio greater than 5 indicates structurally controlled development of the drainage network (Strahler 1957). The bifurcation ratio (R_l) of these watersheds are found to be within 5.0, indicating that geomorphic control is more than structural control on drainage network.

The form factor, elongation ratio and circularity ratio of Barureva watershed are found to be much higher than those of Sher and Umar watersheds indicating that Barureva watershed is more circular than the watersheds of Sher and Umar. Sher watershed has denser drainage pattern (2.68 km/km^2) and higher drainage frequency (3.62 no./km^2).

Low drainage density (D_d=1.72 km/km^2) of Umar watershed indicates the dominance of overland flow (Lg=0.29 km) over the channel flow. The constant of channel maintenance (C_m) is a direct indication of permeability of underlying rock formation. The value of C_m for Umar watershed is 0.58 km/km^2 much higher than for Sher and Umar watersheds. The Umar watershed on an average has permeable or comparatively soft geological formation. The length ratio (R_l) is also indicative of underlying geological formation. Higher value of R_l (4.06) in Umar watershed indicates the larger length of higher order streams (Table 4.2).The large length of higher order stream is also an indication of permeable topography or soft formation. Thus in overall Umar watershed is more permeable and has soft geological formation. This inference is consistent with the available geological information of the study area (Figure 4.11). The Umar watershed has highest areal coverage of alluvium plain as compared to Barureva and Sher watersheds.

Table 4.2: Stream orders distribution in study area

Stream order	Barureva			Sher			Umar		
	Number	Length km	Average Length km	Number	Length km	Average Length km	Number	Length km	Average Length km
1st	849	502.106	0.59	4463	2563.64	0.57	1145.	633.60	0.55
2nd	182	203.905	1.12	1140	874.85	0.77	272	233.96	0.86
3rd	41	142.565	3.48	254	427.71	1.68	56	149.76	2.67
4th	**10**	**67.3**	**6.73**	**46**	**259.03**	**5.63**	**12**	**102.90**	**8.58**
5th	4	69.962	17.49	11	108.44	9.86	3	16.19	5.40
6th	1	20.85	20.85	3	77.85	25.95	1	63.79	63.79
7th	0	0	0.00	1	62.07	62.07	0	0.00	0.00
total	1087	1006.688	0.93	5918.00	4373.59	0.74	1489.00	1200.20	0.81

4.4.2 Slope Zone Distribution of Three Watersheds

The study area is classified into seven different slope zones (Figure 4.2). The slope zone distributions in the three watersheds are presented in Table 4.3. About 89 % of area in Umar watershed is in slope range of 0-3%. Therefore, Umar watershed may be described to have averagely flat topography. The Barureva watershed follows nearly the same pattern of distribution with 77.35% of the watershed area in 0-3 % slope range. Sher watershed shows considerable variation in slope zones. The hilly portion of Sher watershed is found in the middle part of the watershed and it covers 21% of watershed area. Hilly region shows decrease in slope values in the north as well as in south directions from the central hilly zone of the area.

Table 4.3: Slope area distribution in study area

Slope range %	Barureva		Sher		Umar	
	Area km^2	% area	Area km^2	% area	Area km^2	% area
0-1	326.7	67.0	478.1	29.2	552.6	79.1
1-3	50.7	10.4	418.6	25.6	69.5	9.9
3-5	23.1	4.7	179.6	11.0	21.2	3.0
5-10	31.8	6.5	207.5	12.7	23.3	3.3
10-15	27.3	5.6	151.8	9.3	15.3	2.2
15-30	22.7	4.7	156.0	9.5	12.9	1.8
>30	5.6	1.2	43.4	2.7	3.9	0.6
	488.00	100.0	1635.0	100.0	699.00	100.0

4.5 ANALYSIS OF FOURTH ORDER SUB WATERSHEDS

4.5.1 Selection of Sub Watersheds

At watershed scale, morphological parameters of the three watersheds reveal average hydrological and geological conditions. However, for sustainable development and utilization of natural resources, analysis needs to be carried out at sub watershed level which may exhibit heterogeneity in physical characteristics. Study area is of seventh order. It is categorized into a number of sub watersheds to understand the influence of geological setting on morphological parameters and for identification of appropriate watershed development measures. The fourth order watershed is found to be an appropriate unit as it is mode of seven orders found in the study area (Table 4.2). Also, fourth order watersheds cover 58.61% study area. By selecting lower order sub watershed as a unit, the number of sub watersheds (sample data) increases but corresponding area of analysis decreases. On the other hand by selecting higher order sub watershed as a unit, the number of sub watersheds (sample data) decreases but corresponding area of analysis increases.

Sixty eight fourth order watersheds are found in the study area. Number of fourth order sub watersheds in Barureva, Sher and Umar watersheds is 10, 46, and 12 respectively (Table 4.2). Average area of fourth order sub watersheds in Sher watershed is smaller (35.54 km^2) as compared to sub watersheds in Barureva

(48.8 km^2) and sub watersheds in Umar watershed (58.25 km^2). The morphological parameters for all the 68 sub watersheds have been computed in GIS environment and are given in Appendix A (Table A1).

Figure 4.3 shows drainage density distribution over the sub watersheds. The drainage density varies from 0.94 km/km^2 to 4.35 km/km^2. Hilly area is located in middle of the study area and has the highest drainage density (3.50 to 4.35 km/km^2). This area is basically a runoff production zone. Drainage density along western watershed boundary is in the range of 2.64 to 3.5 km/km^2. Sub watershed number 53S on south-eastern side boundary of study area has low drainage density and low drainage frequency similar to those existing in lower part of the study area. Figure 4.4 shows drainage frequency distribution over the sub watersheds. In general, drainage frequency distribution is similar to drainage frequency distribution. Sub watersheds along the southern boundary have low drainage frequency due to plateau formation (0.78 to 3.09 $/km^2$) compared to sub watersheds along the western boundary.

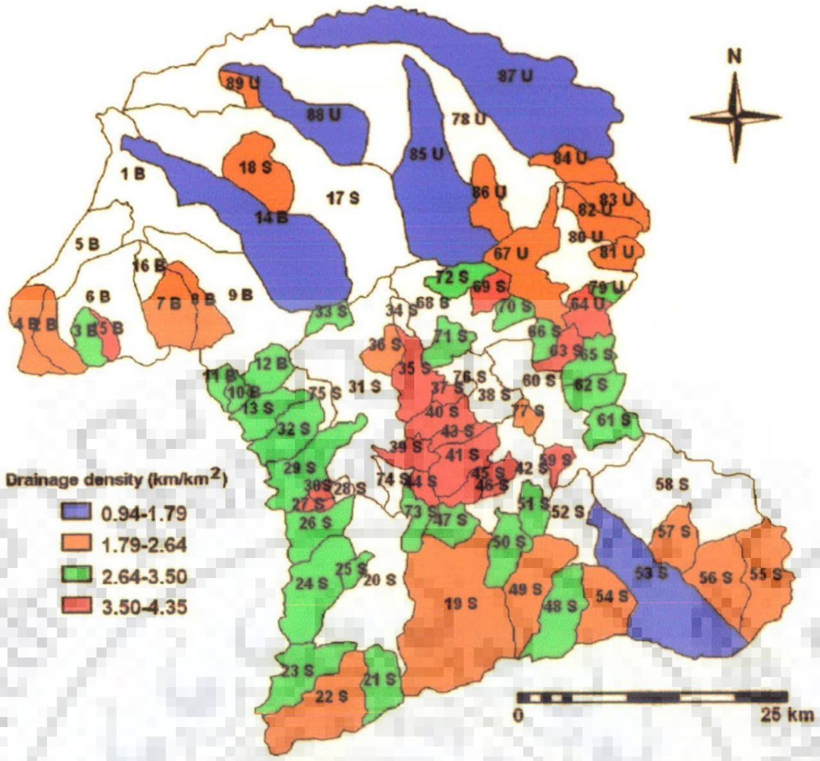


Figure 4.3 : Drainage density(D_d) in fourth order sub watersheds

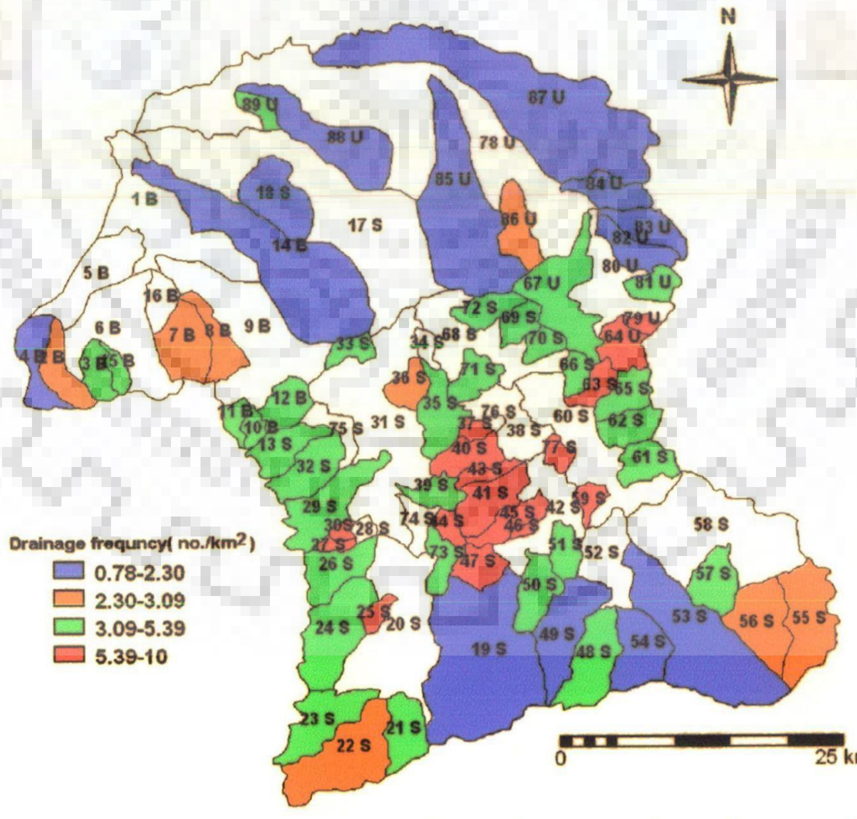


Figure 4.4: Drainage frequency (D_f) in fourth order sub watersheds

4.5.2 Statistical Analysis

Q-Q Plots and frequency histograms are two simple classical statistical methods for illustrating frequency distributions (Cheng et al., 2001).These have been applied to show the frequency distribution of the length of various stream orders over the 68 sub watersheds. Q-Q Plots show the plot of natural log values of stream length verses their expected log normal values (Figures 4.5a to 4.5e). Straight line fit (linear scattering pattern) is generally observed in all the plots. The frequency histograms of stream lengths of order 1-3 and for sum of all order lengths show normal distribution (Figures 4.6a to 4.6e). Therefore all fourth order sub watersheds have been retained for further analysis.

4.5.3 Correlation and Regression Analysis

The Pearson Correlation Coefficient measures linear association between two variables (Hirsch et al., 1992). Correlation coefficient matrix is computed using morphological parameters for the fourth order sub watersheds and is given in Appendix A (Table A2). Perimeter (L_p), basin length (L_b), longest stream length (L_{ms}) cumulative stream length ($\sum Lu$) and cumulative stream number ($\sum N_u$) are found to be highly correlated with the watershed area (A). Therefore with knowledge of area, these parameters can be reliably assessed using developed regression equations.

Correlation matrix has been used to assess the presence, or otherwise, of groups of inter-correlated variables. Following four major groups exist. Strong correlations have been observed between the parameters of same group.

(i) linear parameters like L_p, L_{ms} and L_b,

(ii) drainage parameters N_u, L_u, D_d, D_f, R_b and R_t,

(iii) shape parameters R_f, R_c and R_e and

(iv) slope parameters R_h, R_N and R_r.

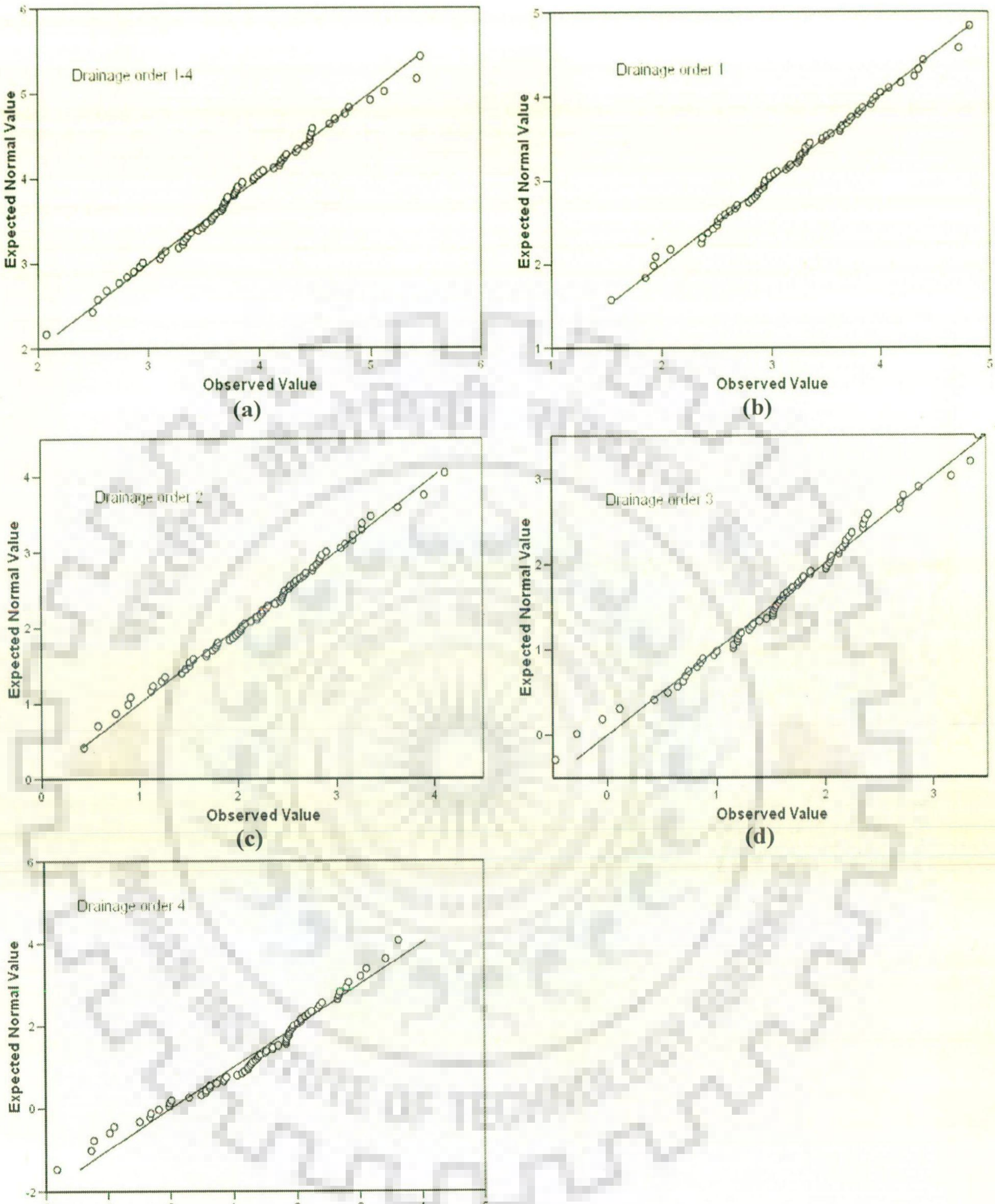


Figure 4.5: Q-Q plots of drainage length of various orders

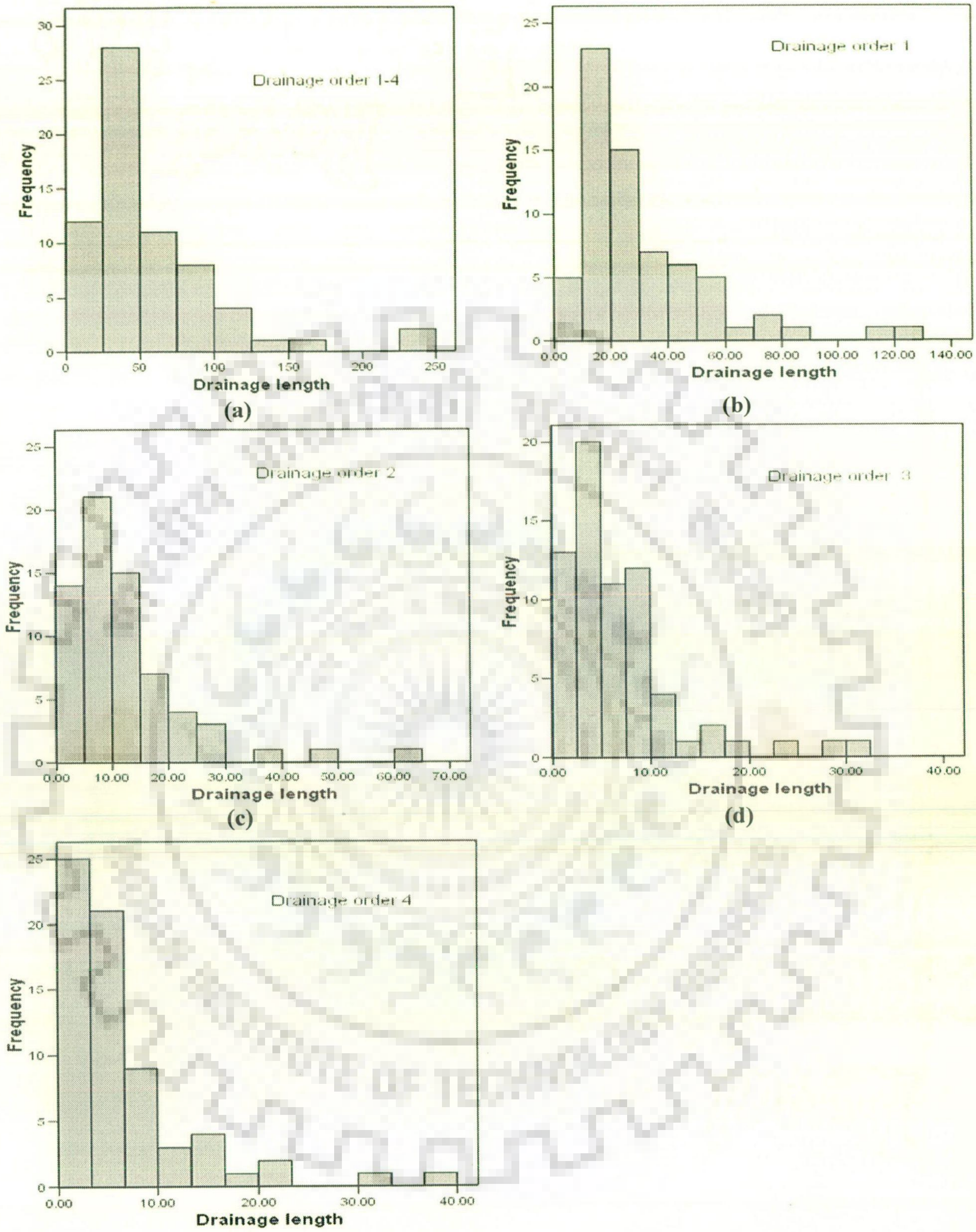


Figure 4.6: Histograms of drainage length of various orders

4.6 FRACTAL ANALYSIS OF FOURTH ORDER SUB WATERSHEDS

4.6.1 Fractal Relation between Morphological Parameters and Area

Model forms such as linear, log linear, power form, exponential form have been tested for scatter data plots of chosen parameters such as L_p, L_b, L_{ms}, $\sum L_u$, $\sum N_u$ D_d and D_f plotted against area. Power form model provides best fit (Figures 4.7a to 4.7e) with coefficient of determination in the range of 0.72 to 0.96. Power law relationship between $\sum Lu$ and A is popularly known as Hack law. It is given as

$\sum Lu = \alpha A^{\beta}$; $\beta = ½ D$ where D is fractal dimension.

The exponent β investigated by Hack (1957) for several rivers in Virginia and Maryland was found to be 0.6 (D=1.2). Hack's analysis was performed on watersheds in different regions, and not for sub-watersheds within a larger watershed. Hack also examined data from Langbein (1947) for 400 streams in the northeastern United States and found β to be different i.e. β =0.7 (D=1.4). In the present study, the exponent β is found to be 0.76 (D=1.52) for the power law relationship developed using data for the 68 fourth order watersheds. Therefore it is concluded that the fractal dimension may vary from region to region. The fractal dimensions computed from the derived power law relationships of chosen parameters with area are given below,

Fractal Relation	Fractal Dimension	
$L_p=4.11\ A^{0.56}$	PDA=1.12	(Figure 4.7a)
$L_b=1.41\ A^{0.58}$	Dp=1.16	(Figure 4.7b)
$\sum N_u=11.24\ A^{0.60}$	Dn=1.2	(Figure 4.7c)
$\sum L_u=5.78\ A^{0.76}$	D=1.52	(Figure 4.7d)
$L_{ms}=1.46\ A^{0.66}$	D_{lm}=1.32	(Figure 4.7e)

Several researchers have used fractal dimension as measure of degree of randomness for stream network evolution or as a measure of lack of geological constraint (Mandelbroat, 1983; Phillips, 1993 and Cheng Q., 2001).The fractal dimension (D) varies from 1 to 2. If D=2, Hack law becomes $\sum L \propto A$ indicating that stream generation in a watershed is just process of space filling and it is not influenced by underlying geology. On other hand D=1 implies that stream network is strongly controlled by underlying geological setting.

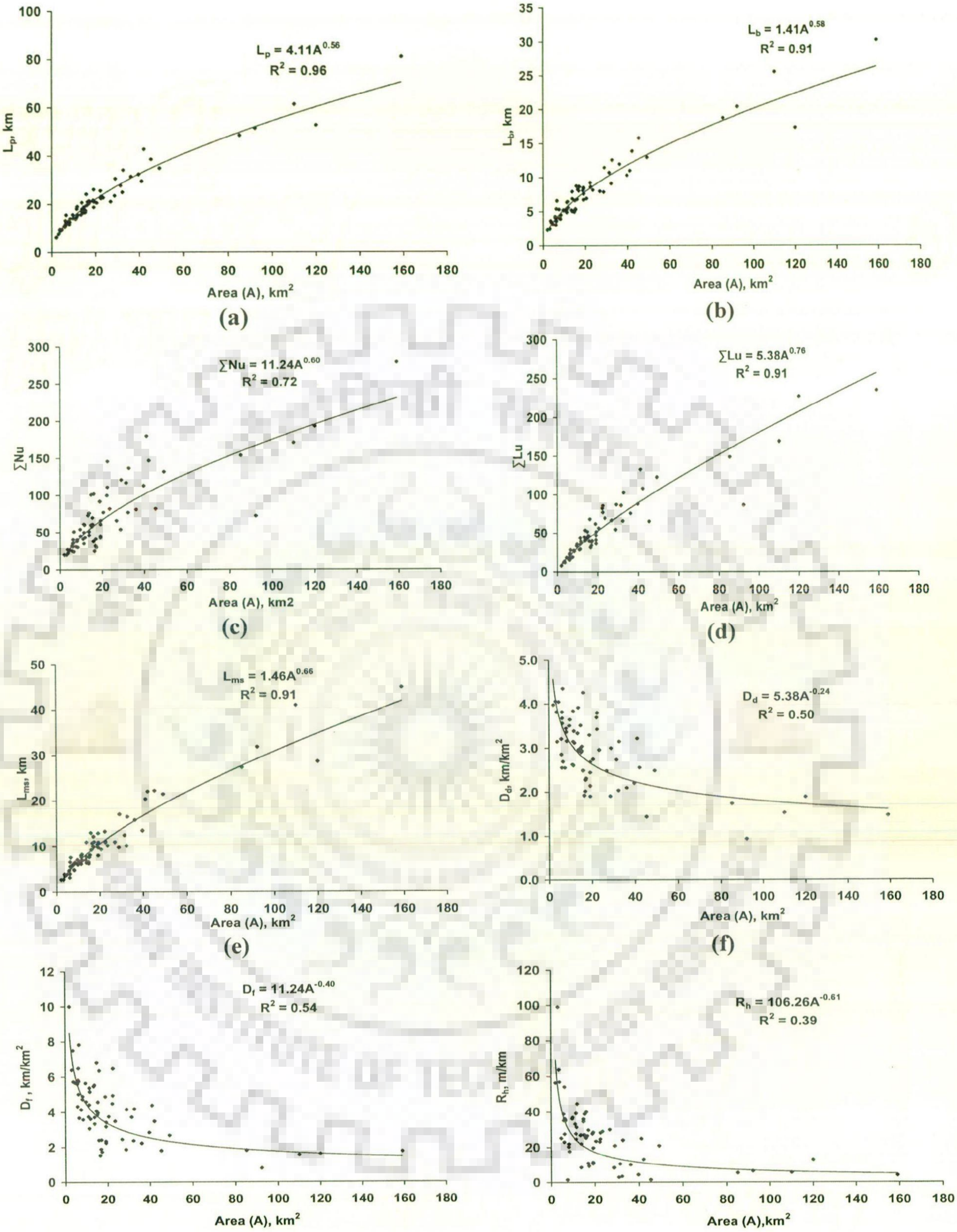


Figure 4.7: Fractal (power law) relationship of (a) L_p and A, (b) L_b and A (c) $\sum N_u$ and A (d) $\sum L_u$ and A (e) L_{ms} and A(f) D_d and A , (g) D_f and A (h) R_h and A.

The fractal dimension D in Hack law relationship for 68 watersheds varies from 0.95 to 1.79 (Figure 4.8) suggesting that evolution of stream network is controlled by the geological formations in the watershed area. The fractal dimensions computed from power relationship of drainage parameters (L_b, L_{ms} and $\sum N_u$) with area (A) of sub watersheds (Dp=1.16, Dlm=1.32, Dn=1.2) also indicate influence of geological setting on the stream pattern evolution.

The fractal dimension (PDA) estimated from power relation of perimeter (Lp) with area (A) is found to be close to 1 (PDA=1.2). PDA close to 1 means that sub watersheds are of regular shape whereas PDA value close to 2 means sub watershed shape is irregular. The PDA values for the sub watersheds are in range of 0.90 to 1.42 (Figure 4.9). The PDA values indicate that the sub watersheds in the study area, in general, have regular shape.

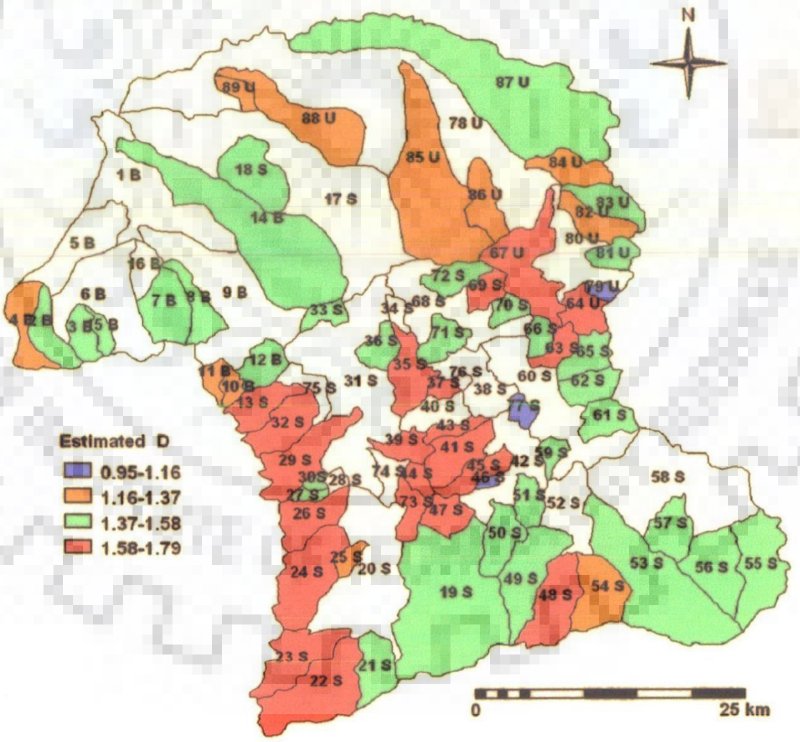


Figure 4.8: Distribution of fractal dimension (D) in fourth order sub watersheds

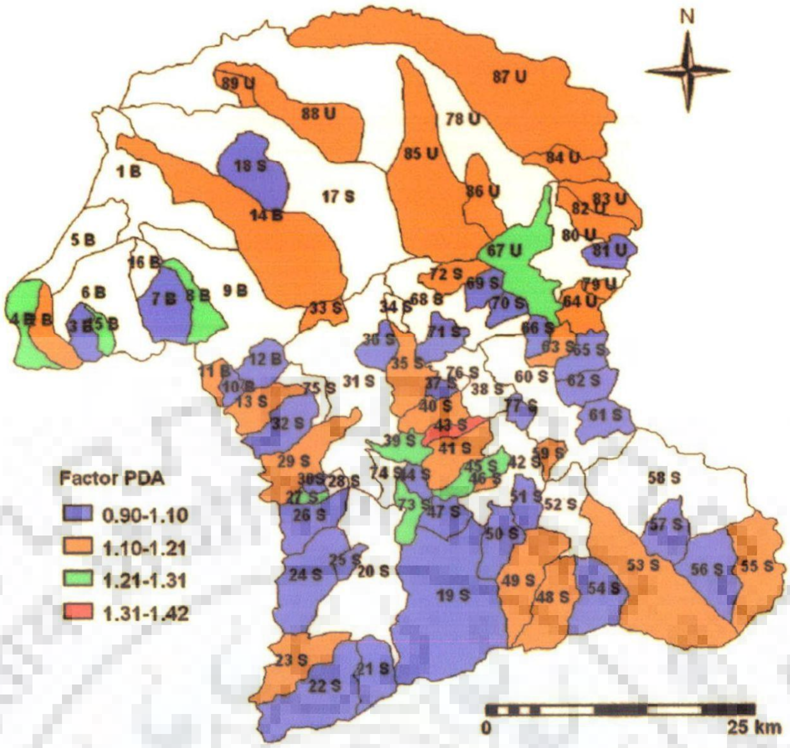


Figure 4.9: Distribution of fractal dimension (PDA) in fourth order sub watersheds

4.6.2 Combined Index of Degree of Randomness in Drainage Network

The analysis in previous section shows that several fractal dimensions have to be analyzed for study of drainage pattern. Principal component analysis (PCA) method is frequently used to reduce several parameters into few combined indices (Cheng, 2001). Each index called as PCA factor consists of additive form of multiplication of factor score and input parameters. The factor score is nothing but the correlation coefficient between computed PCA factor and input parameter.

In this study input variables for PCA are various fractal dimensions such as D, D1, D2, D3, D4, PDA, ratio Rbl and Slope (Table 4.4). These variables have been calculated for each sub watershed using derived power law relationships between morphological parameters and area. The results of PCA are presented in Table 4.5 and Table 4.6. Four indices (PCA1 to PCA4) have been created. Table 4.5 shows the significance (amount of variance explained) of PCA factors and Table 4.6 show the contribution of each variable to constitute PCA factor. The first PCA factor explains 28.47% variance of given input variable. Therefore PCA1 is chosen as representative index which denotes the degree of randomness of the evolution of drainage network. The PCA1 factor obtained for each sub watershed is shown in Figure 4.10. The map of degree of randomness has been used in multilayer integration studies to observe influence of geological setting on drainage network of sub watersheds in study area.

Table 4.4: Variables for the PCA analysis and their value range for the 68 sub watersheds

Variable name	Formula used	Value range	Source
D	D=Log (∑Lu /5.37)/(Log(√A) $\sum L_u$= sum of length all order of streams	0.95-1.79	Derived power law relation $\sum Lu=5.37\ A^{0.76}$
D1	D1=Log(∑L1 /3.54)/(Log(√A) ∑L1= sum of length first order stream	0.76-1.79	Derived power law relation $\sum L1=3.54\ A^{0.76}$
D2	D2=Log(∑L2 /1.10)/(Log(√A) ∑L2= sum of length second order stream	0.33-2.07	Derived power law relation $\sum L2= 1.1A^{0.76}$
D3	D3=Log(∑L3 /0.59)/(Log(√A) ∑L3= sum of length third order stream	0.07-2.95	Derived power law relation $\sum L3=0.59A^{0.76}$
D4	D4=Log(L4 /0.17)/(Log(√A) L4= length of fourth order stream	-0.09-3.29	Derived power law relation $\sum L4=0.17\ A^{0.76}$
PDA	PDA=2*[(Log(L_p/ 4.11)/ (log A)]	0.99-1.42	Derived power law relation $Lp=4.11\ A^{0.56}$
Rbl	Rbl=Rb/Rt	0.59-10.26	-
Slope	Slope=H/Lms	0.001-0.087	-

Log=Natural logarithm to the base e.

Table 4.5: Total variance explained by various principal component factors

PCA factor	Initial Eigen values			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.412	30.154	30.154	2.278	28.474	28.474
2	1.710	21.377	51.531	1.695	21.191	49.665
3	1.626	20.328	71.858	1.638	20.473	70.137
4	1.147	14.334	86.192	1.284	16.055	86.192
5	0.506	6.327	92.519			
6	0.444	5.556	98.075			
7	0.149	1.857	99.932			
8	0.005	0.068	100.000			

Table 4.6: Component score coefficient matrix

Input Parameters	PCA factor			
	1	2	3	4
D	0.437	-0.056	-0.001	0.014
D1	0.402	-0.041	-0.055	0.011
D2	0.279	0.178	0.338	-0.234
D3	0.082	-0.533	-0.020	0.175
D4	0.023	0.512	-0.036	0.327
PDA	0.001	0.059	0.124	0.764
Slope	0.055	-0.095	0.514	0.155
Rbl	-0.082	0.081	0.486	0.040

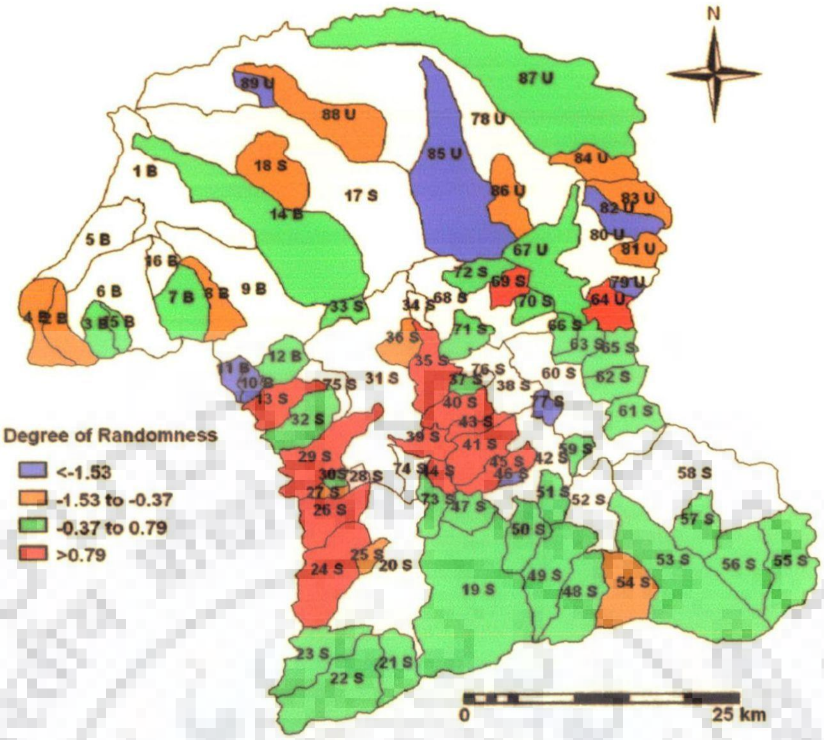


Figure 4.10: Distribution of degree of randomness in fourth order sub watersheds

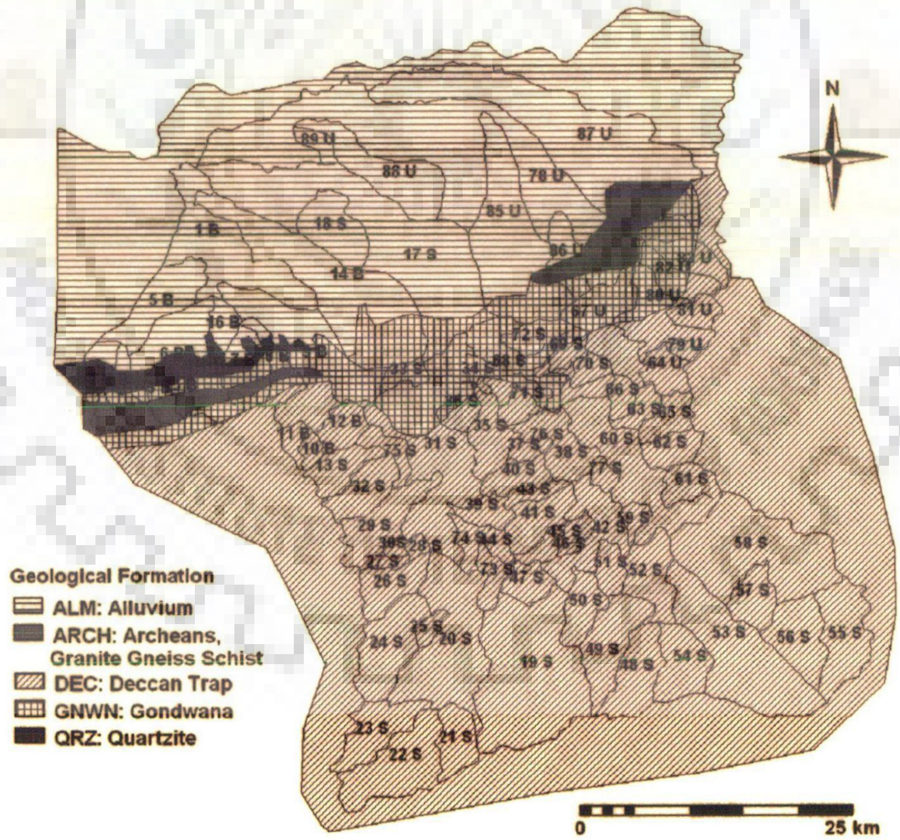


Figure 4.11: The geological formation in various sub watersheds

4.7 INFLUENCE OF GEOLOGICAL FORMATION ON DRAINAGE NETWORK

The geological formations underneath the sub watersheds are shown in Figure 4.11. The associated fractal dimensions and degree of randomness computed from PCA analysis are discussed below.

4.7.1 Sub Watersheds Having Single Geological Formation

Table 4.7 pertains to 51 sub watersheds having single geological formation such as Alluvium, Deccan trap, Deccan trap with lineaments and Gondwana. Drainage pattern of alluvium watersheds is much more regular in shape (PDA=1.01-1.17) than sub watersheds on other geological formations. Sub watersheds of Deccan trap are inclined toward irregular shape and these are formed in the hilly region. Sub watersheds of Gondwana and Deccan trap with fault zone are also regular shaped. The fractal dimension D and Rbl can also be used to describe the nature of control of underlying geological formation over the drainage network pattern. The values of D vary from 1 to 2 and which is the zone of explanation.

Table 4.7: Fractal dimensions of sub watersheds having single geological formation

Sl. No.	Geological formation present in sub watersheds.	Name of sub-watersheds	D	PDA	Rbl	Degree of randomness
1	Alluvium	18S,88U,89U (Total=3)	1.20-1.36	1.01-1.17	2.01-3.81	-2.05 to -0.38
2	Deccan trap	10B,11B,12B,13S,25S,26S,27S,30S,35S,37S,39S,40S,43S,44S,45S,46S,47S,51S,59S,61S,62S,63S,64U,65S,66S,70S,73S,77S,79U,81U,41S,,52S,57S,50 S (Total=34)	0.95-1.78	0.99-1.41	0.87-10.25	-2.68 to 1.94
3	Deccan trap with Lineaments i.e. Faults zone	19S,24S,29S,48S,49S,53S,54S,55S,56S,21S,22S,23S (Total=12)	1.34-1.69	1.03-1.21	1.06-2.39	-0.66 to 0.34
4	Gondwana	33S, 72S (Total =2)	1.44-1.50	1.12-1.18	0.89-0.98	-0.28 to -0.01

The values of Rbl lie very much outside the range of explanation. Therefore values of D have been considered for further explanation of geological control over the drainage network evolution. The control of alluvium is stronger (D=1.20 to 1.36) on the drainage evolution pattern in comparison to sub watersheds having other geological formations underneath. Sub watersheds of Deccan trap show wide range of fractal dimension D from 0.98 to 1.78 indicating that some sub watersheds such as 26S, 46S, 77S and 79S have strong geological control on the drainage pattern evolution. These sub watersheds are small in size and are located in hilly areas. Values of fractal dimension D for remaining 30 sub watersheds show that control of Deccan trap on evolution of the drainage network is not so strong and they are inclined toward space filling properties of drainage network. Deccan trap sub watersheds are very large in size (Figure 4.11) and have the property to lose control over the evolution of drainage pattern.

The degree of randomness of alluvium sub watersheds is in the range of -2.05 to 0.38. Most of the sub watersheds of Deccan trap are associated with high positive degree of randomness and very few such as 10B, 11B, 46S, 77S and 79S sub watersheds show high negatively values. Low degree of randomness is associated with sub watersheds of Gondwana and sub watersheds of Deccan trap with lineaments (-0.66 to 0.34).

4.7.2 Sub Watersheds Having Multiple Geological Formations

Table 4.8 and Table 4.9 pertain to sub watersheds having alluvium and other hard rock geological formations. The alluvium with other geological formations is grouped into three distinctive classes. The fractal dimension (D) varies from 1.20 to 1.49 for three classes. This range is almost similar as found for sub watersheds with alluvium as single geological formation. The PDA factor range (1.12 to 1.28) is also similar as that for the alluvium sub watersheds. It is concluded that presence of alluvium formation in sub watersheds has greater control over the drainage formation as compared to remaining formations which may also be present in sub watersheds with alluvium. Table 4.9 corresponds to sub watersheds having multiple hard rock formations such as Gondwana, Decaan trap, Archeans and Quartzite in various proportions but no alluvium. The fractal dimension D varies from 1.26 to 1.60 indicating that in these types of sub watersheds, geological formation has only partial control over the drainage pattern evolution.

The fractal dimension PDA ranges from 1.05-1.28 suggesting that the sub watersheds formed on these types of hard rocks have regular shape. The degree of randomness varies in a wide range indicating that pattern of drainage formation is random.

Table 4.8: Fractal dimensions of sub watersheds having alluvium formation associated with other geological formations

Sl. No.	Geological formation present in sub-watershed	Name of sub-watershed	D	PDA	Rbl	Degree of randomness
1	Alluvium (74-92% area)+ Gondwana or Quartzite or both	14B, 85U, 87U (Total =3)	1.20-1.46	1.12-1.18	0.89-0.98	-0.28 to -0.01
2	Alluvium (37-51% area)+ Deccan trap or Gondwana or Quartzite or all	86U (Total =1)	1.25	1.12	0.82	-1.25
3	Alluvium (16-28% area)+ Deccan trap or Gondwana or Quartzite or Archeans or all	2B,4B,7B,8B (Total =4)	1.33-1.49	0.99-1.28	1.23-1.87	-0.82 to 0.28

Table 4.9: Fractal dimensions of sub watersheds having Gondwana formation along with other geological formations

Sl. No.	Geological formation present in sub-watershed	Name of sub-watershed	D	PDA	Rbl	Degree of randomness
1	Deccan trap(>50%) is dominant over Gondwana	36S, 69S,71S (Total =3)	1.35-1.60	1.05-1.09	1.50-2.19	-0.56 to 1.00
2	Gondwana is dominant (>50%) over Deccan trap	67U, 82U, 83U (Total =3)	1.22-1.57	1.15-1.25	0.59-0.88	-1.53 to 0.61
3	Gondwana (54%) and Quartzite (46%)	84U (Total =1)	1.26	1.13	1.41	-1.26
4	Archeans is dominant (47 to 50%) with Gondwana (21-29%) and Quartzite (18-31%)	3B,15B (Total =2)	1.51	1.07-1.28	1.75-1.96	0.19 to 0.30

4.8 CONCLUSIONS

At watershed scale, morphological parameters of three watersheds reveal average hydrological and geological conditions. Sustainable development and utilization of natural resources by local population necessitates planning exercise to be carried out at sub watershed level. The study area is of seventh order. It is divided into a number of sub watersheds for better understanding of the influence of geological setting on the drainage evolution pattern and for identification of appropriate watershed development measures The fourth order watershed unit is found to be an appropriate option as it is mode of highest order found in the study area and group of fourth order watersheds also covers 58.61% of the study area. By selecting lower order, sub watershed as a unit, the number of sub watersheds (sample data) increases but corresponding area of analysis decreases. On the other hand by selecting higher order sub watershed as an unit, the number of sub watersheds (sample data) decreases but corresponding area of analysis increases.

Sixty eight fourth order watersheds are found in the study area. The Q-Q plots and frequency histograms show normal distribution. Therefore all the 68 sub watersheds have been retained for analysis. Morphological parameters fall into four major groups having strong inter-correlation within group. Principal Component Analysis (PCA) method has been used to evolve an appropriate index to assess degree of randomness in drainage evolution. PCA1 can be chosen as an appropriate index for this purpose.

Control of Deccan trap formation on drainage evolution is not as strong as that of the alluvium formation. Sub watersheds with Deccan formation show varied type of drainage pattern. The low degree of randomness is associated with sub watersheds having single geological formation such as Deccan trap with lineaments, Gondwana and alluvium (greater than 74%) indicating greater influence of geological setting on the drainage evolution pattern. Sub watersheds having multiple hard rock geological formation show very low as well as high degree of randomness.

CHAPTER 5

GEOMORPHOLOGICAL PERMEABILITY INDEX AND ITS RELATION WITH UNDERLYING GEOLOGICAL FORMATION

5.1 INTRODUCTION

Permeability in hard rock areas is low and infiltration is restricted to the weathered and fractured zones. Such areas may be prone to water crisis because of low porosity of aquifers and erratic rainfall. Quantitative geomorphological analysis can be useful in understanding hydrological nature of geological setting in a watershed.

Conventionally watershed development in India refers to development of ground water recharge, runoff harvesting schemes and soil erosion control measures to meet local needs at village level. Ground water recharge schemes may not succeed if rock surface permeability is not considered or if the sites are mistakenly located in natural ground water discharge areas. Groundwater recharge sites have often been selected based on topographic considerations only. Geomorphological and geological characteristics of the areas have often been neglected.

5.2 INFLUENCE OF MORPHOLOGICAL PARAMETERS ON PERMEABILITY

Unlike surface water, it is generally more difficult to detect ground water bearing zones. Geohydrological characteristics of an area are assessed by drilling test holes and conducting well log study which is costly and time consuming process especially in hilly terrain and or when area of study is large. In this context GIS based hydrogeomorphological studies can be useful in identifying ground water potential zones as illustrated by Agarwal (1989) and Saraf and Choudhury (1998). A combination of hydrogeological and drainage analysis could be used for selecting sites for artificial recharge and groundwater targeting (Pakhmode et al., 2003; Srinivasan et al., 1999) in a watershed located in Wardha district in Central India.

In areas of poor rock outcrop, the drainage pattern provides valuable guidance about the type of underlying geological formations. It has been observed that rock fabric shows the effect on drainage pattern at very fine scales. Pakhmode et al. (2003) have studied the relationship between drainage pattern and underlying geological formation. In relation to nature of permeability of underling rock formation, watershed parameters particularly drainage density (D_d), drainage frequency (D_f), length ratio (R_t) with associated relief ratio (R_h) show specific value range. These parameters in relation to natural permeability of geological formation have been discussed in Chapter 4.

Low drainage density (D_d) areas provide more opportunity time to infiltrate overland flow which subsequently may have better ground water recharge condition under same rainfall condition. Under the same slope condition, hard geological formation show high drainage frequency (D_f) value compared to soft geological formation in the watershed. Higher order streams show high length values in a basin having soft or permeable geological formation. Watershed with low relief ratio (R_h) provides more time to infiltrate the generated runoff and subsequently build ground water storage.

5.3 FORMULATION OF GEOMORPHOLOGICAL PERMEABILITY INDEX (GPI)

One way to describe hydrogeomorphological character of a watershed such as permeability is to list out the values of all relevant primary and derived parameters. Such list would normally be quite long. Comparison of hydrogeomorphological character of different watersheds becomes cumbersome in terms of several parameters. Prioritization of micro watersheds for development and management also can not be done easily by comparing a long list of individual parameters of each micro watershed. An index aims at giving a single representative value to those geomorphologic parameters which influence a dependant watershed property of interest. Indices have been used in ecology (Shannon Index and Simpson's Index) to represent species richness, evenness, diversity etc. Water quality indices are now commonly used to compare different samples of water and to indicate overall quality of water. Thus there are Horton's Index, National Sanitation Foundation's Water Quality Index (NSFWQI) or Brown's Index and many others as listed in Abbasi (2002).

The following four steps are often associated with development of a geomorphological index.

1. Parameter selection.
2. Transformation of the parameters of different units and dimensions to a common scale.
3. Assignment of weightages to all parameters.
4. Aggregation of sub indices to produce a final index score.

The overall process to form index can be illustrated as below in Figure 5.1.

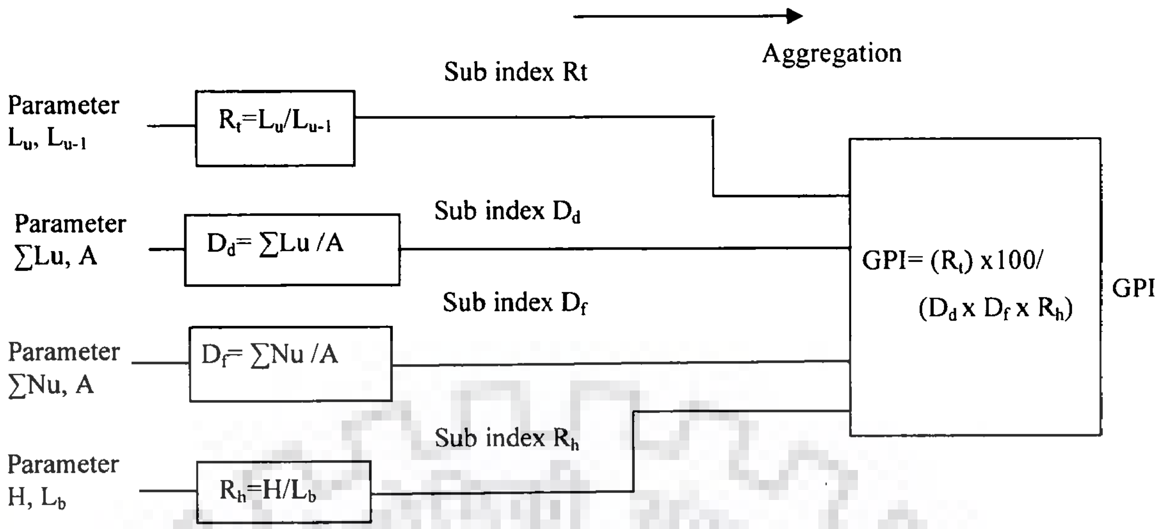


Figure 5.1: Formulation of a Geomorphological Permeability Index (GPI)

A GPI should be such as to directly indicate degree or magnitude of permeability of underlying geological formation to infiltrate the generated runoff in a watershed and that is intrinsically associated with degree of permeability of a formation. Values of GPI of various watersheds provide a basis to compare watersheds having different types of geological formations underneath. GPI also helps to predict the condition of ground water availability, soil erosion condition and weathered condition of geological formation. As discussed earlier D_d, D_f and R_h are inversely proportional to the nature of rock permeability. Permeability of rock is directly proportional to length ratio (R_t), and constant channel maintenance (C_m). Higher the value of D_d, D_f, and R_h and/or lower the value of R_t and C_m for a watershed, less permeable is underlying geological formation. Parameter C_m is inverse form of D_d, therefore it is not necessary to include it as an independent variable. Keeping this response of watershed parameters in relation to nature of permeability of geological formation, an index has been proposed to know about the nature of permeability and the availability of ground water storage in the watershed. GPI is computed as follows.

$$GPI = (R_t)*100/(D_d \times D_f \times R_h) \quad (5.1)$$

This study has been made in GIS environment using topographic map (Scale 1: 50 000), geological map and data of ground water observation wells in the study area.

5.4 ANALYSIS AND DISCUSSION

GPI index has been computed on sub watershed basis spread over Barureva, Sher and Umar watersheds. Sub watersheds are classified on the basis of stream order suggested by Strahler (1964). The classified sub watersheds are fourth order watersheds and other sub-watersheds formed around fifth, sixth and seventh order of stream wherein fourth order is absent while first, second and third order is associated with fifth or sixth or seventh order. The geological setting of the study area has been discussed in Chapter 3.

The study area was subdivided into eighty nine sub watersheds. GPI has been calculated for each of the sub watersheds on the basis of a large number of related morphological parameters. GPI values are given in Appendix A (Table A3). GPI values are in the range of 0.05 to 119 (Figure 5.2). The most important contributing factor in GPI is the relative slope (R_h) among all parameters used in the computation of GPI. Comparison and validation of the map of GPI values (Figure 5.2) with the hydrogeological map reveals that the GPI is a direct indication of permeability of underlying geological formation and capacity to store ground water. Higher range of GPI is indicated by the sub watersheds situated in lower parts Barureva, Sher and Umar watersheds and also in the upper most part of Sher Watershed. The range of GPI associated with these sub watersheds suggest good permeable zone and better storage potential of aquifers as confirmed by data of observation wells and the fact that these sub watersheds are able to sustain cultivation of sugarcane crop (Plate 5.1) in absence of surface water irrigation facilities. There are two large sugar factories and several small scale sugar factories in the area which is the leading producer of Gurh (crude brown form of massive sugar) in the central India. Those sub watersheds which have lower values of GPI are located in hilly upper part of Barureva and Umar watershed and in middle reaches of Sher watershed. These sub watersheds with low GPI values are the most impermeable and not suitable for ground water recharging. Field observations have shown that these hilly areas do not have established agriculture practices, and have only sparse settlements.

GPI values of sub watersheds have been compared with the properties of existing geological formations in relation to availability of ground water storage as discussed below.

Plate 5.1: Sugarcane crop with perennial tube well irrigation in sub watershed 17S (GPI -21.73)

Plate 5.2: Weathered top layers of Decaan trap in sub watershed 53S (GPI-23.84)

Plate 5.3: Dug well (good ground water storage) in Decaan trap in sub watershed 53S (GPI-23.84)

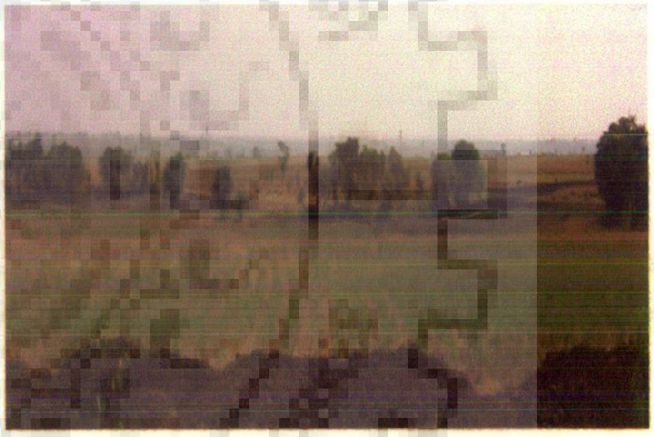


Plate 5.4: Sustained agriculture based on ground water irrigation in Decaan trap in sub watershed 53S (GPI-23.84)

5.4.1 Sub Watersheds Having Single Geological Formation

The sub watersheds have been classified into various groups (Table 5.1a) on the basis of their existing geological formations.

Table 5.1a: GPI of sub-watersheds having a single geological formation underneath

Sl. No.	GPI Range	Name of Sub-watersheds	Geological formation present in sub watersheds	Properties of geological formations
1	19.98-68.06	18S,88U,89U,1B,5B (Total=5)	Alluvium	It consists of soils, sands, gravels, pebbles etc, Alluvium shows maximum yielding capacity.
2	0.05-2.55	10B,11B,12B,13S,25S,26S,27S, 30S,35S,37S,39S,40S,43S,44S, 45S,46S,47S,51S,59S,61S,62S,63S,64U,65S,66S,70S,73S,77S,79U,81U,41S,28S,76S,42S,74S, 52S,38S,75S,60S,57S,50S (Total=41)	Deccan trap	Deccan trap are dark colored, fine to medium grained. The vesicles, joints and fractures are generally filled with the secondary minerals like zeolites etc. compactness of traps gives rise to low porosity.
3	0.97-23.84	19S,24S,29S,32S,48S,49S,53S, 54S,55S,56S,21S,22S,23S,20S, 58S (Total=15)	Deccan trap with Lineaments i.e. Faults zone	Ground water occurs in weathered basalts openings.
4	0.76-1.07	33S, 72S (Total =2)	Gondwana	Gondwana: The formation comprised of Jabalpur sand-stone. The sand stone is medium to coarse grained, moderately compact and fairly good permeability.

The classification helps to understand relationship between GPI and the availability of ground water in exiting geological formations in the sub watersheds. In Table 5.1a, sixty three sub watersheds (Out of 89 sub watersheds) have been classified into four groups such as sub watersheds having Alluvium, or Deccan trap or Deccan trap with lineaments or Gondwana formation underneath. The remaining twenty six sub watersheds contain two or more geological formations in successive laps.

Sub watersheds with high GPI values in the range of 19.98-68.06 are associated with Alluvium formation. The Alluvium formation is most permeable formation and it has large capacity to infiltrate the overland flow. The yield capacity of well and tube wells is found in the of range of 20-60 liter per second which is nearly 10 times more than that of wells/tube wells in other hard rock formations (CGWB, 1998).

Forty one sub watersheds (second group) have GPI values in the range of 0.05-2.55. These watersheds are formed on the Deccan trap which is massive compact and fine grained and this type of formation is very impermeable. Out of forty one sub watersheds, only four sub watersheds namely 26S, 35S, 50S, and 57S have GPI values in range of 1.0-2.55, which is the highest range observed on the Deccan trap in absence of fault zone. The remaining thirty eight sub-watersheds of Deccan trap formation have the GPI values in range of 0.05-0.77. Due to associated higher values of D_d, D_f and R_h and lower values of R_t these watersheds cause quick removal of overland flow from these sub watersheds. This is the lowest range observed among all sub watersheds over the different geological formations. This range illustrates that these sub watersheds are the most impermeable in the study area and availability of ground water storage is very less. In these types of particular watersheds (having GPI values less than 1), ground water structures are either very less or absent. Settlements in these watersheds were also found to be very less as compared with sub watersheds having higher GPI values such as in the sub watersheds of Alluvium formation. Most impermeable sub-watershed is 46S with GPI value 0.05 which spreads on Deccan trap and is also associated with high relief.

Third group has fifteen sub-watersheds located in the uppermost part of Sher watershed with comparatively higher values of GPI (0.97-23.84) than the sub watersheds which are formed on Deccan trap (basalt) without lineaments. The sub watershed parameters such as D_d, D_f, R_h and R_t show comparatively lower values, therefore, they may be inferred to act as better sites for the infiltration of generated overland flow. Their higher GPI values denote the presence of ground water storage. In these sub watersheds, observed presence of lineaments (Figure 5.2) is an indication of availability of ground water storage. In these sub watersheds longer runs of lineaments are an indication of weathered condition of Deccan trap. Weathered basalt along with lower slope helps to infiltrate the generated runoff and builds good ground water storage which sustains agriculture (Plates 5.2, 5.3 & 5.4). The sub watersheds 19S, 49S, 53S, 54S, 55S and 56S show higher values of GPI in the range of 5.92-23.84 and are found to very permeable sub watersheds next to the sub-watersheds of Alluvium formations. The presence of denser settlement, purely dependent on ground water source for their water needs is noticed in the area. Hence GPI values can be capable of recognizing availability of ground water on hard rock without knowing its state of massiveness or weathered condition.

Fourth group consists of sub watersheds 33S and 72S with Gondwana as a single formation underneath. The GPI values of these sub watersheds are 0.76 and 1.02 comparatively little more than GPI values of sub watersheds of Deccan traps. These sub watersheds are also impermeable and not suitable for ground water development.

As discussed below, sub watersheds which have Gondwana rocks in association with Deccan basalt or Quartzite show better GPI values than sub watersheds having only Gondwana rock underneath. Thus presence of two or more formation in a single sub watershed provide joints and fractures along the contact zone of formations and it presents nothing but possibility of better storage of ground water.

Table 5.1b: GPI of sub-watersheds having Alluvium formation associated with other multiple Geological formations underneath

Sl. No.	Range of GPI	Name of sub-watersheds	% Coverage geological formation sub watersheds	Properties
I	15.11-119.88	14B, 16B, 17S, 78U, 85U, 87U (Total =6)	Alluvium (74-92% watershed area) + remaining Gondwana or Quartzite or both	Gondwana: T his formation comprised of Jabalpur sand-stone. The sand stone is medium to coarse grained, moderately compact and fairly good permeability. Quartzite: These rocks have low porosity and permeability. IF it is weathered zone provide good scope for accumulation of ground water. Archeans: This formation is the oldest and comprised of granite and gneisses. The rocks are hard and compact in nature. The presence of appreciable thickness of weathered zone provides good scope for accumulation of ground water.
2	4.82-6.26	6B,9B,86U (Total =3)	Alluvium (37-51% watershed area)+ remaining comprised of Deccan trap or Gondwana or Quartzite or all	
3	1.17-1.84	2B,4B,7B,8B (Total =4)	Alluvium (16-28% watershed area)+remaining comprised of Deccan trap or Gondwana or Quartzite or Archeans or all	

5.4.2 Sub Watersheds Having Alluvium and Other Hard Rock Formation

The sub watersheds having different proportions of Alluvium with associations of other hard rock formations underneath have been classified in Table 5.1b. It is observed from the table that as the percentage area of the Alluvium in sub-watersheds decreases, their GPI values also decrease simultaneously. Thus, the presence of Alluvium in sub-watersheds considerably increases the overall permeability of a particular sub-watershed.

GPI values greater than 15 (group 1) assure the presence of soft formations and consequently high water yielding zones and capacity to store considerable amount of overland flow. This particular group of sub watersheds has high potential for ground water exploration. A large number of tube wells including high yielding tube wells (yield 0.06 to 0.290 million liters per day) have been observed in these sub watersheds.

Sub watersheds comprise of 74-92% Alluvium area. Sub watersheds fully covered with Alluviums (Table 5.1a), are damaged by gullying and soil loss and therefore their GPI values are reduced as much as nearly 50%-60%. Sub watershed 85U has highest value of GPI (119.88) among all sub watersheds present in the study area. The Geohydrological survey (1978-81) which contains information about tube well distribution (Figure 5.2) shows that tube wells are more equally distributed and greater number of tube wells have been recorded in this sub watershed compared to other sub watersheds. The highest GPI of 85 U is attributed to the lowest values of D_d (0.94km/km^2) and D_f (0.78 number/km^{-2}) of the sub watershed. This sub-watershed is also associated with longer streams of higher order (R_t=4.30) and very low slope (R_h=4.9m/km). The tube well distribution in sub watersheds 14B (GPI=43.90), 78U (GPI=32.94), 87U (GPI=45.39) and 88U (GPI=45.33) is also consistent with high GPI values. Thus, sub-watersheds of Alluvium having GPI greater than 15 are favorite sugar-cane growing area completely depending on ground water for irrigation.

Sub watersheds comprising of 37-51% of watershed area under Alluvium show GPI value range with minimum variation (4.82-6.26). These sub watersheds in general have underlying formations possessing same magnitude of watershed permeability and offer same response for the runoff infiltration. In comparison with other sub watersheds of high GPI values, this group of sub watersheds is comparatively less permeable. Alluvium formation is observed in lower part while upper part is dominated by hilly and hard rock formations in these sub watersheds. This type of situation provides good ground availability near the sub-watershed outlet. Tube well distribution in sub watersheds 6B and 9B is concentrated in lower part where Alluvium formation prevails. Hence these sub watersheds are partially suitable for ground water storage. Moreover, these sub watersheds can also be useful for rain water harvesting structures owing to availability of good runoff volume from the upper hilly and hard rock catchment part.

Sub watersheds comprising of 16-28% Alluvium formation along with other hard rock formation (Table 5.1b), show very low values of GPI (1.17-1.84) which can be attributed to presence of hard rock formations along with strong relief. Sub watersheds in this group are found to be quite similar in terms of morphological and geological behavior as they have nearly same values of morphological parameters D_d, D_f, R_t and R_h. Interestingly 2B sub watershed shows good number of tube wells but these are present in Alluvium formation. While 4B, 7B and 8B sub watersheds do not show considerable presence of tube wells. Owing to impermeable nature of geological formation and due to high slope, these sub watersheds are not suitable for ground water exploration and ground water storage; however, these can be used for surface water storage for controlling soil erosion.

Eleven sub-watersheds are associated with Gondwana combined with other hard rock formation. GPI values vary from 0.34 to 5.18 (Table 5.1c).

Table 5.1c: GPI of sub-watersheds having Gondwana formation along with Deccan trap and Quartzite formation

Sl. No.	Range of GPI	Name of Sub-watersheds	% Coverage geological formation sub watersheds
1	0.34-1.89	31S, 36S, 69S,71S (Total =4)	Deccan trap is dominant (>50%) over Gondwana formation (<50%)
2	2.47-5.18	34S, 67U, 68S, 80U, 82U 83U (Total =6)	Gondwana is dominant (>50%) over Deccan trap formation (<50%)
3	3.79	84U (Total =1)	Gondwana (54%) and Quartzite (46%)
4	0.34-0.40	3B,15B (Total =2)	Archeans is dominant (47 to 50%) with Gondwana (21-29%) and Quartzite (18-31%)

The Deccan trap formation is dominant in sub watersheds 31S, 36S, 69S and 71S over the Gondwana formation. The GPI values of these sub-watersheds are found in the range of 0.34-1.89. Gondwana dominant sub watersheds show higher values of GPI in the range of 2.47-5.18 compared to Deccan trap dominated group. Gondwana is comparatively more permeable than Deccan trap formation unless it is weathered. Sub watershed 33S and 72S with underlying formation of Gondwana only in their watershed area (Table 5.1a) show comparatively low values of GPI in range of 0.76-1.07 but these values are found to be more when compared with sub watersheds having Deccan trap as single formation in the watershed. Above analysis suggests that when sub watersheds contain multiple hard rock formations their GPI values increases and they are found to be more permeable than sub watersheds having single hard rock formation underneath. Presence of multiple formations in successive laps in sub watersheds may be a situation of contact plane, unconformity, fault zone, cleavages or joints which facilitate ample opportunity for yield and chances of ground water storage.

High yielding tube wells have been observed in sub watersheds 34S, 82U and 84 U. These are capable of supplying water from 0.040 to 0.122 million liters per day (CGWB report, 1998). Therefore sub watersheds having GPI values in range of 2.27-5.18 are capable of providing ground water storage; however, these sub watersheds are not as resourceful in ground water as those of Alluvium having GPI values greater than 15. It is observed from Appendix A (Table A3), that the presence of fault or lineaments in the sub-watersheds of Gondwana does not increase the GPI value as much as it increases in sub watersheds of Deccan trap. Normally, faults/lineaments in Gondwana have exposed impervious clays, and hence the lower values of GPI. Thus sub watersheds which contain GPI values in the range of 3.0-5.18, indicate moderate chance of ground water storage.

Archeans dominant sub watersheds 3B and 15B are having very low values of GPI are very impermeable in nature and it may be used as runoff producing areas.

5.5 CONCLUSIONS

Proposed index can be used to evaluate geo-hydrological condition of small watersheds in absence of observed field data. On the basis of GPI values of sub watersheds in relation to geological formation, a watershed may be classified into sub watersheds according to various GPI value ranges for identification of ground water recharge areas, rain water harvesting areas and areas requiring erosion control measures. Figure 5.2 shows distribution of various permeability zones in the study area.

The sub watersheds of the study area have been grouped according to various ranges of GPI such as 3-5, 5-10, 10-25, and 25-75 and greater than 75. On the basis of these GPI value ranges, the sub watersheds have been identified for suitable treatment measures (Table 5.2).

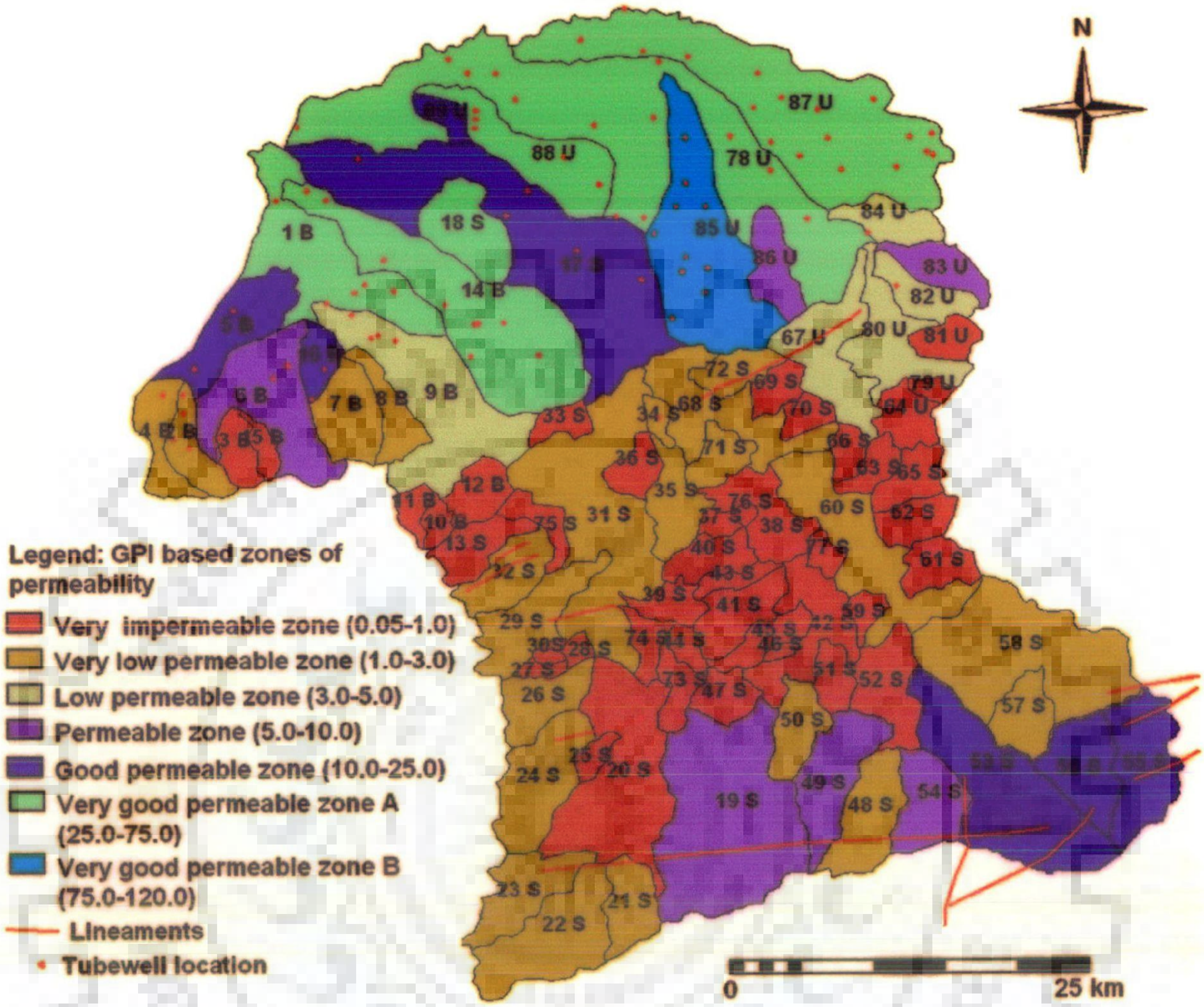


Figure 5.2: GPI based zones of permeability, tube well distribution and lineaments

Table 5.2: Availability of ground water and watershed treatments based on GPI

Sl. No.	GPI range	No. sub watersheds	Permeability and availability of ground water storage.	Recommended watershed treatment
1	0.05-1.0	42	Very impermeable zone, possibility of ground water storage is nil	Runoff production area.
2	1.0-3.0	22	Very low permeable zone, Ground water storage along joints and fractures	Rainwater harvesting
3	3-5	5	Low permeable zone, ground water available at the sub watershed outlet.	
4	5-10	6	Permeable zone, ground water availability is good in lower part	Rain water harvesting in upper part and ground water recharge in lower part of sub watershed
5	10-25	7	Good permeable zone, dug wells and shallow tube wells can be established. Gully prone area.	Ground water recharge and gully control measures
6	25-75	6	Very good permeable zone, shallow and deep tube wells can be established but these areas may develop gullies near outlet of sub watersheds.	Ground water recharge and gully control measures
7	>75	1	Very good permeable zone	Ground water recharge

Forty two sub watersheds are in very impermeable zone and having the property of quick runoff, and should be used properly for runoff production along with erosion control measures. Possibility of ground water storage increases with the increase in GPI values. The gully encroachment in sub watersheds 1B, 14 B 17S, 18S, 78U, 87U, 88U and 89U caused heavy loss of water and soil which eventually depleted the capacity to store ground water as well as capacity to produce crops. Gully encroachments convert flat alluvium areas into highly dissected topography rendering the land unsuitable for settlement as well as agriculture development. Thus GPI values lower than expected in sub watersheds on soft formation are an indication of highly erosive conditions in those sub watersheds. Morphological analysis of highly eroded areas (badlands) is discussed in next chapter.

CHAPTER 6

MORPHOLOGICAL ANALYIS OF BADLAND AREA

6.1 INTRODUCTION

The conditions which favor the rain induced erosion in a watershed are:

(i) High intensity rains.

(ii) Considerable height difference between the table land and the stream receiving water from the table land. It causes steep gradient and hence erosive velocity of flow in channels and gullies feeding the stream.

(iii) Soft and deep alluvium soil liable to scouring.

(iv) Uncontrolled biotic interference in the watershed by way of excessive grazing, burning and cutting of vegetation for crop cultivation, fodder and fuel collection. It increases the potential erosion and storm runoff.

A ravine is a deep gorge which is formed due to linear fluvial erosion of loose unconsolidated and bare soils by rills and gullies. Once a ravine is formed, it grows by the phenomenon of saturation and slip off from its head and sides. These ravines go on increasing in size and invading the upper table land under the condition of high intensity rains. Govt. of India report (GOI, 1996) classifies ravines as (i) shallow ravine: depth 1 m, side slope 3%, undulating topography, moderately eroded. (ii) Medium ravine: depth 5 m, slope >15%, very severely eroded land, (iii) Deep ravine: depth more than 10m, slope > 15%, very severely eroded land.

Land degradation is a general term which refers to land becoming unproductive partially or completely due to various reasons such as water erosion, wind erosion, chemical deterioration, inadequate drainage etc. Hence badlands are a particular form of land degradation.

Badlands are densely dissected areas, which have been severely degraded and where soil has disappeared or lost most of its fertility. The combined effect of climate and continuous use of erosive land for agriculture prevents the soil from forming or recovering its fertility and the erosion continues (Fairbridge, 1968). Formation of badlands gets activated through several processes such as head cutting in gully, scouring, selective erosion transport of sediment (Kirkby and Bull 2000). Badland formation exhibits particular land topography and stream morphology, which determine the rate of development of badlands (Smith and Bretherton, 1972; Howard and Kerby, 1983).

The subject of gully expansion and badland formation has been widely attempted in various parts of the world. Present study aims to analyze morphological parameters of badland and geological and river network setting so as to develop a better understanding of process of formation of badlands and to evolve a morphological index of erodibility for comparing severity of erosion in different watersheds.

6.2 RAVINE AFFECTED LAND IN INDIA

In India ravine land was about 3.975 million ha in the year 1971 (NCA, 1976). As a result of various land reclamation measures it reduced to 2.678 million ha in 1996 (GOI, 1996). On the other hand, degraded forest had increased from 19.494 million ha in the year 1971 to 24.897 million ha in the year 1996. No systematic survey of various categories of land degradation in the country has been carried out by any agency on agreed terms. The figures quoted or reported by various agencies are only based on material available from scattered sources or broad observations. Data generated by National Remote Sensing Agency and Natural Bureau of Soil Survey and Land Use Planning (NBBS&LUP) are based on 1:10,00,000 scale map. Soil degradation map prepared by NBBS &LUP is of derivative nature from soil resource map at 1: 2,50,000 with soil profile information collected at 10 km grid (GOI, 1996). The estimate of ravine affected area (2.678 M ha) stated in Govt. of India report (GOI, 1996) is based on discussion with various_agencies. The data is not based on ground surveys. It is at best an improvement over other existing estimates.

Ravine affected land in the state of Madhya Pradesh where the study area lies was 0.883 million ha in the year 1971. It reduced to 0.623 million ha in the year 1996 (GOI, 1996).

6.3 LOCATION OF BADLAND IN THE STUDY AREA

Survey of India Toposheets (1972) show that part of Sher, Barureva and Umar watersheds near the confluence with Narmada river and entire area of small tributaries like Dhamani and Saras rivers were affected by badland formation in the year 1972 (Figure 6.1). These badland areas are located between latitude $22^0 50'$ N to 23^0 04'N and longitude 79^0E to 79^0 25'E. These badland areas have been selected for study.

6.4 SOCIO-ECONOMIC REASONS FOR FORMATION OF BADLAND

Owing to social, economical and political conditions in the pre independence period, mass migration of population from north and north central region of India to the central valley of Narmada was prevalent. Besides mass human settlements, livestock also increased proportionally. There were many nomadic and permanent settlements of shepherd (local name gadarias; gadar means sheep) in Narsinghpur district. A number of villages in the region have derived their names meaning shepherd settlements such as Gadarawara, Gadariakhera (village of shepherds), Chhota Gadarawara etc. Thus the area has a long history of over grazing of grasslands (Tignath et al., 2005).

On the other hand, the original tribal inhabitants had several classes such as Raj Gonds (Ruler Gonds), plain inhabitants, forest dwellers (Dhahia means those who burn). Forest produces and shifting cultivation provided means of livelihood to these tribal people. Mass migration of people from outside areas forced local tribal people to shift to upper parts (Satpura forest) causing deforestation.

6.5 PROCESS OF BADLAND FORMATION

Origin of ravine channel systems owes to gullying processes which gradually or rapidly grow in dimensions and network. Brice (1966) defined a gully as a 'recently extended drainage channel that transmits ephemeral flow, has steep sides, a steeply sloping or vertical head scarp, a width greater than 0.3 m and a depth greater than 0.6 m'. Apparently, Brice fixed the lowest dimension of a gully, while the ravineous limit of gully development has dimensions of many meters, more than 150 m in width at places between upper edges and in depth up to 50 m or even more, for example, Chambal ravines in north Central India. However field observations show that ravines at some places in the study area have average width of the order of 40 - 80 m and depth between 5 m and 10 m. Cross-section geometry varies from U-shaped in nonresistant to V-shaped in resistant subsoils in the channels.

In the study area, the gully-channel network extends from the main channel of entrenched nature, distinguished as the streams flowing in steep walled trench cut in alluvium, from the valley slope gullies which are small, steep walled and steeply incised (Plate 6.1 to Plate 6.6). Normally, for the initiation of gully, a continuum of erosion is visualized ranging from sheet erosion to micro channel or rill erosion, and then gully erosion when water concentrates in definite channels, often succeeding the two previous stages (Gregory and Walling, 1972). This description however (a) does not incorporate other factors governing gully initiation and (b) does not distinguish stream entrenchment from gullying in the off-shoot network. It is of common experience that the gully erosion is attributed to scouring on the sides and erosion over well defined headscarp.

Brice (1966) and Tuckfield (1964) among many others estimated the rate of gully development, which may not be uniform or continuous. According to Brice

(1966), one gully extended 228 m in fifteen years, and 107 m of this length developed in only one year as a result of very high run-off. About 15 km south of the present study area in Kareli Block in Narsinghpur district, the channel entrenchment along some of the 2nd and 3rd order tributaries of Sakkar river near Imalia-Khari village is seen to be of the order of 1000 m which occurred in the span of about fifty years (Tignath et al., 2005). In valley-floor gullies, the scarp normally advances up-valley, facilitated by sloughing of material around the margins of plunge pool, and this process leads to increase in height of the head scarp (Blong, 1966). Tuckfield (1964) showed the development of gullies to start from evenly spaced pits on valley floor.

6.6 METHODOLOGY

6.6.1 Morphological Analysis of the Badland

The base map of the area has been delineated on the basis of divide of badland and other land with the help of topographic survey map (Survey of India toposheets of the year 1972). The two badlands; one along the Narmada river and the other on the Sher river have been identified for their morphological characterization. Different map layers have been created using GIS (ILWIS 3.0 package). These consist of drainage pattern (Figure 6.1), isopach map (The line joining equal magnitude of alluvium deposits depth) (Figure 6.2), encroachment distance map (distance of badland encroachment from major river track as origin) (Figure 6.3), and digital elevation map (DEM) (Figure 6.4). Slope map of the study area has been constructed using DEM of the study area. The extracted attributes of map layers are used for computation of various morphological parameters as given below in Table 6.1.

Table 6.1: Description of morphological parameters

Morphological parameters	Description of parameters
Drainage Density, $D_d = \sum L / A$ Stream frequency, $D_F = N / A$ Bifurcation ratio, $R_b = N_u / N_{u+1}$ Length ratio, $R_t = L_u / L_{u-1}$ Form factor, $R_F = A / L_b^2$ Elongation ratio, $R_e = 1.128 A^{0.5} / L_b$ Circularity ratio, $R_c = 12.57 A / P^2$ Texture ratio, T=N1/P Relief ratio, $R_h = H/L_b$	A= Area, km^2 P= Perimeter, km. L= length of channels of all order, km L_b=Watershed length, km. N= total number of streams N_1=number of first order stream N_u=Number of stream of order u N_{u+1}= Number of stream of next higher order L_u= Length of stream of order u, km L_{u+1}=Length of stream of next higher order, km L_b= Watershed length, km H= Total relief, m

6.6.2 Morphological Index of Erodibility (MIE)

A badland area (ravine affected area) consists of large number of micro watersheds which need to be separately analyzed for assessment of severity of degradation and for identification of specific measures required for reclamation. Researchers have made use of remote sensing, GIS technique and sediment yield index model in prioritization of micro watersheds (Chakraborti, 1991 a; Biswas et al., 1999; Nookaratnam et al., 2005,). Nookaratnam et al., (2005) made use of morphometeric analysis in prioritization of micro watersheds. Linear parameters (D_d, D_f, T and R_h) favor erodibility of watersheds whereas shape parameters (R_c, R_e, and R_f) have inverse relationship with erodibility. Biswas et al., (1999) and Nookaratnam et al., (2005) used ranking system to compare degradation of watersheds. Ranking system is thus useful for prioritization of watershed within a specified area. However it can not be used as a measure of morphological influence on erodibility. Comparison of watersheds in terms of large number of parameters is usually complicated and confusing. In the present study a morphological index of erodibility (MIE) as defined below has been proposed for assessing combined influence of several morphological parameters on erodibility.

$$MIE = (D_d \times D_f \times T \times R_h) / (R_c \times R_e \times R_f) \quad (6.1)$$

6.7 RESULT AND DISCUSSION

The analysis is based on topographical information available for the year 1972 only. Since then changes in land use and land cover have occurred which have been analyzed and discussed in Chapter 7. It is observed that part reach of river Sher (49.67 km), Barureva (66.26 km), Dhamani (23.21 km) and entire length of river Saras approaching toward the confluence of Narmada exhibit extensive badland development. The badland area have stream network upto maximum of fourth order (Figure 6.1).

Area of badland formation is rigorous along Narmada tract i.e. Barureva, Dhamani and Saras rivers ($A=161.53\ km^2$) as compared to badland network of Sher river ($A=91.41\ km^2$). Comparison of morphological parameters (Table 6.2) reveals that selected badlands have nearly similar magnitude of drainage density and drainage frequency. However, texture ratio of Narmada tract is twice as that of the Sher badland indicating relatively extensive badland formation in the tract of Narmada.

Table 6.2: Morphological parameters of the badland area

Sl. No.	Morphological parameters	Badland along Narmada river	Badland along Sher river
1.	Area (A), km^2	161.53	91.41
2.	Perimeter (P), km	114.01	111.11
3.	Circularity ratio (R_c)	0.39	0.31
4.	Drainage density (D_d), km/km^2	2.45	2.22
5.	Drainage frequency (D_N), $no./km^2$	4.74	4.74
6.	Texture ratio (T)	5.27	2.52
7.	Relief (H), m	44	70
8.	Average slope (S), %	5.86	3.30
9.	Constant channel maintenance (Cm), km^2/km	0.41	0.45

First order streams have major share in selected badlands with 78.46% and 64.66 % of total stream length in Narmada and Sher badlands respectively (Table 6.3). Stream lengths of the remaining orders show similar distribution pattern in both badlands. The observed values of bifurcation ratio R_b for both badlands are higher than 5.0 suggesting presence of structural control (of badland process) on the drainage network over the geomorphic control (Strahler, 1957). High bifurcation ratios of both badlands indicate the presence of soft geological foundation. It is validated from the isopach map (Figure 6.2) showing alluvium deposits underneath, in the range of 30 m to more than 150 m in depth. Wide variation is observed in length ratios of different orders in Sher badland indicating less homogeneity in the structure of underneath rock.

Table 6.3: Drainage analysis of the badland area

Order of stream	Number of streams (N_u)	Percent to total stream number %	Stream length (L_u) km	Percent to total stream length %	Av. stream length $(L_u)_{av}$ km	Bifurcation ratio(R_b)	Length ratio (L_u)
Badland along the selected Narmada river track							
First order	601	78.46	271.03	68.44	0.45	4.32	-
Second order	139	18.14	72.21	18.24	0.52	6.04	1.15
Third order	23	3.00	46.95	11.86	2.04	7.66	3.93
Fourth order	3	0.39	5.82	1.46	1.94	-	0.95
Total/average	766	100	396.01	100.00		$(R_b)_{av}$ =6.01	$(L_u)_{av}$=2.54
Badland along the selected Sher river track							
First order	280	64.66	130.81	64.51	0.46	1.97	-
Second order	142	32.80	45.00	22.19	0.32	14.20	0.68
Third order	10	2.31	25.98	12.81	2.60	10.0	8.20
Fourth order	1	0.23	0.97	0.48	0.96	-	0.37
Total/average	433	100	202.77	100		$(R_b)_{av}$ =8.72	$(L_u)_{av}$ 4.43

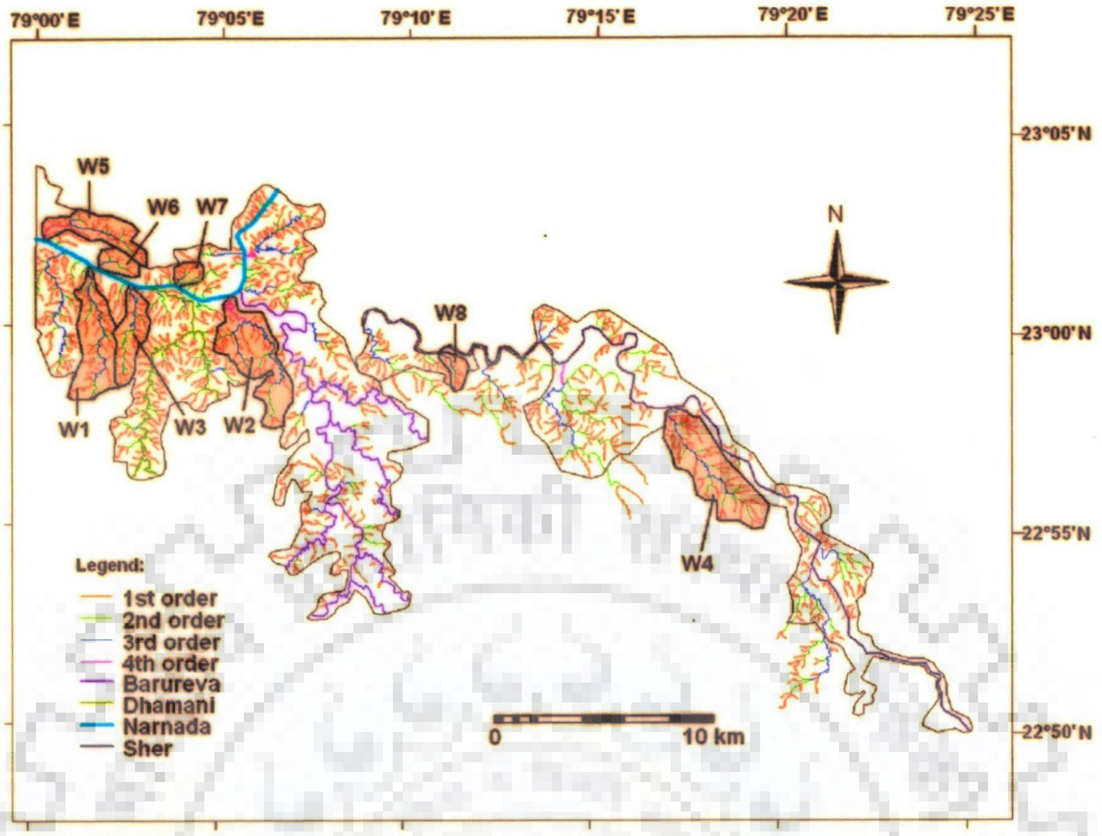


Figure 6.1: Drainage pattern in bad land area and location of selected watersheds

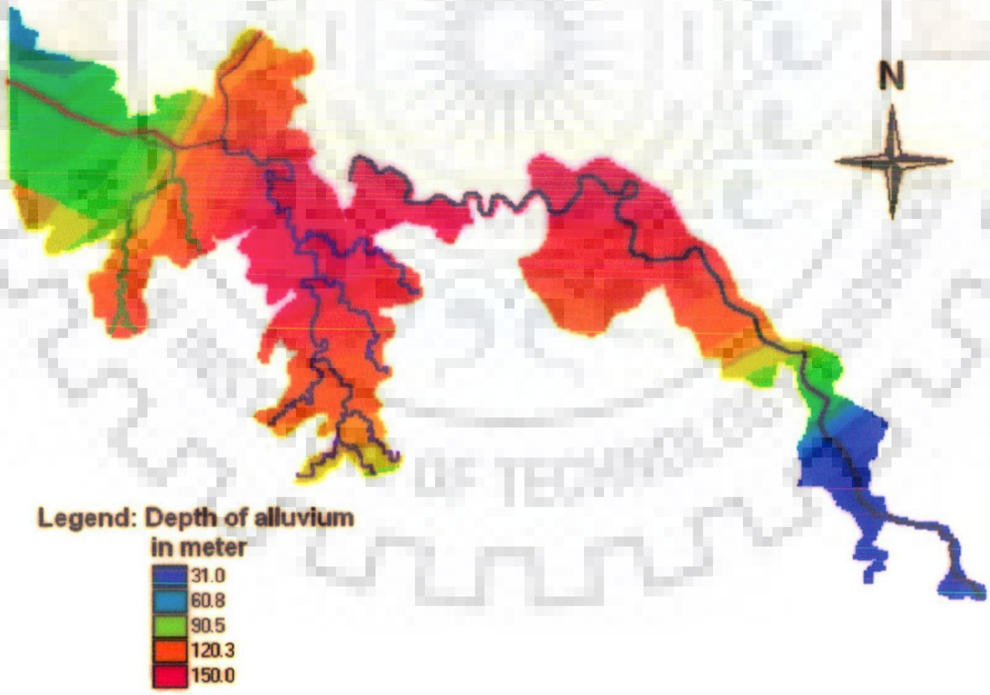


Figure 6.2: Isopach (depth of alluvium deposit) of badland area

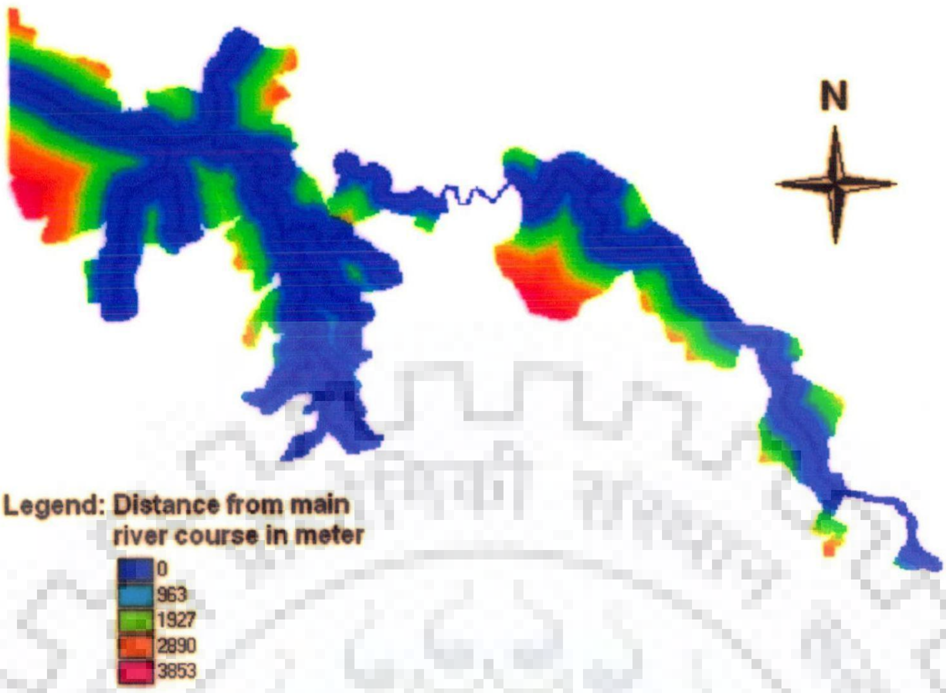


Figure 6.3: Encroachment distance of badland area from the main river course

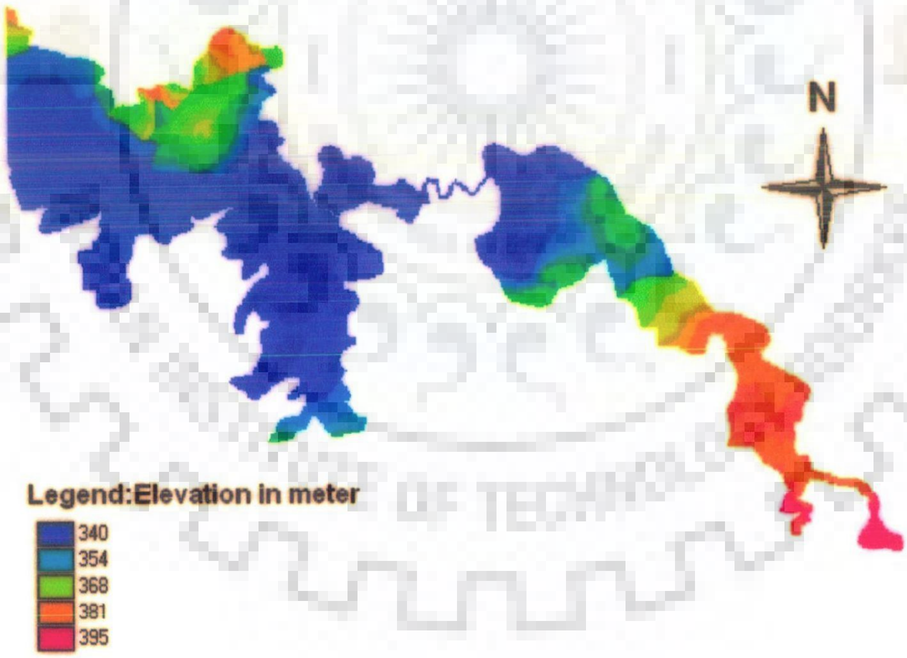


Figure 6.4: DEM of the badland area

Formation of badland is abundant (66.57% area) within 1km distance to major river course as seen in Plate 6.1 to Plate 6.6. Formation area goes on decreasing farther from the major river course. Maximum distance of badland encroachment from the river course is 4.6 km (Figure 6.3). Encroachment of badland is found to be more intense (about 75% badland area) in alluvium with depth more than 120 m.

Eight watersheds (W1 to W8) adjacent to Narmada river (Figure 6.1) have been selected for analysis of erodibility. Morphological parameters of these eight watersheds and one agricultural watershed are compared in Table 6.4. Proposed morphological index of erodibility has been computed using equation (6.1). Watershed number W5 is highly degraded whereas watershed number W6 has the least degradation. The agricultural sub watershed 88U (in Umar watershed) in alluvial formation is not affected by badland formation. It has MIE value of 201. MIE of watershed number W6 is 811 i.e. nearly 400% of the MIE value of agricultural watershed number 88U. Therefore a watershed in this region may be characterized as badland if its MIE is more than or equal to 400 % of MIE of normal watershed under agricultural use having same geological formation (alluvium).

Table 6.4: Morphological parameters and MIE for selected sub watersheds

Watershed parameter	Unit	Sub watersheds								
		W1	W2	W3	W4	W5	W6	W7	W8	88U (Agriculture Watershed)
A	km^2	4.57	10.22	8.38	11.75	5.17	1.78	1.22	1.33	45.33
P	km	8	18.56	15.38	16.45	13.06	5.33	4.2	5.04	38.61
L_b	km	6.02	6.46	4.71	6.86	4.90	1.80	1.46	1.80	15.79
R_c	-	0.90	0.37	0.45	0.55	0.38	0.79	0.87	0.66	0.38
R_e	-	0.40	0.56	0.69	0.56	0.52	0.84	0.85	0.72	0.48
R_f	-	0.13	0.24	0.38	0.25	0.22	0.55	0.57	0.41	0.18
D_d	km/km^2	4.21	3.72	3.87	3.57	4.01	2.33	5.23	5.04	1.44
D_f	$no./km^2$	6.57	5.09	6.8	5.62	9.67	10.12	18.89	14.99	1.81
T	-	2.29	2.1	2.66	2.98	2.53	1.13	2.38	1.98	1.76
C_m	km^2/km	0.24	0.27	0.26	0.28	0.25	0.43	0.19	0.21	0.69
H	m	16	15	16	17	20	20	15	15	23
R_h	m/km	2.66	2.32	3.40	2.48	4.08	11.11	10.27	8.33	1.44
MIE		3600	1855	2017	1926	9208	811	5729	6396	201
Rank of degradation		4	7	5	6	1	8	3	2	-

Plate 6.1: Gully development process along Narmada river in sub watershed W5

Plate 6.2: Gully cutting and its advancement stage along Narmada river in sub watershed W5

Plate 6.3: Vertical cutting along main water course of Sher river

Plate 6.4: Series of vertical cutting of gullies along main water course of Sher river

Plate 6.5: Badland area along the main water course of Sher river

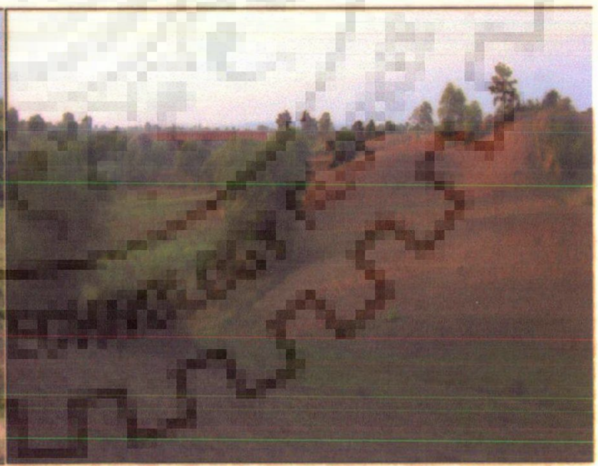


Plate 6.6: Badland area along Barureva river in W2 sub watershed

6.8 CONCLUSIONS

Dense network of tributaries of Narmada and their meeting with Narmada within closer vicinity had brought rich foundation of alluvium deposits. Deep layers of alluvium deposits existing in the study area keep alive aggressive head-cutting in gullies which could be the main cause of badland formation. Morphology of the selected watersheds from the badland tract indicates presence of uncontrolled growth of streams which is triggered by rain induced erosive forces. A morphological index of erodibility (MIE) for comparing severity of erosion in micro watersheds has been applied and verified by field observations. A watershed in the study area may be characterized as badland if its MIE values is more than four times MIE of an agricultural watershed. It is possible to reclaim the badlands and convert these into productive land by applying innovative concepts. However accelerating human pressure on land due to various socio-economic factors needs to be fully recognized and understood. Driving factors for change in land use and land cover are analyzed in Chapter 8.

CHAPTER 7
ANALYSIS OF LAND USE AND LAND COVER CHANGES

7.1 INTRODUCTION

Land use and land cover (LULC) changes have been studied by several researchers for different purposes. Following aspects are relevant in the context of watershed management.

(1) Quantification of changes in LULC over time. This aspect is analyzed in this Chapter.

(2) Analysis of driving factors for changes in LULC. This aspect is analyzed in Chapter 8.

(3) Quantification of effect of changes in LULC on surface runoff potential. This aspect is analyzed in Chapter 9.

For sustainable development and management of natural resources in a watershed, it is required to identify and quantify the change in LULC in terms of the area affected and rate of change over the years. Review of literature shows that research effort is needed to analyze and integrate changes in LULC with the development and management of a watershed.

Watershed inhabitants practice multiple uses which involve production of food, fiber, fuel and fodder. In addition, most of the development activities are closely associated with the development and use of water resources. Therefore dynamics of land use land cover and the driving factors for changes in LULC need to be analyzed to make watershed planning exercise more realistic and effective. This chapter is concerned with Remote Sensing and GIS based classification and analysis of LULC.

7.2 REMOTE SENSING DATA

Data Acquisition: To determine primary land use and land cover of the area, various band layers of the satellite imagery have been obtained from the Global Land Cover Facility Data Center of Maryland University USA (Source: www.landcover.org). The Geo-cover data set provides global Landsat imagery of three years i.e. 1972, 1989 and 2000 utilizing, the Landsat MSS, TM and ETM+ sensors respectively. Landsat (Land + Satellite) imagery is available since 1972 from six satellites of the Landsat series. These satellites have been a major component of NASA's Earth observation program, with three primary sensors evolving over thirty years: MSS (Multi-spectral Scanner), TM (Thematic Mapper), and ETM+ (Enhanced Thematic Mapper Plus).

All data is orthorectified i.e. corrected for terrain displacement and errors in image geometry. The Geo-Cover data set is provided in a standard GeoTIFF format with a UTM (Universal Transverse Mercator) projection, using the WGS-84 (World Geodetic system of year 1984) datum. Each scene is provided with bands as separate files. The Satellite imagery type and characteristics are shown in Table 7.1.

Table 7.1: Type and characteristics of satellite imagery

Satellite	Corresponding Month and Year	Sensor	Spectral rage	Band number available	Pixel size (in meter)
L 1-4	Nov 1972	MSS	0.5-1.1μm	1,2,3,4	57
L 4-5	Nov 1989	TM	0.45-2.35 μm	1,2,3,4,5,7	28.5
L 7	Dec 2000	ETM+	0.45-2.35 μm	1,2,3,4,5,7	28.5

7.3 CHARACTERISTICS OF THE BANDS

Band 1 (0.45-0.52 μm, blue-green): Since short wavelength of light penetrates better than the other bands it is often the band of choice for aquatic ecosystems. It is used to monitor sediment in water, mapping coral reefs, and water depth. But this is the noisiest of the Landsat bands since short wavelength blue light is scattered more than in the other bands. For this reason it is rarely used for "pretty picture" type images.

Band 2 (0.52-0.60 μm, green): Qualities of this band are similar to band 1. The band matches the wavelength for the green which is seen when looking at vegetation.

Band 3 (0.63-0.69 μm, red): Vegetation absorbs nearly all red light therefore it is sometimes called the chlorophyll absorption band. This band can be useful for distinguishing between vegetation and soil and in monitoring vegetation health.

Band 4 (0.76-0.90 μm, near infrared): Since water absorbs nearly all light at this wavelength, water bodies appear very dark. This contrasts with bright reflectance for soil and vegetation so it is a good band for defining the water/land interface.

Band 5 (1.55-1.75 μm, mid-infrared): This band is very sensitive to moisture and is therefore used to monitor vegetation and soil moisture. It is also good at differentiating between clouds and snow.

Band 6 (10.40-12.50 μm, thermal infrared): This is a thermal band. It can be used to measure surface temperature. It is primarily used for geological applications but it is sometime used to measure plant heat stress. This is also used to differentiate clouds from bright soils since clouds tend to be very cold. One other difference between this band and the other multispectral ETM bands is that the resolution is half of the other bands (60 m instead of 30 m).

Band 7 (2.08-2.35 μm mid-infrared): This band is also used for vegetation moisture although generally band 5 is preferred for that application, as well as for mapping of soil and geology.

7.4 METHODOLOGY

7.4.1 Selection of Band Combination

Popular band combinations have been used in this study to recognize land class from the available Landsat data set with different type o f sensors. T he details of visually appearance of colour patches of land classes for selected band combinations of satellite imageries of years 1972, 1989 and 2000 are given in Table 7.2.

7.4.1.1 Landsat MSS (Nov 1972)

It is often selected on the basis of what types of land covers are required to be classified. The most common and popular band combination for Landsat MSS sensor is 3 2 1 shown by Red Green Blue (RGB) color combination. Band combination 3 2 1 makes land and water boundaries more clear and agricultural and forest area are clearly differentiated.

7.4.1.2 Landsat TM (Nov 1989)

The band combination 4 5 3 for RGB is found to be crisper than 1 2 3 band combination as the two shortest wavelength bands (bands 1 and 2) are not included. The 4 5 3 band combination makes different vegetation types more clearly defined and the land/water interface is clear. Variations in moisture content are evident with this set of bands. This is probably the most common band combination for Landsat imagery.

7.4.1.3 Landsat ETM+ (Dec 2000)

This satellite sensor has extra panchromatic band in addition to other bands of Landsat TM imageries. However same band combination of 4 5 3 is used likewise of Landsat TM band combination for land use land cover classification. This band combination shown by RGB color combination interactive tool offers better spectral vision for separation of land, water and vegetation areas.

Table 7.2: Band combination and its visual colour appearance for land classes

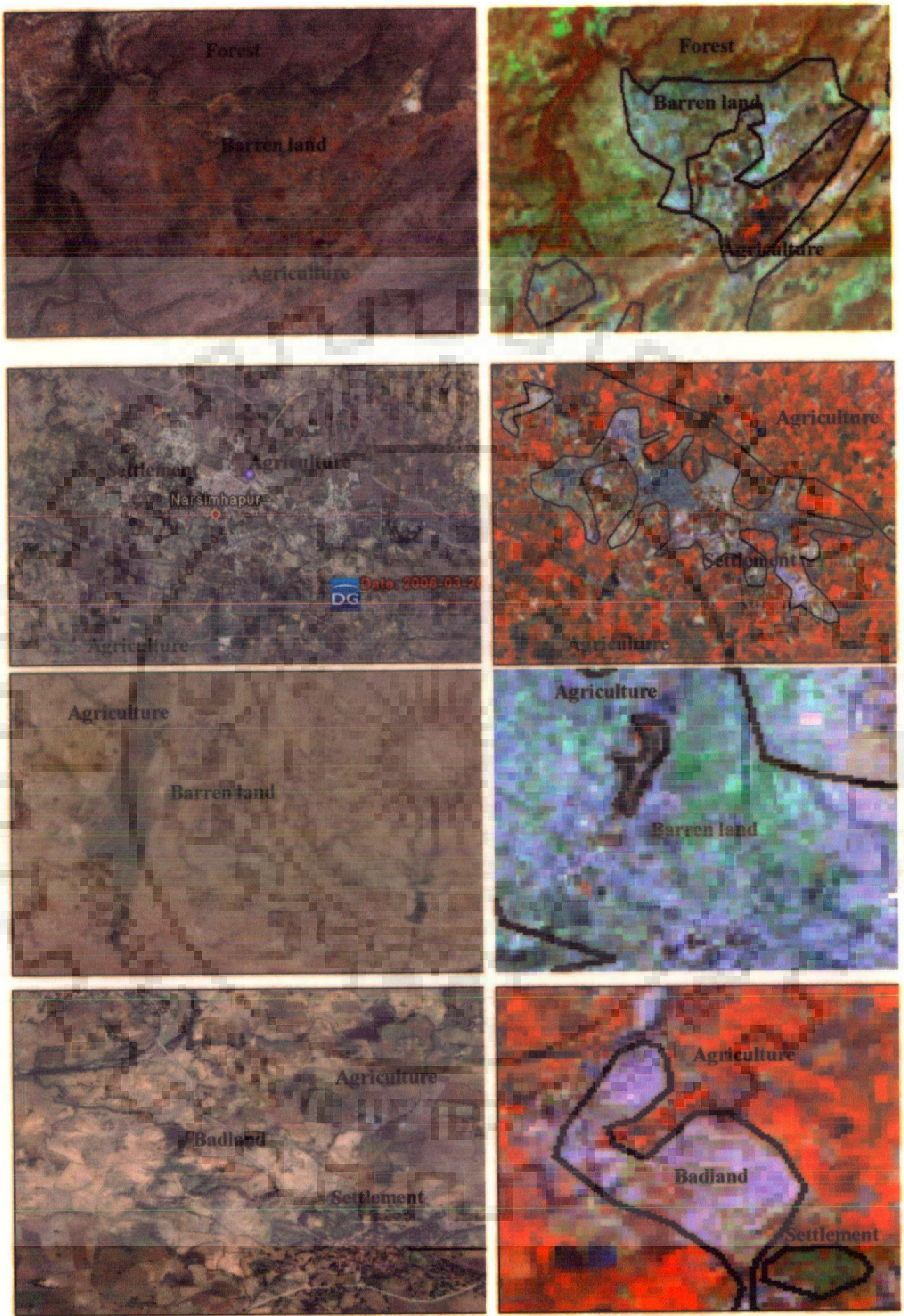
Satellite imagery	Agriculture	Forest	Badland	Barren land	Settlement	Water body
ETM+2000 (4 5 3)	Mixture of Orange red with some dark slate colour	Mixture of orange and pale green	Light lavender colour	Colour mixture of light cyan and lavender	Mixture of light steel blue and light green	Dark black to dark blue
TM1989 (4 5 3)	Mixture of light orange and dark slate	Orange to red colour shade	Light pink Colour shades	Lavender Colour shade	Corn flower blue	Dark black to dark blue
MSS 1972 (4 3 2)	dark slate gray with pinkish scatterings	Red colour	Very pale white pinkish	Dark sea green	Light shade of cyan	dark blue to sky blue

7.4.2 Land Use and Land Cover Classification Procedure

Classification of satellite imageries has been done in reverse of chronological time period. The method of classification in reverse of chronological order helps to classify the imagery of earlier years from the recent imagery as base for which ground truth data is available.

7.4.2.1 Visual Interpretation of Imagery-2000

The recent satellite imagery of November 2000 is selected first for classification. Band combination of 4 5 3 has been used to recognize the patches of agriculture, settlement, badland, barren land and water bodies. The recognized patches have been verified using recent spatial data base information and high resolution real world images of recent years (2004 to 2006) from Google Earth Launch Programme (http://earth.google.com). The patches of agriculture and barren land in upper part of Sher watershed have very different spectral characteristics than the land class patches in lower part of the watershed (Figure 7.1) due to difference in crop pattern, moisture conditions and soil type. Intended land use land cover classes are based on the information available in literature for the study area. Polygons are created with the help of digitization work in ILWIS 3.0 GIS software which encloses the recognized and verified patches of forest, agriculture, badland around the main network, barren land with very sparse vegetation and water bodies and settlement. The polygons created on the superimposed imagery with band combination have been assigned the recognized land class.



Google Earth View **Satellite imagery**

Figure 7.1: Identification of land use land cover in satellite imagery (year 2000) with help of real world imagery (Google Earth)

7.4.2.2 Visual Interpretation of Imagery-1989

Classified land use polygon layers of year 2000 are superimposed over the imagery of November 1989 having band combination 4 5 3. The superimposed polygons of recent classified imagery (year 2000) help to identify the changes in shape and size land classes. The polygon boundaries of different classes of land use and land cover have been edited according to expansion or shrinkage in the patches. The edited boundaries of the 1989 land use map are converted into polygons and named accordingly.

7.4.2.3 Visual Interpretation of Imagery-1972

The satellite imagery of November 1972 has been classified using classified polygons of land use land cover of 1989. Procedure is same as adopted in classification of imagery for the year 1989 discussed above.

7.5. ANALYSIS OF LAND USE AND LAND COVER CHANGES

Study area is spread over three watersheds; Barureva (488 km^2), Sher (1635 km^2) and Umar (699 km^2). These watersheds differ in terms of terrain topography and underlying geological formations. L and use and land cover in these watersheds is discussed below.

7.5.1. Visual Comparison of Land Use Maps

Six major land classes namely agriculture, forest, barren land, badland (highly eroded area), settlement and water bodies have been derived from the satellite imageries. The classified maps of land classes for the years 1972, 1989, 2000 are shown in Figures 7.2, 7.3 and 7.3 respectively. Forest land is the dominant land class in Sher watershed which has prevailed though successive period of time. Second largest class in Sher watershed is of agricultural land which exists mainly in lower part and scattered in the middle part in vicinity of major river course and in upper part mostly in south western side. The barren land is mostly found in between the forest area and agricultural area. Emergence of water bodies in the middle of developed agricultural area in upper part of Sher watershed in year 2000 (Figure 7.3) shows an attempt to maintain and enlarge agriculture area in recent years.Badland (gully eroded area) which once existed in lower part of Sher watershed in year 1972 has vanished over the period from 1972 to 2000.

In contrast to Sher watershed, agricultural area is the most dominant land class in Umar and Barureva watersheds. Forest in these two watersheds is mostly found in upper most part over the hilly terrain.

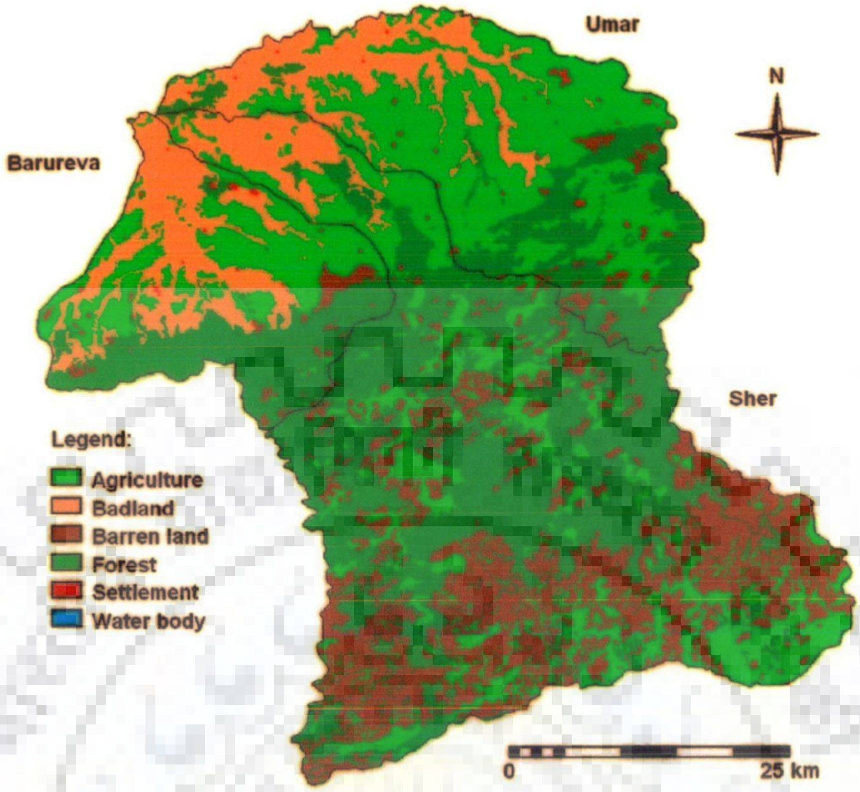


Figure 7.2: Land use land cover of Barureva, Sher and Umar watersheds in year 1972

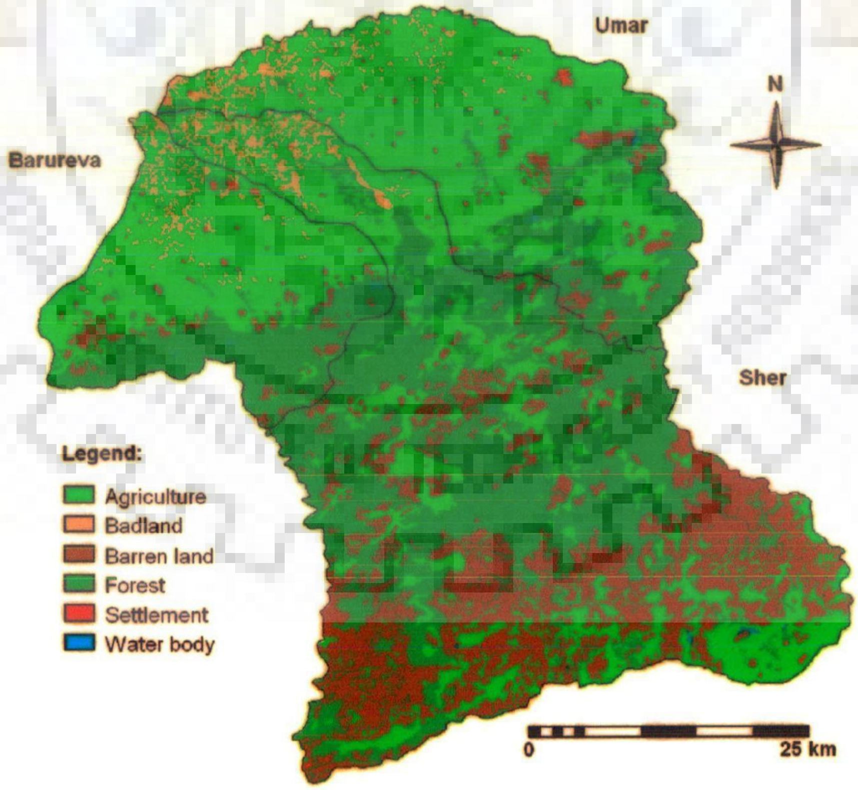


Figure 7.3: Land use land cover of Barureva, Sher and Umar watersheds in year 1989

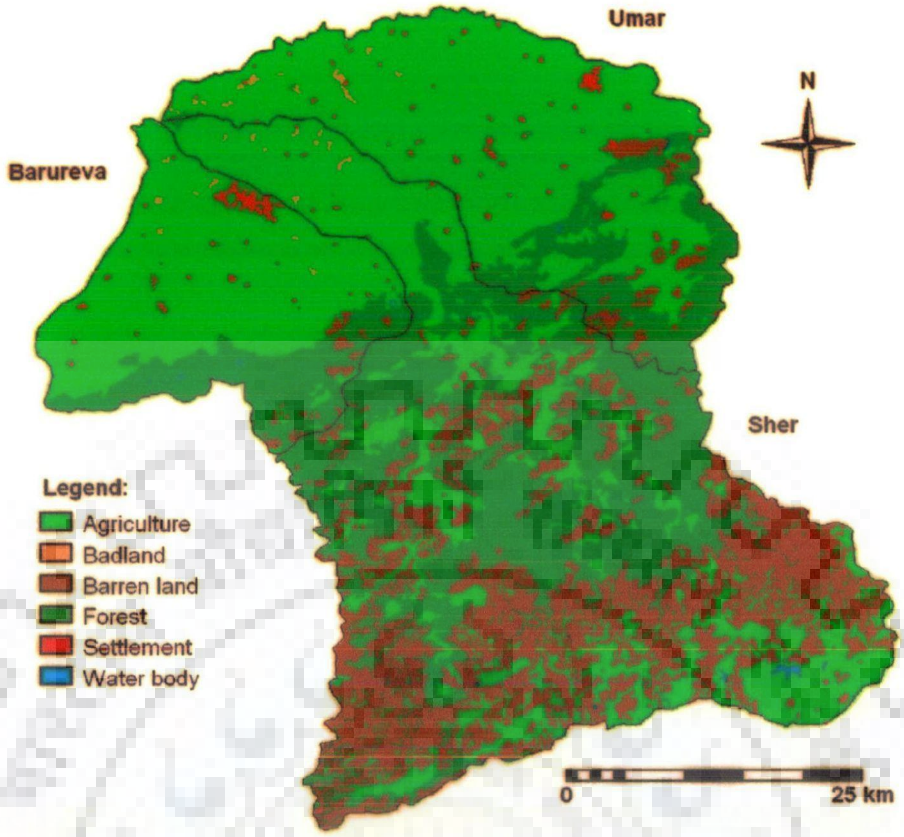


Figure 7.4: Land use land cover of Barureva, Sher and Umar watersheds in year 2000

Umar watershed has more agricultural area in upper part in comparison to small and scattered patches of agriculture in upper part of Barureva watershed. Though badland was once dominant land class in year 1972 in Barureva and Umar watershed, this has been converted into agricultural area over the period.

Agriculture expansion over the years has mostly occurred in lower parts of the three watersheds. Along with expansion of agriculture area, urban settlements also show expansion mainly in lower part of Barureva and Umar watersheds. Increase in agricultural area in lower parts of the study area is due to reclamation of badland area. Highly eroded badland area existed in year 1973 along the Barureva Sher and Umar rivers as discussed in Chapter 6. Conversion of badland into agricultural area during 1972 to 1989 is found to be more intense. The emergence of water bodies (mostly in upper part of three watersheds) is related to the development of agriculture area in hilly terrain. Moreover, the visual comparison shows that increase in agriculture in upper parts of the three watersheds is not as intense as in lower parts.

7.5.2 Extent of Land Use Change and Rate of Change at Watershed Level

Recognizable changes have taken place in land classes in the three watersheds during 17 year period0 from 1972 to 1989 and during 11 year period from 1989 to 2000. The change in land use (magnitude and percentage) and dynamic rate of change in Barureva, Sher and Umar watersheds are given in Tables 7.3, 7.4 and 7.5 respectively.

7.5.2.1 Barureva Watershed

Table 7.3 shows extent and dynamic rate of land use change in Barureva watershed. Changes in LULC during 1972 to 1989 and during 1989 to 2000 are compared in Figure 7.5.

Table 7.3: Land use land cover changes in Barureva watershed

	Agriculture	Forest	Barren land	Badland	Settlement	Water body
1972 (km^2)	161.29	157.66	14.59	152.07	2.38	0.01
1989(km^2)	299.94	144.30	17.79	22.05	3.07	0.85
2000 (km^2)	351.35	118.82	8.29	1.30	7.26	0.98
Area change (km^2) during 72-89	138.65	-13.36	3.20	-130.02	0.69	0.84
during 89-2000	51.41	-25.48	-9.50	-20.75	4.19	0.13
Percent (%) during 72-89	85.96	-8.47	21.93	-85.50	28.99	8400.00
during 89-2000	17.14	-17.66	-53.40	-94.10	136.48	15.29
Dynamic rate (%/year) during 72-89	5.06	-0.50	1.29	-5.03	1.71	494.12
during 89-2000	1.56	-1.61	-4.85	-8.55	12.41	1.39

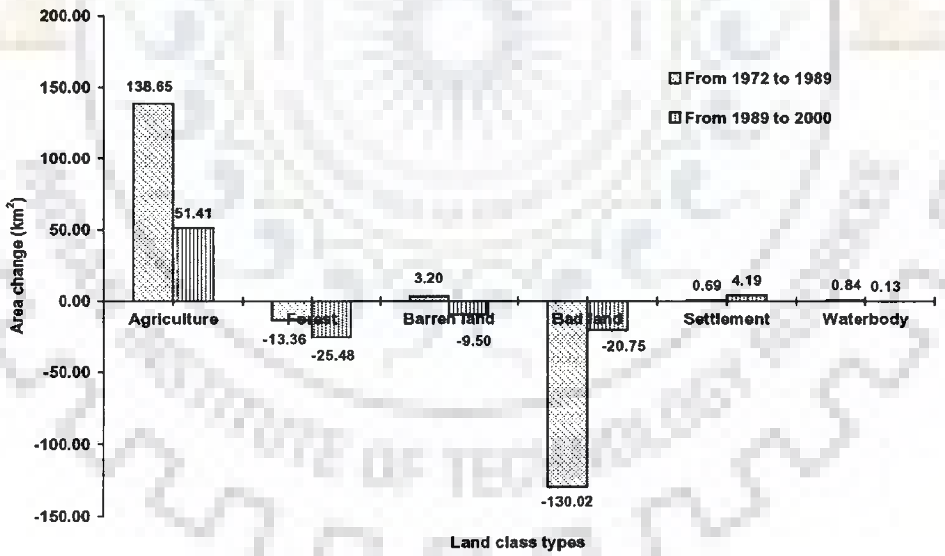


Figure 7.5: Change in land use and land cover in Barureva watershed

Agricultural area increased by 85.96 % in year 1989 over the agricultural area of year 1972 with dynamic rate of 5.06 percent increase per year. In the next period (1989 to 2000), the dynamic rate was slower (1.56% per year). The agricultural area in year 2000 is 72 % of the watershed area while it was 61.46% and 33.05% in year 1989 and 1973 respectively. The rate of decrease of forest area during period of 1972 to 1989 was slower (0.50 % per year) compared to 1.61 % per year during recent period of 1989-2000. The badland area which was once dominant (31.16% to total watershed area) in year 1972 has progressively decreased. In year 2000, the badland area has almost diminished (Table 7.3).

7.5.2.2 Sher watershed

The Sher watershed exhibits somewhat different pattern of change in land classes. The absolute and percent changes in land classes are shown in Table 7.4 and compared schematically in Figure 7.6.

Table 7.4: Land use land cover changes in Sher watershed

	Agriculture	Forest	Barren land	Badland	Settlement	Water body
1972 (km^2)	479.93	662.71	418.33	70.99	2.98	0.06
1989(km^2)	532.43	653.18	413.84	30.02	3.50	2.03
2000 (km^2)	605.98	549.52	470.59	1.89	3.85	3.17
Area change (km^2) during 72-89	52.50	-9.53	-4.49	-40.97	0.52	1.97
during 89-2000	73.55	-103.66	56.75	-28.13	0.35	1.14
Percent (%) during 72-89	10.94	-1.44	-1.07	-57.71	17.45	3283.33
during 89-2000	13.81	-15.87	13.71	-93.70	10.00	56.16
Dynamic rate (%/year) during 72-89	0.64	-0.08	-0.06	-3.39	1.03	193.14
during 89-2000	1.26	-1.44	1.25	-8.52	0.91	5.11

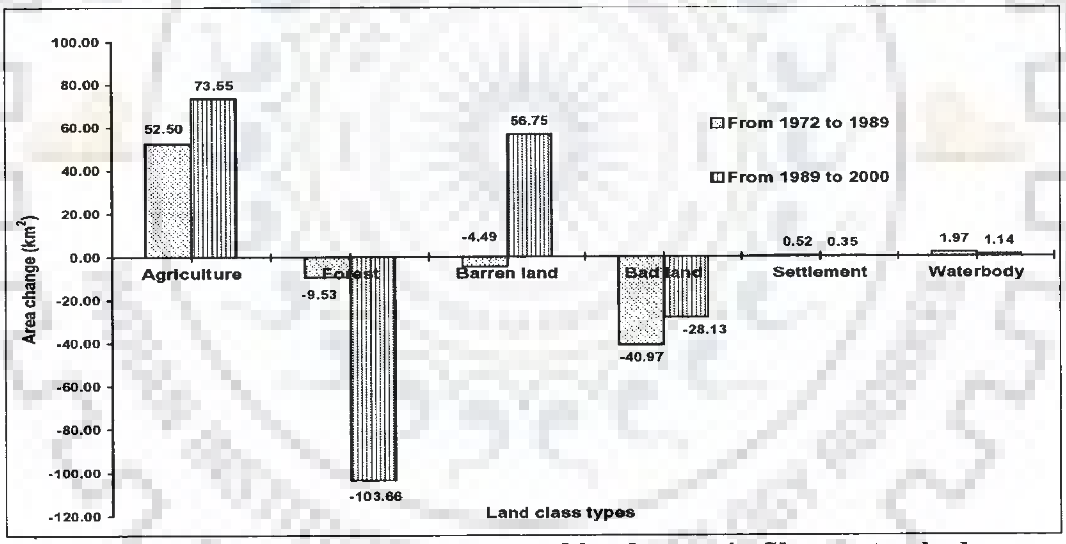


Figure 7.6: Change in land use and land cover in Sher watershed

The agricultural land class shows substantial increase from 479.93 km^2 to 532.43 km^2 during period from 1972 to 1989 and then to 605 km^2 in year 2000. The rate of increase in second phase of period is nearly twice (1.26% per year) than that in the previous time period (0.64% per year). In the year 2000, agricultural area covers 37.06% of the watershed area and it becomes dominant land class.

Forest area was once a major land class (40.53% of the watershed area) in year 1972. It decreased to 39.65% in year 1989 with dynamic rate decrease 0.08% per year.

It decreased to 33.61% in year 2000 with faster rate of 1.44% per year. The barren land has higher share in Sher watershed as compared to Barureva and Umar watersheds. The barren land in Sher watershed has remained at almost same level during 1972 to 1989 with area coverage of 25%. However during the period of 1989 to 2000, the barren land increased at the rate of 1.25% per year covering 28.71% of the area.

The badland (70.99 km^2) existed in the lower part of and near to the confluence in the year 1972. There has been significant reduction in badland area. Rate of decrease was 3.39% per year during 1972 to 1989 and it was 8.52% per year during 1989 to 2000. The area of badland in year 2000 is almost negligible (1.89 km^2) compared to area of badland in year 1972 (70.99 km^2). The reclamation of badland for agricultural use in lower part has been the major positive change showing impact of population pressure. Rate of increase in settlement area during period 1972 to 1989 and during 1989 to 2000 are almost similar (about 1% per year). The appearance of water bodies is seen in year 1989 and 2000. The increase in water bodies is observed mainly in upper part showing the dependence of agriculture on surface water storage in the upper part of watershed.

7.5.2.3 Umar watershed

The absolute and percent changes in land classes are shown in Table 7.5 and compared schematically in Figure 7.7.

Like Barureva watershed, Umar watershed is also dominated by agriculture land class. The area of agriculture was 376.44 km^2 (53.85% of watershed area) in the year 1972. There is substantial increase over the period of time. The agricultural area increased to 492.36 km^2 in the year 1989 at the rate of 1.89% per year. It covered 76.99% of watershed area in year 2000 with the dynamic increase rate of 0.85% per year. The development of agricultural land is due to conversion of badland area into agricultural area.

Table 7.5: Land use land cover changes in Umar watershed

	Agriculture	Forest	Barren land	Badland	Settlement	Water body
1972 (km^2)	376.44	157.61	15.46	145.62	3.71	0.16
1989(km^2)	492.36	143.72	23.11	32.85	5.31	1.65
2000 (km^2)	538.18	129.36	20.39	3.05	7.32	0.70
Area change (km^2) during 72-89	115.92	-13.89	7.65	-112.77	1.60	1.49
during 89-2000	45.82	-14.36	-2.72	-29.80	2.01	-0.95
Percent (%) during 72-89	30.79	-8.81	49.48	-77.44	43.13	931.25
during 89-2000	9.31	-9.99	-11.77	-90.72	37.85	-57.58
Dynamic rate (%/year) during 72-89	1.81	-0.52	2.91	-4.56	2.54	54.78
during 89-2000	0.85	-0.91	-1.07	-8.25	3.44	-5.23

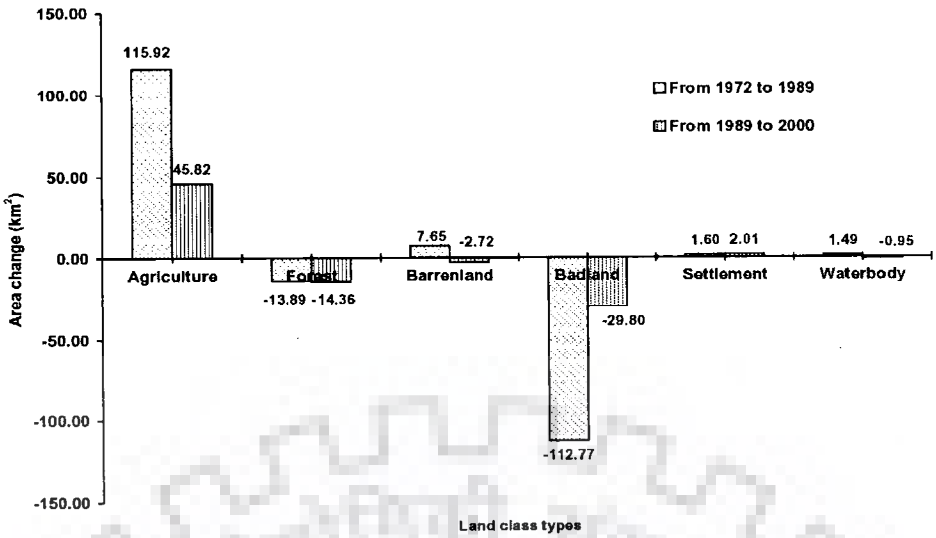


Figure 7.7: Change in land use and land cover in Umar watershed

The forest area is second leading land class. It has decreased at the rate of 0.52% per year during period 1972 to 1989 and at the rate of 0.91% per year during 1989 to 2000. The area of forest land in year 2000 is 18.51% of the watershed area.

Settlement area in Umar watershed is larger compared to Barureva and Sher watersheds. The rate of increase in settlement area was more (3.44% per year) during period 1989 to 2000 compared to the rate of 2.54 % per year during period of 1972 to 1989. In contrast to Barureva and Sher watersheds, the waterbodies in Umar watershed show decreasing trend during period of 1989 to 2000.

7.5.3 Dynamic Transition Matrices at Watershed Level

Conversion among six land classes during two periods (1972 to 1989 and 1989 to 2000) in each of the three watersheds is shown in Table 7.6 to Table 7.11.

7.5.3.1 Barureva watershed

Table 7.6 shows transition matrix for the period 1972 to 1989 and Table 7.7 shows transition matrix for the period 1989 to 2000. Increase in agricultural area from 1972 to 1989 has been brought through reclamation of the badland area. In addition, agricultural area also shows substantial increase through deforestation. During the period 1989 to 2000, increase in agricultural area has been brought through deforestation, reclamation of badland and barren land. During period 1989 to 2000, increase in barren land has mainly come through deforestation. On the other hand, new badland area formed in year 1989 due to gully invasion in agricultural area. The encroachment by gullies in agriculture area during period 1989 to 2000 is almost negligible. The settlement area (3.07 km^2) in year 1989 came through extension of settlement area into agriculture and forest land. The share of agriculture land into conversion to settlement is relatively less during period of 1989 to 2000(0.46 km^2). The water body came into existence in forest land in year 1989 and further increased in year 2000.

Table 7.6: The dynamic transition matrix of LULC (1972-1989) in Barureva watershed (km^2)

1972	1989						1972 total
	Agriculture	Forest	Barren land	Badland	Settlement	Water body	
Agriculture	156.58	0.29	2.43	1.61	0.35	0.03	161.29
Forest	10.76	142.57	3.03	0.16	0.33	0.81	157.66
Barren land	7.37	0	7.19	0.03	0	0	14.59
Badland	125.23	1.44	5.14	20.25	0.01	0	152.07
Settlement	0.00	0	0	0	2.38	0	2.38
Water body	0	0	0	0	0	0.01	0.01
1989 total	299.94	144.3	17.79	22.05	3.07	0.85	Total 488

Table 7.7: The dynamic transition matrix of LULC (1989-2000) in Barureva watershed (km^2)

1989	2000						1989 total
	Agriculture	Forest	Barren land	Badland	Settlement	Water body	
Agriculture	295.83	0.41	0.4	0.28	3.02	0	299.94
Forest	22.62	117.84	3.24	0	0.27	0.33	144.3
Barren land	12.72	0.56	4.49	0	0.01	0.01	17.79
Badland	19.91	0	0.16	1.02	0.96	0	22.05
Settlement	0.08	0	0	0	2.99	0	3.07
Water body	0.19	0.01	0	0	0.01	0.64	0.85
2000 total	351.35	118.82	8.29	1.3	7.26	0.98	Total 488

7.5.3.2 Sher watershed

The conversion matrices of land classes during period of 1972 to 1989 and during period of 1989 to 2000 are shown in Table 7.8 and Table 7.9. The increase in agriculture area in Sher watershed during 1972 to 1989 has been brought through conversion of badland (45.75 km^2), forest (10.4 km^2) and barren land (9.54 km^2). During 1989 to 2000 agriculture area further increased due to conversion of forest land (33.02 km^2) followed by badland (28.4 km^2) and barren land (15.09 km^2). However, some parts of agriculture land (5.11 km^2), barren land (3.32 km^2) and badland (1.38 km^2) got converted into forest land during period of 1972 to 1989. These land classes do not show significant conversion to forest land during 1989 to 2000. During period from 1989 to 2000, the increase in barren land is intense and it is brought through conversion of forest land (71.19 km^2). In some parts badland formation has occurred during 1972 t0 1989 through gully encroachments in agricultural area and forest area. However during 1989 to 2000 bad land formation ceased. Increase in settlement area has mainly come through conversion of agricultural land during period 1972 to 1989 while in the next time period from 1989 to 2000 it came through partly from agriculture land and partly from forest land.

Table 7.8: The dynamic transition matrix of LULC (1972-1989) in Sher watershed (km^2)

1972	1989						1972 total
	Agriculture	Forest	Barren land	Badland	Settlement	Water body	
Agriculture	466.92	5.11	2.24	3.48	0.46	1.72	479.93
Forest	10.4	643.17	6.35	2.56	0	0.23	662.71
Barren land	9.54	3.52	405.25	0	0	0.02	418.33
Badland	45.57	1.38	0	23.98	0.06	0	70.99
Settlement	0	0	0	0	2.98	0	2.98
Water body	0	0	0	0	0	0.06	0.06
1989 total	532.43	653.18	413.84	30.02	3.5	2.03	Total 1635

Table 7.9: The dynamic transition matrix of LULC (1989-2000) in Sher watershed (km^2)

1989	2000						1989 total
	Agriculture	Forest	Barren land	Badland	Settlement	Water body	
Agriculture	529.35	0.28	1.37	0.3	0.17	0.96	532.43
Forest	33.02	548.69	71.19	0	0.11	0.17	653.18
Barren land	15.09	0.49	398.02	0	0.1	0.14	413.84
Badland	28.4	0	0	1.59	0.03	0	30.02
Settlement	0.04	0	0.01	0	3.44	0.01	3.5
Water body	0.08	0.06	0	0	0	1.89	2.03
2000 total	605.98	549.52	470.59	1.89	3.85	3.17	Total 1635

7.5.3.3 Umar watershed

The conversion matrices of land classes during period of 1972 to 1989 and during period of 1989 to 2000 are shown in Table 7.10 and Table 7.11. Umar watershed is substantially agriculture watershed. In the considered time periods, it is observed that agricultural area has primarily increased through reclamation of badland and barren land and through deforestation. Reclamation of badland (117.13 km^2) is significantly higher during period 1972 to 1989 compared to 30.52 km^2 during period of 1989 to 2000. Barren land in both periods has mainly evolved due to deforestation and according to trend it will be used for agriculture development. Badland have formed on agriculture land (2.03 km^2) and forest land (4.27 km^2) during period 1972 to 1989 while in the next time period 1989 to 2000 encroachment of badland on agriculture and forest land has completely ceased. The increase in area of water bodies is mainly in forest land.

Dynamic conversion matrices of both time periods suggest that conversion of land classes has been mainly activated by need to increase agriculture area. Future increase in agriculture area is likely to occur through deforestation as badland area is completely reclaimed for agriculture.

Table 7.10: The dynamic transition matrix of LULC (1972-1989) in Umar watershed (km^2)

1972	1989						1972 total
	Agriculture	Forest	Barren land	Badland	Settlement	Water body	
Agriculture	368.16	0.31	2.03	4.22	1.42	0.3	376.44
Forest	6.11	142.31	4.27	3.48	0.13	1.31	157.61
Barren land	0.83	0.48	14.13	0	0.02	0	15.46
Badland	117.13	0.54	2.62	25.15	0.18	0	145.62
Settlement	0.06	0	0.06	0	3.56	0.03	3.71
Water body	0.07	0.08	0	0	0	0.01	0.16
1989 total	492.36	143.72	23.11	32.85	5.31	1.65	Total 699

Table 7.11: The dynamic transition matrix of LULC (1989-2000) in Umar watershed (km^2)

1989	2000						1989 total
	Agriculture	Forest	Barren land	Badland	Settlement	Water body	
Agriculture	490.19	0.28	0.05	0.35	1.49	0	492.36
Forest	11.72	128.55	2.34	0.24	0.73	0.14	143.72
Barren land	5.21	0.04	17.83	0	0.03	0	23.11
Badland	30.32	0	0.06	2.46	0.01	0	32.85
Settlement	0.21	0	0.04	0	5.06	0	5.31
Water body	0.53	0.49	0.07	0	0	0.56	1.65
2000 total	538.18	129.36	20.39	3.05	7.32	0.7	Total 699

7.6 CHANGES IN LAND USE AND LAND COVER AT SUB WATERSHED LEVEL

Changes in land use and land cover on watershed scale have been analyzed in previous sections. These changes have not occurred uniformly over the entire study area as shown in Figure 7.8.

Planning and implementation of structural and nonstructural measures in small watersheds requires site specific and reliable information on dynamic changes and the driving factors. Such information along with geomorphological parameters are required not only for modeling of physical processes at sub watershed level but will also result in realistic and effective measures for addressing basic human needs at village level. Study area comprising of Barureva, Umar and Sher watersheds consists of a large number of 4th order and higher order sub watersheds (Chapter 4). Land use in the fourth and higher order sub watersheds of Barureva, Sher and Umar watersheds are given in Appendix B. Deforestation has taken place to increase agriculture area in all sub watersheds of study area. Waterbodies, settlements and badland occur only in some of the sub watersheds whereas agriculture, forest and barren land occur in all the sub watersheds. Spatial distribution and dynamic change in land classes have been related with Geomorphological Permeability Index as discussed below.

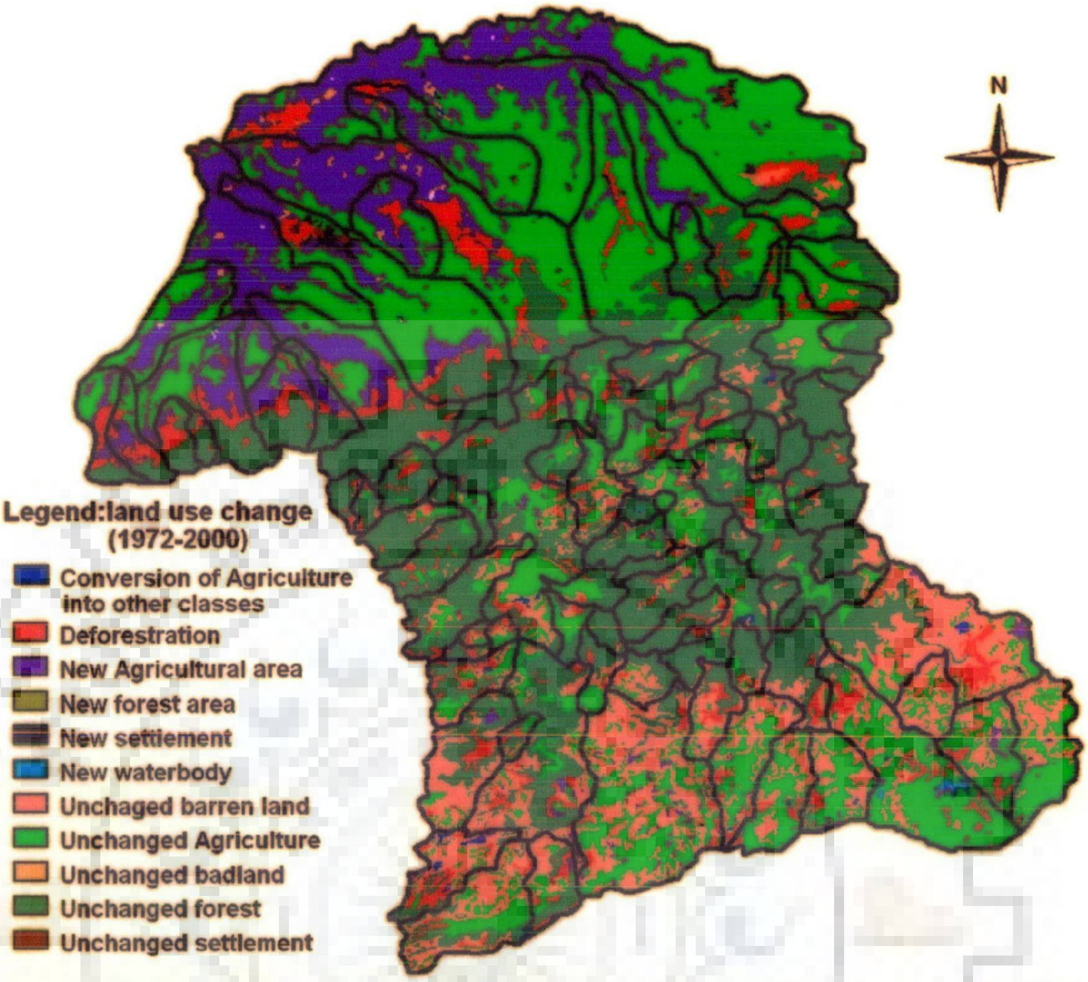


Figure 7.8: Land use and land cover change at sub watershed level during 1972-2000

7.6.1 Change in LULC in Relation to Geomorphological Permeability Index (GPI)

Appendix B shows values of GPI also for each sub watershed. Based on analysis of change in LULC and GPI in the sub watersheds following inferences are drawn.

Increase in surface water bodies has occurred in those sub watersheds whose GPI values are less than 15.

Barureva: 6B, 7B, 8B, 10B, 12B, 15B; Sher: 19S, 49S, 50S, 54S, 71S 31S, 55S, 56S; Umar: 84U and 86U

Increase in water body area followed by decrease in water body area is observed in the following sub watersheds having GPI greater than 15.

Barureva: 14B; Umar: 78U, 87 U, 85U; Sher: 17S

1) Settlement has significantly increased in 14B (1.30 km^2 to 5.65 km^2), 78U (1.21 km^2 to 1.85 km^2), 84U (0.53 km^2 to 1.38 km^2), 87U (1.59 km^2 to 3.33 km^2). Elsewhere settlement size is less than 0.5 km^2.

2) There is no definite correlation between increase in settlement size and increase in water bodies suggesting that water supply is not dependant on surface water. On the other hand, increase in settlements has occurred in sub watersheds having GPI greater than 15 suggesting groundwater as main source of water supply to the settlements.

3) Increase in settlement area has direct relation to increase in agricultural area as observed in the following sub watersheds.

   Barureva: 1B, 2B, 5B, 9B, 10B, 14B; Umar: 78U, 85U, 86U, 87U, 88U; Sher: 17S, 18S, 19S, 31S, 58S, 71S

7) Most of the badland existed in lower parts of Barureva, Sher and Umar watersheds. These badlands have been reclaimed and converted into agricultural land. Increase in agricultural land in the following sub watersheds has occurred mainly account of reclamation of badlands.

   Barureva: 1B, 2B, 3B, 4B, 5B, 6B, 7B, 8B, 9B, 14B, 15B, 16B; Umar: 78U, 85U, 86U, 87U, 88U, 89U; Sher: 17S, 18S.

8) Barren land existed in sub watersheds having GPI less than 10 but have now been converted agricultural land. Sub watershed having GPI greater than 15 do not depend on water bodies for increase in agriculture and water supply to settlements.

9) Water bodies are created in following sub watersheds having settlement area and are showing increase in rainfed agriculture. These sub watersheds have low GPI value

   Barureva: 2B, 6B, 9B, 10B, 16B; Umar: 80U, 82U, 86U; Sher: 20S, 21S, 22S, 24S, 31S, 38S, 48S, 49S, 55S, 58S 68S.

It is expected that without increase in water bodies these sub watersheds will undergo further deforestation to increase the rainfed agriculture area for meeting food demand of remotely located human settlements.

Sub watersheds with static land use

Water body and settlement occupy small area. Small changes in water bodies and settlement area are not considered in identification of dynamic and static nature of land use. Sub watersheds listed below have remained mostly static during period 1972 to 2000.

Barureva: 10B; Umar: 64U, 79U, 80U, 81 U, 83U; Sher: 38S & 54S.

Elsewhere changes have occurred in terms of reclamation of badland and barren land for agriculture use, conversion of forest land into agriculture land.

7.7 CONCLUSIONS

1. The study makes use of satellite remote sensing and GIS technique in providing spatially distributed information on land use and land cover changes in a watershed which otherwise is difficult and time consuming. Assessment of land use changes in small watersheds based on remote sensing data could have been refined using high resolution imageries data and ground truth data for several years.
2. A watershed is normally assumed to be hydrologically static i.e. catchment properties (land use, land cover, topography etc.) are considered to be time invariant. The study makes use of remote sensing and GIS based procedure to identify and quantify changes in land use and land cover which should lead to more realistic hydrologic models of small watersheds.
3. The transition matrix of changes among various land classes is useful in monitoring and analyzing the dynamic and directional changes in watersheds. Comparison of transition matrices for different time periods and for different watersheds can be useful in understanding various driving factors such as the impact of population pressure and accordingly plan suitable resource conservation measures.
4. Appropriate methods for eco-environmental planning, and development of surface and ground water resources at micro level can be selected based on dynamic analysis of land use and land cover changes presented in this chapter.
5. Conversion of bad land into agriculture land is a major positive eco-environmental change in Barureva, Umar and Sher watersheds. Increase in barren land in Sher watershed during 1989 to 2000 has been significantly large. It is a major adverse eco-environmental change.
6. Increase in agricultural area in sub watersheds has direct relation to increase in settlement area.
7. There is no definite correlation between increase in settlement size and increase in water bodies suggesting water supply is not dependant on surface water. On the other hand, increase in settlements has occurred in sub watersheds having GPI greater than 15 suggesting groundwater as main source of water supply to the settlements.

8. Barren land existed in sub watersheds having GPI less than 10 but has now been converted into agricultural land. Sub watersheds having GPI greater than 15 do not depend on water bodies for increase in agriculture area and for water supply to settlements.

9. Water bodies have been created in some sub watersheds which have GPI value less than 15, have settlement area and are showing increase in rainfed agriculture. It is expected that without increase in water bodies these sub watersheds may undergo further deforestation to increase the rainfed agriculture area for meeting food demand of remotely located human settlements.

CHAPTER 8

DRIVING FACTORS FOR CHANGE IN LAND USE AND LAND COVER

8.1 INTRODUCTION

Drivers of change in land use and land cover in a watershed could be natural and or manmade. Natural drivers such as earthquake, flood, drought, forest fire can be managed only to limited extent. Manmade drivers are related to various land based activities such as development of infrastructure facilities, supply of food, fuel, fodder, commercial use of natural resources, settlements etc. Driving factors may differ significantly in industrialized and underdeveloped regions of the world. At regional level driving factors in general are urbanization, land tenure and economical development policies (Schneider, 2001; Fox et al., 2005; Fan et al., 2007). In rural watersheds of India driving factors are related to basic human needs (food, fodder and fuel) and economic dependence on agriculture. Extensive rural poverty and severe population pressures create environmental stress on agricultural land including cultivation of ecologically fragile lands and soil salinization due to improper irrigation.

The study area is located in upper part of Narmada basin. The basin though rich in natural resources has remained underdeveloped in several parts due to shortage of infrastructure facilities (transport, water supply, energy and education etc.). All the indicators of underdevelopment such as low electricity consumption (50% of natural average), slow urban growth (urban population 10%), below average agriculture yield and average literacy rate (28%) are present in underdeveloped areas (Chaube, 1989; GOMP, 2001).

Population in the study area is mostly engaged in agriculture and forest based activities. Due to the large number of small and marginal farmers (over 40%) and high percentage of tribal and scheduled caste population (above 50%), unemployment and underemployment are wide spread. About 50% of the population lives below the poverty line (Chaube, 1989; GOMP, 2001). The upland area is quite backward.

8.2 PRESSURE OF HUMAN POPULATION AND FOOD, FODDER DEMAND

Food, fodder and fuel demand of human and animal population have been estimated using census data. Appendix C provides census data, unit requirements of food, fodder and computation of food, fodder demand in different years. The analysis pertains to the part of block areas within the study area. Changes in land use land cover

over the years and on watershed and sub watershed level have been analyzed in previous chapter. Detailed census data at watershed and sub watershed level are not available to relate change in land use (Chapter 7) with change in food, fodder demand over the years. However it is observed that a major part of the Umar watershed is within Gotegaon block. Total area of Umar watershed is 699 sq km. Gotegaon block has area of 924 sq km out of which 691 sq km is within study area (74.77%) mostly in Umar watershed. It is therefore reasonable to assume that changes in land use in Umar watershed could be related to changes in population, food, and fodder demand of Gotegaon block. Similar assumption may not be reasonable to relate block level changes with changes in Barureva and Sher watersheds. Therefore following analysis is limited to Umar watershed.

Table 8.1 provides summary results for the Umar watershed and for the years 1971, 1991, 2001. Changes have been analyzed with reference to the year 1971.Table shows (i) changes in area of agriculture land, barren land, forest land obtained from analysis in chapter 7 and (ii) population, food demand (equivalent calorie requirement), fodder demand (metric tons) obtained from analysis in Appendix C (Table C3 and Table C6).

8.2.1 Population Pressure

It is expressed as population per sq km of the watershed area. Pressure on available land has increased at faster rate during 1991 to 2001(48.93% per decade compared to the preceding period of 1971 to 1991(15.25% per decade).

8.2.2 Food Demand and Its Pressure on Agriculture Land

It has been assumed that entire food requirement is met by cereals, pulses and milk as vegetarian diet is mostly used by population in the study area. Food demand has increased in direct proportion to increase in human population.

Increase in agriculture area: Whereas population has increased by 79.42% during thirty years period of analysis, agriculture area increased by 42.97% only. Increase in agriculture area (30.79%) in 20 years during 1971 to 1991 similar to increase in population (30.49%). But during 1991 to 2001 increase in agriculture area is 12.18% whereas population increased by 48.93%. Umar is an agricultural watershed with 67.02 percent area under alluvium. Pressure of food demand on available agriculture land has tremendously increased necessitating improvement in crop production through irrigation. As discussed in next section there has been over exploitation of ground water resource in recent years due to increase agricultural production.

8.2.3 Fodder Demand and Its Pressure on Forest and Barren Land

Fodder requirement of growing animal population is assumed to be met through open grazing in forest land and barren land. Crop residue is also a source of fodder. It could not be included in the analysis due to lack of data. There has been decrease in forest area and increase in barren land over the thirty years period of analysis. Pressure of fodder demand on forest and barren land has increased by 107.36% over 30 years period. It is reasonable to believe that crop residue might have eased part of this pressure.

Table 8.1: Pressure of food, fodder demand on land use in Umar watershed in different years

Year	Population in Umar watershed	Population pressure No./ km2	Food energy Demand X 10^6 Kcal	Agriculture Area km^2	Food demand per unit agr. land X 10^6 Kcal/km^2	Fodder demand MT	Forest Area km^2	Barren land Area km^2	Total of forest and barren land km^2	Fodder demand Pressure* MT/ km^2
1971	48762	70.58	48188.684	376.44	128.0	56773.49	157.61	15.46	173.07	328.04
1991	63630	92.09	62881.762	492.36	127.7	74084.137	143.72	23.11	166.83	444.07
2001	87490	126.63	86461.926	538.18	160.7	101865.1	129.36	20.39	149.75	680.23
% change (1971-1991)	30.49	30.49	30.50	30.79	-0.23	30.49	-8.81	49.48	-3.60	35.37
% change (1971-2001)	79.42	79.42	79.43	42.97	25.54	79.42	-17.92	31.89	-13.47	107.36

* Pressure of fodder demand is assumed on forest and barren land area

8.3 GROUND WATER EXPLOITATION

Ground water continues to be main source for irrigation of agriculture crops and to meet domestic water requirement (urban as well as rural areas) in the absence of substantial surface water storage schemes. A large number of shallow and deep tube wells have been developed in the alluvial area mainly for the purpose of the irrigation.

Fluctuations in ground water table for pre and post monsoon condition were observed for period of 1993 to 1999. During this period water table falls remarkably about 1 to 2 m for pre-monsoon and 2 to 5 m fall for post monsoon seasons for lower part of the study area (Alluvium). On the other hand rise of 1 to 4 m and 1 to 2 m were observed in upper part of study area (Deccan trap) for pre-monsoon and post monsoon seasons. These conditions denote that exploitation in ground water source is intense in alluvium area due to increasing agricultural area while ground water rise in upper part of area is result of surface water storage in the study area. Ground water level data of eighteen observation wells and over the period varying from 10 years to 30 years have been analyzed to quantify the rising or falling trend of ground water levels. The procedure suggested by the CGWB (Appendix D) has been used to analyze the trend. Appendix D provides pre and post monsoon water level data and computations. Long term trend in rise/fall in ground water level are shown in Table 8.2.

Table 8.2: Trend analysis of ground water table data for the study area

Geological Formation	Well locations	No. of years	Pre-monsoon			Post-monsoon		
			Std. Dev.	Coeff. of variance	Trend cm/year	Std. Dev.	Coeff. of variance	Trend cm/year
Alluvium	Kareli	14	1.69	0.0049	76.89	3.45	0.0099	68.85
	Narsinghpur	26	0.81	0.0023	39.94	3.45	0.0094	37.78
	Gotegaon	22	3.53	0.0097	61.32	1.59	0.0046	46.50
	Manegaon	10	0.46	0.0013	-8.55	1.70	0.0047	23.87
	Gundrai(I)	15	0.91	0.0025	56.55	1.20	0.0033	45.62
	Dokerghat	14	0.81	0.0023	37.70	1.66	0.0047	44.59
	Dangidhana	10	0.28	0.0008	-3.30	1.66	0.0045	-24.42
	Bachai	10	0.74	0.0027	-5.14	0.79	0.0021	-2.91
Gondwana	Joteshwar	13	0.67	0.0017	30.75	0.70	0.0017	22.96
	Mugwani	26	1.10	0.0027	36.52	1.10	0.0027	25.06
Deccan	Lakhnadon	9	0.76	0.0013	-20.36	0.44	0.0007	-2.84
	Khamariya	10	1.08	0.0024	-3.87	1.30	0.0028	-9.56
	Madli	10	1.23	0.0020	-32.39	0.98	0.0015	-16.39
	Madai	10	1.84	0.0031	-29.33	1.05	0.0017	-27.87
	Nayadeori	10	1.08	0.0024	-18.82	1.30	0.0028	-14.69
	Dhuma	10	0.61	0.0010	-8.67	0.68	0.0012	-18.21

Positive values indicate falling trend. Exploitation of ground water for irrigation started from the year 1963-64 onwards after the ground water exploration studies revealed existence of potential aquifers in alluvial part of the study area (CGWB, 1998). As against the state average of command area of a dug well and a tube well of 1.2 ha and 6 ha respectively, the average command area of dug well/dug cum bore well was 3.88 ha and the average command area of tube well was 9.87 ha for Narsinghpur district in 1996 (CGWB, 1998).

Feasible	23554	9013
Existing in 1996	16976	3361

All the blocks of Narsinghpur District were in 'white' category in 1996. Tube wells have continued to be constructed unabatedly without much consideration for sustainability of development and management of groundwater. Clustering of ground water structures in small pockets has caused complete de-saturation of phreatic aquifer at places. Groundwater is declining due to heavy pumping in alluvial plains.

8.4 EFFECT OF AGRICULTURAL PRACTICE ON RECHARGE

Narmada alluvial belt is covered with black loam soils of great deltas. Though the soil is very fertile, it has characteristics of clodding quickly upon drying. In the past usual practice was to grow crops only in winter season (post monsoon i.e. rabi season). The land was left fallow during the monsoon season which resulted in large quantity of rich top soil being washed away by intense rain during monsoon season. As part of Government sponsored development measures, a large number of field bunds (small height embankments) in agricultural land were constructed. Such areas are locally known as Haveli areas. The field bunds checked monsoon runoff resulting in good recharge of soil moisture and ground water. However farmers now have taken up cultivation of cash crops like soybean, sunflower and sugarcane. Haveli system has been destroyed as for soybean cultivation during monsoon season the fields are required to be kept well drained resulting in lesser ground water recharge. On the other hand ground water extraction has increased as farmers are now cultivating both kharif (monsoon) and rabi season (winter season) crops and at places even summer crops using ground water as source of irrigation.

8.5 GROUND WATER UTILIZATION AND LAND USE CHANGE SCENARIO IN SAMPLE SUB WATERSHEDS

Long term trend of 18 observation wells are given in Table 8.2. These observation wells are located in nine sub watersheds. Table 8.3 shows changes in land use land cover of these nine sub watersheds along with information on geology, permeability (GPI) and trend of ground water level. Falling trends in ground water level are observed in alluvial sub watersheds wherein agricultural area has increased over the years. On the other hand rising trend is observed in wells located in upper part of study area over Deccan trap formation (19S, 53S, and 55S). Agriculture area in these sub watersheds has remained nearly static. Rise in water table is probably due to creation of water bodies in these sub watersheds. CGWB report (1998) states that during period 1981-90 number of dug wells in north-west part of Sher watershed had gone dry. However the data from 1990 to 1999 for Madai, Madli and Lakhnadon (Table 8.3) shows rising trend in pre-monsoon water table.

Table 8.3: Changes in land use land cover along with geological formation, GPI and ground water trend

Sub watershed	Geological formation	Area	GPI	Well name	Trend		Agricultural Area km²			Settlement Area km²			Water body Area km²		
					Pre mon-soon	Post mon-soon	1972	1989	2000	1972	1989	2000	1972	1989	2000
14B	Alluvium 74%	110.19	43.90	Narsinghpur	39.94	37.78	57.94	79.13	84.12	1.3	1.63	5.65	0.01	0.49	0.31
				Dangidhana	-3.30	-24.42									
				Bachai	-5.14	-2.91									
18S	Alluvium 100%	68.06	30.73	Dokerghat	37.70	44.59	11.96	23.94	30.26	0.09	0.13	0.19	0	0	0
71S	Deccan (62.88%)	13.65	1.89	Mugwani	36.52	25.06	7.00	7.21	7.56	0.05	0.05	0.07	0	0.03	0.03
84U	Gondwana 54.07%	16.73	3.79	Joteshwar	30.75	22.96	8.98	8.85	10.96	0	0	0	0	0.13	0
85U	Alluvium 76.07%	92.21	119.88	Manegaon	-8.55	23.87	65.25	70.33	74.10	0.53	0.66	1.38	0	0.39	0.06
				Gundrai	56.55	45.62									
87U	Alluvium 86.83%	158.95	45.39	Gotegaon	61.32	46.50	104.87	132.44	138.01	1.59	2.63	3.33	0.08	0.71	0.30
19S	Deccan (100%)	119.92	8.71	Madli	-32.39	-16.39	42.64	43.19	47.9	0.21	0.27	0.31	0	0.09	0.11
53S	Deccan (100%)	84.94	23.84	Lakhnadon	-20.36	-2.84	56.46	55.10	58.34	0.54	0.54	0.54	0	1.36	2.19
55S	Deccan (100%)	39.59	10.27	Khamariya	-3.87	-9.56	24.30	24.16	24.3	0.48	0.62	0.66	0.01	0.03	0.09

8.6 CONCLUSIONS

The study area consists of rural watersheds. Driving factors for change in land use and land cover are related to basic human needs (food, fodder and fuel) and economic dependence on agriculture in the study area. Demand of food, fodder has to be met locally in absence of adequate infrastructure facilities and low purchasing power of population in the remotely located sub watersheds. The land use and land cover analysis in Chapter 7 (Tables 7.3, 7.4 and 7.5) shows that the rate of deforestation has accelerated in recent period. It is due to increasing population pressure for expansion of agricultural area to meet their basic needs and to improve their economic status.

Analysis of Umar watershed illustrates the following:

Whereas population has increased by 79.42% during thirty years period of analysis, agriculture area increased by 42.97% only. Umar is an agricultural watershed with 67.02% percent area under alluvium. Pressure of food demand on available agriculture land has tremendously increased necessitating improvement in crop production through use of ground water for irrigation.

Falling trends in ground water level are observed in alluvial sub watersheds. On the other hand rising trend is observed in wells located in upper part of study area over Deccan trap formation (19S, 53S, and 55S). Agriculture area in these sub watersheds has remained nearly static. Rise in water table is probably due to creation of water bodies in these sub watersheds.

Pressure of fodder demand on forest and barren land has increased by 107.36% over 30 years period. However it is reasonable to believe that part of this pressure might have been eased by crop residue which is also used as fodder.

CHAPTER 9

RUNOFF POTENTIAL AND EFFECT OF CHANGE IN LAND USE AND LAND COVER

9.1 INTRODUCTION

Rainfall generated runoff in a watershed is an important input in design of hydraulic structures and erosion control measures. On long term basis, change in runoff volume and its time distribution indicates dynamic changes occurring in a watershed. Poor land use planning and land management practices may adversely impact surface runoff quantities and quality through the reduction of land cover and increase in imperviousness of surface areas (Harr et al., 1975; Minner, 1998; Beighley and Moglen, 2002; Tong and Chen, 2002; Booth et al., 2002). Urbanization, deforestation, changes in agricultural practices, open grazing etc. are part of land use change. Thus, a hydrologic model that uses land use land cover as input is useful to quantify the effect of land use and land cover changes on runoff. One such widely used model is the SCS-CN method. It computes the surface runoff volume for a given rainfall event from small agricultural, forest, and urban watersheds (SCS, 1956 and 1986). The method is simple to use and requires basic descriptive inputs that are converted to numeric values for estimation of direct runoff volume (Bonta, 1997). "Curve number" that is descriptive of runoff potential of watershed is the most important factor in the method. The SCS-CN method is widely used by engineers, hydrologists and watershed managers as a simple watershed model, and as the runoff estimating component in more complex watershed models. In words of Ponce and Hawkins (1996) "The SCS-CN method is a conceptual model of hydrologic abstraction of storm rainfall, supported by empirical data. Its objective is to estimate direct runoff volume from storm rainfall depth, based on a curve number CN".

Despite widespread use of SCS-CN methodology, realistic estimation of parameter CN has been a topic of discussion among hydrologists and water resources community (McCuen, 2002; Simanton et al., 1996; Steenhuis et al., 1995; Bonta, 1997; Ponce and Hawkins, 1996; Sahu et al., 2005; and Mishra and Singh, 2006). The present chapter deals with application of SCS-CN method for analysis of runoff potential in Sher watershed. The analysis has been carried out to (1) use observed data sets of rainfall (P) and runoff (Q) events of period greater than 1-day and develop year wise series of Curve Number (CN(PQ)), (2) estimate yearly series of Curve Number using land use and hydrological soil cover data (CN(LU)) and compare with observed CN(PQ), (3) forecast runoff potential i.e. CN(LU) on the basis of change in land use,(4) test the performance efficiency of SCS-CN method on gauged Sher watershed and its application to nearby ungauged Barureva and Umar watersheds and (5) compare the CN values of popular SCS-CN method and slope adjusted SCS-CN method at watershed level and at sub watershed level for assessing effect of slope on runoff potential.

9.2 SCS-CN METHOD

The SCS-CN method has been reviewed in Chapter 2, section 2.3. Popular form of the equation is:

$$Q = \frac{(P - Ia)^2}{(P - Ia + S)} \quad \text{for } P \geq Ia \tag{9.1}$$

$$= 0 \text{ otherwise}$$

Where, P = total rainfall; Ia = initial abstraction; F = cumulative infiltration excluding Ia; Q = direct runoff; and S = potential maximum retention.

In general λ is taken as 0.2; the Equation (9.1) reduces to

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{for } P \geq 0.2S \tag{9.2}$$

$$Q = 0, \quad \text{for } P \leq 0.2S$$

The parameter S of the SCS-CN method depends on soil type, land use, hydrologic condition, and antecedent moisture condition (AMC), it is obtained from equation (9.2) solving for S (Hawkins, 1993).

$$S = 5\left[P + 2Q - (4Q^2 + 5PQ)^{1/2}\right] \tag{9.3}$$

Since parameter S can vary in the range of $0 \leq S \leq \infty$, it is mapped onto a dimensionless curve number CN, varying in a more appealing range $0 \leq CN \leq 100$, as:

$$CN = \frac{25400}{(254 + S)} \tag{9.4}$$

Where, S is in mm. The difference between S and CN is that the former is a dimensional quantity (L) whereas the later is non-dimensional. CN = 100 represents a condition of zero potential maximum retention (S = 0), that is, an impermeable watershed. Conversely, CN = 0 represents a theoretical upper bound to potential maximum retention (S = ∞), that is an infinitely abstracting watershed. However, the practical design values validated by experience lie in the range (40, 98) (Van Mullem, 1989). CN has no intrinsic meaning; it is only a convenient transformation of S to establish a 0-100 scale (Hawkins, 1978).

9.3 CN FROM OBSERVED RAINFALL AND RUNOFF EVENTS (CN(PQ))

The gauging site at Belkheri (Figure 3.2 in Chapter 3) monitors the discharge of Sher watershed of area 1488 km^2. The daily discharge data is available for the period 26 years (1977-2002). Corresponding daily rainfall data of three major stations namely Narsinghpur, Harai and Lakhnadon are available. The daily discharge data and areal average daily rainfall have been used in the analysis.

9.3.1 Event Selection and Estimation of (CN(PQ))

CN values computed from observed event based pairs of the P and Q are termed as CN(PQ). Most of the events are selected from the period of June to September during each year. Several events of small as well as large magnitude have been taken for estimation of curve number. For the pair of direct runoff and corresponding rainfall, the potential maximum retention (S) is computed using equation (9.3) and curve number is computed from relationship between S and CN (equation 9.4). The procedure is illustrated below.

1) The daily runoff volume is computed from the observed daily discharge and expressed in depth unit (mm).
2) A single event from July, 1986 is separated (Figure 9.1) by identifying rise and end point of runoff hydrograph plotted against time. The corresponding rainfall is also plotted.
3) This particular event started on 13th July and ceased on 21st July.
4) The base flow separation line of magnitude 0.412 mm is identified from the flood ordinate of date 12th July prior to start of flood event.
5) Direct runoff depth is estimated by deducting base flow (0.412 mm). Direct runoff depth for selected flood event is 26.61 mm and corresponding event rainfall is 84.58 mm.
6) For known P and Q, value of S is computed from equation 9.3 (Hawkins, 1993) S=95.61 mm
7) Therefore CN(PQ) for selected event is computed from equation (9.4). CN(PQ) =72.65

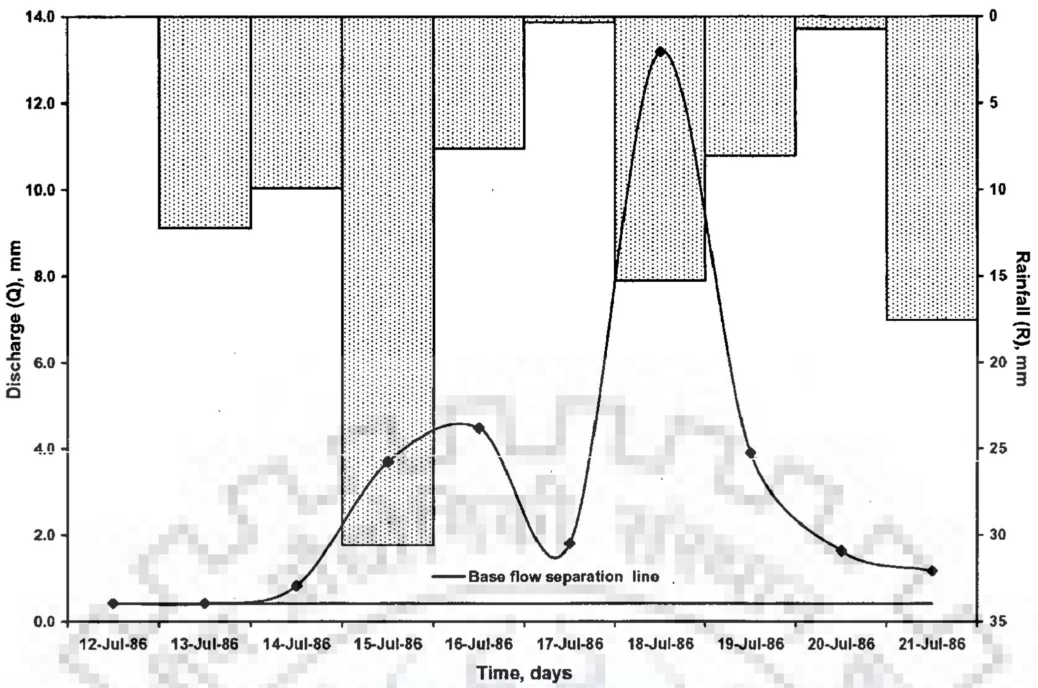


Figure 9.1: Event selection and separation of base flow by straight line method

8) Same procedure is repeated for other observed flood events in each year.

9) To compute the year value of CN(PQ) for AMCII condition, median value criteria (Bonta, 1993 and Mishra et al., 2005) is applied to the group of computed CN(PQ) from the selected events of a year.

S and CN(PQ) values computed from the selected events for each year are presented in Table E6 of Appendix E for period of 1977-2002.

The number of events selected in a year depends upon the amount of rainfall and its daily distribution in watershed. The year 1997 yields highest number of flood events (13) while only 2 events are considered in year 1989 due to unavailability of daily rainfall data. The duration varies from 3 to 13 days for the observed events and most of the selected events have duration of 4-7 days. Observed events mostly occur in month of July, August and September. The rainfall received in month of June helps in raising the soil moisture levels in the watershed area which get depleted during prolonged non-monsoon dry period. It is also observed that events having higher number of consecutive rainy days produced higher CN(PQ) which may be termed as CN(PQ) of AMCIII condition. Moreover, events preceded by dry spell produce low runoff and result in low CN(PQ). The low CN(PQ) values are mostly observed for events belonging to month of June and July. The high values of CN(PQ) are mostly found for events in the month of August due to high soil moisture level caused in previous rainy months of June and July as well as August month itself receiving on an average 30-33% annual rainfall.

9.3.2 Variation in Annual CN(PQ)

The event CN(PQ) values for selected events in each year have been computed and the median value of the group of events CN(PQ) is selected to represent CN(PQ) of the year the for AMC II condition. The variation of annual CN(PQ) with year is depicted in Figure 9.2.

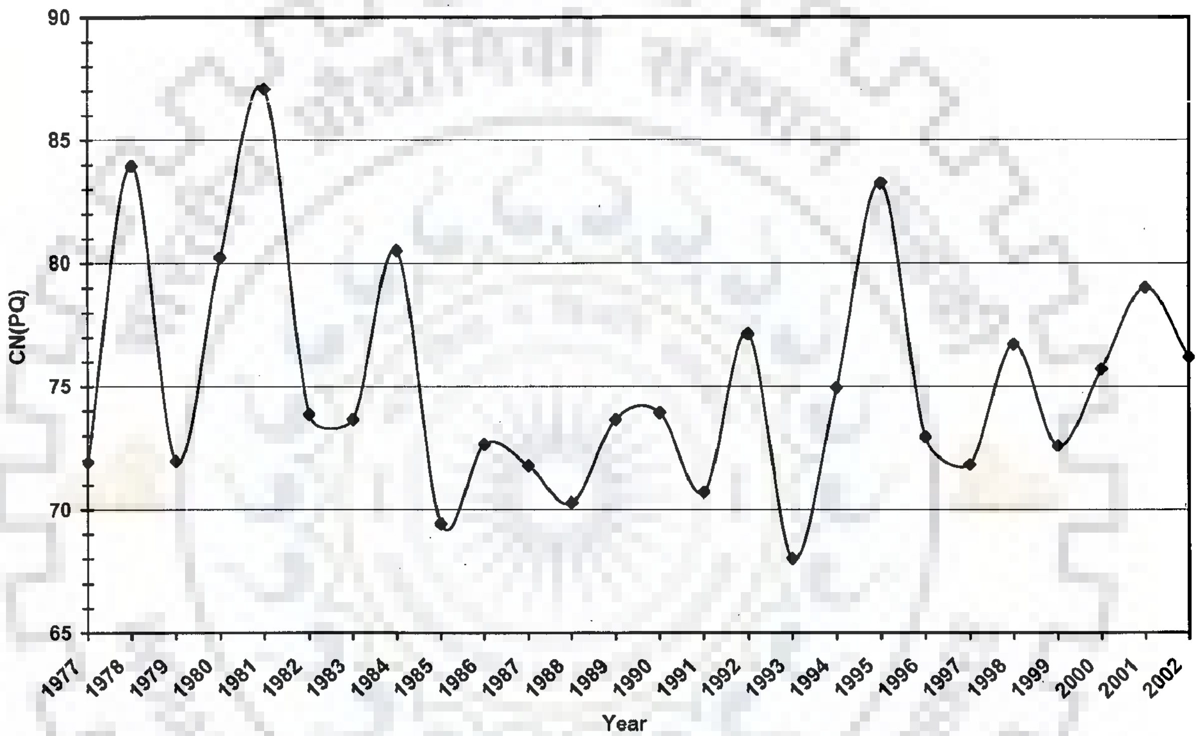


Figure 9.2: Annual CN(PQ) values for AMCII condition for gauged Sher watershed

The annual CN(PQ) shows variation in the range of 69 to 87. The CN(PQ) values greater than 80 are observed in year 1978,1980,1981,1984 and in 1995. The low CN(PQ) values less than 70 are observed in year 1985 and 1993. Remaining years show CN(PQ) in between range of 70-79. The median value of CN(PQ) for observed data period is about 74 and average value is about 75. So it can be said that values in the range of 70-79 are most significant values and they truly represent the AMC II condition of the Sher watershed.

9.4 CN FROM LAND USE, LAND COVER AND SOIL (CN(LU))

The CN(LU) is a dimensionless runoff index based on hydrologic soil group (HSG), land use, land treatment, hydrologic conditions and antecedent moisture condition (AMC) which counts on previous 5 days rainfall total. It is termed as 'CN(LU)' to distinguish from CN(PQ).

In present study, land use land cover maps of three different years (1972, 1989 and 2000) have been derived from satellite imageries by visual interpretation. The classified land use maps showing six major classes such as agriculture, forest, barren land, badland, and settlement and water bodies are given in Figures 7.2, 7.3 and 7.4 of Chapter 7.

9.4.1 Soil Type and Hydrologic Soil Group

Soil map of the study area (Figure 9.3) has been prepared using available information and maps from various sources as mentioned in Appendix E.

Lower part of study area has soil which is clayey in texture and black in color and its depth is more than 9 m near the confluence of the three rivers. (NIH, 1995 & 1997 and NBSS, 2007). Based on dominance of clay having low value of hydraulic conductivity (Appendix E, Tables E2 & E3) in lower part of study area, it is classified in hydrological soil group D (HSG D).

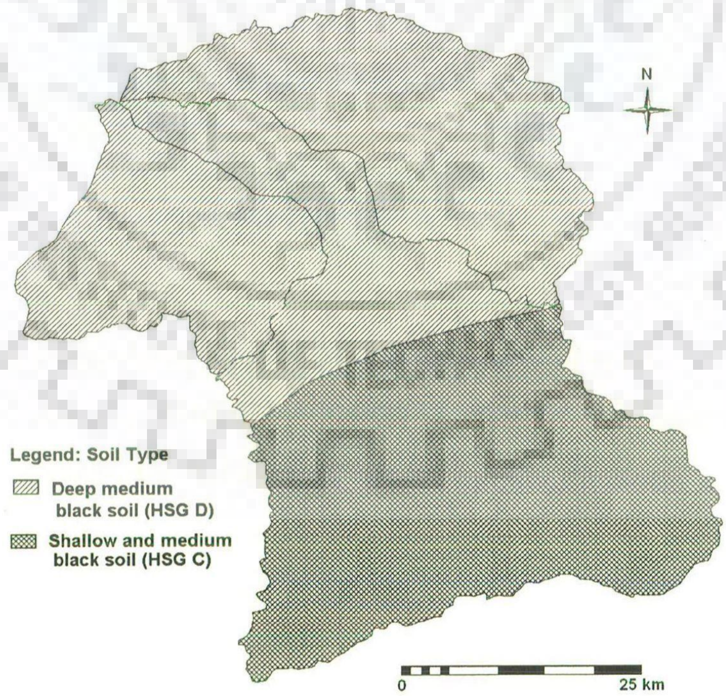


Figure 9.3: Soil type in the of study area

Soil type and its textural properties in upper part of study area have been obtained from the Soil map of Madhya Pradesh (http://www.mpmandiboard.com /Comp2005/Chapter-I/7.htm) and NBSS report on Madhya Pradesh Soils (Soils of MP, 2005; NBSS-59, 2007). The soils of this area are loamy in texture and blended with the clay content. The depth of the soil is very shallow and stony with loam texture on the steep sloping hills and soil is shallow to medium deep clay on medium and gently sloping Deccan plateau. The loam with clay soil have better infiltration capacities than clay and silt clay therefore the area of this soil is classified into hydrological soil group C (HSG C).

9.4.2 Spatial Distribution of CN(LU)

Curve Number is obtained from reference table (Appendix E, Table E1) appropriate for Indian condition and using land use and hydrological soil cover data (Handbook of hydrology, 1972). Distributed CN(LU) map have been prepared in GIS environment as per procedure depicted in Figure 9.4.

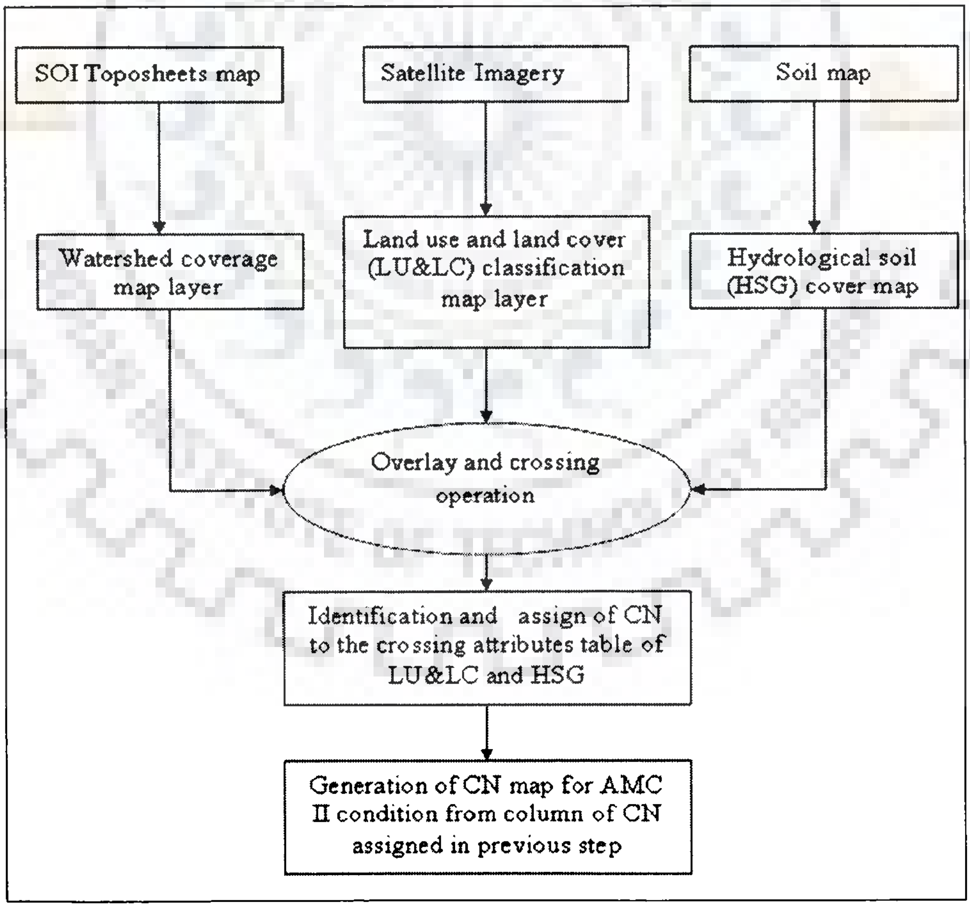


Figure 9.4: Procedure for determination of CN(LU) map for AMC II

The weighted CN of a watershed is computed from the following formula.

$$CN\ (LU) = \frac{\sum (CNi \times Ai)}{A} \tag{9.5}$$

Where,

CN(LU) =Weighted Curve number

CNi = Curve number of area i assigned on the basis of land use and land cover and hydrologic soil group conditions. It varies from 0 to 100.

Ai = area having CNi

A =Total area of watershed.

The collective layers with their assigned CN values have been used to generate distributed CN map of three different years 1972, 1989 and 2000 as shown in Figures 9.5, 9.6 and 9.7.

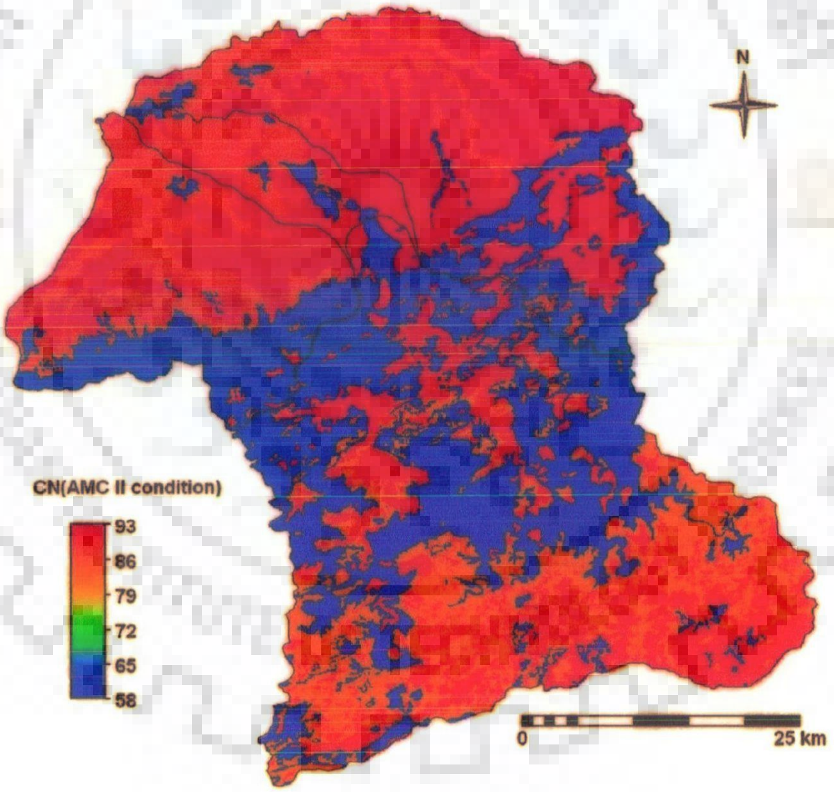


Figure 9.5: Spatial distribution of runoff potential i.e. CN(LU) in the year 1972

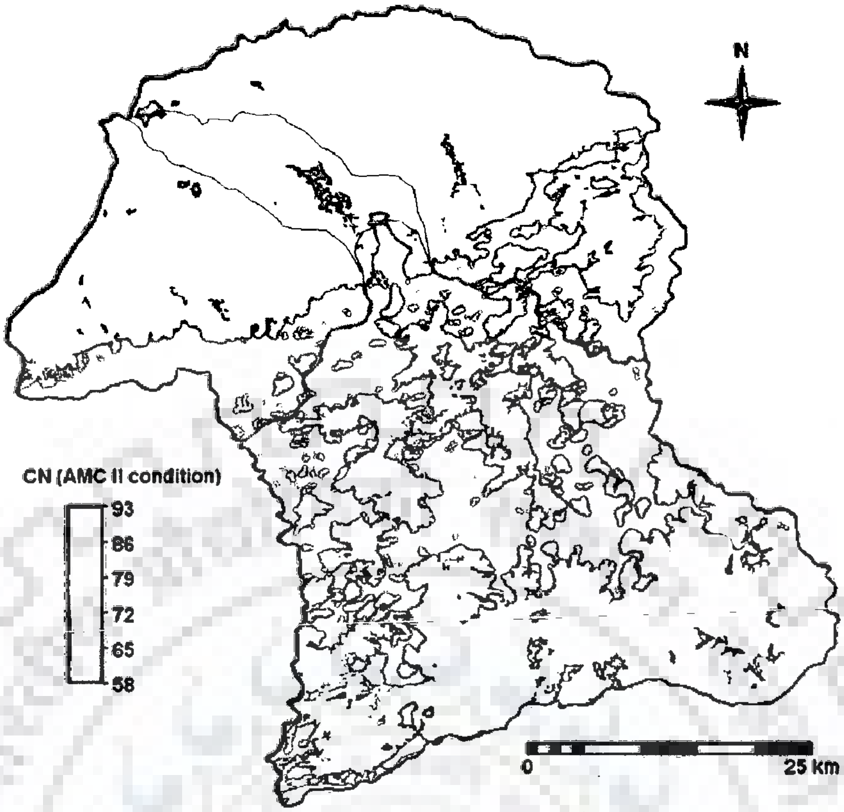


Figure 9.6: Spatial distribution of runoff potential i.e. CN(LU) in the year 1989

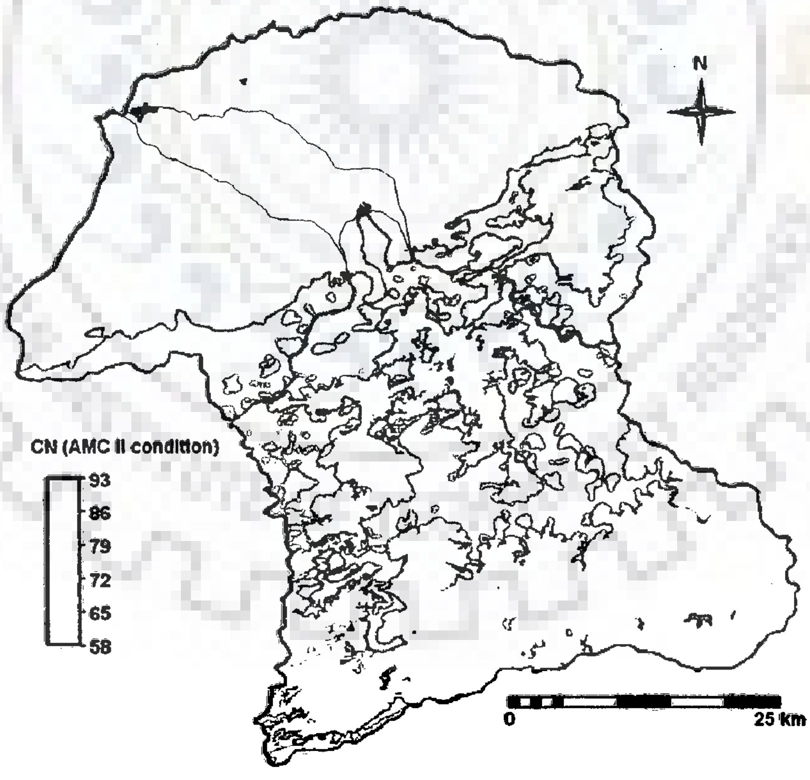


Figure 9.7: Spatial distribution of runoff potential i.e. CN(LU) in the year 2000

The generated CN maps are again crossed with watershed boundaries of Sher (upto gauge site) watershed, Barureva watershed and Umar watershed to get their respective weighted CN values. The weighted CN(LU) values for classified watersheds are given in Table 9.1.

Table 9.1: CN(LU) for AMCII condition for different watersheds in study area

Watershed Name	Area (km^2)	CN(LU)		
		1972	1989	2000
Barureva	488	81.24	82.98	84.86
Umar	699	84.79	85.8	86.77
Sher(u/s gauge site)	1488	75.31	75.28	77.06
Sher(d/s gauge site)	147	87.37	89.88	92.48
Sher	1635	76.40	76.60	78.46

9.4.3 Variation in CN(LU) over the Years

CN(LU) distribution maps of three different years depict gradual increase in CN values from 1972 to 1989 and from 1989 to 2000. The increase in CN values is more apparent in lower part of the three watersheds where badland (CN=89) and forest land (CN=61) has been significantly converted into the agriculture land (CN=93). The change in CN values in Barureva and Umar watersheds are caused by reclamation of badland for agriculture purpose. Isolated patches of forest (Figure 9.5, 9.6 and 9.7) which existed near the confluence of three rivers in year 1972 and 1989 have been completely replaced by agriculture area in year 2000. The changes in CN(LU) gauged Sher watershed are not as remarkable as observed in Barureva and Umar watersheds and also in the downstream of gauge site of Sher watershed. Forest cover (CN=58) and barren land (CN=88) are replaced by agriculture area (CN=90) in upper south-west part of gauged Sher watershed. Conversion of forest cover (58) into the barren land (89) in the middle part of gauged Sher watershed caused increase in CN values with the successive time period. Deforestation has lead to emergence of barren land along the boundaries of forest and agriculture land and resulted increase in CN values.

Among three watersheds, Umar watershed shows highest CN(LU) value for AMC II condition while Sher watershed shows the lowest CN(LU) for selected years. Consequently, Umar watershed has highest runoff potential under the same magnitude of received rainfall in comparison to other watersheds. The variation of CN(LU) with year in different watersheds are depicted in Figures (9.8 (a, b, c, d, e)).

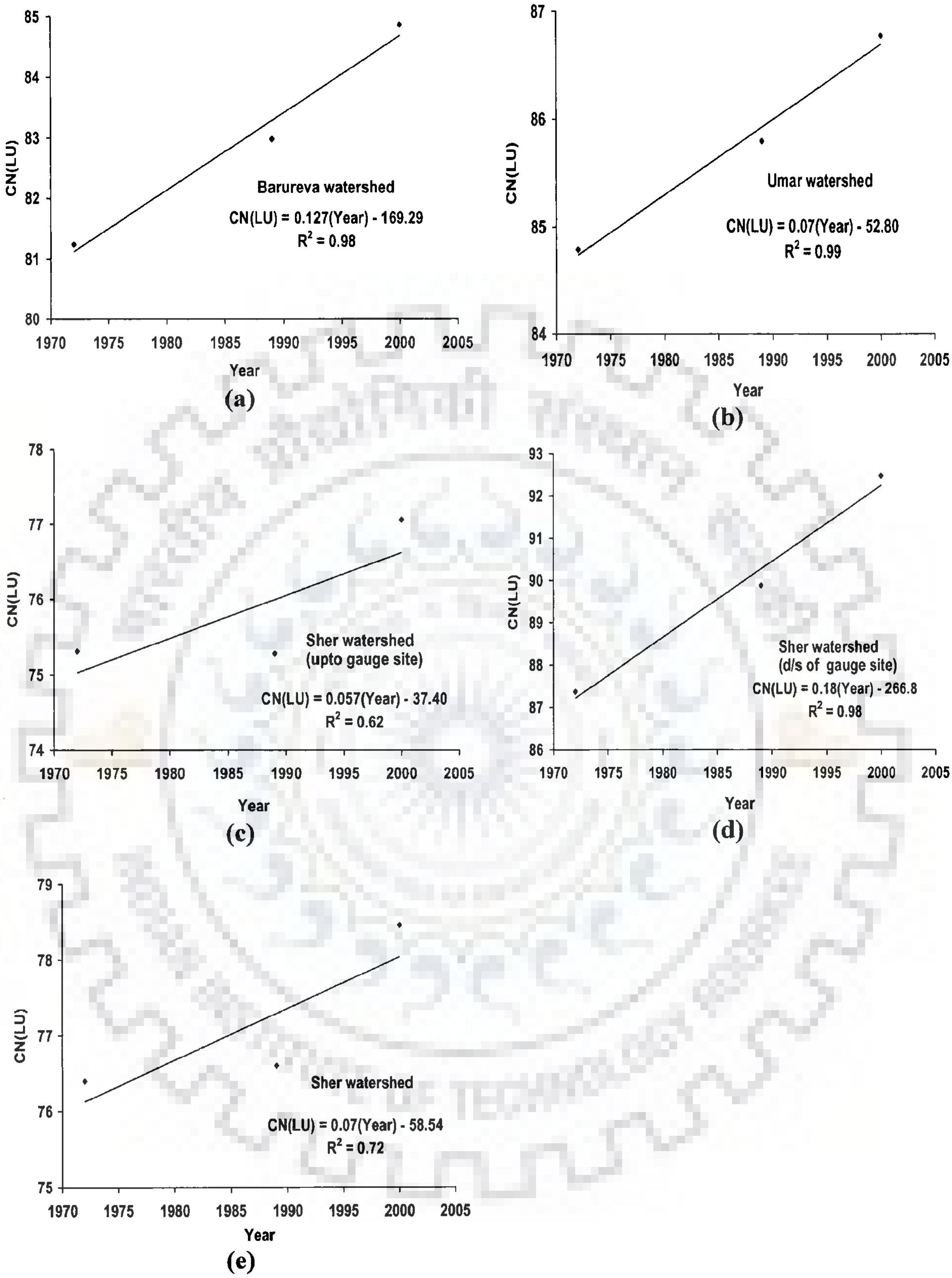


Figure 9.8: Change in runoff potential of various watersheds over the years

The CN(LU) values particularly for Sher watershed do not show significant increase despite the spatial changes in land use and land cover with progressive time. The agriculture area in Barureva, Umar and part of Sher watershed downstream of gauge site have almost become stabilized and further increase is not expected as agriculture area has almost replaced previous existed land classes such as bad land area and forest cover area. On the other hand, agriculture area in Sher watershed upstream of the gauge site is expected to increase in place of barren land. Rate of increase in agriculture area in upper part of Sher watershed (upto Gauge site) in recent time period of 1989 to 2000 is slow (Chapter 7). The development of surface water storage structures may cause expansion in agriculture area in the upper part of Sher watershed resulting in increase in CN(LU).

9.5. VALIDATION OF COMPUTED CN(LU) USING CN(PQ)

Study area has one gauge site at Belkheri which monitors the daily discharge for Sher river watershed of area 1488km^2. Therefore CN(LU) derived from the land use and land cover and hydrological soil cover data for this gaged watershed have been compared with observed CN(PQ) value. The agreement between CN(LU) and CN(PQ) for gauged Sher watershed is depicted in Figure 9.9.

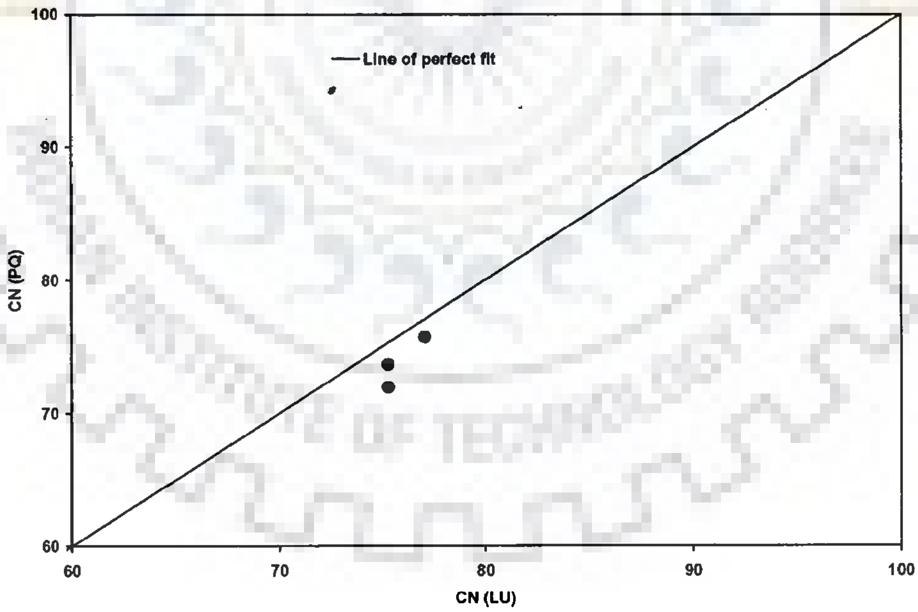


Figure 9.9: Comparison of CN(LU) and CN(PQ) for gauged Sher watershed

The CN(PQ) for year 1972 is not available therefore CN(PQ) for year 1977 has been taken for analysis and its corresponding CN(LU) was computed from the developed relationship between CN(LU) and year. The values of CN(LU) are available for corresponding CN(PQ) of years 1989 and 2000. Therefore it is concluded that CN(LU) obtained using reference table of popular SCS CN method has close association with the observed data. Moreover, derived land use land cover data from satellite imageries from years 1972, 1989 and 2000 also gets validated by comparison of computed CN(LU) and observed CN(PQ).

9.6 PERFORMANCE OF SCS METHOD USING VARIABLE ANNUAL CN(LU)

The observed data sets of daily rainfall and runoff are available for Sher watershed. As discussed in previous section 9.5.1, events of P and Q data sets have been used for computation of CN(PQ). For the same events, runoffs have been estimated for corresponding P and using existing SCS-CN method. The CN(LU) estimated for each year from the developed relationship of CN(LU) and year are used for the daily simulation of existing SCS-CN method. Event runoff values Q_{obs} are taken from the simulated daily runoff values. The observed and computed event Q values for each year are given in Appendix E (Table E7). The root mean square error and NS efficiency parameter are used to determine degree of agreement between observed and computed data sets of event runoff. The Table E7 in Appendix E shows observed and computed values of event runoff along with the yearly computed values of NS efficiency and root mean square to evaluate the performance of SCS-CN method and its applicability for the Sher watershed.

Performance of SCS-CN method on gauged Sher watershed has been evaluated using model efficiency and root mean square error (RMSE) criteria. The model efficiency is generally recognized by Nash-Sutcliffe (NS) efficiency (Nash and Sutcliffe, 1970).

9.6.1 Nash-Sutcliffe (NS) Efficiency

Based on computed and observed data sets of direct runoff of selected long term events, NS efficiency is computed by formula,

$$NS = 1 - \frac{\sum (Q_{obs} - Q_{comp})^2}{\sum (Q_{obs} - \overline{Q_{obs}})^2} \times 100 \qquad (9.6)$$

Where, Q_{obs} is the observed runoff, Q_{comp} and $\overline{Qobs}$ stand for computed and the mean of the observed runoff, respectively. The efficiency varies on the scale of 0-100. It can also assume a negative value if $\sum (Q_{obs} - Q_{comp})^2 > \sum (Q_{obs} - \overline{Q_{comp}})^2$, implying that the variance in the observed and computed runoff values is greater than the model variance. In such a case, the mean of the observed data fits better than does the proposed model. The efficiency of 100 implies that the computed values are in perfect agreement with the observed data.

9.6.2 Root Mean Square Error (RMSE)

The RMSE is computed for observed and computed data sets using following formula,

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Q_{obs} - Q_{comp})_i^2} \tag{9.7}$$

Where Q_{obs} and Q_{comp} are observed and computed values and N is the data sample size. Higher the value of RMSE, poorer is the performance of the model, and vice versa. The values of RMSE =0 indicate a perfect fit.

In this study, the SCS–CN model uses variable annual CN(LU) values for computation of direct runoff under daily simulation of model. The annual CN(LU) values for AMCII condition are obtained from the developed relationship of CN(LU) with historical year as discussed earlier for gauged Sher watershed. Daily direct runoff output are summed for the corresponding event duration to compare with observed direct runoff values. The agreement between computed and observed event direct runoff values have been judged on the basis of the NS efficiency and RMSE values enlisted year wise in Appendix E (Table E7). NS efficiency values vary from 19.55 to 96.29, however high negative values are also observed for years 1987, 1992, 1995,1996,1997,1998 and 2001 due to underestimates of model output values against observed direct runoff. The SCS model simulates well for years 1977, 1978, 1982,1984,1999,2000 and 2002 with NS efficiency values in the range of 70% to 97%. The NS efficiencies values are found in the range of 40% to 70% for years 1980, 1983, 1985,1988,1989,1991 and 1993. In this case for some events predicted value of direct runoff are less than 50% of observed direct runoff values, however other events of these years show good agreement between computed and observed direct runoff values. Years such as 1979, 1981, 1986 and 1990 show poor performance of model in prediction of direct runoff values with NS efficiency value in the range of 19 to 40% due to either lack of sufficient events or due to one or two redundant event predictions. Therefore it is necessary to consider overall efficiency for all data sets for model performance. The NS efficiency for entire data set (events for all years) is observed to be around 75 % which is quite satisfactory. The RMSE values for all years of data set vary in the range of 5 to 48 mm and average RMSE value is 21 mm. The performance of RMSE is not as good as the NS efficiency therefore model performance is again checked by plotting computed and observed direct runoff values with the line of perfect fit graph as shown in Figure 9.10. It is observed that paired data sets of observed and computed values have closeness with line of perfect fit. It is concluded that the SCS model under dynamic annual CN(LU) is capable to predict direct runoff satisfactory for low as well as high rainfall events in the gauged Sher watershed. Therefore the CN(LU) computed for ungauged Barureva and Umar watersheds can be satisfactorily used for runoff prediction.

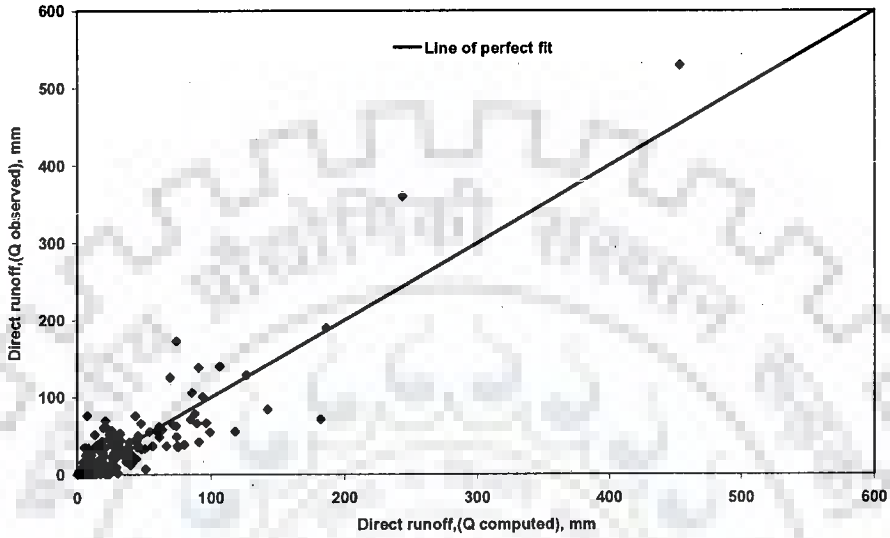


Figure 9.10: Observed and computed event runoff values for gauged Sher watershed

9.7 FUTURE PREDICTION OF CN(LU)

The developed relationship of CN(LU) with historical year may be used for prediction of CN(LU) in future if the ongoing rate of changes in land use and land cover persists in the watersheds. CN(LU) values for each watershed have been predicted for time period upto 2100 as shown in Table 9.2.

Table 9.2: Predicted CN(LU) values using developed relationships

Watershed Name	Equation developed	Predicted CN(LU) for future years				Predicted year for CN(LU) =100
		2025	2050	2075	2100	
Barureva	CN(LU) = 0.127(Year) - 169.29, R^2 = 0.98	87.88	91.06	94.23	97.41	2120
Umar	CN(LU) = 0.07(Year) - 52.80, R^2 = 0.99	88.95	90.70	92.45	94.20	2183
Sher (u/s gauge site)	CN(LU) = 0.057(Year) - 37.40, R^2 = 0.62	84.10	85.60	87.10	88.60	2290
Sher	CN(LU) = 0.07(Year) - 58.54, R^2 = 0.72	83.21	84.96	88.46	89.16	2265

Predicted CN(LU) values for selected watersheds show that Sher watershed has much lower CN increments due to slow rate of agriculture expansion. Barureva and Umar watersheds have the alluvium formation with plenty of ground water storage. These factors along with population pressure have been responsible for conversion of badland area into the agricultural area during period of year 1989-2000. On other hand Sher watershed (u/s gauge site) have the adequate scope for further increase in agricultural area in place of barren land which is possible by introducing surface water storage structures. Therefore CN(LU) prediction for Sher watershed may follow the current trend of CN(LU) values in future year as shown in Table 9.2. If the predicted trend of CN(LU) continues, CN(LU) for all watersheds will attain the theoretically ultimate values of 100 sometime in future. The Barureva and Umar may attain CN(LU) at 100 much earlier. Sher watershed has lower human interference in terms of agricultural area expansion which has partly kept control on CN(LU) of watershed. The value of CN(LU) = 100 represents completely impermeable state of watershed which is practically not possible. Therefore possible upper limit of CN(LU) for all watersheds is 90 to 93 which is representative of CN(LU) of agriculture for hydrological soil group of C and D respectively. This situation expected to be reached around year 2075.

9.8 EFFECT OF SLOPE ON CN

Due to increase in population, land availability per capita is decreasing. Increase in food production is being brought about by increasing the agriculture area through deforestation and cultivation of hill slope areas. The SCS-CN method for estimation of runoff was originally developed for agricultural watersheds with land slope near about 5%. However over the years its application has been extended to watersheds having multiple land use without considering effect of topography. Huang et al (2005) has reviewed various studies on the effect of soil slope on the runoff. An increase in surface runoff due to steeper slopes is due to i) reduction of initial abstraction (Chaplot and Bissonnais, 2003), ii) decrease in infiltration (Philip, 1991) and iii) reduction of the recession time of overland flow (Evet and Dutt, 1985). The reduced recession time results in less opportunity for infiltration and consequently more runoff.

Although the effect of the slope on runoff volume has been clearly established by research studies, few attempts have been made to study effect of topography in the SCS-CN method. Sharpley and Williams (1990) has proposed the following equation to obtain slope adjusted CN value but it does not appear to have been verified in field (Huang et al 2005).

$$SACN_2 = \frac{1}{3}(CN_3 - CN_2) - (1 - 2e^{-13.86\alpha}) + CN_2 \qquad (9.8)$$

Where,

$SACN_2$: Slope adjusted CN for antecedent soil moisture condition II

CN_2: CN for antecedent soil moisture condition II

CN_3: CN for antecedent soil moisture condition III

α: Soil slope (m/m)

CN_2 and CN_3 correspond to a soil slope of 5%

In the present study, equation 9.8 has been used to study the spatial effect of slope on runoff potential at watershed and sub watershed level in Barureva, Umar and Sher watersheds. This exercise was performed for three different years of land use and land cover i.e. year 1972, 1989 and 2000. SCS-CN value have been compared with slope adjusted CN (SA-CN) in Table 9.3. It is seen that the difference between SCS-CN and SA-CN values is insignificant at watershed level suggesting negligible effect of slope.

Table 9.3: CN_{slope} (LU) for AMCII condition for different watersheds in study area

Watershed Name	Area (km^2)	Year		
		1972	1989	2000
Barureva	488	80.22	82.19	84.23
Umar	699	83.61	84.75	85.79
Sher(gauge)	1488	75.29	75.26	77.04
Sher(d/s gauge)	147	86.14	88.84	91.58
Sher	1635	76.28	76.51	78.37

However since slope may vary significantly within a watershed, the exercise was carried out to assess slope adjusted CN (SA-CN) values at sub watershed level. Table 4.3 in Chapter 4 shows the slope range which exist in the Barureva, Umar and Sher watersheds. Figure 9.11 shows spatial distribution of difference in SA-CN and SCS-CN corresponding to land use and land cover in the year 2000. Effect of slope on CN in areas under different land use and land cover is shown in Table 9.4.

Table 9.4: Effect of slope on CN of different land use and land cover of the study area

Land use and land cover	Slope (%)						
	0-1	1-3	3-5	5-10	10-15	15-30	>30
Agriculture	-3 to -1	- 1 to -2	-1 to 0	0-1	1 to 2	1 to 3	2 to 3
Forest	-7 to -5	-5 to -2	-2 to 0	0 to 3	3 to 5	5 to 7	6 to 7
Barren land	-4 to -2	-3 to -1	-1 to 0	0 to 2	2 to 3	2 to 4	3 to 4
Badland	-3 to -2	-2 to -1	-1 to 0	0 to 1	-	-	-
Settlement	-4 to -2	-3 to -1	-1 to 0	0 to 2	-	-	-
Water body	0	0	0	0	-	-	-

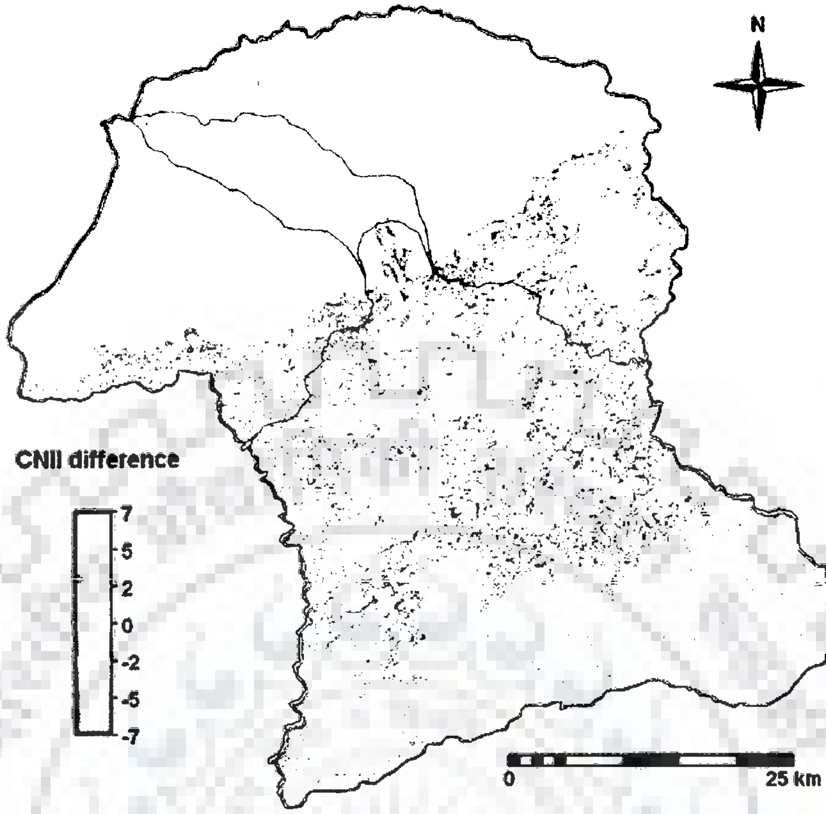


Figure 9.11: Spatial distribution of difference in SA-CN and SCS-CN

Following inferences can be drawn from the table.

i) SA-CN is less than SCS-CN over land with slope less than 5% and it is more than SCS-CN with slopes more than 5%. Higher the deviation from 5% slope more is the difference.

ii) Significant difference in CN is observed in the forest lands which are usually located on slopes. Therefore land slope should be considered in SCS-CN method for evaluating runoff potential.

iii) Effect of slope on CN is relatively less significant in watersheds having agriculture and other land use and land covers.

iv) For micro watershed planning, SCS-CN method can be modified to incorporate effect of change in land use also in addition to effect of slope.

9.9 CONCLUSIONS

The spatial and temporal changes in land use and land cover affect the surface runoff potential from a watershed. Such changes in runoff potential will have influence on sustainable utilization of water resource for the watershed development and management. The developed relationship of CN(LU) with historical year can be used for prediction of CN(LU) in future if the ongoing changes persist in the watersheds. CN(LU) values for each watershed have been predicted for time period upto 2100.

Median value of CN computed from the observed data sets of rainfall and runoff events is taken as annual CN(PQ) as per well known criterion (Bonta, 1993 and Mishra et al., 2005).

Analysis in Chapter 7 shows that the rate of deforestation has accelerated in recent period. Analysis in Chapter 8 shows that a large number of field bunds (small height embankments) constructed earlier have now been destroyed as the farmers have taken up cultivation of cash crops like soyabean for which fields are required to be kept well drained. This has resulted in more runoff and lesser ground water recharge.

CN(LU) distribution maps depict gradual increase in CN values from 1972 to 1989 and from1989 to 2000. The increase in CN values is more apparent in lower part of three watersheds where badland (CN=89) and forest land (CN=61) has been significantly converted into the agriculture land (CN=93). Conversion of forest cover (58) into the barren land (89) in the middle part of gauged Sher watershed caused increase in CN values in the successive time period.

Among three watersheds, Umar watershed has higher CN(LU) value for AMC II condition indicating higher runoff potential under the same magnitude of received rainfall in comparison to other watersheds.

Three paired data sets of CN(LU) and CN(PQ) values for year 1977, 1989 and 2000 have been validated though their closeness with the line of perfect fit.

NS efficiency for entire data set (events for all years) is around 75 % which is quite satisfactory. The RMSE values for annual data set vary in the range of 5 to 48 mm with average RMSE value of 21 mm. Model performance is again checked by plotting computed and observed direct runoff values with the line of perfect fit. It is observed that paired data sets of observed and computed values have closeness with line of perfect fit. It is concluded that the SCS model under dynamic annual CN(LU) can be used to predict direct runoff potential in ungaged watersheds.

Although the effect of the slope on runoff volume has been clearly established by research studies, few attempts have been made to study effect of topography in the SCS-CN method. The present study shows that slope adjusted CN is less than conventional CN over areas with slope less than 5% and more than conventional CN for areas with slope more than 5%. Higher the deviation from 5% slope more is the difference. Si gnificant difference in CN is observed in the forest lands which are usually located on slopes. For micro watershed planning, SCS-CN method should be modified to incorporate effect of change in land use also in addition to effect of slope. Further research is needed to study effect of morphological parameters on the curve number.

CHAPTER 10

RELATION BETWEEN MORPHOLOGICAL PARAMETERS, NONLINEARITY OF WATERSHED AND FLOOD DISCHARGE

10.1 INTRODUCTION

Several methods such as SCS-CN method are available in literature for estimation of runoff volume in the absence of observed discharge data. However, in addition to runoff volume, estimation of peak flood discharge is also required in design of various engineering measures. Discharge observations for every new project site are neither practical nor economically feasible for a large number of such sites. In such a situation geomorphological parameters based regional approach is recommended in literature. Snyder's Unit Hydrograph is one such example which is based on the assumption of linearity and stationary character of watershed parameters. Dynamic character of the Curve Number which is an indication of resource potential of a watershed has been analyzed in Chapter 9.

Serious error in hydrologic design can occur by over estimating or underestimating discharge when a watershed is assumed to be linear while in fact it may be nonlinear in terms of catchment's response to rainfall. Watershed linearity is a basic assumption in the unit hydrograph theory (Sherman, 1932), which also assumes that peak discharge is directly proportional to the runoff volume. The widely accepted usage of UH theory makes it imperative to develop a criteria for validity of the UH theory and thus the linearity in the rainfall-runoff process.

Regional approach to synthesize unit hydrograph and its application in flood estimation is based on the concept of hydrologic similarity of watersheds. It is rather impractical to identify hydrological similarity of different watersheds by comparing a large number of influencing factors. This chapter is concerned with morphological analysis of hydrologic nonlinearity and similarity of watersheds and estimation of flood.

10.2 LINEAR AND NONLINEAR HYDROLOGIC SYSTEM

As the rainfall-runoff process is complicated, very often a simpler process of effective rainfall-direct surface runoff (DSRO) is studied. The DSRO may be considered as the response of the watershed system to the input of effective rainfall. The watershed system may be linear and nonlinear.

When the runoff volume (output) from watershed is directly proportional to the precipitation volume (input) for a range of precipitation volumes, the watershed is said to exhibit linear runoff or it is said to be hydrologically linear. If all hydrologic losses are distributed uniformly, then the runoff volume must equal the precipitation volume minus a constant loss. In other words, output must be directly proportional to input and the watershed is hydrologically linear.

Nonlinearity refers to nonlinear dependence of the storm response on the magnitude of the rainfall inputs. In the present study, degree of nonlinearity of a watershed is proposed to be identified through analysis of relationship between peak discharge, runoff volume and geomorphological parameters.

10.3 PEAK DISCHARGE -VOLUME RELATION

Relationship between peak discharge and volume of runoff (PDVR) was first proposed by Rogers (1980) who termed it as standardized peak discharge distribution. Singh (1994) termed it as peak discharge rating curve because peak discharge runoff volume relation is transformation of the stream gage rating curve. PDVR is defined as the distribution of the logarithm of peak discharge Q_p (m^3/s) plotted against the logarithm of the runoff volume V (cm) of the total hydrograph producing that peak discharge. An equation for this plot can be determined using the least square method and a measure of the fit can be determined. The equation takes the form:

$$Q_p = a V^m$$

or

$$\text{Log } Q_p = b + m \log V \qquad (10.1)$$

Where,

b (= Log a) is the intercept

Q_p = peak discharge in m^3/s

V = runoff volume under the hydrograph converted to centimeter uniformly distributed over the entire watershed

m = slope of the line fitting the data

For hydrologically linear watersheds meeting the UH conditions, slope in equation 1 must be equal to 1.0. Smaller slope indicates hydrologic nonlinearity. Rogers (1980) developed the peak discharge distribution using runoff data of 43 watersheds ranging from 5 to 700 km^2. Mimikou (1983) in his study on catchments in Greece found that equation (10.1) by itself is sufficient for checking hydrologic linearity and predicting peak discharge.

10.4 DEPENDENCE OF PEAK DISCHARGE ON WATERSHED LAG

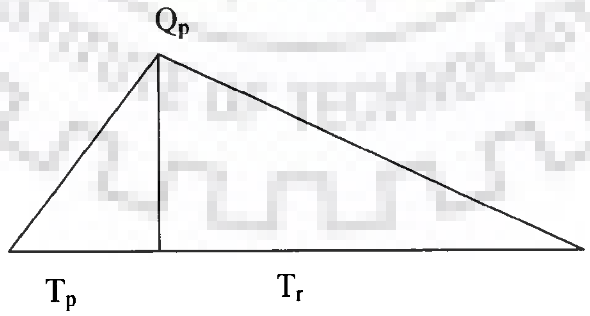
Equation (10.1) suggests that catchment having same values of b and m will produce same peak discharge if volume of runoff is same. It is well known that peak discharge depends on watershed lag. Watershed lag (also known as lag time) is the time difference between center of mass of rainfall and center of mass of hydrograph. Snyder (1938) defined watershed lag (t_p) as the time interval from the midpoint of the unit rainfall excess to the peak of the unit hydrograph and related it to the watershed length (L) and length from outlet to a point along main water course nearest to the centroid of catchment (L_c). Linsley at al (1958) found that watershed lag is better correlated with the catchment parameters ($L L_c/\sqrt{S}$) where S is watershed slope. Snyder (1938) related peak discharge of a unit hydrograph to a catchment (A) and watershed lag (t_p).

$$Q_p = 2.78\, C_p \times A / t_p \tag{10.2}$$

This equation is based on the assumption that peak discharge is proportional to the average discharge of (1cm x catchment area)/ (duration of rainfall excess). A large number of formulae have been proposed in literature to estimate t_p based on geomorphological parameters such as L, S, Manning's roughness coefficient (n), rainfall intensity, curve number etc (Chow and Maidment, 1988).

Peak discharge is known to depend not only on volume of runoff but also on time to peak (Mockus, 1957 as given in Chow 1988). Therefore relation between peak discharge (Q_p), time to peak (T_p) and runoff volume (V) termed as peak discharge, time and volume relationship (PDTVR) needs to be investigated as discussed below.

For triangular unit hydrograph



$$Q_P = \frac{2V}{T_P + T_R} \tag{10.3}$$

Mockus (1957) assumed, $T_b = 2.67\, T_p$ (10.4)

In general, $T_b = C\, T_p$ (10.5)

Then $$Q_p = \frac{2V}{C \times T_p} \tag{10.6}$$

$$\log Q_p = \log\left(\frac{2}{C}\right) + \log\left(\frac{1}{T_p}\right) + \log V \tag{10.7}$$

In general,

$$\log Q_p = b' + b'' \log T_p + m' \log V \tag{10.8}$$

Where b', b" and m' are constants.

Or $$\log Q_p = b_1 + m' \log V \tag{10.9}$$

Where, $$b_1 = b' + b'' \log T_p \tag{10.10}$$

Equation 10.9 is similar to equation 10.1.Assumption inherent in PDVR is that T_p is constant and ratio of T_b and T_p is constant.

To extend the work of Rogers (1982) and Mimikou (1983), Singh and Aminian (1986) developed relationship between volume and peak of direct runoff by employing a large number (134) of watersheds from the United States, Australia, Italy and Greece:

$$\log q_p = b + \alpha \log V \tag{10.11}$$

In which q_p is peak discharge of direct runoff per unit area (cm/hr), V is the direct runoff volume per unit area (cm), b is the intercept (cm/hr) and α is dimensionless slope. Subtracting 2 logV from both side of equation (10.11) following.

$$\log\left(q_p / V^2\right) = b + m \log V \tag{10.12}$$

Where m= α -2.

10.5 DATA USED

Two sets of data have been used in the present study. First set consists of 30 flood hydrographs of four watersheds in upper Narmada basin. Morphological characteristics, source of data and derived OPDD coefficients are shown in Table 10.1.

Second data set consists of representative one hour unit hydrographs of the 18 small watersheds in Narmada basin derived by Central Water Commission (CWC 1983) using 138 observed flood events in these watersheds (Table 10.3).

10.6 RESULT AND DISCUSSION

10.6.1 Analysis of PDVR and PDTVR

The equation 10.1 was applied to the four sub watersheds. The intercept (b), slope (m) and coefficient of determination r^2 for the peak discharge distribution of four drainage sub watersheds are given in Table 10.1.

Table 10.1: Watershed Characteristics and PDVR Coefficients

No.	River	Station	Area A Km^2	Length L, Km	Slope S (%)	Intercept b	PDVR m	r^2	No. of Hydro graphs	Source of data
1	Temur	Bridge no. 249	518.6	56.6	0.303	2.196	0.720	0.974	7	CWC, 1983: NIH 1995
2	Teriya	Bridge no. 253	114.2	35.4	0.321	1.816	0.723	0.852	11	CWC, 1883; NIH, 1995
3	Umar	Bridge no. 930	223.8	33.6	0.250	2.005	0.647	0.903	6	CWC, 1883; NIH, 1995
4	Kolar	Satrana	903.9	75.3	0.530	2.729	0.667	0.953	6	Jain et al 1995

The magnitude of data scatter around the regression line has been statistically checked for each sample by analysis of variance and 95% confidence and 95% confidence limits. All r^2 values of the original peak distribution are found to be significant at the 95% confidence level. Slope m of original peak discharge distribution (PDVR) varies from 0.647 to 0.723, indicating that these watersheds exhibit nonlinear hydrologic character. Regression analysis using equation (10.1) shows strong correlation between peak discharge and runoff volume (0.852 to 0.974) for the watersheds.

Regression analysis between peak discharge, time to peak and runoff volume was also carried out (Table 10.2). Analysis shows that correlation between peak discharge and time to peak is strong for Umar watershed (r=0.838) but weak in other watersheds. Flood hydrographs of several other watersheds need to be analyzed for assessing strength of dependence of peak discharge on time to peak.

Table 10.2: Peak discharge, time to peak and volume relationship (PDTVR)

No.	River	b'	Intercept b"	m"	Partial correlation coefficient (r^2)		Multiple correlation coefficient (r^2)
					Between log Q_p & log T_p	Between log Q_p & log V	
1	Temur	2.177	0.021	0.718	0.002	0.971	0.975
2	Teriya	2.048	-0.324	0.750	0.14	0.872	0.873
3	Umar	2.353	-0.400	0.777	0.838	0.983	0.984
4	Kolar	2.858	-.0189	0.727	0.187	0.939	0.962

10.6.2 Relationship between Unit Hydrograph Peak and Morphological Characteristics

Usefulness of developing peak discharge-volume relationship (equation 10.1) lies in predicting peak discharge in ungaged watersheds. Intercept b is equal log Q_p when runoff volume V is equal to 1cm. Thus b represents Unit Hydrograph peak. Based on a study in Greece, Mimikou (1983) found that variation in b is significantly explained by the logarithm of any of the two watershed morphological indices AS/L and A/L.

Singh and Aminian (1986) studied 134 watersheds and found that watershed area alone explains variance of b by more than 86% (r^2=0.861). Inclusion of bed slope S and stream length L increased r^2 marginally to 86.9%. Singh and Aminian (1986) therefore concluded that relationship between b and A alone is satisfactory.

In the present study, regional intercept prediction equation has been developed by using A, L, S data of the four watersheds (Table 10.1). The intercept prediction equations, calibrated with least square method are as follows.

$$b = -0.171 + 0.935 \log A \qquad r^2=0.887 \qquad (10.13)$$

$$b = 0.997 + 1.41 \log(A/L) \qquad r^2=0.778 \qquad (10.14)$$

and

$$b = 1.758 + 1.155 \log(AS/L) \qquad r^2=0.980 \qquad (10.15)$$

The above mentioned equations corroborate with the findings of Singh and Aminian(1986) that inclusion of S and L increases strength of correlation. The relationship in equation (10.15) is almost linear in semi log space. Since log Q_p = b for V=1, Equations 10.15 can be rewritten as:

$$Q'_p = 10^{1.758}(AS/L)^{1.155} \qquad (10.16)$$

Where, Q'_p is peak discharge in m^3/s when runoff volume is one cm.

Chaube and Suarbawa (2003) in their study of several watersheds in Himalayan region and in central part of India (Narmada basin and Godavari basin) found that by considering catchment area alone as an independent variable influencing b, the distinguishing features of regional geomorphology are not incorporated which would lead to incorrect evaluation of b and hence the peak discharge per unit runoff volume. In this context analysis was carried out of second data set consisting of 1-hour unit hydrographs pertaining to 18 watersheds situated in Narmada-Tapi zone of India. Original data of observed flood events are not available for these watersheds.

Central Water Commission (CWC, 1983) analyzed 138 flood events in 18 watersheds spread over upper Narmada and Tapi sub zone which includes the study area of present study. The catchment area of watersheds vary from 30.01 sq km to 2110.85 sq km. Representative one hour unit hydrograph for each of the 18 watersheds were derived using the observed flood events and assuming the watersheds to be linear. Table 10.3 shows number of flood events considered, peak discharge (Q_p) of the derived 1 hr Unit Hydrograph (average), and morphological parameters for these watersheds. These data have been used in the present study for regression analysis between peak discharge of UH and morphological parameters. The regression equations are given below.

$$b=0.277+0.775\log(A) \qquad R^2=0.929 \qquad (10.17)$$

$$b=0.911+1.584\log(A/L) \qquad R^2=0.855 \qquad (10.18)$$

$$b=1.897+1.110\log(AS/L) \qquad R^2=0.712 \qquad (10.19)$$

These equations suggest that correlation between b and catchment area is strong if duration of excess rainfall is same which in this case is one hour.

It is important to note that the 1 hour unit hydrographs given in CWC (1983) were derived assuming that the 18 watersheds are hydrologically linear. Original data on observed flood events (flood hydrograph, storm rainfall hyetograph) are not available. Therefore, further studies are required to establish correlation between b and morphological parameters.

Table 10.3: Watersheds in Upper Narmada Tapi Zone

Sl No.	Basin name	A km^2	Qp m^3/s	L km	S%	A/L	AS/L	b= log Qp	Log A	Log (A/L)	Log (AS/L)
1	Sakkar	2110.9	920.0	160.4	0.26	13.16	3.46	2.96	3.32	1.12	0.54
2	Chandrabhaga	989.8	323.0	87.0	0.27	11.38	3.11	2.51	3.00	1.06	0.49
3	Machana	945.2	342.0	113.5	0.20	8.33	1.67	2.53	2.98	0.92	0.22
4	Sukta	676.0	366.0	99.8	0.40	6.77	2.72	2.56	2.83	0.83	0.43
5	Kalimachak	535.4	254.0	64.4	0.45	8.31	3.74	2.40	2.73	0.92	0.57
6	Temur	518.7	173.0	56.5	0.30	9.18	2.78	2.24	2.71	0.96	0.44
7	Uma	348.9	155.0	46.5	0.25	7.50	1.84	2.19	2.54	0.87	0.26
8	Balooreva	343.2	145.0	47.2	0.15	7.28	1.11	2.16	2.54	0.86	0.04
9	Katepurna	321.2	271.0	35.6	0.37	9.02	3.29	2.43	2.51	0.96	0.52
10	Umar	223.8	152.0	33.6	0.25	6.66	1.67	2.18	2.35	0.82	0.22
11	Sakatwar	179.9	137.0	22.9	0.42	7.84	3.31	2.14	2.26	0.89	0.52
12	Lakhora	139.1	76.0	27.0	0.22	5.16	1.14	1.88	2.14	0.71	0.06
13	Hatear	118.5	48.0	34.4	0.18	3.45	0.62	1.68	2.07	0.54	-0.20
14	Tyria	114.2	54.0	35.4	0.32	3.22	1.04	1.73	2.06	0.51	0.01
15	Passa	70.2	51.0	23.1	0.32	3.04	0.97	1.71	1.85	0.48	-0.01
16	Ol-nadi	55.2	54.0	16.1	0.43	3.43	1.48	1.73	1.74	0.53	0.17
17	Khara	41.5	40.0	20.9	0.32	1.98	0.63	1.60	1.62	0.30	-0.20
18	Kareli	30.1	27.0	12.1	0.11	2.49	0.28	1.43	1.48	0.40	-0.55

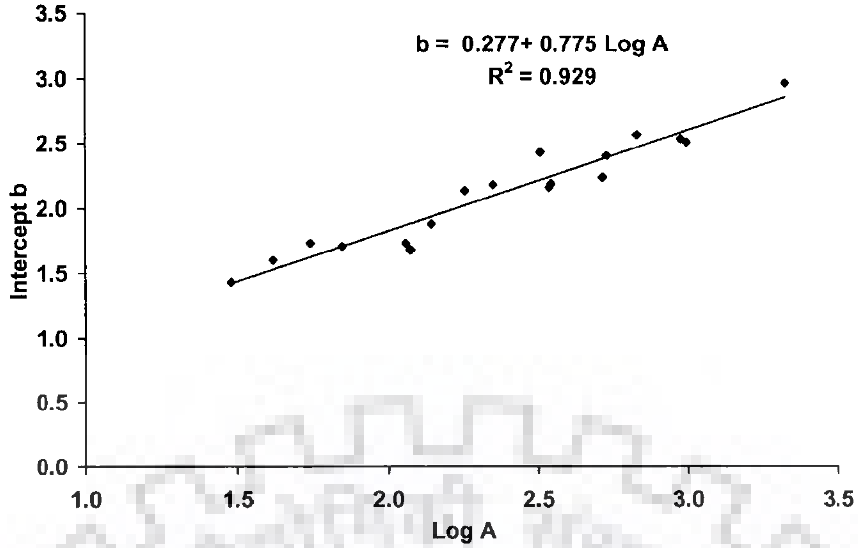


Figure 10.1: Relationship between the intercept b and the basin morphological index A

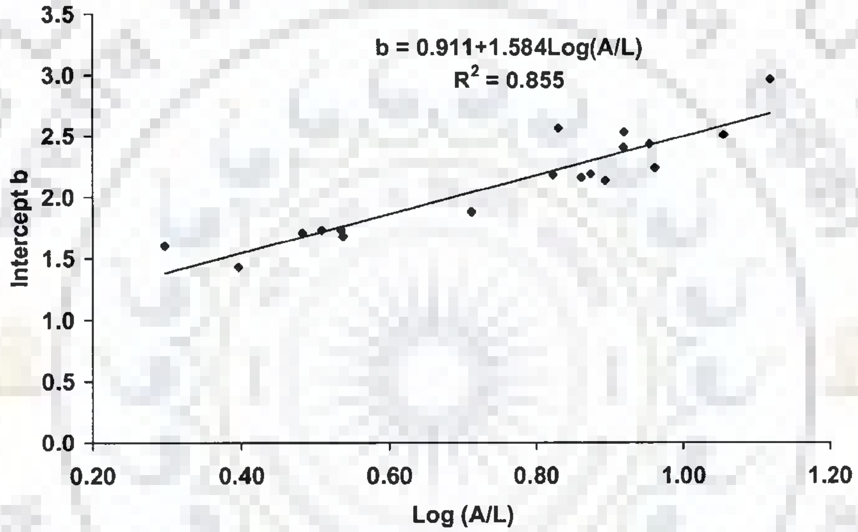


Figure 10.2: Relationship between the intercept b and the basin morphological index A/L

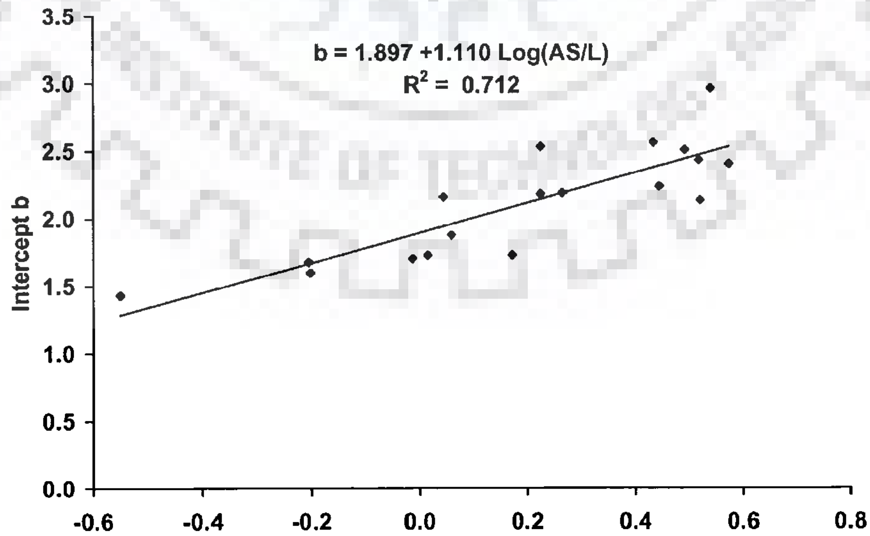


Figure 10.3: Relationship between the intercept b and the basin morphological index AS/L

10.6.3 Prediction of Peak Discharge

The peak discharge distribution in equation (10.1) constitutes a simple peak discharge prediction method, provided that the total input runoff volume is known. The method is applicable to both hydrologically linear and nonlinear watersheds, unlike unit hydrograph method, which is applicable for hydrologically linear watersheds.

In order to verify the reliability of equation (10.)1 to predict peak discharges accurately, a comparison has been made between observed flood peak outside those used for the calibration of the distributions and their estimates from equation (10.1).

In Umar sub watershed, a 4-hr rainfall with runoff volume 2.54 cm produced a peak discharge of 195.5 m^3/s (CWC, 1983). Its estimate from equation (10.1) by using the runoff volume 2.54 cm is 185 m^3/s, which is close (error 5.37%) to the actual discharge.

Example given below, illustrates the error which may be caused due to application of UH theory for estimation of flood in a nonlinear watershed (Umar watershed, m=0.647).

Probable maximum precipitation (PMP) in Umar watershed is 14.03 cm with rainfall duration equal to 5 hr. The average infiltration rate is 0.30 cm/hr, and base flow is 0.05 m^3/s per km^2 (CWC, 1983). Therefore, the total input runoff volume for the PMF is 12.53 cm, and PMF by using equation 10.1 is 530.44 m^3/s. By using 1-hr UH of the watershed and the above rainfall and runoff characteristics, PMF is 1413.42 m^3/s (CWC, 1983), which overestimates the design peak discharge by 62.47 %. It is concluded that hydrologic linearity of a watershed should be checked before using UH model. For prediction of peak discharge only equation (10.1) can be successfully used both in hydrologically linear as well as nonlinear watersheds.

10.6.4 Watershed Similarity

When equation (10.12) is developed and plotted for several watersheds having observed flood hydrographs, families of straight lines may be identified such that each family has more or less parallel lines but with different intercepts. It is reasoned that each family represents similar watersheds. This implies that parameters m can also be considered as a measure of watershed similarity, and that for a family of hydrologic similar watersheds, only one value of parameter m would suffice. This value of parameter m can be obtained for the watersheds having observed rainfall-runoff records and transferred to those members of the family not having such records. This concept can be gainfully employed to assume a peak discharge distribution for ungaged watershed belonging to a family of similar watersheds having known peak discharge distribution. As an example equation (10.12) is used to determine watershed similarity. Four watersheds (30 flood hydrographs) are considered in the present study. Umar watershed is part of study area and other watersheds are in the vicinity. The data for four watersheds are given in Table 10.4. Figure 10.4 shows relation in logarithm space between V and q_p/V^2 based on equation (10.12). Similar slope of the lines suggests hydrologic similarity between all the four watersheds.

Table 10.4: Direct Runoff Volume (V) and Peak of Direct Runoff per V^2 for four watersheds

Umar sub watershed		Temur sub watershed		Teriya sub watershed		Kolar sub watershed	
V (cm)	q_p/V^2 cm/hr/cm^2	V (cm)	q_p/V^2 cm/hr/cm^2	V (cm)	q_p/V^2 cm/hr/cm^2	V (cm)	q_p/V^2 cm/hr/cm^2
2.56	0.048	4.75	0.010	4.32	0.027	24.01	0.003
3.91	0.018	1.08	0.110	1.49	0.171	7.44	0.015
1.91	0.059	0.67	0.210	1.79	0.081	5.22	0.019
1.00	0.169	1.32	0.090	2.72	0.048	4.47	0.028
1.13	0.165	0.81	0.130	2.38	0.066	6.54	0.018
8.15	0.013	0.26	0.600	2.92	0.048	1.72	0.119
14.73	0.004	0.31	0.430	2.07	0.065		
				2.04	0.081		
				4.40	0.050		
				21.21	0.004		
				2.10	0.090		

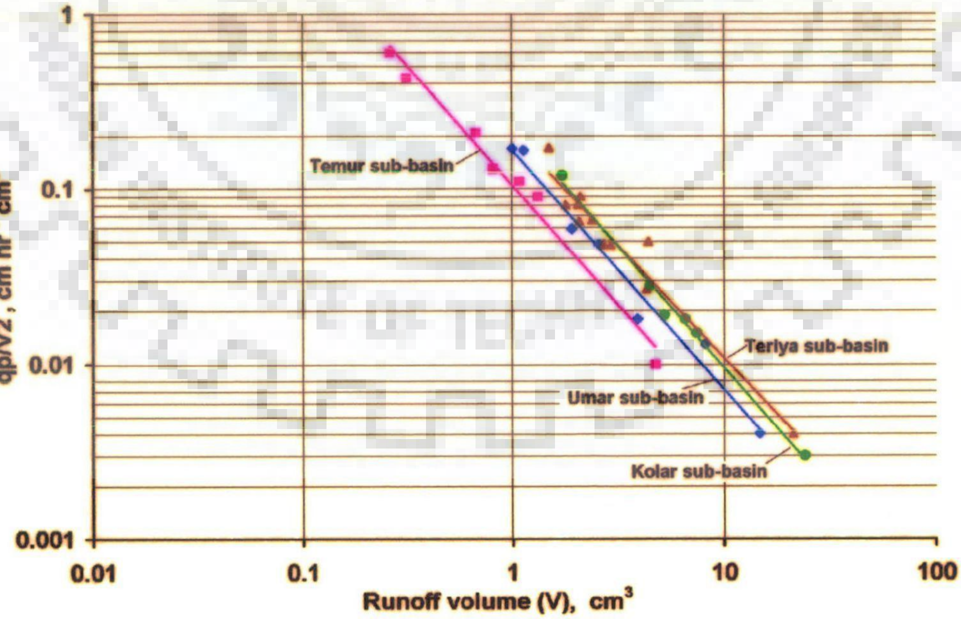


Figure 10.4: Identification of Watershed Similarity

10.6.5 Spatial distribution of Flood Generation Potential

Flood generation potential of different watersheds can be compared in terms of the peak discharges per unit area per unit excess rainfall. Peak discharge per unit excess rainfall in the 89 sub watersheds have been estimated using equation 10.16 and the geomorphological parameters A, S and L.

Figure 10.5 shows the spatial distribution of peak discharge per unit area in different watersheds caused by 1 cm excess rainfall in the entire area. A large part of watershed is found to have low flood potential in the range of 0.2 to 5 m^3 per second per sq km of the watershed.

In a more realistic study, flood potential should be assessed for unit rainfall and not for unit excess rainfall.

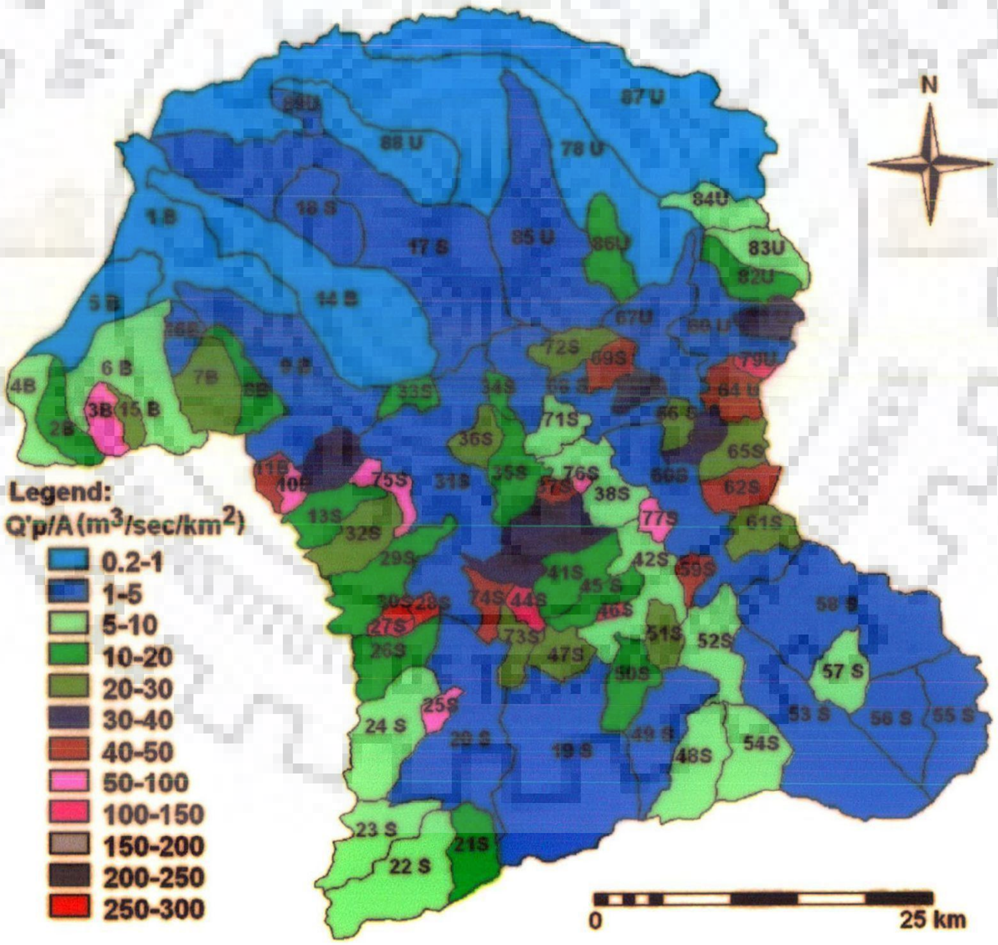


Figure 10.5: Spatial distribution of peak discharge per unit area in sub watersheds

10.7 CONCLUSIONS

Hydrologists think of hydrologic linearity as relating to the mutual proportionality of hydrograph peaks and runoff depths for storms of same duration. The idea that linearity is only meaningful within the concept of storm duration is the thing that is lost in relationship proposed by Rogers (1980). And yet, peak discharge volume relation has been used by several researchers in hydrological studies, particularly of ungaged watersheds.

Parameter b (peak discharge per unit runoff volume) depends on storm duration and morphological parameters (and hence watershed lag) as explained in Section 10.4. Basin area alone can not be used to explain variance of b if duration of storm is not same in various flood events. Present study shows better correlation between b and A, S and L.

Watershed similarity: Parameter m can be considered as a measure of watershed similarity. Analysis shows that hydrologic similarity exists between Umar, Kolar, Teriya and Temur sub watersheds.

Identification and quantification of nonlinearity of a watershed: Value of m near to 1 indicates linearity. Lesser the value of m, more nonlinear is the watershed. Analysis of 30 flood hydrographs of four watersheds in upper Narmada basin shows that these watersheds exhibit nonlinear hydrologic character. Case study shows that UH model is not applicable in Umar watershed which is nonlinear. Therefore, it is necessary to check the hydrologic linearity of a watershed with the slope m of the peak discharge distribution in equation (10.1) before using UH model.

For prediction of peak discharge only equation (10.1) is needed which can be successfully used both in hydrologically linear as well as nonlinear watersheds. Case study of Umar watershed shows that a 4-hr rainfall produced a peak discharge of 195.5 m^3/s (observed). Its estimate from equation (10.1) is 185 m^3/s, which is close (error 5.37%) to the actual discharge.

Flood generation potential of different watersheds can be compared in terms of the peak discharges per unit area per unit excess rainfall. Peak discharge per unit excess rainfall in the 89 sub watersheds have been estimated using equation (10.16) and the geomorphological parameters A, S and L. A large part of watershed is found to have low flood potential in the range of 0.2 to 5 m^3 per second per sq km of the watershed.

CHAPTER 11

SUMMARY AND CONCLUSIONS

Watershed development and management activities in India have focus on agriculture development through utilization of land and water resources in rural watersheds. Observations based on review of literature (section 1.1 in Chapter 1) provided motivation to undertake this applied research work.

The chosen area for study exhibits heterogeneity in characteristics providing scope for the intended research work. The study area covers three adjacent watersheds which conjoin together to form an important southern sub-basin of Narmada basin in its upper reaches in Madhya Pradesh State of India. Whereas Barureva and Umar watersheds have flat topography, Sher watershed is relatively hilly and has undulating topography.

Along the river courses, vertical bank cutting gullies are in active stage. The drainage pattern is dendritic with higher drainage density in Sher watershed. Annual rainfall is highly variable causing draught like situation in some years. The three watersheds are geologically and morphologically different with significant spatial variations. Most of the area is ungaged.

Integrated watershed planning and management of the study area requires data from several disciplines (morphology, geology, soil science, land use land cover, forestry, hydrology, agriculture etc). Scrutiny of the available data shows that planning exercises can be greatly improved using GIS and Remote Sensing.

Morphological Analysis of the Study Area

At watershed scale, morphological parameters of three watersheds reveal average hydrological and geological conditions. The study area is of seventh order. It is required to divide it into a number of sub watersheds for greater understanding of the influence of geological setting and for identification of appropriate watershed treatment measures. The fourth order watershed unit is found to be an appropriate option as it is mode of highest order found in the study area and group of fourth order watersheds also covers 58.61% of the study area.

Morphological analysis of sixty eight fourth order sub watersheds covers (i) assessment and comparison of morphological parameters (ii) analysis of inter-correlation among morphological parameters and (iii) fractal analysis and principal component analysis to study influence of various geological formations on drainage pattern evolution.

The spatially distributed data base has been used in subsequent studies for identification of erosion risk areas, surface storage sites, ground water recharge sites, bad land characterization, runoff potential and nonlinearity in hydrological behavior of small ungaged watersheds.

Control of Deccan trap formation on drainage evolution is not as strong as that of the alluvium formation. Sub watersheds with Deccan formation show varied type of drainage pattern. Low degree of randomness is associated with greater influence of geological setting. The sub watersheds having single geological formation such as Deccan trap with lineaments, Gondwana or alluvium (greater than 74%) have low degree of randomness. Sub watersheds having multiple hard rock geological formation show very low as well as high degree of randomness.

Geomorphological Permeability Index

A Geomorphological Permeability Index (GPI) has been proposed. The sub watersheds of the study area have been grouped according to various ranges of GPI. On the basis of these GPI ranges, suitable treatment measures have been identified in various sub watersheds.

Based on GPI, forty two sub watersheds are in very impermeable zone and show the property of quick runoff. These can be treated as runoff production zones along with erosion control measures. Twenty seven sub watersheds are in low permeability zone with possibility of ground water storage in joints, in fissures of underlying rocks and in alluviums near the outlets. Rain water harvesting is suitable in these sub watersheds. Possibility of ground water storage increases with the increase in GPI values in remaining twenty sub watersheds offering possibility of ground water recharge. GPI values lower than expected in some of the sub watersheds (1B, 14 B 17S, 18S, 78U, 87U, 88U and 89U) on alluvim formation are an indication of highly erosive conditions in these sub watersheds.

Morphological Index of Erodibility

Part of Sher, Barureva and Umar watersheds near the confluence with Narmada river and entire area of small tributaries like Dhamani and Saras rivers were affected by badland formation in the year 1972. Over the years, these badlands have been mostly reclaimed for agriculture use as discussed in Chapter 7. However the proposed index of erodibility can be used to identify and compare severity of erosion in different watersheds.

Dense network of tributaries of Narmada and their meeting with Narmada within closer vicinity has brought rich foundation of alluvium deposits. Deep layers of alluvium deposits existing in the study area keep alive aggressive head-cutting in gullies which could be the main cause of badland formation. Morphology of the selected watersheds from the badland tract indicates presence of uncontrolled growth of streams which is triggered by rain induced erosive forces. A morphological index of erodibility (MIE) for comparing severity of erosion in micro watersheds has been applied and verified by field observations. A watershed in the study area may be characterized as badland if its MIE is more than four times MIE of an agricultural watershed.

Analysis of Land Use and Land Cover Changes

The study makes use of satellite remote sensing and GIS technique in providing spatially distributed information on land use and land cover changes in the study area which otherwise is tedious and time consuming. Assessment of land use changes in small watersheds could have been further refined using high resolution imageries data and ground truth data for several years which is not available.

Watershed properties (land use, land cover, topography etc.) have often been considered to be static in hydrological studies. A procedure has been developed to identify and quantify dynamic changes in land use and land cover and relate these with runoff potential. This should lead to more realistic hydrologic models of small watersheds.

The transition matrix of changes among various land classes have been prepared to analyze the dynamic and directional changes in watersheds. Comparison of transition matrices for different time periods and different watersheds are useful in relating dynamic changes with various driving factors.

Appropriate methods for eco-environmental planning, and development of surface and ground water resources can be selected based on dynamic analysis of land use and land cover changes. Conversion of bad land into agriculture land is a major positive eco-environmental change in Barureva, Umar and Sher watersheds. Increase in barren land in Sher watershed during 1989 to 2000 has been significantly large. It is a major adverse eco-environmental change.

Changes in LULC have been related with Geomorphological Permeability Index (GPI). Analysis shows that increase in surface water bodies has occurred in those sub watersheds whose GPI values is less than 15.

There is no definite correlation between increase in settlement size and increase in water bodies suggesting water supply is not dependant on surface water. On the other hand increase in settlements and agricultural area has occurred in sub watersheds having GPI greater than 15 suggesting groundwater as main source of water supply to the settlements and agriculture development.

Barren land existed in sub watersheds having GPI less than 10 but has now been converted into agricultural land facilitated by creation of small water bodies. These sub watersheds have settlement area also. It is expected that without increase in water bodies these sub watersheds may undergo further deforestation to increase the rainfed agriculture area for meeting food demand of remotely located human settlements.

Driving Factors for Change in Land Use and Land Cover

The study area consists of rural watersheds. Driving factors for change in land use and land cover are related to basic human needs (food, fodder and fuel) and economic dependence of people on agriculture. Demand of food, fodder has to be met locally in absence of adequate infrastructure facilities and low purchasing power of population in the remotely located sub watersheds. The rate of deforestation has accelerated in recent period. It is related to increasing population pressure for expansion of agricultural area to meet their basic needs and to improve their economic status.

Detailed census data at watershed and sub watershed level are not available to relate change in land use with change in food, fodder demand over the years. However it is observed that 74.77% of the Gotegaon block area is within study area (mostly in Umar watershed). It is therefore reasonable to assume that changes in land use in Umar watershed could be related to changes in population, food, and fodder demand in the area of Gotegaon block within the Umar watershed. Analysis of Umar watershed illustrates the following.

Whereas population has increased by 79.42% during thirty years period of analysis, agriculture area increased by 42.97% only. Umar is an agricultural watershed with 67.02% percent area under alluvium. Pressure of food demand on available agriculture land has tremendously increased necessitating improvement in crop production through use of ground water for irrigation. Pressure of fodder demand on forest and barren land has increased by 107.36% over 30 years period.

Falling trends in ground water level are observed in alluvial sub watersheds .On the other hand rising trend is observed in wells located in upper part of study area over Deccan trap formation (19S, 53S, and 55S). Agriculture area in these sub watersheds has remained nearly static. Rise in water table could be partly attributed to creation of water bodies in these sub watersheds.

Runoff Potential under Varying Land Use and Land Cover

Surface runoff potential of a watershed is influenced by the spatial and temporal changes in land use and land cover. Quantification of changes in runoff potential is needed for sustainable development and management of water resource. Curve Number (CN) in the SCS method is indicative of runoff potential of a watershed. CN(PQ) refers to curve number estimated from observed rainfall runoff events. CN(LU) refers to curve number estimated from land use and soil cover information. The developed relationship of CN(LU) with historical year can be used for prediction of CN(LU) in future if the ongoing changes persist in the watersheds. CN(LU) values for each watershed have been predicted for time period up to 2100.

Median value of annual CN(PQ) computed from the observed data sets of rainfall and runoff events of each year (1977 to 2002)) is 74 and average value is about 75. Median value is taken as annual CN(PQ) as per well known criterion (Bonta., 1993 and Mishra et. al., 2005).

Annual CN(PQ) values show rising trend from the year 1985 onward. Rate of deforestation has accelerated in recent period. Further, farmers have taken up extensive cultivation of cash crops like soyabean for which fields are required to be kept well drained. A large number of field bunds (small height embankments) constructed earlier have therefore been destroyed. This has resulted in more runoff and lesser ground water recharge.

CN (LU) distribution maps also depict gradual increase in CN values from 1972 to 1989 and from1989 to 2000. The increase in CN values is more apparent in lower part of study area where badland (CN=89) and forest land (CN=61) has been significantly converted into the agriculture land (CN=93). Conversion of forest cover (58) into the barren land (89) in the middle part of gauged Sher watershed has caused increase in CN values in the successive time period. Among three watersheds, Umar watershed has higher CN (LU) value for AMC II condition indicating higher runoff potential under the same magnitude of received rainfall in comparison to other watersheds.

Three paired data sets of annual CN(LU) and annual CN(PQ) values for year 1977, 1989 and 2000 have been validated through their closeness with the line of perfect fit. The agreement between computed and observed event runoff has been judged on the basis of the NS efficiency and RMSE values. The NS efficiency for entire data set (for all events spread over 26 years) is about 75 % which is quite satisfactory. Model performance is again verified by plotting computed and observed runoff with the line of perfect fit. It is concluded that the SCS method with dynamic annual CN (LU) is capable to predict direct runoff satisfactorily in gauged Sher watershed. Therefore the dynamic CN (LU) estimated for ungauged Barureva and Umar watersheds can be used for runoff prediction being under same hydrometerological zone.

The study shows that slope adjusted CN is less than conventional CN over areas with slope less than 5% and more than SCS-CN for areas with slope more than 5%. Higher the deviation from 5% slope more is the difference. Significant difference in CN is observed in the forest lands which are usually located on slopes. Therefore CN should be modified to incorporate effect of change in land use and effect of slope particularly in small watersheds.

Hydrologic Nonlinearity of Watersheds

Hydrologic linearity is related to the mutual proportionality of hydrograph peaks and runoff depths for storms of same duration. The peak discharge volume relationship ($\log Q_p = b + m\log V$) proposed by Rogers (1980) without consideration of storm duration is empirical in nature. In spite of its criticism, the relation between peak discharge-runoff volume has been subject of research around the world due to its simplicity and potential application.

Peak discharge of unit hydrograph depends on storm duration and morphological parameters (and hence watershed lag). Analysis of 1 hour unit hydrographs (V=1 cm) of 18 watersheds in Narmada basin shows strong correlation between peak discharge and catchment area (in log space) as the duration of rainfall excess is same (1 hour). However, in general, basin area alone can not be used to explain variance of b ($b=\log Q_p$ for unit hydrographs) if duration of storm is not same.

Slope of PDVR in log-log space (m) can be used as a measure of watershed similarity, and that for a family of hydrologic similar watersheds, only one value of parameter m would suffice. This concept can be gainfully employed to assume a peak discharge distribution for ungaged watershed belonging to a family of similar watersheds having known peak discharge distribution. Analysis of 30 flood hydrographs of four watersheds (Umar, Kolar, Teriya and Temur) in upper Narmada basin shows that these watersheds exhibit nonlinear hydrologic character. Regression analysis shows strong correlation between peak discharge and runoff volume (0.872 to 0.983) for these four watersheds. Analysis of relation in logarithm space between V and q_p/V^2 suggests hydrologic similarity between all the four watersheds.

Error in hydrologic design can occur by over estimating or underestimating flood discharge when a watershed is assumed to be linear while in fact it may be nonlinear in terms of catchment's response to rainfall. As an example, UH model is not applicable in nonlinear Umar watershed. Estimate of peak discharge using PDVR is 530.44 m^3/s. Using unit hydrograph model, Central Water Commission estimated it to be 1413.42 m^3/s (CWC, 1983), which overestimates the peak discharge by 62.47 %.

Accuracy of PDVR to predict peak discharge in non linear watershed (Umar watershed) has been verified by comparison between an observed flood peak (195.5 m^3/s) and its estimate using PDVR (185 m^3/s). Error in estimate is only 5.37%. Therefore PDVR can be reliably used both in hydrologically linear as well as nonlinear watersheds for prediction of peak discharge. Therefore the popular usage of UH theory necessitates validation of linearity concept in the rainfall-runoff process.

Peak discharge per unit excess rainfall in the 89 sub watersheds have been estimated using relation between b and the geomorphological parameters such as A, S and L. A large part of watershed is found to have flood potential in the range of 0.2 to 5 $m^3/s/km^2$ of the watershed. In a more realistic study, flood potential of different sub watersheds should be compared for unit rainfall and not for unit excess rainfall. However the value of m (degree of non linearity) is required for these ungaged sub watersheds.

CLOSURE:

The present study is in the area of applied research work dealing with small ungaged watersheds. It is extensive in nature covering various aspects which should necessarily be considered to ensure sustainability in watershed development and management. GIS based procedures have been developed to derive meaningful information and use the same to improve watershed planning.

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APPENDIX A: MORPHOLOGICAL ANALYSIS

Table A 1. Morphological parameters of sub watersheds in the study area

Basin Id	Highest stream order	A km^2	L_p km	L_b km	R_f	Re	Rc	∑Nu	$\sum L_u$ km	L_{MS} km	Rb	Rt	D_d km/km^2	L_g km	D_f $No./km^2$	C_m km^2/km	T No./km	H m	R_h m/km	RN	R_r m/km
1 B	6th	68.95	60.29	18.57	0.20	0.50	0.49	142	127.40	27.54	4.93	4.03	1.85	0.27	2.06	0.54	2.36	26	1.42	0.05	0.44
2 B	4th	16.96	21.33	8.71	0.22	0.53	0.68	41	38.69	12.19	3.31	2.66	2.28	0.22	2.42	0.44	1.92	260	29.85	0.59	12.19
3 B	4th	11.90	15.48	5.59	0.38	0.70	0.79	43	37.14	6.96	3.33	1.99	3.12	0.16	3.61	0.32	2.78	250	44.65	0.78	16.12
4 B	4th	19.16	26.07	8.40	0.27	0.59	0.60	43	41.05	12.90	3.31	2.53	2.14	0.23	2.24	0.47	1.65	240	28.57	0.51	9.21
5 B	5th	34.45	31.30	12.58	0.22	0.53	0.66	55	51.10	17.68	5.10	8.77	1.48	0.34	1.60	0.67	1.76	25	2.01	0.04	0.81
6 B	5th	57.19	45.50	11.96	0.40	0.71	0.59	115	124.72	17.93	5.61	4.05	2.18	0.23	2.01	0.46	2.53	241	20.17	0.53	5.30
7 B	4th	26.86	21.07	7.99	0.42	0.73	0.87	66	66.75	10.96	4.17	2.14	2.49	0.20	2.46	0.40	3.13	240	30.04	0.60	11.39
8 B	4th	15.81	24.14	8.75	0.21	0.51	0.58	38	39.42	12.99	3.50	2.61	2.49	0.20	2.40	0.40	1.57	222	25.39	0.55	9.20
9 B	5th	81.33	55.45	18.24	0.24	0.56	0.58	201	188.26	37.00	5.47	13.92	2.31	0.22	2.47	0.43	3.62	194	10.63	0.45	3.50
10 B	4th	5.79	10.83	4.08	0.35	0.67	0.79	25	16.53	4.78	2.83	1.66	2.86	0.17	4.32	0.35	2.31	144	35.29	0.41	13.30
11 B	4th	6.53	12.30	4.06	0.40	0.71	0.74	24	17.59	5.59	2.75	1.48	2.69	0.19	3.67	0.37	1.95	142	35.05	0.38	11.57
12 B	4th	15.31	16.55	5.40	0.53	0.82	0.84	70	45.03	8.17	3.89	2.03	2.94	0.17	4.57	0.34	4.23	210	38.89	0.62	12.69
13 S	4th	18.85	21.56	8.11	0.29	0.60	0.71	92	62.14	10.46	4.28	2.55	3.30	0.15	4.88	0.30	3.34	225	27.74	0.74	10.43
14 B	4th	110.06	61.31	25.49	0.17	0.46	0.61	171	168.80	40.99	5.16	5.75	1.53	0.33	1.55	0.65	2.79	140	5.49	0.21	2.28
15 B	4th	6.19	13.15	5.41	0.21	0.52	0.67	31	22.77	6.60	2.89	1.72	3.68	0.14	5.01	0.27	2.36	150	27.65	0.55	11.37
16 B	4th	11.36	18.03	6.36	0.28	0.59	0.66	61	43.67	7.73	4.05	2.16	3.84	0.13	5.37	0.26	2.44	250	39.30	0.96	13.87
17 S	7th	157.72	72.82	29.35	0.18	0.48	0.61	448	305.03	8.20	6.17	3.59	1.93	0.26	2.84	0.52	3.15	60	2.04	0.12	0.82
18 S	4th	30.79	23.08	8.32	0.44	0.75	0.85	66	59.41	12.08	7.69	8.12	1.93	0.26	2.14	0.52	2.42	24	2.88	0.05	1.04
19 S	4th	120.02	52.62	17.30	0.40	0.71	0.74	193	226.62	28.62	5.69	3.37	1.89	0.26	1.61	0.53	2.62	220	12.71	0.42	4.18
20 S	5th	80.73	56.33	17.72	0.26	0.57	0.57	307	219.99	30.50	6.79	9.22	2.73	0.18	3.80	0.37	4.30	262	14.78	0.71	4.65
21 S	4th	20.53	20.59	6.93	0.43	0.73	0.78	77	56.49	9.39	3.96	2.55	2.75	0.18	3.75	0.36	2.77	163	23.52	0.45	7.92
22 S	4th	49.23	34.86	12.94	0.29	0.61	0.71	132	122.56	21.46	4.91	3.11	2.49	0.20	2.68	0.40	2.78	270	20.86	0.67	7.75
23 S	4th	29.06	30.59	11.46	0.22	0.53	0.62	121	87.20	17.08	4.68	3.07	3.00	0.17	4.16	0.33	3.07	240	20.94	0.72	7.85
24 S	4th	41.08	29.55	10.99	0.34	0.65	0.77	180	132.61	20.37	7.62	3.79	3.22	0.17	4.38	0.31	4.87	274	24.93	0.79	9.27
25 S	4th	5.71	10.75	4.26	0.31	0.63	0.79	37	18.25	4.67	3.71	1.87	3.21	0.17	5.60	0.32	2.05	166	38.96	0.95	15.44

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26 S	4th	22.46	22.44	8.61	0.30	0.62	0.75	111	77.09	11.13	4.72	4.83	3.43	0.15	4.94	0.29	3.39	213	24.73	0.73	9.49
27 S	4th	3.60	9.31	3.65	0.27	0.58	0.72	27	13.75	3.95	3.00	1.24	3.82	0.13	7.50	0.26	2.15	233	63.83	0.89	25.03
28 S	5th	3.75	8.04	2.43	0.64	0.90	0.85	17	13.13	2.42	2.67	1.71	3.50	0.14	4.53	0.29	1.49	183	75.30	0.64	22.75
29 S	4th	32.68	34.15	12.58	0.21	0.51	0.59	137	102.82	16.55	5.00	4.55	3.15	0.16	4.19	0.32	2.75	303	24.08	0.95	8.87
30 S	4th	3.13	7.54	2.42	0.53	0.82	0.83	20	12.70	2.76	2.28	1.53	4.06	0.12	6.39	0.25	1.46	240	99.17	0.97	31.82
31 S	6th	103.96	79.47	20.96	0.24	0.55	0.45	389	285.78	36.38	8.70	8.98	2.75	0.18	3.74	0.36	3.71	239	11.40	0.66	3.01
32 S	4th	23.51	22.70	8.16	0.35	0.67	0.76	82	69.56	10.19	3.96	3.79	2.96	0.17	3.49	0.34	2.60	237	29.04	0.70	10.44
33 S	4th	8.38	13.93	4.51	0.41	0.72	0.74	30	26.50	6.54	2.83	1.53	3.16	0.16	3.58	0.32	1.51	80	17.73	0.25	5.74
34 S	5th	4.82	10.37	4.21	0.27	0.59	0.75	16	12.95	3.08	4.25	2.61	2.69	0.19	3.32	0.37	1.25	31	7.36	0.08	2.99
35 S	4th	22.25	25.59	9.23	0.26	0.57	0.65	100	82.38	13.30	4.23	3.88	3.70	0.14	4.49	0.27	2.85	214	23.18	0.79	8.36
36 S	4th	11.35	14.63	4.88	0.48	0.77	0.82	35	29.57	6.16	3.02	1.96	2.61	0.19	3.08	0.38	1.57	121	24.79	0.32	8.27
37 S	4th	4.58	9.23	3.16	0.46	0.76	0.82	26	18.58	3.82	2.60	2.65	4.05	0.12	5.67	0.25	1.73	80	25.31	0.32	8.67
38 S	6th	26.87	30.51	7.10	0.53	0.82	0.60	147	96.02	10.68	4.94	3.41	3.57	0.14	5.47	0.28	3.90	93	13.09	0.33	3.05
39 S	5th	11.40	14.88	6.01	0.32	0.63	0.80	22	21.44	6.53	4.10	2.98	1.88	0.27	1.93	0.53	1.48	26	4.38	0.05	1.77
40 S	4th	16.06	19.57	6.81	0.35	0.66	0.73	102	68.35	9.29	4.29	2.59	4.26	0.12	6.35	0.23	3.99	273	40.08	1.16	13.95
41 S	4th	22.53	23.21	8.65	0.30	0.61	0.73	146	85.64	10.91	4.89	2.83	3.80	0.13	6.48	0.26	4.74	245	28.32	0.93	10.56
42 S	5th	33.60	45.45	10.40	0.31	0.63	0.45	201	113.08	21.38	5.73	10.90	3.37	0.15	5.98	0.30	3.19	200	19.23	0.67	4.40
43 S	4th	6.52	15.52	6.60	0.15	0.43	0.58	51	28.32	7.60	3.67	2.68	4.35	0.12	7.83	0.23	2.32	235	35.60	1.02	15.14
44 S	4th	6.17	10.96	3.60	0.48	0.77	0.80	40	23.56	4.00	3.26	1.41	3.82	0.13	6.49	0.26	2.74	195	54.16	0.75	17.79
45 S	4th	13.73	20.66	7.94	0.22	0.52	0.64	76	53.78	10.92	4.69	2.57	3.92	0.13	5.54	0.26	2.66	215	27.07	0.84	10.40
46 S	4th	2.00	6.09	2.30	0.38	0.69	0.82	20	7.97	2.75	2.42	1.09	3.98	0.13	10.00	0.25	2.13	130	56.52	0.52	21.33
47 S	4th	13.37	15.65	5.20	0.49	0.79	0.83	73	44.73	7.04	3.76	1.99	3.34	0.15	5.46	0.30	3.39	140	26.92	0.47	8.94
48 S	4th	31.41	27.75	10.72	0.27	0.58	0.72	117	86.12	12.47	4.48	2.55	2.74	0.18	3.73	0.36	3.10	112	10.44	0.31	4.04
49 S	4th	36.17	31.45	11.97	0.25	0.56	0.68	81	75.87	15.84	4.04	3.60	2.10	0.24	2.24	0.48	1.78	120	10.02	0.25	3.82
50 S	4th	19.17	18.73	6.72	0.42	0.73	0.83	61	46.92	8.04	3.94	2.25	2.45	0.20	3.18	0.41	2.46	76	11.30	0.19	4.06
51 S	4th	11.30	14.52	5.40	0.39	0.70	0.82	50	35.59	8.05	3.37	2.67	3.15	0.16	4.42	0.32	2.55	150	27.77	0.47	10.33
52 S	5th	28.01	28.24	8.56	0.38	0.70	0.66	126	87.15	16.25	4.95	8.15	3.11	0.16	4.50	0.32	3.72	130	15.18	0.40	4.60
53 S	4th	85.19	48.36	18.72	0.24	0.55	0.68	154	148.55	27.31	5.00	4.01	1.74	0.29	1.81	0.57	2.42	100	5.34	0.17	2.07
54 S	4th	28.71	23.50	7.87	0.46	0.76	0.81	54	54.71	9.83	3.97	1.78	1.91	0.26	1.88	0.52	1.53	66	8.38	0.13	2.81

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55 S	4th	39.71	32.33	10.31	0.37	0.68	0.69	113	87.94	13.51	4.42	2.82	2.21	0.23	2.85	0.45	2.57	45	4.36	0.10	1.39
56 S	4th	32.29	24.97	9.12	0.39	0.70	0.81	77	65.90	10.17	3.85	2.65	2.04	0.24	2.38	0.49	2.04	31	3.39	0.06	1.24
57 S	4th	19.16	21.42	8.52	0.26	0.58	0.72	45	36.51	9.77	2.36	2.83	1.91	0.26	2.35	0.52	1.49	91	10.68	0.17	4.25
58 S	5th	94.53	50.66	16.26	0.36	0.67	0.68	397	261.23	23.13	7.83	5.81	2.76	0.18	4.20	0.36	6.24	130	7.99	0.36	2.57
59 S	4th	6.27	11.52	3.59	0.49	0.78	0.77	36	22.39	5.64	3.06	2.07	3.57	0.14	5.74	0.28	2.08	130	36.21	0.46	11.29
60 S	5th	60.86	60.56	17.00	0.21	0.52	0.46	235	169.16	30.79	4.81	7.15	2.78	0.18	3.66	0.36	3.09	190	11.17	0.53	3.14
61 S	4th	15.40	17.21	5.27	0.55	0.84	0.81	61	46.79	8.15	4.12	1.85	3.04	0.16	3.96	0.33	2.50	140	26.56	0.43	8.14
62 S	4th	14.79	18.84	5.16	0.56	0.84	0.72	101	52.08	6.27	3.50	2.09	3.52	0.14	6.83	0.28	4.09	186	36.05	0.65	9.87
63 S	4th	9.56	15.60	5.24	0.35	0.66	0.70	54	33.55	7.10	3.39	2.32	3.51	0.14	5.65	0.28	2.37	190	36.25	0.67	12.18
64 U	4th	14.75	16.56	4.95	0.60	0.87	0.82	60	44.30	6.60	3.56	1.53	3.00	0.17	4.07	0.33	2.66	172	34.74	0.52	10.39
65 S	4th	15.07	17.79	6.62	0.34	0.66	0.77	58	43.89	7.63	3.83	1.81	2.91	0.17	3.85	0.34	2.47	180	27.19	0.52	10.12
66 S	4th	8.03	11.58	4.18	0.46	0.76	0.87	38	27.66	4.93	3.13	1.55	3.45	0.15	4.73	0.29	2.25	85	20.33	0.29	7.34
67 U	4th	42.16	42.79	13.88	0.22	0.53	0.54	147	107.92	22.06	2.81	5.76	2.56	0.20	3.49	0.39	2.57	180	12.97	0.46	4.21
68 S	6th	44.74	56.31	14.27	0.22	0.53	0.42	155	119.38	15.61	4.98	3.78	2.67	0.19	3.46	0.37	2.13	130	9.11	0.35	2.31
69 S	4th	9.79	14.16	5.14	0.37	0.68	0.78	45	35.73	6.01	3.14	2.14	3.65	0.14	4.60	0.27	2.05	190	36.96	0.69	13.41
70 S	4th	8.18	12.50	3.91	0.54	0.82	0.81	40	27.59	4.78	3.21	1.74	3.37	0.15	4.89	0.30	2.32	86	21.99	0.29	6.88
71 S	4th	13.74	17.07	5.04	0.54	0.82	0.77	51	40.24	6.41	3.41	1.75	2.93	0.17	3.71	0.34	2.23	43	8.53	0.13	2.52
72 S	4th	13.78	18.02	6.88	0.29	0.60	0.73	46	40.94	7.74	3.47	2.34	2.97	0.17	3.34	0.34	1.78	152	22.09	0.45	8.43
73 S	4th	11.62	18.96	6.47	0.28	0.59	0.64	60	39.37	8.28	3.53	4.25	3.39	0.15	5.16	0.30	2.27	204	31.53	0.69	10.76
74 S	5th	9.49	16.97	5.87	0.28	0.59	0.64	38	27.95	5.37	3.17	2.47	2.95	0.17	4.01	0.34	1.65	188	32.02	0.55	11.08
75 S	5th	10.87	20.40	4.95	0.44	0.75	0.57	42	31.17	2.60	3.50	1.90	2.87	0.17	3.86	0.35	1.62	129	26.06	0.37	6.32
76 S	5th	1.77	5.07	1.62	0.68	0.93	0.93	8	6.08	1.99	3.50	3.54	3.43	0.15	4.51	0.29	1.18	28	16.97	0.09	5.42
77 S	4th	6.02	10.45	3.02	0.66	0.91	0.83	35	15.42	3.20	3.11	1.68	2.56	0.20	5.82	0.39	2.49	70	23.17	0.18	6.70
78 U	6th	218.83	144.56	41.84	0.13	0.40	0.36	507	368.95	63.78	6.38	2.02	1.69	0.30	2.32	0.59	2.73	93	2.22	0.16	0.64
79 U	4th	3.84	8.81	3.37	0.34	0.66	0.79	22	12.10	3.52	2.15	1.79	3.15	0.16	5.72	0.32	1.70	192	56.97	0.60	21.79
80 U	5th	34.37	44.00	12.05	0.24	0.55	0.47	75	83.11	16.82	3.41	2.34	2.42	0.21	2.18	0.41	1.30	110	9.13	0.27	2.50
81 U	4th	10.95	13.87	5.11	0.42	0.73	0.85	41	28.75	6.49	2.31	2.22	2.63	0.19	3.75	0.38	2.02	170	33.27	0.45	12.26
82 U	4th	16.41	21.01	8.21	0.24	0.56	0.68	25	31.58	10.73	2.06	2.28	1.92	0.26	1.52	0.52	0.76	218	26.55	0.42	10.38
83 U	4th	17.25	21.16	8.65	0.23	0.54	0.70	30	39.96	10.99	2.31	2.60	2.32	0.22	1.74	0.43	0.99	80	9.25	0.19	3.78

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84 U	4th	16.85	20.23	8.05	0.26	0.58	0.72	32	34.04	10.02	2.53	1.93	2.02	0.25	1.90	0.49	1.09	87	10.81	0.18	4.30
85 U	4th	92.25	51.41	20.38	0.22	0.53	0.66	72	86.33	31.82	4.18	4.30	0.94	0.53	0.78	1.07	1.15	130	6.38	0.12	2.53
86 U	4th	19.25	21.00	7.61	0.33	0.65	0.74	66	51.80	10.91	3.65	2.22	2.69	0.19	3.43	0.37	2.29	150	19.71	0.40	7.14
87 U	4th	159.06	81.08	30.18	0.17	0.47	0.55	279	234.39	44.93	3.85	4.59	1.47	0.34	1.75	0.68	2.75	118	3.91	0.17	1.46
88 U	4th	45.33	38.62	15.79	0.18	0.48	0.62	82	65.40	22.23	4.22	2.53	1.44	0.35	1.81	0.69	1.76	23	1.44	0.03	0.59
89 U	4th	7.48	12.77	5.31	0.27	0.58	0.76	31	19.09	6.05	3.69	3.11	2.55	0.20	4.15	0.39	1.72	8	1.47	0.02	0.61

Table A 2. Regression matrix for inter-relationship of morphological parameters of fourth order watersheds

	A	L_p	L_b	R_f	R_e	R_c	$\sum N_u$	$\sum L_u$	L_{MS}	R_b	R_t	D_d	L_g	D_f	C_m	T	H	R_h	R_N	R_r
A	1.00																			
L_p	**0.96**	1.00																		
L_b	**0.95**	**0.99**	1.00																	
R_f	-0.35	-0.49	-0.56	1.00																
R_e	-0.37	-0.51	-0.58	**1.00**	1.00															
R_c	-0.43	-0.60	-0.61	**0.80**	**0.83**	1.00														
$\sum N_u$	**0.82**	**0.85**	**0.81**	-0.31	-0.32	-0.44	1.00													
$\sum L_u$	**0.92**	**0.92**	**0.89**	-0.34	-0.35	-0.43	**0.95**	1.00												
L_{MS}	**0.95**	**0.98**	**0.99**	-0.52	-0.54	-0.59	**0.82**	**0.90**	1.00											
R_b	0.50	0.52	0.51	-0.20	-0.20	-0.21	**0.72**	0.69	0.54	1.00										
R_t	0.65	**0.75**	**0.76**	-0.55	-0.56	-0.61	**0.71**	**0.71**	**0.76**	0.49	1.00									
D_d	-0.63	-0.65	-0.66	0.25	0.25	0.23	-0.29	-0.45	-0.63	-0.11	-0.35	1.00								
L_g	**0.71**	**0.71**	**0.74**	-0.33	-0.34	-0.31	0.31	0.47	**0.72**	0.15	0.41	**-0.90**	1.00							
D_f	-0.55	-0.60	-0.60	0.29	0.27	0.25	-0.27	-0.45	-0.59	-0.17	-0.38	**0.89**	**-0.76**	1.00						
C_m	**0.71**	**0.71**	**0.73**	-0.33	-0.33	-0.30	0.30	0.46	**0.71**	0.14	0.41	**-0.90**	**1.00**	**-0.76**	1.00					
T	0.11	0.12	0.08	0.15	0.15	0.07	0.55	0.36	0.11	0.64	0.19	0.36	-0.34	0.35	-0.35	1.00				
H	-0.05	0.00	-0.01	-0.21	-0.20	-0.23	0.19	0.14	0.03	0.28	0.16	0.40	-0.34	0.26	-0.34	0.42	1.00			
R_h	**-0.50**	-0.57	-0.57	0.29	0.30	0.30	-0.40	-0.47	-0.53	-0.34	-0.46	0.67	-0.58	0.69	-0.58	0.09	0.55	1.00		
R_N	-0.31	-0.27	-0.27	-0.10	-0.09	-0.10	0.02	-0.10	-0.25	0.17	-0.03	**0.72**	-0.61	0.60	-0.62	0.46	**0.88**	**0.70**	1.00	
R_r	-0.50	-0.56	-0.55	0.18	0.19	0.26	-0.41	-0.47	-0.52	-0.33	-0.44	0.67	-0.58	0.69	-0.58	0.07	0.58	**0.98**	**0.73**	1.00

Table A 3: Morphological parameters and GPI (Geomorphological permeability factor) of the sub watersheds of study area

Basin Id	Basin order	Fault or Lineaments	% Distribution of basin area on existed geological formation					A km^2	L_b km	$\sum Nu$ no.	$\sum L_u$ km	Rt	D_d km/km^2	D_f $no./km^2$	H m	R_h m/km	GPI
			Alluvium	Gondwana	Deccan Trap	Quartzite	Archeans, Granite Gneiss Schist										
1 B	6th		100.00	0.00	0.00	0.00	0.00	68.95	18.57	142	127.40	2.20	1.85	2.06	26.40	1.42	40.66
2 B	4th		16.35	16.05		24.26	43.34	16.96	8.71	41	38.69	2.66	2.28	2.42	260.00	29.85	1.61
3 B	4th		0.00	21.55		31.03	47.42	11.90	5.59	43	37.14	1.99	3.12	3.61	249.60	44.65	0.40
4 B	4th		27.91	4.18		32.51	35.41	19.16	8.40	43	41.05	2.53	2.14	2.24	240.00	28.57	1.84
5 B	5th		100.00					34.45	12.58	55	51.10	1.11	1.48	1.60	25.30	2.01	23.31
6 B	5th		48.38	18.80	0.35	23.54	8.93	57.19	11.96	115	124.72	5.54	2.18	2.01	241.20	20.17	6.26
7 B	4th		22.52	34.04	0.56	25.51	17.36	26.86	7.99	66	66.75	2.14	2.49	2.46	240.00	30.04	1.17
8 B	4th		17.93	41.88	18.12	7.84	14.23	15.81	8.75	38	39.42	2.61	2.49	2.40	222.20	25.39	1.72
9 B	5th		37.53	34.94	22.02	2.95	2.57	81.33	18.24	201	188.26	2.93	2.31	2.47	193.90	10.63	4.82
10 B	4th				100.00			5.79	4.08	25	16.53	1.66	2.86	4.32	144.00	35.29	0.38
11 B	4th				100.00			6.53	4.06	24	17.59	1.48	2.69	3.67	142.30	35.05	0.43
12 B	4th			1.55	98.45			15.31	5.40	70	45.03	2.03	2.94	4.57	210.00	38.89	0.39
13 S	4th	Present			100.00			18.85	8.11	92	62.14	2.55	3.30	4.88	225.00	27.74	0.57
14 B	4th		74.00	26.00				110.06	25.49	171	168.80	5.75	1.53	1.55	140.00	5.49	43.90
15 B	4th			29.65		18.27	52.08	6.19	5.41	31	22.77	1.72	3.68	5.01	149.60	27.65	0.34
16 B	5th		87.95			12.05		11.40	6.01	22	21.44	2.40	1.88	1.93	26.30	4.38	15.11
17 S	7th		91.46	8.54				157.72	29.35	448	305.03	2.44	1.93	2.84	60.00	2.04	21.73
18 S	4th		100.00					30.79	8.32	66	59.41	8.12	1.93	2.14	24.00	2.88	68.06
19 S	4th	Present			100.00			120.02	17.30	193	226.62	3.37	1.89	1.61	220.00	12.72	8.71
20 S	5th	Present			100.00			80.73	17.72	307	219.99	1.49	2.73	3.80	262.00	14.79	0.97
21 S	4th	Present			100.00			20.53	6.93	77	56.49	2.55	2.75	3.75	163.00	23.52	1.05
22 S	4th	Present			100.00			49.23	12.94	132	122.56	3.11	2.49	2.68	270.00	20.87	2.23
23 S	4th	Present			100.00			29.06	11.46	121	87.20	3.07	3.00	4.16	240.00	20.94	1.17
24 S	4th	Present			100.00			41.08	10.99	180	132.61	3.79	3.22	4.38	274.00	24.93	1.08
25 S	4th				100.00			5.71	4.26	37	18.25	1.87	3.21	5.60	166.00	38.97	0.27
26 S	4th				100.00			22.46	8.61	111	77.09	4.83	3.43	4.94	213.00	24.74	1.15
27 S	4th				100.00			3.60	3.65	27	13.75	1.24	3.82	7.50	233.00	63.84	0.07
28 S	5th				100.00			3.75	2.43	17	13.13	1.19	3.50	4.53	183.00	75.31	0.10

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29 S	4th	Present			100.00			32.68	12.58	137	102.82	4.55	3.15	4.19	303.00	24.09	1.43
30 S	4th				100.00			3.13	2.42	20	12.70	1.53	4.06	6.39	240.00	99.17	0.06
31 S	6th	Present		39.45	60.55			103.96	20.96	389	285.78	1.70	2.75	3.74	239.00	11.40	1.45
32 S	4th	Present			100.00			23.51	8.16	82	69.56	3.79	2.96	3.49	237.00	29.04	1.26
33 S	4th			100.00				8.38	4.51	30	26.50	1.53	3.16	3.58	80.00	17.74	0.76
34 S	5th			74.48	25.52			4.82	4.21	16	12.95	1.97	2.69	3.32	31.00	7.36	3.00
35 S	4th			0.50	99.50			22.25	9.23	100	82.38	3.88	3.70	4.49	214.00	23.19	1.01
36 S	4th			38.16	61.84			11.35	4.88	35	29.57	1.96	2.61	3.08	121.00	24.80	0.98
37 S	4th				100.00			4.58	3.16	26	18.58	2.65	4.05	5.67	80.00	25.32	0.46
38 S	6th			0.11	99.89			26.87	7.10	147	96.02	1.87	3.57	5.47	93.00	13.10	0.73
39 S	4th				100.00			11.36	6.36	61	43.67	2.16	3.84	5.37	250.00	39.31	0.27
40 S	4th				100.00			16.06	6.81	102	68.35	2.59	4.26	6.35	273.00	40.09	0.24
41 S	4th				100.00			22.53	8.65	146	85.64	2.83	3.80	6.48	245.00	28.32	0.41
42 S	5th				100.00			33.60	10.40	201	113.08	1.32	3.37	5.98	200.00	19.23	0.34
43 S	4th				100.00			6.52	6.60	51	28.32	2.68	4.35	7.83	235.00	35.61	0.22
44 S	4th				100.00			6.17	3.60	40	23.56	1.41	3.82	6.49	195.00	54.17	0.10
45 S	4th				100.00			13.73	7.94	76	53.78	2.57	3.92	5.54	215.00	27.08	0.44
46 S	4th				100.00			2.00	2.30	20	7.97	1.09	3.98	10.00	130.00	56.52	0.05
47 S	4th				100.00			13.37	5.20	73	44.73	1.99	3.34	5.46	140.00	26.92	0.41
48 S	4th	Present			100.00			31.41	10.72	117	86.12	2.55	2.74	3.73	112.00	10.45	2.39
49 S	4th	Present			100.00			36.17	11.97	81	75.87	3.60	2.10	2.24	120.00	10.03	7.63
50 S	4th				100.00			19.25	7.61	66	51.80	2.22	2.69	3.43	150.00	19.71	1.22
51 S	4th				100.00			11.30	5.40	50	35.59	2.67	3.15	4.42	150.00	27.78	0.69
52 S	5th				100.00			28.01	8.56	126	87.15	1.15	3.11	4.50	130.00	15.19	0.54
53 S	4th	Present			100.00			85.19	18.72	154	148.55	4.01	1.74	1.81	100.00	5.34	23.84
54 S	4th	Present			100.00			28.71	7.87	54	54.71	1.78	1.91	1.88	66.00	8.39	5.91
55 S	4th	Present			100.00			39.71	10.31	113	87.94	2.82	2.21	2.85	45.00	4.36	10.26
56 S	4th	Present			100.00			32.29	9.12	77	65.90	2.65	2.04	2.38	31.00	3.40	16.06
57 S	4th				100.00			19.17	6.72	61	46.92	2.25	2.45	3.18	76.00	11.31	2.55
58 S	5th	Present			100.00			94.53	16.26	397	261.23	1.96	2.76	4.20	130.00	8.00	2.11
59 S	4th				100.00			6.27	3.59	36	22.39	2.07	3.57	5.74	130.00	36.21	0.28
60 S	5th				100.00			60.86	17.00	235	169.16	1.78	2.78	3.66	190.00	11.18	1.57
61 S	4th				100.00			15.40	5.27	61	46.79	1.85	3.04	3.96	140.00	26.57	0.58
62 S	4th				100.00			14.75	4.95	60	44.30	1.53	3.00	4.07	172.00	34.75	0.36
63 S	4th				100.00			9.56	5.24	54	33.55	2.32	3.51	5.65	190.00	36.26	0.32

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64 U	4th				100.00			14.79	5.16	101	52.08	2.09	3.52	6.83	186.00	36.05	0.24
65 S	4th				100.00			15.07	6.62	58	43.89	1.81	2.91	3.85	180.00	27.19	0.59
66 S	4th				100.00			8.03	4.18	38	27.66	1.55	3.45	4.73	85.00	20.33	0.47
67 U	4th	Present		53.55	42.64	3.81		42.16	13.88	147	107.92	5.76	2.56	3.49	180.00	12.97	4.98
68 S	6th	Present		67.05	32.95			44.74	14.27	155	119.38	2.08	2.67	3.46	130.00	9.11	2.47
69 S	4th			34.91	65.09			9.79	5.14	45	35.73	2.14	3.65	4.60	190.00	36.96	0.34
70 S	4th				100.00			8.18	3.91	40	27.59	1.74	3.37	4.89	86.00	21.99	0.48
71 S	4th			37.12	62.88			13.74	5.04	51	40.24	1.75	2.93	3.71	43.00	8.53	1.89
72 S	4th	Present		100.00				13.78	6.88	46	40.94	2.34	2.97	3.34	152.00	22.09	1.07
73 S	4th				100.00			11.62	6.47	60	39.37	4.25	3.39	5.16	204.00	31.53	0.77
74 S	5th				100.00			9.49	5.87	38	27.95	1.63	2.95	4.01	188.00	32.03	0.43
75 S	5th				100.00			10.87	4.95	42	31.17	2.38	2.87	3.86	129.00	26.06	0.82
76 S	5th				100.00			1.77	1.62	8	6.08	0.48	3.43	4.51	27.50	16.98	0.18
77 S	4th				100.00			6.02	3.02	35	15.42	1.68	2.56	5.82	70.00	23.18	0.49
78 U	6th		90.00	1.93		8.07		218.83	41.84	507	368.95	2.86	1.69	2.32	93.00	2.22	32.94
79 U	4th				100.00			3.84	3.37	22	12.10	1.79	3.15	5.72	192.00	56.97	0.17
80 U	5th			42.44	56.33	1.23		34.37	12.05	75	83.11	2.60	2.42	2.18	180.00	14.94	3.30
81 U	4th				100.00			10.95	5.11	41	28.75	2.22	2.63	3.75	170.00	33.27	0.68
82 U	4th			64.65	35.35			16.41	8.21	25	31.58	2.28	1.92	1.52	140.00	17.05	4.56
83 U	4th			53.07	46.93			17.25	8.65	30	39.96	2.60	2.32	1.74	100.00	11.56	5.58
84 U	4th			54.07		45.60		16.85	8.05	32	34.04	1.93	2.02	1.90	107.00	13.29	3.79
85 U	4th		76.07	22.18		1.76		92.25	20.38	72	86.33	4.30	0.94	0.78	100.00	4.91	119.88
86 U	4th		51.04	20.63		28.33		19.16	8.52	45	36.51	2.83	1.91	2.35	91.00	10.68	5.93
87 U	4th		86.83	2.10		11.07		159.06	30.18	279	234.39	4.59	1.47	1.75	118.00	3.91	45.39
88 U	4th		100.00					45.33	15.79	82	65.40	2.53	1.44	1.81	22.80	1.44	67.26
89 U	4th		100.00					7.48	5.31	31	19.09	3.11	2.55	4.15	7.80	1.47	19.98

APPENDIX B

Table B 1: Land use (km²) in sub watersheds of Barureva watershed in year 1972, 1989 and 2000

Sub watershed ID	Order	GPI	year	Agri culture	Forest	Barren land	Bad land	Settle ment	Water body	Total area
1 B	6th	40.66	1972	22.87	0.23	0	45.14	0.26	0	68.5
			1989	55.54	0.5	0	12.2	0.26	0	
			2000	67.83	0	0	0.33	0.31	0	
2 B	4th	1.61	1972	3.2	7.83	1.11	4.64	0.04	0	16.82
			1989	7.75	6.31	2.59	0	0.17	0	
			2000	12.81	3.81	0	0	0.2	0	
3 B	4th	0.40	1972	1.45	9.13	0.24	1.2	0	0	12.02
			1989	3.06	8.33	0.63	0	0	0	
			2000	6.46	5.56	0	0	0	0	
4 B	4th	1.84	1972	6.68	7.48	0.77	3.97	0	0	18.9
			1989	13.23	5.27	0.36	0	0	0	
			2000	14.72	4.16	0	0	0	0	
5 B	5th	23.31	1972	19.14	0	0	15.33	0.18	0	34.65
			1989	32.03	0.24	0	2.2	0.18	0	
			2000	34.02	0	0.15	0.22	0.26	0	
6 B	5th	6.26	1972	19.71	17.07	0.3	19.9	0.36	0	57.34
			1989	36.78	15.81	3.86	0.41	0.36	0.12	
			2000	43.9	12.46	0.33	0	0.36	0.29	
7 B	4th	1.17	1972	2.25	16	0	8.48	0	0	26.73
			1989	10.53	15.06	0.87	0.11	0	0.16	
			2000	14.45	12.11	0	0	0	0.17	
8 B	4th	1.72	1972	2.17	8.11	0.15	5.52	0	0	15.95
			1989	7.79	7.47	0.39	0.25	0	0.05	
			2000	8.96	6.89	0	0	0	0.1	
9 B	5th	4.82	1972	19.24	38.09	1.73	22.16	0.13	0	81.35
			1989	40.09	35.72	3.63	1.55	0.36	0	
			2000	47.85	30.77	2.37	0	0.36	0	
10 B	4th	0.38	1972	0.34	4.62	0.81	0	0.03	0	5.8
			1989	0.31	4.62	0.81	0	0.03	0.03	
			2000	0.82	4	0.91	0	0.04	0.03	
11 B	4th	0.43	1972	0.03	5.74	0.77	0	0	0	6.54
			1989	0.04	5.55	0.95	0	0	0	
			2000	0.59	5.03	0.92	0	0	0	
12 B	4th	0.39	1972	0.9	13.79	0.78	0	0	0	15.47
			1989	1.95	12.59	0.93	0	0	0	
			2000	1.98	12.51	0.97	0	0	0.01	
14 B	4th	43.90	1972	57.94	23.79	7.87	19.28	1.3	0.01	110.19
			1989	79.13	21.24	2.45	5.25	1.63	0.49	
			2000	84.12	16.72	2.64	0.75	5.65	0.31	
15 B	4th	0.34	1972	0.44	5.51	0.06	0.23	0	0	6.24
			1989	0.73	5.32	0.19	0	0	0	
			2000	1.58	4.59	0	0	0	0.07	
16 B	5th	15.11	1972	4.96	0.08	0	6.25	0.08	0	11.37
			1989	10.99	0.08	0.13	0.09	0.08	0	
			2000	11.29	0	0	0	0.08	0	

Table B 2: Land use (km^2) in sub watersheds of Sher watershed in year 1972, 1989 and 2000

Sub watershed ID	Order	GPI	year	Agri culture	Forest	Barren land	Bad land	Settle ment	Water body	Total area
13 S	4th	0.57	1972	1.5	15.19	1.76	0	0	0	18.45
			1989	1.61	15.07	1.77	0	0	0	
			2000	2	14.62	1.83	0	0	0	
17 S	7th	21.73	1972	63.15	38.96	0.6	54.2	0.24	0.02	157.17
			1989	99.06	34.31	0	23.4	0.38	0.02	
			2000	132.84	22.2	0	1.61	0.44	0.08	
18 S	4th	68.06	1972	11.96	1.92	0	16.76	0.09	0	30.73
			1989	23.94	0.04	0	6.62	0.13	0	
			2000	30.26	0	0	0.28	0.19	0	
19 S	4th	8.71	1972	42.64	11.13	65.94	0	0.21	0	119.92
			1989	43.19	11.37	65	0	0.27	0.09	
			2000	47.9	7.15	64.45	0	0.31	0.11	
20 S	5th	0.97	1972	12.56	40.39	27.45	0	0.08	0	80.48
			1989	14.37	40.52	25.51	0	0.08	0	
			2000	15.02	35.12	30.25	0	0.09	0	
21 S	4th	1.05	1972	4.79	8.57	7.1	0	0.17	0	20.63
			1989	4.33	8.54	7.59	0	0.17	0	
			2000	4.71	5.62	10.06	0	0.24	0	
22 S	4th	2.23	1972	13.77	11.92	23.18	0	0.31	0	49.18
			1989	13.41	11.93	23.53	0	0.31	0	
			2000	13.48	9.22	26.17	0	0.31	0	
23 S	4th	1.17	1972	3.95	10.66	14.48	0	0	0	29.09
			1989	2.76	11.85	14.48	0	0	0	
			2000	3.97	4.81	20.32	0	0	0	
24 S	4th	1.08	1972	3.18	17.82	20.07	0	0.08	0	41.15
			1989	3.18	17.25	20.64	0	0.08	0	
			2000	4.24	14.34	22.49	0	0.08	0	
25 S	4th	0.27	1972	1.21	3.05	1.39	0	0	0	5.65
			1989	1.21	3.05	1.39	0	0	0	
			2000	1.21	2.36	2.08	0	0	0	
26 S	4th	1.15	1972	5.57	11.86	5.02	0	0	0	22.45
			1989	5.69	10.03	6.73	0	0	0	
			2000	5.79	7.41	9.25	0	0	0	
27 S	4th	0.07	1972	0.45	2.8	0.41	0	0	0	3.66
			1989	0.45	2.78	0.43	0	0	0	
			2000	0.45	1.85	1.36	0	0	0	
	5th	0.10	1972	1.4	1.53	0.79	0	0	0	3.72
28 S			1989	1.41	1.46	0.85	0	0	0	
			2000	1.53	0.5	1.69	0	0	0	
29 S	4th	1.43	1972	6.78	20.9	5.06	0	0	0	32.74
			1989	6.78	20.66	5.3	0	0	0	
			2000	7.05	18.7	6.99	0	0	0	
30 S	4th	0.06	1972	0.58	1.86	0.62	0	0	0	3.06
			1989	0.58	1.86	0.62	0	0	0	
			2000	0.59	1.26	1.21	0	0	0	

Contd...

Sub watershed ID	Order	GPI	year	Agri culture	Forest	Barren land	Bad land	Settle ment	Water body	Total area
31 S	6th	1.45	1972	26.9	61.25	15.12	0	0.01	0.17	103.45
			1989	29.14	61.57	12.56	0	0.01	0.17	
			2000	31.94	53.98	17.3	0	0.22	0.01	
32 S	4th	1.26	1972	2.16	20.3	1.09	0	0	0	23.55
			1989	2.39	19.76	1.4	0	0	0	
			2000	3.03	18.84	1.68	0	0	0	
33 S	4th	0.76	1972	0.06	8.28	0.03	0	0	0	8.37
			1989	0.14	8.23	0	0	0	0	
			2000	0.23	8.14	0	0	0	0	
34 S	5th	3.00	1972	2.91	1.33	0.54	0	0	0	4.78
			1989	3.67	0.97	0.14	0	0	0	
			2000	3.88	0.56	0.34	0	0	0	
35 S	4th	1.01	1972	6.41	9.02	6.7	0	0	0	22.13
			1989	6.71	8.72	6.7	0	0	0	
			2000	7.26	7.2	7.68	0	0	0	
36 S	4th	0.98	1972	3.03	7.48	0.81	0	0	0	11.32
			1989	3.25	7.26	0.81	0	0	0	
			2000	3.34	6.82	1.16	0	0	0	
37 S	4th	0.46	1972	0.58	3.55	0.44	0	0	0	4.57
			1989	0.42	3.55	0.44	0	0	0.16	
			2000	0.42	3.6	0.42	0	0	0.13	
38 S	6th	0.73	1972	12.86	8.69	5.31	0	0.04	0	26.9
			1989	12.64	8.68	5.54	0	0.04	0	
			2000	13.53	7.73	5.6	0	0.04	0	
39 S	4th	0.27	1972	4.01	6.63	0.74	0	0	0	11.38
			1989	4.01	6.62	0.75	0	0	0	
			2000	4.12	6.12	1.14	0	0	0	
40 S	4th	0.24	1972	1.93	12.15	2.18	0	0	0	16.26
			1989	2.37	12.21	1.68	0	0	0	
			2000	2.4	11.82	2.04	0	0	0	
41 S	4th	0.41	1972	1.81	19.02	1.75	0	0	0	22.58
			1989	1.92	18.94	1.72	0	0	0	
			2000	2.42	17.96	2.2	0	0	0	
42 S	5th	0.34	1972	7.85	23.15	2.52	0	0	0	33.52
			1989	7.15	23.55	2.82	0	0	0	
			2000	7.73	22.17	3.62	0	0	0	
43 S	4th	0.22	1972	0.98	4.8	0.66	0	0	0	6.44
			1989	0.98	4.8	0.66	0	0	0	
			2000	1.19	4.5	0.75	0	0	0	
44 S	4th	0.11	1972	0.21	5.85	0.09	0	0	0	6.15
			1989	0.21	5.85	0.09	0	0	0	
			2000	0.21	5.75	0.19	0	0	0	
45 S	4th	0.44	1972	0.48	12.04	1.13	0	0	0	13.65
			1989	0.58	11.68	1.39	0	0	0	
			2000	1.02	11.06	1.57	0	0	0	
46 S	4th	0.05	1972	0.08	1.84	0.11	0	0	0	2.03
			1989	0.08	1.84	0.11	0	0	0	
			2000	0.08	1.25	0.7	0	0	0	

Contd...

Sub watershed ID	Order	GPI	Year	Agri culture	Forest	Barren land	Bad land	Settle ment	Water body	Total area
47 S	4th	0.41	1972	1.45	6	5.89	0	0	0	13.34
			1989	1.45	6	5.89	0	0	0	
			2000	1.75	5.65	5.94	0	0	0	
48 S	4th	2.39	1972	17.1	3.24	10.92	0	0.06	0	31.32
			1989	17.1	3.24	10.92	0	0.06	0	
			2000	17.05	1.42	12.79	0	0.06	0	
49 S	4th	7.64	1972	16.64	3.08	16.72	0	0.01	0.01	36.46
			1989	16.59	3.08	16.69	0	0.01	0.09	
			2000	17.29	0.83	18.19	0	0.01	0.14	
50 S	4th	1.22	1972	2.42	8.11	8.66	0	0	0.01	19.2
			1989	2.42	8.11	8.66	0	0	0.01	
			2000	2.72	4.65	11.76	0	0	0.07	
51 S	4th	0.69	1972	1.51	7.57	2.23	0	0	0	11.31
			1989	1.42	7.66	2.23	0	0	0	
			2000	1.72	7.21	2.38	0	0	0	
52 S	5th	0.54	1972	1.6	19.79	6.65	0	0	0	28.04
			1989	1.6	19.79	6.65	0	0	0	
			2000	1.64	17.77	8.63	0	0	0	
53 S	4th	23.84	1972	56.46	8.21	19.73	0	0.54	0	84.94
			1989	55.1	7.85	20.09	0	0.54	1.36	
			2000	58.34	1.97	21.9	0	0.54	2.19	
54 S	4th	5.92	1972	14.43	2.39	11.73	0	0.14	0	28.69
			1989	14.4	2.39	11.73	0	0.14	0.03	
			2000	15.83	1.06	11.59	0	0.14	0.05	
55 S	4th	10.27	1972	24.3	0.03	14.77	0	0.48	0.01	39.59
			1989	24.16	0.03	14.75	0	0.62	0.03	
			2000	24.3	0	14.54	0	0.66	0.09	
56 S	4th	16.10	1972	18.51	2.23	11.6	0	0.13	0	32.47
			1989	18.47	1.85	11.82	0	0.13	0.2	
			2000	22.13	0	9.96	0	0.13	0.25	
57 S	4th	2.56	1972	5.34	0.51	13.26	0	0	0	19.11
			1989	5.34	0.51	13.26	0	0	0	
			2000	5.41	0	13.7	0	0	0	
58 S	5th	2.12	1972	15.7	22.72	55.75	0	0.18	0	94.35
			1989	16.03	24.11	53.89	0	0.32	0	
			2000	16.8	17.18	60.05	0	0.32	0	
59 S	4th	0.28	1972	0.57	5.27	0.52	0	0	0	6.36
			1989	0.57	5.27	0.52	0	0	0	
			2000	0.58	5.2	0.58	0	0	0	
60 S	5th	1.57	1972	13.09	40.3	7.36	0	0	0	60.75
			1989	13.49	39.73	7.53	0	0	0	
			2000	13.96	38.12	8.67	0	0	0	
61 S	4th	0.58	1972	0.71	11.1	3.69	0	0	0	15.5
			1989	0.71	11.1	3.69	0	0	0	
			2000	0.71	11.05	3.74	0	0	0	
62 S	4th	0.36	1972	0.64	13.33	0.89	0	0	0	14.86
			1989	0.64	13.33	0.89	0	0	0	
			2000	0.75	13.12	0.99	0	0	0	

Contd...

Sub watershed ID	Order	GPI	Year	Agri culture	Forest	Barren land	Bad land	Settle ment	Water body	Total area
63 S	4th	0.32	1972	0.13	8.73	0.76	0	0	0	9.62
			1989	0.13	8.73	0.76	0	0	0	
			2000	0.13	8.41	1.08	0	0	0	
65 S	4th	0.59	1972	0.72	13.76	0.6	0	0	0	15.08
			1989	0.72	13.74	0.62	0	0	0	
			2000	0.73	12.44	1.91	0	0	0	
66 S	4th	0.47	1972	1.21	5.99	0.75	0	0	0	7.95
			1989	1.21	5.99	0.75	0	.0	0	
			2000	1.21	5.97	0.77	0	0	0	
68 S	6th	2.47	1972	15.1	27.44	2.31	0	0	0	44.85
			1989	16.45	26.97	1.43	0	0	0	
			2000	19.85	22.3	2.68	0	0.02	0	
69 S	4th	0.34	1972	2.82	6.46	0.43	0	0	0	9.71
			1989	2.82	6.46	0.43	0	0	0	
			2000	2.94	6.24	0.53	0	0	0	
70 S	4th	0.48	1972	0.91	5.78	1.5	0	0	0	8.19
			1989	0.91	5.78	1.5	0	0	0	
			2000	1.28	4.7	2.21	0	0	0	
71 S	4th	1.89	1972	7.00	4.71	1.89	0	0.05	0	13.65
			1989	7.21	4.68	1.68	0	0.05	0.03	
			2000	7.56	2.35	3.65	0	0.07	0.03	
72 S	4th	1.07	1972	2.11	10.52	1.23	0	0	0	13.86
			1989	2.03	10.4	1.43	0	0	0	
			2000	2.56	9.39	1.91	0	0	0	
73 S	4th	0.77	1972	3.39	5.67	2.65	0	0	0	11.71
			1989	3.39	5.67	2.65	0	0	0	
			2000	3.45	4.76	3.5	0	0	0	
74 S	5th	0.43	1972	4.5	3.86	1.2	0	0	0	9.56
			1989	4.54	3.8	1.22	0	0	0	
			2000	5.01	3.32	1.23	0	0	0	
75 S	5th	0.82	1972	3.23	6.64	0.86	0	0	0	10.73
			1989	3.28	6.63	0.82	0	0	0	
			2000	3.8	6.45	0.48	0	0	0	
76 S	5th	0.18	1972	1.77	0	0.07	0	0	0	1.84
			1989	1.77	0	0.07	0	0	0	
			2000	1.77	0	0.07	0	0	0	
77 S	4th	0.49	1972	0.83	4.62	0.58	0	0	0	6.03
			1989	0.83	4.62	0.58	0	0	0	
			2000	0.83	4.61	0.59	0	0	0	

Table B 3: Land use (km^2) in sub watersheds of Umar watershed in year 1972, 1989 and 2000

Sub watershed ID	Order	GPI	year	Agri culture	Forest	Barren land	Bad land	Settle ment	Water body	Total area
64 U	4th	0.24	1972	0.32	14.16	0.31	0	0	0	14.79
			1989	0.32	14.16	0.31	0	0	0	
			2000	0.32	14.16	0.31	0	0	0	
67 U	4th	4.98	1972	9.31	26.98	5.71	0	0	0	42
			1989	9.38	27.49	5.13	0	0	0	
			2000	10.71	25.22	6.07	0	0	0	
78 U	6th	32.94	1972	107.46	22.86	0.15	87.24	1.21	0.08	219
			1989	174.44	17.23	3.42	22.14	1.44	0.35	
			2000	201.27	13.28	0.05	2.57	1.85	0.09	
79 U	4th	0.17	1972	0.44	3.44	0.05	0	0	0	3.93
			1989	0.44	3.44	0.05	0	0	0	
			2000	0.44	3.44	0.05	0	0	0	
80 U	5th	3.18	1972	19.15	12.51	2.55	0	0.06	0	34.27
			1989	19.15	12.17	2.89	0	0.06	0	
			2000	19.41	11.25	3.55	0	0.06	0	
81 U	4th	0.68	1972	2.49	8.27	0.15	0	0	0	10.91
			1989	2.49	8.27	0.15	0	0	0	
			2000	2.49	8.27	0.15	0	0	0	
82 U	4th	4.56	1972	10.12	5.51	0.78	0	0.11	0	16.52
			1989	10.12	3.96	2.33	0	0.11	0	
			2000	10.08	3.94	2.35	0	0.15	0	
83 U	4th	5.18	1972	7.54	9.67	0.03	0	0	0	17.24
			1989	7.54	9.67	0.03	0	0	0	
			2000	7.88	9.33	0.03	0	0	0	
84 U	4th	3.79	1972	8.98	7.05	0.7	0	0	0	16.73
			1989	8.85	7.05	0.7	0	0	0.13	
			2000	10.96	5.05	0.72	0	0	0	
85 U	4th	119.88	1972	65.25	20.61	0.21	5.61	0.53	0	92.21
			1989	70.33	20.1	0.73	0	0.66	0.39	
			2000	74.1	16.31	0.36	0	1.38	0.06	
86 U	4th	5.93	1972	8.62	8.96	0.18	1.48	0	0	19.24
			1989	9.33	8.5	0.87	0	0.08	0.46	
			2000	10.38	8.5	0	0	0.11	0.25	
87 U	4th	45.39	1972	104.87	15.18	4.68	32.55	1.59	0.08	158.95
			1989	132.44	11.17	6.54	5.49	2.63	0.71	
			2000	138.01	10.39	6.79	0.18	3.33	0.3	
88 U	4th	67.26	1972	28.64	1.87	0	15.11	0.21	0	45.83
			1989	41.8	0.01	0	3.69	0.33	0	
			2000	45.32	0.01	0	0.09	0.41	0	
89 U	4th	19.98	1972	3.26	0.58	0	3.63	0	0	7.47
			1989	5.76	0.54	0	1.17	0	0	
			2000	6.98	0.25	0	0.24	0	0	

Note: GPI in the range 5-10 suggests rain water harvesting in upper part and ground water storage in lower part of the sub watershed.
GPI greater than 10 suitable for ground water recharge.
GPI less than 5 shows low permeable to impermeable zone suitable only for rain water harvesting and soil conservation treatment.

APPENDIX C
POPULATION AND FOOD, FODDER DEMAND

HUMAN AND LIVESTOCK POPULATION

Census data are available on the block basis. A block is an administrative area comprising of several villages. A district consists of several blocks. The study area is mostly spread over part of the Narsinghpur, Kareli and Gotegaon blocks in Narsinghpur district and over part of the Lakhnadon block in Seoni district as shown in Table C1. A small part of the study area (6.18%) is in the Harai block of Chhindwara district for which census data is not available. Further, census data for the Lakhnadon block is available only for the year 2001. These areas of Lakhnadon and Harai block occupy upper part of the Sher watershed for which adequate census data are not available. Therefore, following analysis may be relevant only for Barureva and Umar watersheds and for lower part of the Sher watershed.

Table C1: Block area distribution

District	Block Name	Block area km^2	Block area in study area km^2	Percent area of block in study area
Narsinghpur	Narsinghpur	1193	818.26	68.59
	Gotegaon	924	690.92	74.77
	Kareli	654	328.75	50.27
Seoni	Lakhnadon	1207	809.27	67.05
Chhindwara	Harai	-	174.49	-
	Sum		2822	100.00

Block level human population data are available for Narsinghpur, Gotegaon, and Kareli blocks for the year 1971, 1991 and 2001. The block level census data has been transferred to the study area on proportionate area basis as shown in Table C3.

ESTIMATION OF FOOD DEMAND

Diet requirement: Human diet consists of cereal, pulses, oil or fat, and milk. Standard diet requirement of the human population is based on data in ICMR 1990(Table C2). Average diet requirement is considered irrespective of the sex or age group.

Table C2: Standard diet requirement of the human population

Food stuff	Per capita standard requirement (gm/day)	Per capita annual demand (kg/year)	Energy supplied in Kcal/ kg	Energy demand Kcal/year
Cereal	520	190	3460	657400.0
Pulses	50	18.30	3450	63135.0
Fats and oils	45	16.40	9000	147600.0
Sugar	35	12.80	3977	50905.6
Milk	200	73.00	948	69204.0
		Per capita total energy demand per year		988244.6

(Source: Advisory committee of ICMR-1990)

Using the population data in Table C3 and per capita diet requirement in Table C2, the annual food demand in metric tones per year and equivalent energy demand have been computed as shown in Table C3.

Table C3: Food and equivalent energy demand in different years in part of four blocks within study area

Block	Year	Block area in study area (%)	Population within study area	Cereal Mt/year	Pulses Mt/Year	Oil/Fat Mt/Year	Sugar Mt/Year	Milk Mt/Year	Energy Demand within study area X 10^6Kcal
Narsinghpur	1971	68.59	58153.35	11049.14	1064.21	953.71	744.36	4245.19	57469.73
	1991	68.59	76916.83	14614.20	1407.58	1261.44	984.54	5614.93	76012.638
	2001	68.59	131744.9	25031.54	2410.93	2160.62	1686.34	9617.38	130196.21
Kareli	1971	50.27	49601.67	9424.32	907.71	813.47	634.90	3620.92	49018.583
	1991	50.27	70634.47	13420.55	1292.61	1158.41	904.12	5156.32	69804.135
	2001	50.27	103534.8	19671.61	1894.69	1697.97	1325.25	7558.04	102317.67
Gotegaon	1971	74.77	48761.9	9264.76	892.34	799.70	624.15	3559.62	48188.684
	1991	74.77	63629.76	12089.65	1164.42	1043.53	814.46	4644.97	62881.762
	2001	74.77	87490.41	16623.18	1601.07	1434.84	1119.88	6386.80	86461.926

ESTIMATION OF FODDER DEMAND

Domestic animals (buffalo, cattle, sheep, goat etc) are mostly fed by dry and green fodders which are supplied by tree leaves and agricultural residues. Sen et al. (1978), considered buffalo as 1 livestock standard unit (LSU) while other cattles are expressed in terms of LSU. There are various recommendations to calculate fodder requirement of the farmstead animal. Gurmel Singh (1981) estimated annual fodder requirement per livestock unit as 2400 kg/year/cattle while Sharma and Bhadra (1986) computed fodder demand to be 2800 kg/year/cattle. In the present study it is taken as 2800 kg/year/ livestock unit. Average fodder requirement of different cattle are shown in Table C4.

Table C4. Livestock standard unit (LSU) and average annual dry fodder requirement

Livestock	Adult female	Dry fodder Requirement (kg/year)
Buffalo/ cross bred cattle	1.00	2800
cow/donkey/horse/mule	0.69	1932
Sheep/Goat	0.22	616

Note: Cross bred is assumed to be equivalent to buffalo. Donkey, horse and mule are assumed to be equivalent to local cattle for their fodder requirement.

Based on data of human and animal population for the year 2003, average ratio of livestock per person for different categories of livestock have been worked out as shown in Table C5.

Table C5: Livestock population for Narsinghpur and Seoni district in year 2003

Livestock	Narsinghpur	Seoni	Average Ratio (livestock/person)
Total crossbred cattle	13899	4454	0.00917
Total Indigenous Cattle	386903	421468	0.38265
Total cattle	400802	425922	0.39181
Total buffaloes	118310	125752	0.11567
Total sheep	241	393	0.00029
Total goats	96913	158340	0.11846
Total horses and ponies	1072	487	0.00077
Total mules	73	6	0.00004
Total donkeys	681	82	0.00039

(Note: Human population of Narsinghpur =957646 and Seoni district = 1166608 in year 2001)

Ratios in Table C5 and data of human population for parts of Narsinghpur, Gotegaon, and Kareli blocks in study area (Table C3) are used to estimate livestock population in the years 1971, 1991 and 2001 (Table C6).

Using the data on cattle population in Table C6 and fodder requirement per unit livestock in Table C4, the annual fodder demand in different years is computed as shown in Table C6.

Table C6: Fodder demand in different years in part of four blocks within study area

Block area in study area and year	Livestock Population								Total Fodder Demand MT/year
	Total Crossbred cattle	Total Indigenous cattle	Total buffaloes	Total sheep	Total goats	Total horses and ponies	Total mules	Total donkeys	
Narsinghpur,1971	533	22252	6727	17	6889	45	2	23	67707.952
1991	705	29432	8897	22	9112	59	3	30	89554.276
2001	1208	50412	15239	38	15607	101	5	51	153390.65
Kareli ,1971	455	18980	5737	14	5876	38	2	19	57751.235
1991	648	27028	8170	20	8367	54	3	28	82239.729
2001	949	39618	11976	30	12265	80	4	40	120545.55
Gotegaon, 1971	447	18659	5640	14	5776	38	2	19	56773.49
1991	583	24348	7360	18	7538	49	3	25	74084.137
2001	802	33478	10120	25	10364	67	3	34	101865.1

APPENDIX D: GROUND WATER ANALYSIS

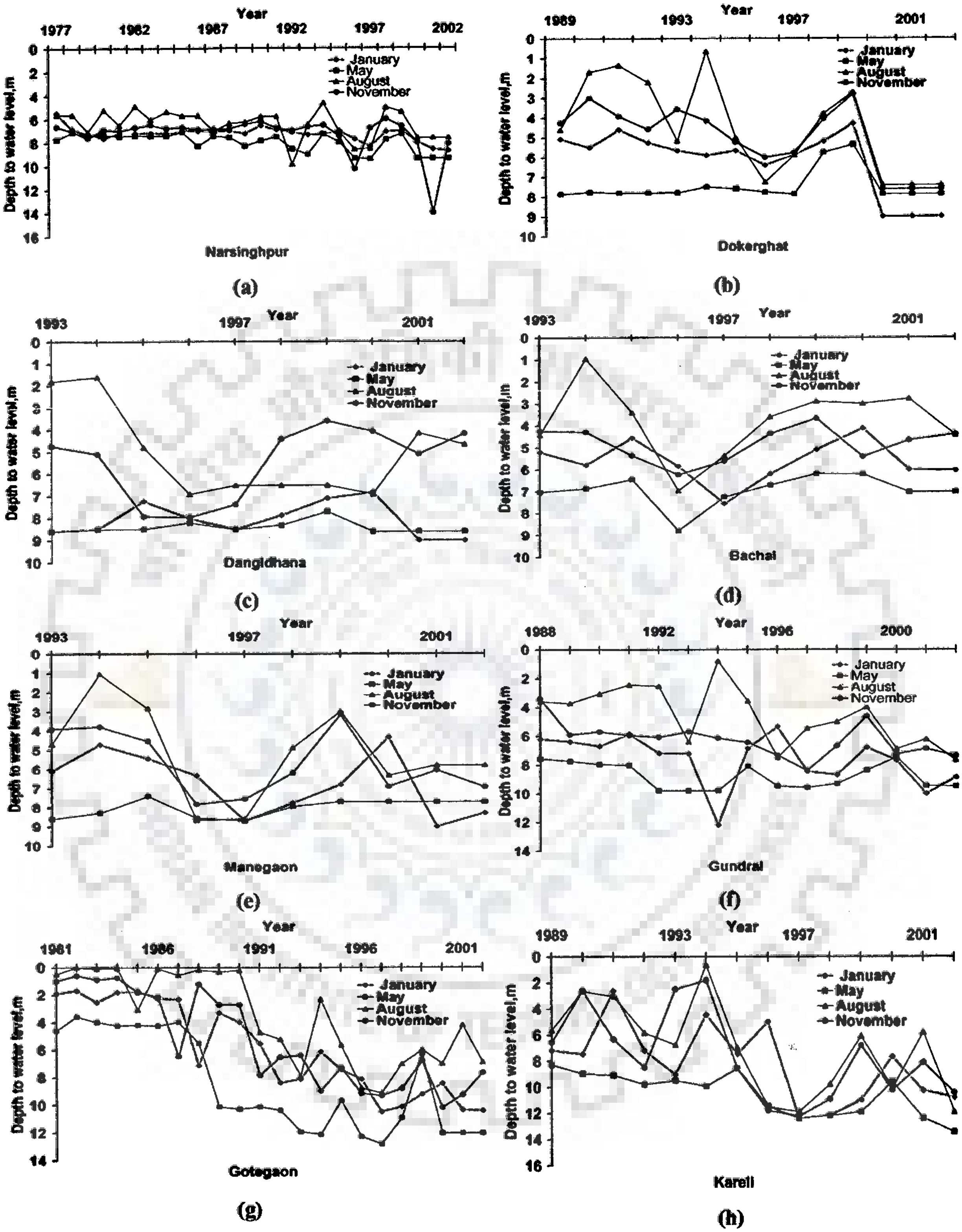

Figure D1: Ground water table fluctuation over the years in alluvium area

Trend Analysis: Sample calculation

Table D1: Trend analysis of pre-monsoon water table depths over the years for Lakhnadon observation well

Sl.No.	Ground water year	Year, X(i)	Depth to water table for pre-monsoon mbgl Yi	$X(i)^2$	X(i) x Y(i)
1	1990	1	6.8	1	6.8
2	1991	2	6.8	4	13.6
3	1992	3	6.8	9	20.4
4	1993	4	6.6	16	26.4
5	1994	5	6.0	25	30
6	1995	6	5.5	36	33
7	1996	7	5.8	49	40.6
8	1997	8	6.4	64	51.2
9	1998	9	4.5	81	40.5
10	1999	10	5.4	100	54
		S_1=55	S_2=60.6	S_3=385	S_4=316.5

Number of data sample (N)=10

Trend of ground water table depth below ground level during pre-monsoon in cm/year

$$= \frac{(N \times S_4) - (S_1 \times S_2)}{\left[(N \times S_3) - S_1^2\right]} \times 100$$

$$= \frac{(10 \times 316.5) - (55 \times 60.6)}{\left[(10 \times 385) - 55^2\right]} \times 100$$

= - 20.36 cm/year rising

In the computation negative value indicate the rising trend while positive value is the falling trend.

APPENDIX E

Table E1: Runoff Curve Numbers for (AMCII) for the Indian conditions

SL No.	Land use	Treatment/practice	Hydrological condition	Hydrologic soil group			
				A	B	C	D
1	Cultivated	Straight row	-	76	86	90	93
		Contoured	Poor	70	79	84	88
			Good	65	75	82	86
		Contoured and terraced	Poor	66	74	80	82
			Good	62	71	77	81
		Bunded	Poor	67	75	81	83
			Good	59	69	76	79
		Paddy(Rice)	-	95	95	95	95
2	Orchards	With under stony	-	39	53	67	71
		Without under stony cover	-	41	55	69	73
3	Forest	Dense	-	26	40	58	61
		Open	-	28	44	60	64
		Shrubs	-	33	47	64	73
4	Pasture	-	Poor	68	79	86	89
			Fair	49	69	79	84
			Good	39	61	74	80
5	Wasted land	-	-	71	80	85	88
6	Hard surfaces	-	-	77	86	91	93

HYDROLOGICAL SOIL PROPERTIES OF AREA BETWEEN SHER AND BARUREVA RIVERS

Figure E1 shows soil types in area between Sher and Barureva rivers. TableE2 shows Hydrological soil properties in area between Sher and Barureva rivers.

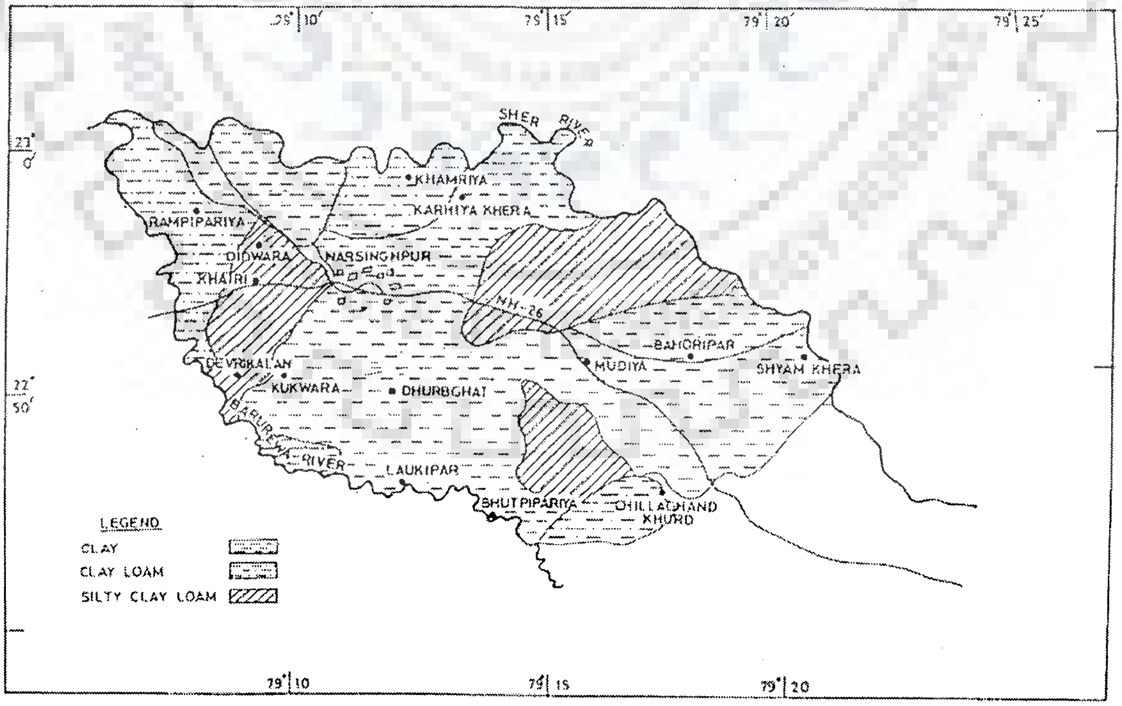

Figure E1: Soil types in area between Sher and Barureva rivers

The major soil parameters generally considered for hydrological soil classification are effective soil depth, soil texture, constant infiltration rate and saturated hydraulic conductivity. The area is classified in hydrologic soil group D.

Table E2: Hydrological soil properties in area between Sher and Barureva rivers

Sl no	Name of village site	Effective depth cm	Texture (clay content) %	Infiltration capacity cm/hr	Permeability cm/hr
1	Chilichawk khurd	>100	Clay(57.0)	1.20	0.15
2	Karhiya khera	>100	Clay(76.0)	0.40	NF
3	Devri kalan	>100	Clay(70.0)	0.20	0.18
4	Kukwara	>100	Clay(79.0)	0.30	0.003
5	Niwari	>100	Clay(66.0)	0.24	NF
6	Mudiya	>100	Clay(81.5)	0.60	0.38
7	Shyamkhera	>100	Clay(83.0)	0.60	0.04
8	Khandarapur	>100	Clay(75.5)	1.20	0.84
9	Laukipar	>100	Clay(49.0)	1.20	4.60
10	Khamariya	>100	Sandy Clay(22.0)	0.30	4.01
11	Dhrubghat	>100	Sandy Clay loam (85.0)	0.30	0.21
12	Didwara	>100	Clay(77.5)	0.40	0.31

HYDROLOGICAL SOIL PROPERTIES OF AREA BETWEEN SHER AND UMAR RIVERS

The area is between right flank of Sher river and left flank of Umar river (Figure E2). The hydrological soil properties are given in Table E 3. Soils of this area are mainly clay and silty clay at the surface level. In deeper layers (30-50 cm and 70-120 cm) soils are clay, silt clay and sandy silt. Soil Survey Organization of Madhya Pradesh shows that 90% area is clay dominant. Due to dominance of clay having low values of hydraulic conductivity, this area is classified in hydrological soil group D.

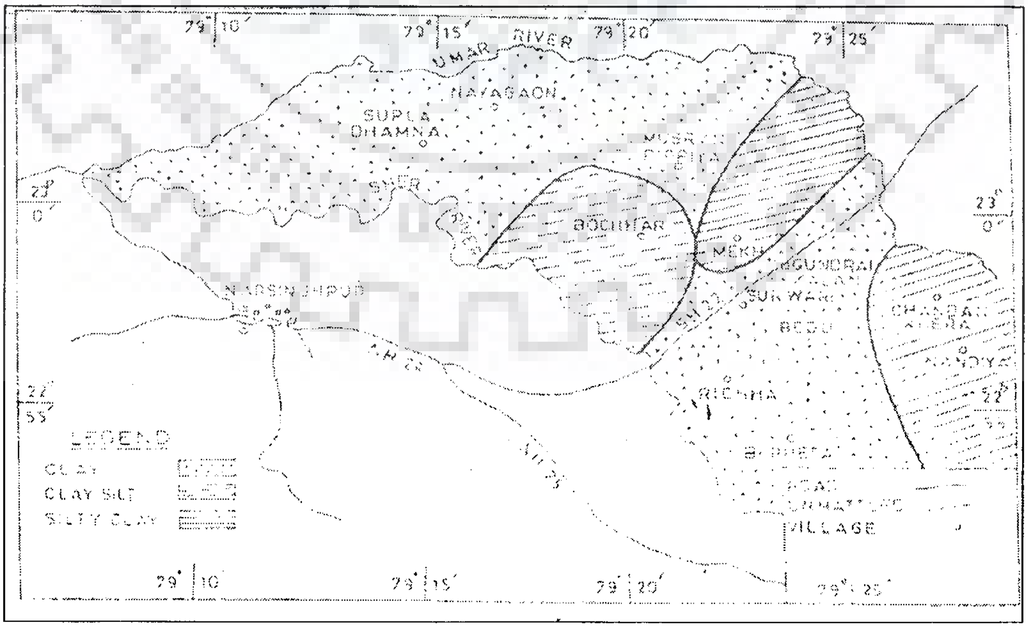

Figure E2: Type of soils in area between Sher and Umar rivers

Table E3: Hydrological soil properties in area between Sher and Umar Rivers

Sl no	Name of village site	Soil depth			Permeability cm/hr
		0-30 cm	30-50 cm	70-120 cm	
1	Nayagaun	Clay	Clay	Clay	2.38
2	Dhamna	Clay	Clay	Silty Clay	1.18
3	Bedu	Clay	Clay	Sandy silt	2.83
4	Gundri Kalan	Clay	Silty Clay	-	13.48
5	Barheta	Clay	Clay	Silt	-
6	Surwari	Clay	Clay	-	-
7	Bochhar	Clay Silt	Clay Silt	Sandy silt	20.45
8	Mekh	Silty Clay	Silty Clay	Clay Silt	34.27
9	Mushran Pipariya	Clay	Clay	Sandy silt	53.73
10	Nandiya	Silty Clay	Silty Clay	-	-
11	Chandan Khera	Silty Clay	Silty Clay	Sandy silt	-
12	Richha	Clay silt	-	-	-

IDENTIFICATION OF WET, NORMAL AND DRY YEARS

A year is classified as drought year, normal year and wet year based on amount of annual rainfall(Y) and its standard deviation(S) (Singh et al., 2007).When particular year receives rainfall less than Y-S, it is drought year and if it is greater than Y+S, it is wet year and years with values of annual rainfall falling in between Y+S and Y-S are normal years (Table E4).

Table E4: Yearly rainfall classification of three rainfall stations

	Narsinghpur		Harai		Lakhnadon	
Year	Annual rainfall mm	classification	Annual rainfall mm	classification	Annual rainfall mm	classification
1970	1719.4	Wet	1607.4	Wet	NA	NA
1971	1436	Normal	1164.8	Normal	NA	NA
1972	1303	Normal	970.5	Normal	NA	NA
1973	1619.8	Wet	1752.6	Wet	1175.6	Normal
1974	1187	Normal	NA	NA	865.3	Drought
1975	1358.6	Normal	1045	Normal	1078.3	Normal
1976	1184.6	Normal	912	Normal	937.3	Normal
1977	1902.8	Wet	1469.2	Normal	1661.2	Wet
1978	1216.1	Normal	1159.1	Normal	1017.1	Normal
1979	704.9	Drought	NA	NA	1016	Normal
1980	1255.1	Normal	NA	NA	1000.3	Normal
1981	1091.4	Normal	996.2	Normal	1087.5	Normal
1982	1139.4	Normal	990.4	Normal	1121	Normal
1983	1444.2	Normal	1187.5	Normal	1264.3	Normal
1984	967.6	Normal	895.8	Normal	1363.9	Wet
1985	1341.2	Normal	1062.1	Normal	1083.2	Normal
1986	983.8	Normal	1212.7	Normal	996.3	Normal
1987	799.7	Drought	893.1	Normal	835.5	Drought
1988	895.6	Normal	1110	Normal	981.7	Normal
1989	1108	Normal	NA	NA	NA	NA
1990	1336.3	Normal	1838.2	Wet	1650.6	Wet

1991	914.6	Normal	756.6	Drought	665	Drought
1992	1051.7	Normal	968	Normal	1195.8	Normal
1993	1217.9	Normal	1249.9	Normal	1028.7	Normal
1994	2004.8	Wet	1786.8	Wet	1618.5	Wet
1995	968.2	Normal	635.8	Drought	948	Normal
1996	700	Drought	NA	NA	918	Normal
1997	992.6	Normal	1257.1	Normal	1334	Normal
1998	974	Normal	1078.5	Normal	1181	Normal
1999	1951.3	Wet	1917.4	Wet	1463	Wet
2000	707.7	Drought	1019.3	Normal	814.4	Drought
2001	1095.7	Normal	1114.9	Normal	920.5	Normal
2002	533.1	Drought	997.2	Normal	1109.8	Normal
2003	NA	NA	1334	Normal	1382	Wet
2004	NA	NA	759.6	Drought	910.3	Normal

Note: NA –No adequate data

Annual Runoff Coefficient

The annual runoff coefficient is defined as ratio of annual runoff to annual rainfall. It exhibits the runoff potential of watershed. The runoff coefficient values depend upon watershed factors such as the land use and land cover, soil type, soil slope, moisture condition and rainfall characteristics such as magnitude, duration of rainfall etc. Among these parameters, rainfall is the most variable characteristic influencing runoff magnitude by changing soil moisture condition when other watershed factors are constant. The annual runoff coefficient values (Table E5) are very much influenced by annual rainfall conditions. In general, runoff coefficient is 0.61 for wet year 1999-2000. On other hand, lowest value of runoff coefficient (0.17) is found in drought year of 1987-88. Extremely high annual runoff coefficient of 0.80 is observed for normal year of 1984-1985 and it may be due to data error because in same year in month of August, runoff (425 mm) is recorded more than rainfall (322 mm).

Table E5: Annual rainfall-runoff variation and rainfall classification for Sher watershed

Year	Areal average rainfall mm	Runoff mm	ratio	classification	Average rainy days (P≥2.5 mm)
1977-78	1693.6	886.0	0.52	Wet	78
1978-79	1114.3	526.7	0.47	Normal	62
1979-80	892.8	302.8	0.34	Normal	NA
1980-81	1079.9	438.0	0.41	Normal	NA
1981-82	1114.4	450.2	0.40	Normal	68
1982-83	986.3	517.1	0.52	Normal	72
1983-84	1316.7	476.2	0.36	Normal	85
1984-85	1188.2	956.2	0.80	Normal	50
1985-86	1233.1	567.3	0.46	Normal	73
1986-87	959.7	435.2	0.45	Normal	58
1987-88	804.3	139.9	0.17	Drought	61
1988-89	1013.3	402.1	0.40	Normal	70
1989-90	1151.8*	315.6	0.27	NA	NA
1990-91	1677.9	810.7	0.48	Wet	89
1991-92	668.8	301.2	0.45	Drought	43
1992-93	1134.5	500.3	0.44	Normal	61
1993-94	1101.0	431.7	0.39	Normal	57
1994-95	1833.3	1111.8	0.61	Wet	78
1995-96	814.4	349.5	0.43	Drought	56
1996-97	706.5	168.3	0.24	Drought	49
1997-98	1449.5	549.0	0.38	Wet	85
1998-99	1027.7	363.9	0.35	Normal	60
1999-2000	1633.3	981.7	0.60	Wet	69
2000-01	928.2	266.1	0.29	Normal	52
2001-02	990.2	543.2	0.55	Normal	56
2002-03	954.1	483.5	0.51	Normal	49
Average	1133.4	510.5	0.43	-	
SD	305.9	248.2	0.13	-	
CV	0.27	0.48	0.30	-	

* Other two stations rainfall data of some months is unavailable

Table E6: Computation of annual CN (PQ) for AMCII condition for gauged Sher watershed

Year	Event	Event period, days	Event Rainfall (R,) mm	Event Direct runoff, mm	S, mm	CN(PQ)	Median CN
1977	1	5	71.06	20.85	85.61	74.79	71.93
	2	8	233.24	126.32	131.89	65.82	
	3	5	130.34	61.21	92.51	73.30	
	4	7	125.24	74.14	59.80	80.94	
	5	7	74.58	13.85	126.32	66.79	
	6	6	112.92	45.08	99.13	71.93	
	7	6	97.83	30.32	112.13	69.37	
1978	1	9	44.60	4.19	106.44	70.47	83.95
	2	7	138.69	63.27	102.57	71.23	
	3	7	125.77	23.23	213.75	54.30	
	4	5	38.79	11.02	48.06	84.09	
	5	6	163.61	142.16	19.67	92.81	
	6	5	50.26	18.84	47.45	84.26	
	7	9	29.45	5.70	48.58	83.95	
1979	1	3	67.43	15.48	98.95	71.97	71.97
	2	5	123.53	32.57	162.98	60.91	
	3	4	136.80	117.85	17.48	93.56	
1980	1	6	138.04	26.51	228.89	52.60	80.23
	2	4	30.20	3.60	64.98	79.63	
	3	5	62.46	18.98	72.89	77.70	
	4	10	73.89	30.39	62.57	80.23	
	5	7	204.19	181.90	20.11	92.66	
	6	5	44.65	11.02	62.05	80.37	
	7	5	34.04	9.68	42.15	85.77	
1981	1	5	76.82	30.60	67.64	78.97	87.08
	2	4	64.81	34.54	37.68	87.08	
	3	4	18.23	13.76	4.50	98.26	
	4	4	31.00	5.69	52.90	82.76	
	5	8	117.61	74.90	47.81	84.16	
	6	5	72.77	44.53	32.40	88.69	
	7	3	56.47	36.58	22.03	92.02	
1982	1	5	78.04	4.08	227.39	52.76	73.88
	2	13	74.90	11.15	144.18	63.79	
	3	8	94.79	38.94	80.39	75.96	
	4	9	120.56	50.52	99.75	71.80	
	5	5	34.87	7.20	55.12	82.17	
	6	5	133.20	89.17	47.79	84.17	
1983	1	7	90.28	15.34	161.38	61.15	73.67
	2	6	86.96	14.89	154.73	62.14	
	3	6	109.16	29.72	140.24	64.43	
	4	3	51.09	9.10	88.76	74.10	
	5	5	58.19	12.07	91.71	73.47	
	6	8	83.25	27.82	88.73	74.11	
	7	5	21.47	5.11	30.69	89.22	
	8	8	218.19	106.28	146.69	63.39	
	9	9	82.84	27.19	89.90	73.86	
	10	6	31.71	8.05	43.11	85.49	

Contd…

1984	1	4	20.76	1.13	59.84	80.93	80.53
	2	7	77.15	6.88	187.90	57.48	
	3	7	79.60	29.23	76.87	76.77	
	4	4	66.37	56.22	9.48	96.40	
	5	5	8.39	2.24	10.95	95.87	
	6	7	31.90	4.52	63.03	80.12	
1985	1	6	62.66	10.66	111.92	69.41	69.43
	2	6	101.50	18.37	174.66	59.25	
	3	6	116.37	23.90	184.62	57.91	
	4	8	81.79	27.04	88.12	74.24	
	5	5	154.19	93.63	69.79	78.45	
	6	5	123.10	44.07	122.19	67.52	
	7	6	40.91	2.64	111.76	69.44	
	8	6	67.52	14.50	103.91	70.97	
1986	1	11	162.63	19.45	349.44	42.09	72.65
	2	8	84.59	26.60	95.62	72.65	
	3	5	178.35	85.58	122.66	67.43	
	4	4	56.70	27.21	38.98	86.69	
	5	7	107.69	99.01	7.67	97.07	
1987	1	3	23.44	3.34	46.20	84.61	71.79
	2	5	83.64	14.03	150.60	62.78	
	3	9	93.84	13.68	182.72	58.16	
	4	8	71.26	29.30	60.37	80.80	
1988	1	8	175.72	43.29	244.60	50.94	70.27
	2	6	72.33	16.37	107.26	70.31	
	3	9	120.45	75.22	51.26	83.21	
	4	8	149.28	60.17	129.58	66.22	
	5	6	113.43	32.43	139.81	64.50	
	6	6	20.43	2.81	40.97	86.11	
	7	10	44.91	4.17	107.63	70.24	
	8	12	20.28	5.97	24.33	91.26	
1989	1	4	35.33	4.57	73.13	77.64	73.65
	2	8	78.09	18.80	110.63	69.66	
1990	1	4	115.84	45.56	103.53	71.04	73.93
	2	6	93.61	45.90	62.31	80.30	
	3	6	87.03	28.88	93.42	73.11	
	4	8	110.24	79.96	31.24	89.05	
	5	6	97.47	38.83	85.80	74.75	
	6	16	160.50	54.04	169.80	59.93	
	7	7	167.65	62.13	160.32	61.31	
	8	7	74.96	40.23	43.08	85.50	
	9	6	61.73	15.39	85.15	74.89	
	10	16	162.00	61.27	151.44	62.65	
1991	1	9	73.44	6.50	179.41	58.60	70.71
	2	10	100.18	10.83	225.36	52.99	
	3	8	73.67	9.27	154.50	62.18	
	4	6	51.49	13.41	68.59	78.74	
	5	8	104.08	36.62	105.22	70.71	
	6	7	115.97	96.30	18.58	93.18	
	7	8	43.83	21.54	29.08	89.73	

Contd…

1992	1	6	61.71	7.90	128.34	66.43	77.13
	2	7	263.40	73.88	330.01	43.49	
	3	6	39.63	6.04	75.31	77.13	
	4	7	126.89	31.95	173.64	59.40	
	5	4	105.30	60.98	52.55	82.86	
	6	7	139.35	71.46	86.44	74.61	
	7	4	32.27	9.11	40.21	86.33	
	8	4	57.57	21.07	55.83	81.98	
	9	4	45.06	15.30	47.25	84.31	
1993	1	9	38.70	2.63	103.92	70.97	68.01
	2	10	63.95	4.02	176.24	59.04	
	3	5	103.93	17.45	187.04	57.59	
	4	6	182.83	90.56	119.82	67.95	
	5	4	84.20	13.02	158.79	61.53	
	6	5	66.70	10.76	122.84	67.40	
	7	5	68.77	47.81	22.22	91.96	
	8	9	95.04	26.63	119.18	68.06	
	9	6	46.10	7.16	86.71	74.55	
	10	10	80.90	39.70	53.79	82.52	
1994	1	9	109.47	23.30	169.49	59.98	74.94
	2	9	498.81	243.58	334.12	43.19	
	3	5	40.98	23.49	20.86	92.41	
	4	7	150.02	47.57	168.29	60.15	
	5	6	139.57	73.90	82.09	75.57	
	6	5	121.45	90.86	30.95	89.14	
	7	4	89.04	32.08	87.80	74.31	
	8	5	84.85	44.62	50.47	83.42	
1995	1	5	73.57	35.17	50.87	83.31	83.25
	2	5	119.06	21.91	202.78	55.61	
	3	5	44.07	42.86	1.03	99.60	
	4	5	39.50	5.26	80.60	75.91	
	5	9	60.42	24.10	53.11	82.71	
	6	6	15.29	12.11	3.10	98.79	
	7	8	53.02	19.43	51.33	83.19	
	8	10	42.67	13.20	48.98	83.83	
1996	1	6	40.05	0.37	160.98	61.21	72.94
	2	6	32.88	4.44	66.58	79.23	
	3	5	68.50	6.26	165.28	60.58	
	4	5	31.64	5.63	54.99	82.20	
	5	10	51.67	19.20	49.27	83.75	
	6	5	62.83	8.51	127.06	66.66	
1997	1	12	48.29	0.07	221.62	53.40	71.82
	2	6	9.45	0.05	40.23	86.33	
	3	6	134.32	7.48	384.19	39.80	
	4	6	201.28	69.15	208.61	54.91	
	5	6	76.29	19.58	102.83	71.18	
	6	6	26.99	6.11	40.03	86.39	
	7	9	95.78	26.98	119.55	68.00	
	8	7	92.02	32.64	92.25	73.36	
	9	9	121.67	28.47	176.08	59.06	
	10	5	79.58	23.17	96.53	72.46	
	11	3	57.75	19.26	61.69	80.46	

Contd…

	12	5	30.45	9.39	35.09	87.86	
1998	1	6	146.83	21.10	288.04	46.86	76.71
	2	8	129.89	13.16	300.47	45.81	
	3	6	21.42	3.80	37.30	87.20	
	4	5	62.45	7.18	136.65	65.02	
	5	13	121.03	25.46	188.94	57.34	
	6	5	17.13	7.50	13.39	94.99	
	7	4	22.60	5.01	34.02	88.19	
	8	9	99.66	43.99	77.10	76.71	
	9	11	90.22	51.05	47.08	84.36	
	10	6	55.72	8.45	106.19	70.52	
	11	6	15.85	1.34	39.37	86.58	
1999	1	6	29.12	0.84	98.03	72.15	72.59
	2	7	108.73	8.37	279.77	47.59	
	3	5	99.73	25.66	134.18	65.43	
	4	5	88.08	43.11	58.81	81.20	
	5	7	132.98	84.34	54.59	82.31	
	6	9	678.89	453.77	244.61	50.94	
	7	3	22.46	4.71	35.15	87.84	
	8	5	68.46	17.20	93.84	73.02	
2000	1	6	118.18	5.19	361.10	41.29	75.71
	2	5	79.29	26.83	83.46	75.27	
	3	3	129.00	87.76	44.31	85.15	
	4	7	60.05	17.44	72.99	77.68	
	5	3	36.71	4.09	81.51	75.71	
2001	1	6	68.98	5.90	170.82	59.79	79.02
	2	4	97.34	23.25	138.71	64.68	
	3	3	32.86	4.32	67.44	79.02	
	4	6	25.57	3.72	49.84	83.60	
	5	3	29.10	23.33	5.58	97.85	
	6	7	112.29	9.00	284.77	47.14	
	7	7	29.37	4.61	54.96	82.21	
2002	1	2	40.12	4.76	86.57	74.58	76.20
	2	5	47.90	10.56	72.39	77.82	
	3	9	56.95	9.21	104.75	70.80	
	4	7	316.98	186.01	154.09	62.24	
	5	6	77.83	66.55	10.46	96.04	
	6	5	30.69	14.42	21.76	92.11	

Table E7: Observed and computed values of direct runoff for selected events and its performance parameters.

Year	Event	Event period, days	Event RF mm	Qcomp mm	Qobs mm	NS efficiency	RMSE mm
1977	1	5	71.06	34.58	20.85	89.28	11.76
	2	8	233.24	128.73	126.32		
	3	5	130.34	61.65	61.21		
	4	7	125.24	48.68	74.14		
	5	7	74.58	13.52	13.85		
	6	6	112.92	38.81	45.08		
	7	6	97.83	39.60	30.32		
1978	1	9	44.60	6.12	4.19	76.16	22.48
	2	7	138.69	57.94	63.27		
	3	7	125.77	38.67	29.56		
	4	5	38.79	8.82	11.02		
	5	6	163.61	84.06	142.16		
	6	5	50.26	16.02	18.84		
	7	9	29.45	0.0	5.70		
1979	1	3	67.43	9.11	15.48	34.69	36.19
	2	5	123.53	34.54	32.57		
	3	4	136.80	55.53	117.85		
1980	1	6	138.04	48.16	26.51	41.83	44.60
	2	4	30.20	0	3.60		
	3	5	62.46	6.30	18.98		
	4	10	73.89	1.63	30.39		
	5	7	204.19	71.27	181.90		
	6	5	44.65	0	11.02		
	7	5	34.04	0	9.68		
1981	1	5	76.82	30.02	30.60	27.07	17.42
	2	4	64.81	28.20	34.54		
	3	4	18.23	0.13	13.76		
	4	4	31.00	3.19	5.69		
	5	8	117.61	36.52	74.90		
	6	5	72.77	35.75	44.53		
	7	3	56.47	16.23	36.58		
1982	1	5	78.04	9.71	4.08	82.87	12.50
	2	13	74.90	3.92	11.15		
	3	8	94.79	34.35	38.94		
	4	9	120.56	33.19	50.52		
	5	5	34.87	9.08	7.20		
	6	5	133.20	66.17	89.17		

Contd…

1983	1	7	90.28	11.62	15.34	67.18	16.14
	2	6	86.96	38.61	14.89		
	3	6	109.16	50.20	29.72		
	4	3	51.09	21.01	9.10		
	5	5	58.19	16.36	12.07		
	6	8	83.25	23.07	27.82		
	7	5	21.47	0	5.11		
	8	8	218.19	139.97	106.28		
	9	9	82.84	12.63	27.19		
	10	6	31.71	0.72	8.05		
1984	1	4	20.76	4.39	1.13	77.43	9.53
	2	7	77.15	18.52	6.88		
	3	7	79.60	31.86	29.23		
	4	4	66.37	36.55	56.22		
	5	5	8.39	0.00	2.24		
	6	7	31.90	3.91	4.52		
1985	1	6	62.66	6.52	10.66	61.94	16.59
	2	6	101.50	43.47	18.58		
	3	6	116.37	51.66	23.90		
	4	8	81.79	28.05	27.04		
	5	5	154.19	100.53	93.63		
	6	5	123.10	20.25	44.07		
	7	6	40.91	0.32	2.64		
	8	6	67.52	1.73	14.50		
1986	1	11	162.63	60.43	19.45	20.73	29.94
	2	8	84.59	20.17	26.60		
	3	5	178.35	105.88	85.58		
	4	4	56.70	7.66	27.21		
	5	7	107.69	54.65	99.01		
1987	1	3	23.44	8.10	3.34	-175.52	15.37
	2	5	83.64	36.75	14.03		
	3	9	93.84	13.29	13.68		
	4	8	71.26	9.14	29.30		
1988	1	8	175.72	76.03	43.29	45.45	19.02
	2	6	72.33	19.29	16.37		
	3	9	120.45	35.28	75.22		
	4	8	149.28	54.30	60.17		
	5	6	113.43	43.62	32.43		
	6	6	20.43	0	2.81		
	7	10	44.91	0.16	4.17		
	8	12	20.28	0	5.97		
1989	1	4	35.33	7.54	4.57	49.42	5.06
	2	8	78.09	25.31	18.80		

Contd…

1990	1	4	115.84	50.35	45.56	19.55	15.57
	2	6	93.61	35.71	45.90		
	3	6	87.03	20.58	28.88		
	4	8	110.24	38.53	79.96		
	5	6	97.47	41.79	38.83		
	6	16	160.50	55.26	54.04		
	7	7	167.65	55.77	62.13		
	8	7	74.96	26.0	40.23		
	9	6	61.73	6.43	15.39		
	10	16	162.00	47.95	61.27		
1991	1	9	73.44	16.16	6.50	67.33	16.88
	2	10	100.18	25.11	10.83		
	3	8	73.67	3.23	9.27		
	4	6	51.49	15.95	13.41		
	5	8	104.08	19.02	36.62		
	6	7	115.97	66.52	96.30		
	7	8	43.83	0.17	21.54		
1992	1	6	61.71	6.24	7.90	-66.37	34.17
	2	7	263.40	172.62	73.88		
	3	6	39.63	8.79	6.04		
	4	7	126.89	53.18	31.95		
	5	4	105.30	59.56	60.98		
	6	7	139.35	64.28	71.46		
	7	4	32.27	1.82	9.11		
	8	4	57.57	7.31	21.07		
	9	4	45.06	13.44	15.30		
1993	1	9	38.69	1.89	2.63	41.55	19.77
	2	9	63.95	0.97	4.02		
	3	10	103.93	29.40	17.45		
	4	5	182.83	138.36	90.56		
	5	6	84.20	13.81	13.02		
	6	4	66.70	29.85	10.76		
	7	5	68.77	32.61	47.81		
	8	5	95.04	17.99	26.63		
	9	9	46.10	1.47	7.16		
	10	6	80.90	11.96	39.70		
1994	1	10	109.47	46.00	23.30	51.97	47.42
	2	9	498.81	360.61	243.58		
	3	9	40.98	0	23.49		
	4	5	150.02	65.92	47.57		
	5	7	139.57	62.74	73.90		
	6	6	121.45	42.15	90.86		
	7	5	89.04	51.99	32.08		
	8	4	84.85	44.38	44.62		

Contd…

Table F2: Eleven Runoff events of Teriya watershed

Event 1 (31.07.1967)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	22.00	39600.00
3	2	37.00	106200.00
4	3	79.00	208800.00
5	4	151.00	414000.00
6	5	161.00	561600.00
7	6	144.00	549000.00
8	7	126.00	486000.00
9	8	106.00	417600.00
10	9	86.00	345600.00
11	10	72.00	284400.00
12	11	61.00	239400.00
13	12	52.00	203400.00
14	13	46.00	176400.00
15	14	39.00	153000.00
16	15	34.00	131400.00
17	16	30.00	115200.00
18	17	26.00	100800.00
19	18	22.00	86400.00
20	19	18.00	72000.00
21	20	15.00	59400.00
22	21	13.00	50400.00
23	22	10.00	41400.00
24	23	8.00	32400.00
25	24	6.00	25200.00
26	25	4.00	18000.00
27	26	2.00	10800.00
28	27	0.00	3600.00
Total runoff volume (m^3)			4932000
Total runoff depth (cm)			4.32

Event 2 (13.08.1970)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	1.00	1800.00
3	2	3.00	7200.00
4	3	15.00	32400.00
5	4	78.00	167400.00
6	5	120.00	356400.00
7	6	82.00	363600.00
8	7	54.00	244800.00
9	8	36.00	162000.00
10	9	26.00	111600.00
11	10	21.00	84600.00
12	11	15.00	64800.00
13	12	11.00	46800.00
14	13	7.00	32400.00
15	14	3.00	18000.00
16	15	0.00	5400.00
Total runoff volume (m^3)			1699200
Total runoff depth (cm)			1.49

Event 3 (16.08.1970)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	4.00	7200.00
3	2	39.50	78300.00
4	3	58.00	175500.00
5	4	70.50	231300.00
6	5	82.50	275400.00
7	6	77.50	288000.00
8	7	50.00	229500.00
9	8	40.00	162000.00
10	9	33.50	132300.00
11	10	28.50	111600.00
12	11	23.00	92700.00
13	12	18.50	74700.00
14	13	14.00	58500.00
15	14	10.00	43200.00
16	15	7.50	31500.00
17	16	5.50	23400.00
18	17	3.50	16200.00
19	18	2.00	9900.00
20	19	0.50	4500.00
21	20	0.00	900.00
Total runoff volume (m^3)			2046600
Total runoff depth (cm)			1.79

Event 4 (28.08.1970)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	10.50	18900.00
3	2	13.50	43200.00
4	3	31.00	80100.00
5	4	69.00	180000.00
6	5	102.00	307800.00
7	6	114.00	388800.00
8	7	100.50	386100.00
9	8	81.50	327600.00
10	9	65.00	263700.00
11	10	55.00	216000.00
12	11	42.00	174600.00
13	12	35.50	139500.00
14	13	31.50	120600.00
15	14	27.00	105300.00
16	15	23.00	90000.00
17	16	19.50	76500.00
18	17	16.00	63900.00
19	18	12.50	51300.00
20	19	8.00	36900.00
21	20	5.00	23400.00
22	21	2.00	12600.00
23	22	0.00	3600.00
Total runoff volume (m^3)			3110400
Total runoff depth (cm)			2.72

Event 5 (02.08.1971)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	3.00	5400.00
3	2	5.00	14400.00
4	3	19.00	43200.00
5	4	39.00	104400.00
6	5	62.00	181800.00
7	6	89.00	271800.00
8	7	118.00	372600.00
9	8	99.00	390600.00
10	9	77.00	316800.00
11	10	55.00	237600.00
12	11	46.00	181800.00
13	12	35.00	145800.00
14	13	26.00	109800.00
15	14	21.00	84600.00
16	15	18.00	70200.00
17	16	13.00	55800.00
18	17	10.00	41400.00
19	18	8.00	32400.00
20	19	6.00	25200.00
21	20	4.00	18000.00
22	21	2.00	10800.00
23	22	1.00	5400.00
24	23	0.00	1800.00
Total runoff volume (m^3)			2721600
Total runoff depth (cm)			2.38

Event 6 (31.08.1971)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	19.00	34200.00
3	2	38.00	102600.00
4	3	65.00	185400.00
5	4	86.00	271800.00
6	5	109.00	351000.00
7	6	131.00	432000.00
8	7	120.00	451800.00
9	8	88.00	374400.00
10	9	65.00	275400.00
11	10	50.00	207000.00
12	11	40.00	162000.00
13	12	30.00	126000.00
14	13	24.00	97200.00
15	14	19.00	77400.00
16	15	16.00	63000.00
17	16	11.00	48600.00
18	17	8.00	34200.00
19	18	5.00	23400.00
20	19	2.00	12600.00
21	20	0.00	3600.00
Total runoff volume (m^3)			3333600
Total runoff depth (cm)			2.92

Event 7 (17.10.1971)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	2.00	3600.00
3	2	5.00	12600.00
4	3	13.00	32400.00
5	4	35.00	86400.00
6	5	53.00	158400.00
7	6	78.00	235800.00
8	7	89.00	300600.00
9	8	79.00	302400.00
10	9	63.00	255600.00
11	10	50.00	203400.00
12	11	40.00	162000.00
13	12	32.00	129600.00
14	13	26.00	104400.00
15	14	22.00	86400.00
16	15	19.00	73800.00
17	16	15.00	61200.00
18	17	12.00	48600.00
19	18	9.00	37800.00
20	19	7.00	28800.00
21	20	5.00	21600.00
22	21	3.00	14400.00
23	22	1.00	7200.00
24	23	0.00	1800.00
Total runoff volume (m^3)			2368800
Total runoff depth (cm)			2.07

Event 8 (28.08.1972)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	17.00	30600.00
3	2	24.00	73800.00
4	3	38.00	111600.00
5	4	54.00	165600.00
6	5	80.00	241200.00
7	6	108.00	338400.00
8	7	115.00	401400.00
9	8	108.00	401400.00
10	9	99.00	372600.00
11	10	78.00	318600.00
12	11	59.00	246600.00
13	12	47.00	190800.00
14	13	41.00	158400.00
15	14	35.00	136800.00
16	15	30.00	117000.00
17	16	25.00	99000.00
18	17	21.00	82800.00
19	18	17.00	68400.00
20	19	13.00	54000.00
21	20	9.00	39600.00
22	21	6.00	27000.00
23	22	3.00	16200.00
24	23	0.00	5400.00
Total runoff volume (m^3)			3697200
Total runoff depth (cm)			3.24

Event 9 (21.07.1973)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	0.00	0.00
3	2	8.00	14400.00
4	3	87.00	171000.00
5	4	225.00	561600.00
6	5	305.00	954000.00
7	6	227.00	957600.00
8	7	155.00	687600.00
9	8	110.00	477000.00
10	9	70.00	324000.00
11	10	57.00	228600.00
12	11	45.00	183600.00
13	12	37.00	147600.00
14	13	22.00	106200.00
15	14	18.00	72000.00
16	15	11.00	52200.00
17	16	9.00	36000.00
18	17	7.00	28800.00
19	18	2.00	16200.00
20	19	0.00	3600.00
Total runoff volume (m^3)			5022000
Total runoff depth (cm)			4.40

Event 10 (30.08.1973)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	6.00	10800.00
3	2	15.10	37980.00
4	3	24.24	70812.00
5	4	303.00	589032.00
6	5	472.70	1396260.00
7	6	557.60	1854540.00
8	7	575.75	2040030.00
9	8	557.60	2040030.00
10	9	524.20	1947240.00
11	10	490.90	1827180.00
12	11	463.64	1718172.00
13	12	424.24	1598184.00
14	13	381.82	1450908.00
15	14	333.33	1287270.00
16	15	303.00	1145394.00
17	16	266.67	1025406.00
18	17	242.42	916362.00
19	18	200.00	796356.00
20	19	175.75	676350.00
21	20	145.40	578070.00
22	21	103.00	447120.00
23	22	66.67	305406.00
24	23	39.40	190926.00
25	24	18.20	103680.00
26	25	12.00	54360.00
27	26	11.50	42300.00
28	27	6.60	32580.00
29	28	6.00	22680.00
30	29	3.00	16200.00
31	30	0.00	5400.00
Total runoff volume (m^3)			24227028
Total runoff depth (cm)			21.21

Event 11 (5.9.1973)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0	0.00
2	1	18	32400.00
3	2	92	198000.00
4	3	127	394200.00
5	4	121	446400.00
6	5	104.5	405900.00
7	6	73	319500.00
8	7	50	221400.00
9	8	34.8	152640.00
10	9	23.6	105120.00
11	10	15.7	70740.00
12	11	7.3	41400.00
13	12	0	13140.00
Total runoff volume (m^3)			2400840
Total runoff depth (cm)			2.10

Table F3: Six Runoff event of Umar watershed

Event 1 (23.07.1962)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	3.00	5400.00
3	2	6.00	16200.00
4	3	9.00	27000.00
5	4	15.00	43200.00
6	5	16.40	56520.00
7	6	19.40	64440.00
8	7	22.40	75240.00
9	8	30.50	95220.00
10	9	45.50	136800.00
11	10	52.20	175860.00
12	11	62.70	206820.00
13	12	73.80	245700.00
14	13	79.80	276480.00
15	14	96.30	316980.00
16	15	97.00	347940.00
17	16	97.00	349200.00
18	17	100.00	354600.00
19	18	103.00	365400.00
20	19	110.40	384120.00
21	20	126.10	425700.00
22	21	131.30	463320.00
23	22	156.70	518400.00
24	23	175.40	597780.00
25	24	158.20	600480.00
26	25	140.30	537300.00
27	26	103.00	437940.00
28	27	82.00	333000.00
29	28	71.60	276480.00
30	29	61.20	239040.00
31	30	61.20	220320.00
32	31	41.80	185400.00
33	32	40.00	147240.00
34	33	27.00	120600.00
35	34	15.00	75600.00
36	35	0.00	27000.00
Total runoff volume (m^3)			8748720
Total runoff depth (cm)			3.91

Event 2 (05.09.1962)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume
1	0	0.00	0.00
2	1	1.70	3060.00
3	2	3.50	9360.00
4	3	5.50	16200.00
5	4	11.70	30960.00
6	5	20.50	57960.00
7	6	50.00	126900.00
8	7	72.20	219960.00
9	8	100.00	309960.00
10	9	124.40	403920.00
11	10	130.50	458820.00
12	11	133.30	474840.00
13	12	117.80	451980.00
14	13	86.70	368100.00
15	14	60.00	264060.00
16	15	38.90	178020.00
17	16	28.90	122040.00
18	17	23.30	93960.00
19	18	18.90	75960.00
20	19	16.10	63000.00
21	20	14.20	54540.00
22	21	12.10	47340.00
23	22	12.10	43560.00
24	23	10.00	39780.00
25	24	8.90	34020.00
26	25	8.90	32040.00
27	26	8.90	32040.00
28	27	8.80	31860.00
29	28	8.80	31680.00
30	29	8.30	30780.00
31	30	7.80	28980.00
32	31	7.70	27900.00
33	32	6.40	25380.00
34	33	5.50	21420.00
35	34	4.40	17820.00
36	35	3.30	13860.00
37	36	2.80	10980.00
38	37	1.70	8100.00
39	38	0.00	3060.00
Total runoff volume (m^3)			4264200
Total runoff depth (cm)			1.91

Event 3 (20.07.1964)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	2.20	3960.00
3	2	4.50	12060.00
4	3	5.50	18000.00
5	4	7.80	23940.00
6	5	17.80	46080.00
7	6	23.30	73980.00
8	7	36.70	108000.00
9	8	46.70	150120.00
10	9	90.00	246060.00
11	10	103.90	349020.00
12	11	100.00	367020.00
13	12	76.70	318060.00
14	13	38.90	208080.00
15	14	27.80	120060.00
16	15	18.30	82980.00
17	16	13.10	56520.00
18	17	5.50	33480.00
19	18	0.00	9900.00
Total runoff volume (m^3)			2227320
Total runoff depth (cm)			1.00

Event 4 (14.08.1964)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	18.90	34020.00
3	2	32.20	91980.00
4	3	50.00	147960.00
5	4	130.30	324540.00
6	5	123.90	457560.00
7	6	102.20	406980.00
8	7	81.10	329940.00
9	8	64.40	261900.00
10	9	42.20	191880.00
11	10	28.90	127980.00
12	11	17.80	84060.00
13	12	7.80	46080.00
14	13	0.00	14040.00
Total runoff volume (m^3)			2518920
Total runoff depth (cm)			1.13

Event 5 (30.08.1965)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	19.50	35100.00
3	2	39.00	105300.00
4	3	100.00	250200.00
5	4	300.00	720000.00
6	5	390.00	1242000.00
7	6	439.00	1492200.00
8	7	500.00	1690200.00
9	8	541.50	1874700.00
10	9	531.70	1931760.00
11	10	463.00	1790460.00
12	11	390.20	1535760.00
13	12	312.20	1264320.00
14	13	253.70	1018620.00
15	14	195.10	807840.00
16	15	141.50	605880.00
17	16	97.60	430380.00
18	17	73.00	307080.00
19	18	48.80	219240.00
20	19	46.30	171180.00
21	20	36.60	149220.00
22	21	33.20	125640.00
23	22	24.40	103680.00
24	23	22.00	83520.00
25	24	17.00	70200.00
26	25	14.60	56880.00
27	26	13.60	50760.00
28	27	10.20	42840.00
29	28	5.00	27360.00
30	29	4.40	16920.00
31	30	0.00	7920.00
Total runoff volume (m^3)			18227160
Total runoff depth (cm)			8.15

Event 6 (07.09.1965)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	1.00	1800.00
3	2	2.20	5760.00
4	3	3.50	10260.00
5	4	4.40	14220.00
6	5	5.30	17460.00
7	6	8.90	25560.00
8	7	11.10	36000.00
9	8	22.20	59940.00
10	9	44.40	119880.00
11	10	68.90	203940.00
12	11	97.70	299880.00
13	12	115.50	383760.00
14	13	151.10	479880.00
15	14	182.20	599940.00
16	15	200.00	687960.00
17	16	231.10	775980.00
18	17	288.90	936000.00
19	18	333.30	1119960.00
20	19	426.70	1368000.00
21	20	466.70	1608120.00
22	21	544.40	1819980.00
23	22	533.30	1939860.00
24	23	493.30	1847880.00
25	24	471.10	1735920.00
26	25	466.50	1687680.00
27	26	457.80	1663740.00
28	27	448.90	1632060.00
29	28	431.10	1584000.00
30	29	408.90	1512000.00
31	30	393.30	1443960.00
32	31	373.30	1379880.00
33	32	351.10	1303920.00
34	33	311.10	1191960.00
35	34	240.00	991980.00
36	35	204.40	799920.00
37	36	155.50	647820.00
38	37	106.70	471960.00
39	38	66.70	312120.00
40	39	22.20	160020.00
41	40	8.90	55980.00
42	41	0.00	16020.00
Total runoff volume (m^3)			32952960
Total runoff depth (cm)			14.73

Table F4: Six Runoff event of Kolar watershed

Event 1 (28.08.1983)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	5.00	9000.00
3	2	15.50	36900.00
4	3	145.40	289620.00
5	4	362.00	913320.00
6	5	690.00	1893600.00
7	6	2800.00	6282000.00
8	7	4035.00	12303000.00
9	8	4724.00	15766200.00
10	9	4795.00	17134200.00
11	10	4871.40	17399520.00
12	11	4744.00	17307720.00
13	12	4617.00	16849800.00
14	13	4472.00	16360200.00
15	14	4326.00	15836400.00
16	15	4180.00	15310800.00
17	16	4000.00	14724000.00
18	17	3890.50	14202900.00
19	18	3600.00	13482900.00
20	19	1960.00	10008000.00
21	20	980.00	5292000.00
22	21	760.00	3132000.00
23	22	630.00	2502000.00
24	23	500.00	2034000.00
25	24	400.00	1620000.00
26	25	325.00	1305000.00
27	26	276.00	1081800.00
28	27	232.00	914400.00
29	28	218.00	810000.00
30	29	167.00	693000.00
31	30	150.00	570600.00
32	31	145.00	531000.00
33	32	123.00	482400.00
34	33	109.00	417600.00
35	34	87.00	352800.00
36	35	80.00	300600.00
37	36	0.00	144000.00
Total runoff volume (m^3)			228293280
Total runoff depth (cm)			25.26

Event 2 (10.08.1984)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	0.00	0.00
3	2	36.36	65448.00
4	3	72.72	196344.00
5	4	200.00	490896.00
6	5	400.00	1080000.00
7	6	618.18	1832724.00
8	7	1054.55	3010914.00
9	8	1527.27	4647276.00
10	9	1981.82	6316362.00
11	10	2032.60	7225956.00
12	11	1872.73	7029594.00
13	12	1636.36	6316362.00
14	13	1581.82	5792724.00
15	14	1654.55	5825466.00
16	15	1363.64	5432742.00
17	16	1036.36	4320000.00
18	17	854.55	3403638.00
19	18	563.64	2552742.00
20	19	327.30	1603692.00
21	20	200.00	949140.00
22	21	72.73	490914.00
23	22	36.36	196362.00
24	23	18.20	98208.00
25	24	0.00	32760.00
Total runoff volume (m^3)			68910264
Total runoff depth (cm)			7.62

Event 3 (31.07.1985)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume
1	0	0.00	0.00
2	1	18.20	32760.00
3	2	72.73	163674.00
4	3	181.82	458190.00
5	4	309.09	883638.00
6	5	572.73	1587276.00
7	6	836.36	2536362.00
8	7	1090.91	3469086.00
9	8	1293.00	4291038.00
10	9	1282.87	4636566.00
11	10	1272.73	4600080.00
12	11	1258.20	4555674.00
13	12	1236.36	4490208.00
14	13	1200.00	4385448.00
15	14	1145.45	4221810.00
16	15	1036.36	3927258.00
17	16	472.73	2716362.00
18	17	181.82	1178190.00
19	18	174.55	641466.00
20	19	145.45	576000.00
21	20	138.20	510570.00
22	21	127.27	477846.00
23	22	121.21	447264.00
24	23	115.15	425448.00
25	24	109.09	403632.00
26	25	103.03	381816.00
27	26	96.97	360000.00
28	27	90.91	338184.00
29	28	84.85	316368.00
30	29	78.79	294552.00
31	30	72.73	272736.00
32	31	60.61	240012.00
33	32	48.49	196380.00
34	33	36.37	152748.00
35	34	24.24	109098.00
36	35	12.12	65448.00
37	36	0.00	21816.00
Total runoff volume (m^3)			54365004
Total runoff depth (cm)			6.01

Event 4 (13.08.1985)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	8.00	14400.00
3	2	20.00	50400.00
4	3	28.00	86400.00
5	4	32.00	108000.00
6	5	40.00	129600.00
7	6	48.00	158400.00
8	7	1120.00	2102400.00
9	8	1140.00	4068000.00
10	9	1200.00	4212000.00
11	10	1220.00	4356000.00
12	11	1381.70	4683060.00
13	12	1240.00	4719060.00
14	13	1040.00	4104000.00
15	14	820.00	3348000.00
16	15	600.00	2556000.00
17	16	400.00	1800000.00
18	17	220.00	1116000.00
19	18	140.00	648000.00
20	19	88.00	410400.00
21	20	80.00	302400.00
22	21	60.00	252000.00
23	22	53.33	203994.00
24	23	46.67	180000.00
25	24	40.00	156006.00
26	25	38.00	140400.00
27	26	36.00	133200.00
28	27	34.00	126000.00
29	28	32.00	118800.00
30	29	30.00	111600.00
31	30	28.00	104400.00
32	31	22.40	90720.00
33	32	16.80	70560.00
34	33	11.20	50400.00
35	34	5.60	30240.00
36	35	0.00	10080.00
Total runoff volume (m^3)			40750920
Total runoff depth (cm)			4.51

Event 5 (15.08.1986)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	15.00	27000.00
3	2	112.00	228600.00
4	3	220.00	597600.00
5	4	400.00	1116000.00
6	5	520.00	1656000.00
7	6	680.00	2160000.00
8	7	860.00	2772000.00
9	8	1080.00	3492000.00
10	9	1600.00	4824000.00
11	10	1900.00	6300000.00
12	11	1968.10	6962580.00
13	12	1940.00	7034580.00
14	13	1620.00	6408000.00
15	14	1000.00	4716000.00
16	15	680.00	3024000.00
17	16	320.00	1800000.00
18	17	248.00	1022400.00
19	18	200.00	806400.00
20	19	190.00	702000.00
21	20	168.00	644400.00
22	21	160.00	590400.00
23	22	153.33	563994.00
24	23	146.67	540000.00
25	24	140.00	516006.00
26	25	136.67	498006.00
27	26	133.33	486000.00
28	27	130.00	473994.00
29	28	126.67	462006.00
30	29	123.33	450000.00
31	30	120.00	437994.00
32	31	100.00	396000.00
33	32	80.00	324000.00
34	33	60.00	252000.00
35	34	40.00	180000.00
36	35	20.00	108000.00
37	36	0.00	36000.00
Total runoff volume (m^3)			62607960
Total runoff depth (cm)			6.93

Event 6 (27.08.1987)			
Sl No.	Time, hr	Discharge m^3/s	Runoff volume m^3
1	0	0.00	0.00
2	1	2.00	3600.00
3	2	4.00	10800.00
4	3	12.00	28800.00
5	4	881.30	1607940.00
6	5	840.00	3098340.00
7	6	770.00	2898000.00
8	7	650.00	2556000.00
9	8	380.00	1854000.00
10	9	290.00	1206000.00
11	10	200.00	882000.00
12	11	150.00	630000.00
13	12	106.00	460800.00
14	13	84.00	342000.00
15	14	76.00	288000.00
16	15	50.00	226800.00
17	16	44.00	169200.00
18	17	40.00	151200.00
19	18	32.00	129600.00
20	19	24.00	100800.00
21	20	20.00	79200.00
22	21	13.33	59994.00
23	22	6.67	36000.00
24	23	0.00	12006.00
Total runoff volume (m^3)			16831080
Total runoff depth (cm)			1.86

Table F5: q_p/V^2 data of Temur watershed (A=518.67 km^2)

Sl.No.	Event	Runoff Volume Q m^3	Peak discharge Q_p, m^3/sec	T_p hrs	Runoff volume V, cm	$q_p = Q_p/A$ cm/hr	q_p/V^2 cm/hr/cm^2
1	23.07.1962	5624568.00	181.23	10.00	1.08	0.13	0.11
2	05.09.1962	3497724.00	135.92	6.00	0.67	0.09	0.21
3	20.07.1964	6868404.00	214.93	8.00	1.32	0.15	0.09
4	14.08.1964	4195476.00	124.59	9.00	0.81	0.09	0.13
5	30.08.1965	1367856.00	58.16	8.00	0.26	0.04	0.60
6	07.09.1965	1594980.00	59.50	6.00	0.31	0.04	0.43
7	24.08.1961		430.39	8.00	4.75	0.30	0.01

Table F6: q_p/V^2 data of Teriya watershed (A=114.22 km^2)

Sl.No.	Event	Runoff Volume Q m^3	Peak discharge Q_p, m^3/sec	T_p hrs	Runoff volume V, cm	$q_p = Q_p/A$ cm/hr	q_p/V^2 cm/hr/cm^2
1	31.07.1967	4932000.00	161.00	5.00	4.32	0.51	0.027
2	13.08.1970	1699200.00	120.00	5.00	1.49	0.38	0.171
3	16.08.1970	2046600.00	82.50	5.00	1.79	0.26	0.081
4	28.08.1970	3110400.00	114.00	6.00	2.72	0.36	0.048
5	02.08.1971	2721600.00	118.00	7.00	2.38	0.37	0.066
6	31.08.1971	3333600.00	131.00	6.00	2.92	0.41	0.048
7	17.10.1971	2368800.00	89.00	7.00	2.07	0.28	0.065
8	28.08.1972	3697200.00	108.00	8.00	2.04	0.34	0.081
9	21.07.1973	5022000.00	305.00	5.00	4.40	0.96	0.050
10	30.08.1973	24227208.00	575.00	7.00	21.21	1.81	0.004
11	05.09.1973	2402280.00	127.00	3.00	2.10	0.40	0.090

Table F7: q_p/V^2 data of Umar watershed (A=223.77 km^2)

Sl.No.	Event	Runoff Volume Q m^3	Peak discharge Q_p, m^3/sec	T_p hrs	Runoff volume V, cm	$q_p = Q_p/A$ cm/hr	q_p/V^2 cm/hr/cm^2
1	23.07.1962	8748720.00	175.40	23.00	3.91	0.28	0.018
2	05.09.1962	4264200.00	133.30	11.00	1.91	0.21	0.059
3	20.07.1964	2227320.00	103.90	10.00	1.00	0.17	0.169
4	14.08.1964	2518920.00	130.30	4.00	1.13	0.21	0.165
5	30.08.1965	18227160.00	541.50	8.00	8.15	0.87	0.013
6	07.09.1965	32952960.00	544.40	21.00	14.73	0.88	0.004

Table F8: q_p/V^2 data of Kolar watershed (A=903.88 km^2)

Sl.No.	Event	Runoff Volume Q m^3	Peak discharge Q_p, m^3/sec	T_p hrs	Runoff volume V, cm	$q_p = Q_p/A$ cm/hr	q_p/V^2 cm/hr/cm^2
1	28.08.1983	228293280.00	4871.40	10	24.01	1.94	0.003
2	10.08.1984	68910264.00	2032.63	10	7.44	0.81	0.015
3	31.07.1985	54364950.00	1293.00	8	5.22	0.51	0.019
4	13.08.1985	40750920.00	1381.70	11	4.47	0.55	0.028
5	15.08.1986	62607960.00	1968.10	11	6.54	0.78	0.018
6	27.08.1987	16831080.00	881.35	4	1.72	0.35	0.119