GROUNDWATER AUGMENTATION PLAN FOR A DEGRADED WESTERN GHAT TERRAIN USING REMOTE SENSING AND GIS

By

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THESIS

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DECLARATION

I hereby declare that this thesis entitled **'GROUNDWATER AUGMENTATION PLAN FOR A DEGRADED WESTERN GHAT TERRAIN USING REMOTE SENSING AND GIS'** is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title of any other University or Society.

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CERTIFICATE

Certified that this thesis entitled **'GROUNDWATER AUGMENTATION PLAN FOR A DEGRADED WESTERN GHAT TERRAIN USING REMOTE SENSING AND GIS'** is a record of research work done independently by **Sri.Sooraj Kannan, P.V.**, under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

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SYMBOLS AND ABBREVIATIONS

Abbreviations	Expansion
AET	Actual Evapotranspiration
AHADS	Attappady Hill Area Development Society
AMC	Antecedent Moisture Content
APWL	Accumulated Potential Water Loss
AWC	Available Water Holding Capacity
BFI	Base Flow Index
CGWB	Central Ground Water Board
CN	Curve Number
CWRDM	Center for Water Resource Development and Management
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ESRI	Environmental Sciences Research Institute
FCC	False Colour Composite
GIS	Geographic Information System
GPS	Global Positioning System
GWR	Ground Water Recharge
HSG	Hydrological Soil Group
ILWIS	Integrated Land and Water Information System
IRS	Indian Remote Sensing Satellite
LISS	Linear Imaging Self-Scanning
Mm3	Million Cubic Metre
NRCS	Natural Resource Conservation Service
PRMS	Precipitation Runoff Modeling System
PWP	Permanent Wilting Point
SCS	Soil Conservation Service
SOI	Survey of India
TIN	Triangulated Irregular Network
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
WGS	World Geodetic Survey

INTRODUCTION

CHAPTER I

INTRODUCTION

Land and water are the two important and crucial natural resources, supporting all forms of life on earth. Availability of water, of course, varies with space and time. As the demand on water is steadily on the increase, it is rapidly becoming more and more a scarce resource. The imbalance between demand and supply, resource degradation and competition calls for new approaches for water harvesting and management.

Groundwater accounts for a major portion of the world's freshwater resources. Estimates of the global water supply show groundwater as 0.6 percent of the world's total water and 60 percent of the available fresh water resources. The total volume of readily available global groundwater is about 4.2 x 10^9 MCM as compared to 0.126 x 10^9 MCM stored in lakes and streams. Thus in the global hydrologic cycle, groundwater reservoirs are the largest source for fresh water, next only to glaciers and icecaps that do not have readily available water.

In India, more than 90% of rural and nearly 30% of urban population depends on groundwater for meeting their drinking and domestic requirements. In addition, it accounts nearly 60% of the irrigation potential created in the country. Surface water may not be available everywhere, while groundwater is more widely distributed and can be extracted through simple means. The rapid and accelerated urbanisation and industrialisation in the country has led to the decline of groundwater level in some regions and consequent stress on groundwater resource. Technological developments in construction of deep wells and pumping devices have also contributed to large-scale exploitation of groundwater from both shallow and deep aquifers. The growth of groundwater abstraction structure from 1950 to 1990 clearly depicts the increasing use of groundwater in domestic, industrial and agricultural sectors. As per available statistics, the number of dug wells increased from 38.6 lakhs (1951) to 94.9 lakhs (1990) and the shallow tube wells from 3000 (1951) to 47.5 lakhs (1990) (Muralidharan and Athvale, 1998). India has substantial water resources. The average annual rainfall is about 1150 mm, but it is unevenly distributed spatially from 100 mm in Rajasthan to 11000 mm in Chirappunji. The total surface flow is about 195 Mha-m of which 69 Mha-m is the utilizable part. The available ground water for irrigation is about 36 Mha-m of which about 11.5 Mha-m is utilised. In many parts of India, especially in arid and semi arid regions, dependence on groundwater resource has increased tremendously in the recent years due to vagarities of monsoon and scarcity of surface water. On the other hand, rapid urbanization and land use changes has drastically decreased the infiltration rate and thereby diminished the natural recharging of aquifers by rainfall.

Kerala State in Indian peninsula enjoys a humid tropic climate. But, being densely populated, it is facing problems like drying up of wells and groundwater pollution due to increased water demand and consequent over-exploitation of groundwater. Despite the incidence of high annual rainfall (3100mm) and a large number of rivers (44 No), the hill tracts and elevated areas along the mid lands of the state experience drought of different order, during summer. This is due to the peculiarity of the terrain characteristics, which promotes high runoff and is therefore hydro-geologically unfavourable for natural groundwater recharge. The recurring incidents of drying up of streams and rivers not only result in the non availability of water resources but also create many environmental problems such as saline water intrusion in the coastal area and general ecological degradation and regional drought.

1.1 Groundwater management: Basin approach

A groundwater basin is defined as a physiographic unit containing one or several connected and interrelated aquifers (Todd, 1980). Groundwater basins can be demarcated using hydro-geologic boundaries like hill ranges, rivers, deep drainage channels, or any other groundwater divides. The occurrence and movements of groundwater is confined to these independent hydrologic units (Murty, 2004). The groundwater basin closely coincides with the drainage basin of a surface stream. The concept of groundwater basin has become important in the recent past. By visualising groundwater basin as a large natural underground reservoir, it is clear that over development of groundwater in one portion of a basin directly affects water supplies throughout the remainder of the basin. This has led to basin-wide planning and development of groundwater. In order to maintain sustainability, a hydrologic equilibrium must exist between all waters entering and leaving the basin. At the same time, economic, quality and legal aspects should be considered.

1.2 Artificial recharge

The imbalance between the rapid and excessive discharge and slow and deficient recharge of the groundwater is the prime reason for the declining of groundwater level. The principal source of replenishment to groundwater is rainfall, which is limited to monsoon months. The sloping high range terrain of the state is not supporting the natural groundwater recharge from the rainfall. Two third of the Indian territory is covered with hard rocks. In hard rocks, primary porosity is absent and rainfall recharge is taking place through secondary porosity. Natural recharge taking place annually in these areas is 5-10 %. In order to arrest the depletion in groundwater potential and to achieve sustainable development, several measures, including artificial recharge are suggested. Artificial recharge is the process of augmenting the movement of surface water into under ground formations by various measures of interventions. Augmentation of ground water resources through artificial recharging of aquifers, which supplements the natural process of recharging, has become relevant for situations prevailing in India, where the rainfall is seasonal and is not spread uniformly across the country, and the quantum of natural recharge is inadequate to meet the increasing demand of groundwater resource. The essential requirements of artificial recharge planning are availability of non committed run-off, suitable site selection and site specific design of recharge structures.

1.3 Suitable site selection for recharge

Recharging will be effective only if the shallow subsurface and underground formation has enough space to hold water that is recharged in to it. Porosity and water holding and releasing capacity of formations and geological structures vary with the presence of lineaments, fractures and folds. Similarly, the surface soil properties like infiltration capacity, terrain slope, drainage density etc. determines the infiltration opportunity time and thereby recharge rate to the aquifer material.

The stability of terrain should be assessed before constructing any recharge structures to avoid risks of landslide. Hence, selection of suitable recharge-site is an important step in the artificial recharge planning. It involves analysis of large number of multidisciplinary data. Selection of site depends of several factors including geology, geomorphology, soil type and characteristics, slope, availability of non-committed runoff etc. Remote sensing, photo-geological, hydro-geological and geophysical methods are deployed to select favourable sites for implementation of artificial recharge structures.

1.4 Remote Sensing and GIS in groundwater

Remote sensing and GIS have emerged as useful techniques for watershed characterisation, assessing watershed processes, conservation planning and management in recent times. The interpretation of satellite data in conjunction with sufficient ground truth information makes it possible to identify and outline various ground features such as geology, structure, geomorphic features and their hydraulic characteristics (Das, *et.al.,*1997), that may serve as direct or indirect indications of the presence of groundwater (Ravindran and Jayaram, 1997). Modern remote sensing techniques facilitate demarcation of suitable areas for groundwater replenishment by taking into account the diversity of factors that influences groundwater recharge. Geology, geomorphology, structure and climatic condition are the controlling factors of ground water storage, occurrence and movement in hard rock terrain. These features cannot be observed on the surface by bare eyes but can be picked up through satellite remote sensing with reasonable accuracy. Better interpretation of hydrogeological data often requires that their spatial reference be incorporated to the analysis. Geographic Information System (GIS) can be used for storing hydrogeologic data as well as their spatial locations in relational database (Shahid and Nath, 2000). GIS, being a computerised data base management system for capture, storage, retrieval, analysis and display of spatially referenced data, is a powerful tool for spatial planning and resource management. . It provides the facility to analyse the spatial data objectively using various logical conditions. As a result, GIS is widely used in these days for spatial modelling of hydrogeological processes of a large area with more ease and reliability. As groundwater management involves large number of multi disciplinary data, decision making through integration and analysis is a tedious task. With its data integration capability, GIS can simplify the integration and analysis of spatially correlated multidisciplinary data. Hence, a study has been conducted in the field of groundwater management with the following objectives.

1.5 Objectives

The specific objectives of this study were the following

1. To estimate the natural recharge in the Siruvani watershed of Bhavani river basin.
2. To formulate a GIS based methodology for identification of suitable areas for artificial groundwater recharge.
3. To delineate the suitable areas for groundwater recharge measures in the Siruvani sub basin.
4. To suggest location specific artificial recharge structures.

REVIEW OF LITERATURE

CHAPTER II

REVIEW OF LITERATURE

Being the natural hydrological unit, watershed based groundwater management is getting more acceptances nowadays. For effectively planning basin wide groundwater management schemes, analysis of a large number of spatially and temporally varying multi disciplinary data are required which is very laborious and time consuming. Remote sensing and GIS are effective tools to generate, analyse, and display these multi disciplined spatially correlated data.

In the last several decades, methodologies have been developed and studies have been conducted for effective groundwater management using remote sensing and GIS. In this chapter, research efforts carried out in India and abroad related to the objective of this study have been reviewed and briefly presented.

2.1 Application of remote sensing and GIS in groundwater studies

A drainage density map has been generated by Das and Kadar (1997) integrating various thematic maps derived from both remote sensing and conventional methods. Satellite imageries of visible to near infrared region of electromagnetic spectrum are very much useful in extracting information on areal aspects of drainage basins and various hydro-geo-morphological features. Using IRS LISS II geocoded FCC's on 1150,000 scale and other collateral data, Sreenivasan *et. al.*,(2000) had generated the thematic maps of geomorphology, geology, soil structure, land use and land cover of Ramganj Mandi tehsil area of Kota district.

Das *et.al.*, (2000) identified groundwater exploration and artificial recharge area in Sali river basin, Bankura district of West Bengal using the GIS softwares *ARC/INFO* and ILWIS 2.1. They found that spatial integration using GIS is very helpful in assessing the groundwater resource. Geologic, land form, drainage and geomorphic condition of the area are analysed. The IRS 1B LISS II FCC data and SOI topographic sheets are used as base maps. Weighted overlay analysis was done for delineating the recharge suitable areas in the catchment.

Singh *et. al.* (2000) identified groundwater potential zones in hard rock areas through integration of different thematic layers / maps in GIS environment. To find out the more realistic ground water potential map of the area, the relevant layers which include hydrogeomorphology, lineament, slope, drainage, overburden thickness and aquifer thickness were integrated in *Arc/Info* grid environment. Criteria for GIS analysis have been defined on the basis of ground water conditions and appropriate weightage has been assigned to each information layer according to relative contribution towards the desired output. The ground water potential zone map generated through the integration, was verified with the water yield data to ascertain the validity of this map. The verification showed that the ground water potential zones identified through the integration are in agreement with the bore well yield.

A groundwater prospect map was generated by Pratap *et. al.*, (2001) integrating various thematic maps derived from both remote sensing and conventional means in the Dala Renukoot area in Sonebhandra district in Uttar Pradesh using GIS.

A ground water map of Uma-Kalhar watershed in Chandrapur district was generated by Adiga *et.al.* (2001). The thematic maps of lithology, landforms, structure, land use, and depth of water table, depth to hard rock, well yield, and socio-economic parameters have been generated on 150,000 scale using LISS III satellite data and other collateral information and put as database in *Arc/Info.*

Satellite remote sensing has become an effective tool for a number of applications related to water resource development. Remote sensing techniques can replace, supplement or compliment the existing system of information generation (Goel, 2002). Space technology outputs have been successful in decision making processes such as water resource assessment, flood management, irrigation water management, groundwater targeting etc. GIS, being a management system for spatially correlated data, can help in analysing and integrating large number of multi disciplinary geographic data and in presenting the results in a map form. Studies carried out by various people in different geographic regions show the applicability of remote sensing and GIS in groundwater resource.

Ramasamy *et. al.*, (2004) identified potential sites in Tamil Nadu State, for groundwater recharge by using a GIS based study. The study provided an overview on the vistas on the spatial technologies in various aspects of groundwater management. A Study for locating areas for groundwater recharge was conducted by Bharadwaj (2004) at Western and South Western parts of NCT-Delhi. From the analysis of DEM, drainage network and subsurface lithology, it has been found that the natural depressions in alluvial plain and areas of medium to gentle topographic gradient with high infiltration rates are the ideal sites for effective fresh groundwater recharge.

2.2 Estimation of natural groundwater recharge

Rainfall is the principal means for replenishment of moisture in the soil water system and recharge to ground water. Moisture movement in the unsaturated zone is controlled by capillary pressure and hydraulic conductivity. The amount of moisture that will eventually reach the water table is defined as natural ground water recharge. The amount of this recharge depends upon the rate and duration of rainfall, the subsequent conditions at the upper boundary, the antecedent soil moisture conditions, the water table depth and the soil type.

Quantification of ground water recharge is a complex function of meteorological conditions, soil, vegetation, physiographic characteristics and properties of the geologic material within the paths of flow. Soil layering in the unsaturated zone plays an important role in facilitating or restricting downward water movement to the water table. Also, the depth to the water table is important in ground water recharge estimations. Recharge estimation can be based on a wide variety of models which are designed to represent the actual physical processes. Methods which are currently in use include soil water balance method (soil moisture budget),zero flux plane method, one-dimensional soil water flow model, two-dimensional ground water flow model, saturated volume fluctuation method (ground water balance) and isotope techniques and solute profile techniques. The two-dimensional ground water flow model and the saturated volume fluctuation method are regarded as indirect methods, because groundwater levels are used to determine the recharge.

2.2.1 Water balance model

Water balance models were developed in the 1940s by Thornthwaite (1948) and revised by Thornthwaite and Mather (1955). The method is essentially a book-keeping procedure which estimates the balance between the inflow and outflow of water. By knowing the precipitation, evapotranspiration, runoff from the watershed and volumetric change in soil moisture storage, groundwater recharge can be estimated. Precipitation data are collected from various meteorological stations around and within the watershed. Runoff is estimated using Soil Conservation Service's (formerly SCS, now NRCS (SCS, 1985)) curve number method and potential evapotranspiration is estimated using Penman model. The runoff curve number method for the estimation of direct runoff from storm rainfall is well established in hydrologic engineering. Its popularity is due to its convenience, simplicity and responsiveness to catchment properties including soil type, land use and treatment, surface conditions and antecedent moisture condition. Penman's Equation (Penman, 1948, 1956, 1963) was adopted to estimate the Potential evapotranspiration. Penman's Equation is based on sound theoretical reasoning and is obtained by a combination of the Energy-balance and Mass transfer approach. Soil moisture content is measured directly from field and storage change is calculated.

An analytical solution for the rise, decline and maximum height of the water table, as well as growth and decay of groundwater mounds in an unconfined aquifer was developed by Sophocleous (1974). He concluded that aquifer receives either time varying or uniform vertical recharge with constant hydraulic conductivity and specific yield.

Steenhuis *et. al.* (1985) estimated the groundwater recharge on eastern long islands, New York, USA by two methods. The first method tested consists of measuring recharge with a direct application of Darcy's law in the vadose zone and the second by calculating recharge by closure of the hydrologic budget equation with evaporation computed from micrometeorological data.

Johansson (1987) applied two methods for estimation of groundwater recharge both based on groundwater level fluctuations. These methods were applied in a moraine area in south eastern Sweden. The first method utilised one dimensional model, which was tested against observed groundwater levels. The boundary conditions were defined by using meteorological data and sub models for precipitations, snow dynamics interception, evapotranspiration and horizontal groundwater outflow. The second method directly transformed groundwater level fluctuations to equivalent amount of water from a constructed recession curve and the specific yield concept.

A technique to estimate recharge from rainfall and to estimate aquifer parameters using groundwater level records and available climatologic data was developed by Gupta and Paudwal (1988). The methodology combines a hydrometeorological model which links rainfall and evaporation to the effective groundwater recharge and a geohydrological model which links the recharge to the water level in the aquifer.

Sophocleous (1991) proposed a combination of water table fluctuation method and water balance model for the effective estimation of aquifer storativity. In this method, the soil water-balance-derived recharge estimate is divided by the corresponding water table rise to obtain an estimate of effective storativity or tillable porosity of the region near the water table.

The spatial and temporal distribution of groundwater recharge has been generated by Potter *et. al.* (1993), using hydrologic, hydro-geologic and geochemical methods. Preliminary hydro-geologic studies included direct measurements of major springs using calibrated weir. Nested piezometers were used for getting the hydraulic gradient. They concluded that recharge occurs in the uplands and forested slopes. Forested slopes have large macropores and maintain the permeability resulting in high recharge.

Accurate calculations of water balance components were achieved by Kerkides *et. al.* (1996), through replacing the Thornthwaite potential evapotranspiration by Penman potential evapotranspiration and by use of more appropriate water capacities of root zone. The evaluation of this modification was carried out in Greece. Major objectives of the study were to give a picture of the soil moisture availability, to evaluate the effects of different evapotranspiration estimates or soil and vegetation characteristics on soil water deficit and to detect possible differences in water balance estimates through the years 1931-1987. The study shown that, Western Greece suffers the least soil moisture deficit throughout the year while, central and southern regions suffer the most.

By combining the physical, chemical and isotopic method of analysis, soil macro pore recharge is estimated by Wood *et.al.* (1997). Techniques for quantifying macro pore recharge were developed for small scale and regional scale. Water balance method, chloride mass balance method and tritium injection method are combined to produce reliable measures of macro pore recharge. It was found that, out of the total regional annual recharge of 11 mm/y, macro pores recharge flux ranges from 60-80%. Between 15% and 35% of the recharge occur by interstitial recharge and only 5% as matrix recharge.

Wittenberg and Sivapalan (1999) estimated the shallow groundwater balance in a semi arid catchment in Western Australia by stream flow recession analysis and base flow separation. A non linear relationship was found to be existing between discharge and storage of aquifer. A relationship is formulated between evapotranspiration loss and storage depth.

For assessing the vulnerability of aquifers in the Manawatu region of the lower North island of New Zealand, Bekazi and Mc Conchie (1999) estimated groundwater recharge using water balance model. Actual evaporation and soil moisture storage was calculated on the basis of a simple daily soil water model.

Gaur (2001) quantified a groundwater budget of a 1381 ha watershed in Ambe Bai village of Uttar Pradesh. Water table fluctuation method was adopted along with groundwater parameter and norms prescribed by CGWB. Study area was a hard rock terrain underlain by granite. Value of specific yield is assumed as 4% and infiltration factor as 15%. Net utilizable recharge is taken as 85% of gross recharge.

Koontanakulvong and Siriputtichikul (2002) estimated natural groundwater recharge rate from soil infiltration and classified soil map and found the results obtained are better compared with normal means. In this study, the soil infiltration rate defined in the soil classification map, sand deposition map surveyed from field and satellite imageries were used to estimate recharge rate. Sixty two soil series were found having infiltration rate from 0.125 to 25 cm/hr. Using GIS, spatial distribution of infiltration rate were generated. Natural recharge was found out through water table fluctuation method and water balance method and was correlated with infiltration rate. The relationship obtained was $Y= 0.24 X + 3.2$ where Y is the recharge rate in cm/hr and X is the soil infiltration in cm/hr.

Kumar (2002) proposed a step by step procedure to estimate the groundwater recharge, based upon modified soil moisture balance approach. The methodology incorporates the SCS curve number method to find the storage index.

An attempt has been made by Kumar and Seethapathi (2002) to derive an empirical relationship between groundwater recharge and rainfall in upper Ganga Canal Command Area based on seasonal groundwater balance study. All components of the water balance equation, other than rainfall recharge were estimated using relevant hydrological and meteorological information. Rainfall recharge of the monsoon season was calculated from water balance equation. It was observed that as rainfall increases recharge also increases but not in a linear proportion. Recharge coefficients for the monsoon seasons were calculated. The recharge coefficients were found to vary from 0.05 to 0.19 for the study area. An empirical relationship connecting rainfall and recharge for the monsoon season was derived through non-linear regression analysis as $R = 0.63 (P – 15.28)^{0.76}$.

A study was conducted by Charkauer (2004) to estimate groundwater recharge. The Precipitation Runoff Modeling System (PRMS) has been selected as the method to quantify recharge in this study. PRMS is a deterministic distributed parameter watershed model which allows a more rigorous subsurface system simulation. The objectives of the study were to check the applicability of PRMS to areas larger than 50 km^2 and whether the results can be extended to ungauged areas. Study was conducted in South Eastern Wisconsin. Input data required for PRMS are climatic and stream-flow time series along with land surface and subsurface conditions. Recharge calculated at the watershed level ranges from 3.5 -18.2 cm/yr and in sub-watershed level it ranges from 1.9 – 20.7 cm/yr. The study concluded that the model can be extrapolated to ungauged areas without much errors.

Katpatal and Dube (2004) found that the weighted average method is most appropriate for groundwater recharge estimation in Bhandara District and is less time consuming and cost effective. Various parameters like geology, geomorphology, slope, lineament density, soil type and runoff are assigned. Using remotely sensed data, survey of India topographic sheet and field data, rasterised maps are generated. Vector files are generated from these maps, which carries only spatial information. Attribute tables are created and linked to the vector features, suitable ranks and weights are assigned to each feature of the thematic maps according to their contribution in groundwater recharge and weighted overlay analysis was carried out. Spatial distribution of groundwater recharge was displayed in maps showing classes as poor, very low, low, average, moderate, moderately good and good. Most of the area of Bhandara district is found to support groundwater recharge.

Based on the ground data and satellite imageries, a water balance model was developed by Sen and Giesko (2005) for Roxo watershed in Portugal. Thornthwaite-Mather method was used for analysing the climatic data. Spatial and temporal distribution of climatological parameters, evapotranspiration, direct runoff, ground water runoff and groundwater recharge are prepared using ILWIS software. Evapotranspiration was found out by using Penman-Monteith method. Direct run off ground water flow and total runoff from the catchment were the major out puts of this model. Groundwater recharge zones are identified and delineated from the water availability for recharge. Total annual runoff from the catchment was estimated as 29 Mm3. Contribution of groundwater flow was found very low in the catchment. Since the area is very dry and rainfall was very less to replenish the soil moisture, total runoff primarily depends on the direct runoff.

Lee et. al. (2006) estimated the long-term mean annual groundwater recharge of Taiwan with the help of a water-balance approach coupled with the base-flow-record estimation and stable-base-flow analysis. Long-term mean annual groundwater recharge was derived by determining the product of estimated long-term mean annual runoff (the difference between precipitation and evapotranspiration) and the base-flow index (BFI). The BFI was calculated from daily stream flow data obtained from stream flow gauging stations in Taiwan. Mapping was achieved by using geographic information systems (GIS) and geostatistic tool.

A study has been conducted by Benjamin et. al. (2007) to check the adoptability of Thornthwaite-Mather water balance method for estimating the groundwater recharge in the southern border of Lake Chad in Cameroon. Effective rainfall after subtracting the runoff, evapotranspiration and soil storage was estimated using the Thornthwaite- Mather water balance method. The balance sheet was calculated monthly for a 16 years period. Empirical equations were employed for estimating evapotranspiration. The results obtained were compared with groundwater level observations considering the hydro-dynamic characteristics of the aquifers. The results indicated that a good agreement exists between the Thornthwaite values and regulating reserve values, showing the Thornthwaite- Mather model remains effective in semi arid area.

A study was conducted in the KCAET campus by Asha Joseph *et. al.* (2007) to assess the salient features of the groundwater resources. Rainfall recharge from the study area was estimated using water table fluctuation method and rainfall infiltration factor method. The utilizable recharge is estimated based on the pre-monsoon and post-monsoon fluctuations of water table for the area receiving south west monsoon. Groundwater recharge was estimated as the product of volume of water table fluctuation and specific yield of the aquifer material. Specific yield of the aquifer was calculated by Jacob's method. In the second method of recharge estimation, the rainfall recharge is considered as a linear function of the quantum of rainfall. The product of total volume of rainfall and rainfall infiltration factor was taken as the recharge. Values of specific yield and rainfall infiltration factor were calculated for different soil formations. Estimated recharge using water table fluctuation method was found greater than the recharge estimated using rainfall infiltration factor method.

Sathian *et. al.* (2007) conducted a study to estimate the recharge and discharge of groundwater in laterite soils of the KCAET Campus. Groundwater recharge was estimated using water table fluctuation method and rainfall infiltration factor method. Groundwater flow pattern and discharge were estimated using tracer techniques. Common salt was used as the tracer. Actual recharge and rejected recharge were calculated for the area. Velocity of groundwater flow was also estimated.

2.3 Site suitability analysis for groundwater recharge

Ground water reservoir in hard rocks is dominantly shallow. The bulk of the ground water is stored in the zone of weathering. Fractures and joints in hard rock function as conduits for rapid transport of water, as they do not provide large space for storage of ground water (fracture porosity of hard rock is as small as 1%) and also the width of fractures and lineaments and weak planes narrows as depth increases.

It is considered as an essential pre-requisite to conceptualise a topographic – hydrogeologic framework of a hard rock region before identifying and evaluating sites for ground water recharging and water harvesting.

In order to implement artificial groundwater recharge systems, it is essential to delineate potential groundwater recharge zones. For the delineation of potential recharge zones, the first task is to identify the factors facilitating recharge. Hydrogeology, subsurface geology, geomorphology, watershed hydrology, topography, soil and land cover etc. are the major factors affecting groundwater recharge. Integration and analysis of these multi disciplinary data is required for finding the suitability of a terrain for artificial recharge.

Ramasami and Anpazhagan (1997) integrated water level fluctuation data, geological data, geomorphologic data and sub-surface geological data for identifying suitable sites for artificial recharge in Ayyar basin belonging to the Cauvery drainage basin of Tamil Nadu. Water level fluctuation data, geologic data, geomorphologic data and hydrogeologic data were used for identifying the suitable areas of recharge. Sites with all the four parameters favourable were classified as first priority sites. Sites with any three parameters including water table fluctuation and hydrogeology favourable for recharge were classified as second priority sites and any two in which one must be water table fluctuation are favourable were classified as third priority classes. They demarcated favourable site for particular artificial recharge structures like percolation ponds, pitting, *en echelon* dams, induced recharge and battery of wells.

Saraf and Choudary (1998) described the potentials of integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites in hard rock terrain in the Sironj area of Vidhisha District of Madhyapradesh. The Study exhibits reservoir induced artificial recharge down stream of surface water reservoirs. The present study attempts to select suitable sites for groundwater recharge in a hard rock area through recharge basins or reservoirs, using an integrated approach of remote sensing and GIS. The integrated study helps in design a suitable groundwater management plan for a hard rock terrain.

Saraf (2002) developed an integrated remote sensing and GIS technique for ground water recharge investigations in hard rock terrain in Silai watershed of West Bengal. He used the weighted overlay analysis and Boolean logic method and found very useful for delineation of recharge suitable areas. The data used were IRS 1A LISS II and IRS 1C LISS III false colour composites, SOI topographic sheets, thematic maps of geology, geomorphology and soil from National Bureau of Soil Survey and Land Use Planning. Water level data from 34 wells, collected by State Water Investigation Directorate were also used for the study. Manual digitisation was done by ILWIS Software. Remote sensing Data were interpreted using supervised classification technique. Arc View 3.1 was used for analysis and processing.

Kshirish and Santhosh (2002) delineated recharge suitable zones using remote sensing data and geographic information system for Rengareddy Dustrict, A.P. Parameters like surface contour, drainage, lineament and groundwater depth are taken into consideration and converted to thematic layers. Overlay of these thematic layers provided the final recharge zone map. Area is classified from excellent to poor zones. The outcome of the study has given clear picture about the recharge suitability of the areas.

Jyothiprakash *et. al.* (2003) delineated potential zones for artificial recharge for Agniar River Basin in Tamil Nadu by integrating various thematic maps which include physiography, geology, permeability, water holding capacity, soil texture, effective soil depth, and drainage intensity. The study area was underlain by hard crystalline rocks in the head reaches and alluvium aquifer in the coastal areas. Weights were assigned to the parameters based on their influence on storage and transmission of groundwater. After overlay analysis, the polygons were reclassified into four classes of recharge suitability. The study showed that the areas having rapid permeability and high water holding capacity in alluvium soil are excellent zones for constructing artificial recharge structures.

A slope stability model was generated by Zaitchik and Van Es (2003) for site specific land slide prevention in Honduras, using GIS. Relative hazard prediction is done by considering the local slope gradient and relative wetness. Local slope gradient is derived from the digital elevation model which is obtained from elevation contours hand digitised using Arc View software. Soil samples were collected from the study area and tested the saturated shear strength and bulk density. According to the slope and wetness entire area was classified to four groups. An area of 7.9 km^2 out of total area of 46.1 km^2 was found unstable.

Monadal and Singh (2004) analysed unconfined aquifer responses in terms of rise in water level due to precipitation for finding out the recharge suitable areas of Sirumalai Watershed in Dindigul district of Tamil Nadu. The rainfall data from Dindigul raingauge station was taken and water tables were monitored for cross correlation. Aquifer responses for each precipitation event were studied. Time lag of one or two months after rainfall had been noted. The cross correlation coefficients were determined between depth of water table and corresponding rainfall. The qualitative estimation of recharge zones was made on the basis of correlation coefficient. Depending on the correlation coefficient, area was divided into four recharge zones.

Ravi Shankar and Mohan (2005) identified zones favourable for the application and adaptation of site-specific artificial recharge techniques for augmentation of groundwater through a GIS based hydrogeomorphic approach in the Bhatsa and Kalu river basins of Thane District. Parameters used are drainage pattern, DEM derived slope, lineament density and drainage density. Using the hydrogeomorphic parameters, areas where the terrain was favourable for artificial recharge were found out. By superimposing the drainage map over suitable area map, site specific mechanism for artificial recharge were identified.

2.4 Artificial groundwater recharge methods

Rao *et. al.* (1996) conducted a study in peninsular India to evaluate the influence of soil conservation measures in groundwater regime. Chinnatekur watershed in Andhra Pradesh was the study area, with an area of 1120 ha. Groundwater recharge was estimated using water balance method along with water table fluctuation analysis. Integrated soil water conservation measures including contour bunds, terraces, diversion ditches, rock fill dams, and *nala* bunds on watershed basis have been found to improve groundwater regime.

An environmental chloride method was applied by Sukhija *et. al.* (1997) to evaluate the artificial recharge through percolation tank in Southern Peninsular India. Assuming that there is no loss of water from the tank except percolation and evaporation, the mass balance of the chloride in the tank was used to estimate the percolated fraction of water. There is no loss of chloride through evaporation, but the concentration of chloride rises with evaporation. But the percolating water carries the dissolved chlorides with it. Chloride concentration in the water sample was measured using mercuric thiocyanate and ferric nitrate method using spectrophotometer.

Damodaram *et.al.* (2000) selected defunct dug well recharge structures in a hard rock area near Hyderabad. A trench of about 100 m in length, 1 m wide and 1 m deep has been made at the lowest surface levels to collect the runoff from the catchment. At the end of the trench, a pit filled with gravel and coarse pebbles and a pipe to carry collected water to the well has been made. Through regular monitoring of water levels, they found water levels in the area were raised to 1.2 to 1.5 m.

Kaledhonkar *et. al.* (2002) studied the possibility of groundwater recharge in the Indo-Gangetic plains using recharge tube wells. They found this method highly suitable and observed the recharge rate to be about 10.5 l/s with a radius of influence of 100 m. they also proposed a site specific design of he recharge tube well.

A study was carried out to find out the roof water harvesting potential of the KCAET campus and to design proper recharge pits to recharge the harvested water by Jyothisson *et. al.* (2004). By taking product of average rainfall depth, roof area and runoff coefficient of the roof material, roof water harvesting potential was estimated using continuity equation; the required sizes of the recharge pits were designed.

Muralidharan *et. al.* (2007) evolved a method to count for the efficiency of a check dam in recharging to groundwater and evaluated the increased quantum of groundwater recharge by comparing with the natural groundwater recharge. The experimental site was a granite terrain. A second order stream generating from a closed high mound was harvested through a mini check dam having a storage capacity of 150 m^3. Site selection for the check dam was done with the help of a cadastral and drainage maps followed by geophysical survey to ascertain the thickness of the weathered zone. The experiment shows that, careful site selection through scientific investigations and harvesting in a cascading manner along a drainage channel would result in high efficiency in groundwater recharge through artificial recharge methods.

MATERIALS AND METHODS

CHAPTER III

MATERIALS AND METHODS

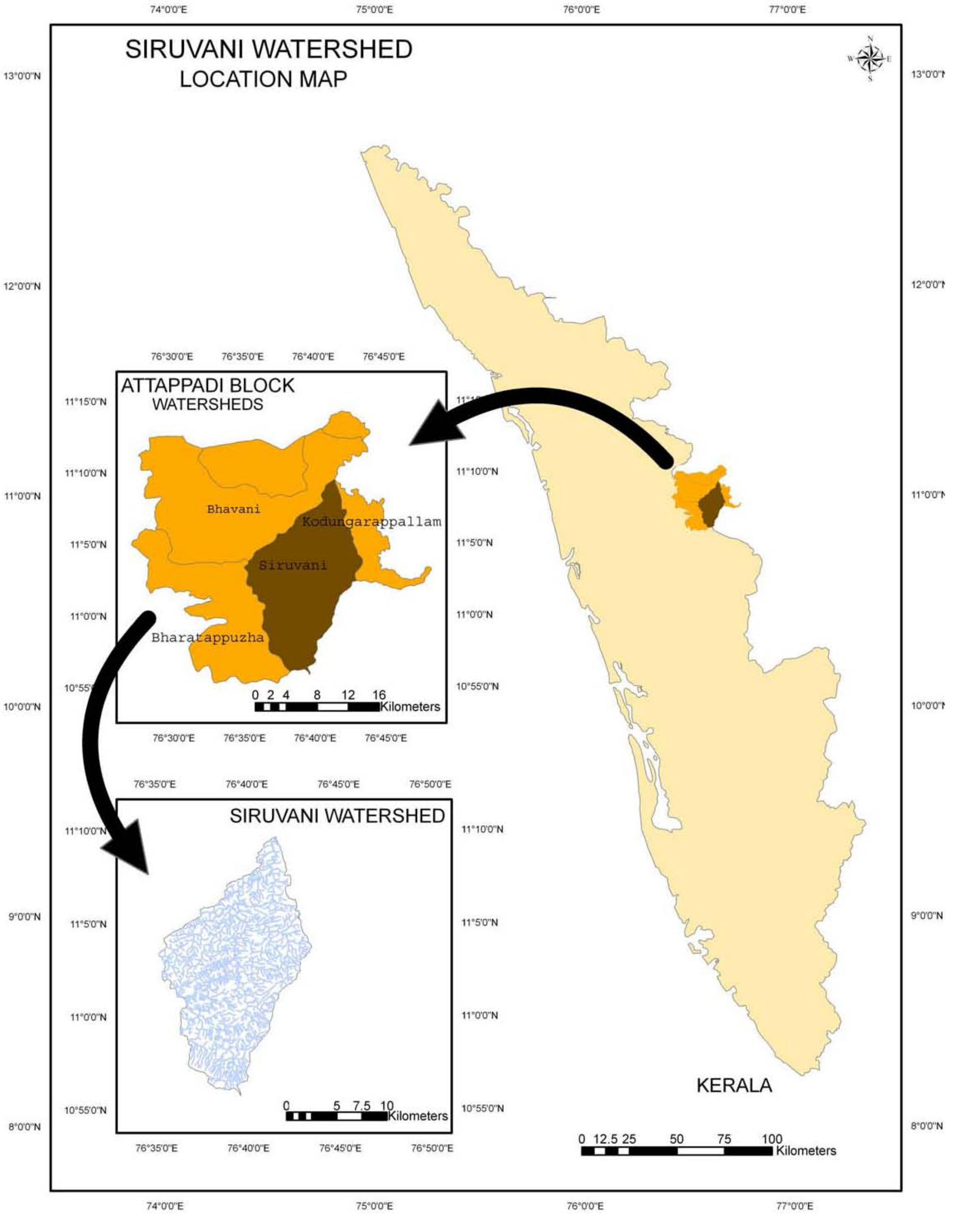
A proper selection of suitable recharge measures and sites for recharge are necessary for the effectiveness of the system. For this, spatial variation of climatic, surface and subsurface parameters has been analysed. Water balance of the catchment and terrain suitability were analysed using remotely sensed and field observation data and GIS. This chapter comprises the steps adopted to achieve the objectives of this study along with the base line information about the study area.

3.1 Study area

Siruvani sub basin of Bhavani river basin is selected as the study area. It is situated in the Attappadi Block of Palakkad district in Kerala State. Attappadi Block lies in between the Nilgris hill ranges in the north and Vellingiri hill ranges in the south, both having a height of over 2000 m. Attappadi is predominantly a tribal Block (Map 1) and is located at $10^{0}55'10''$ and $11^{0}14'19''$ N latitudes and $76^{0}\ 27'11''$ and $76^{0}48'8''$ E longitudes. Total geographical area of Siruvani watershed is 200.17 km^2. This area is an undulating terrain with elongated hill ranges alternating valleys. The eastern part of this Block is undulating and merges with the Coimbatore plain. Figure 1 shows the IRS IC LISS III image of the Attappadi area. The area is typical due to severe soil erosion and land degradation. Siruvani, originating from the south western corner of Attappadi Plateau in the high, rain drenched and heavily forested Muthikulam hills, descends rapidly and flows across Attappadi and joins Bhavani. The 35 km long Siruvani now flows as a small muddy trickle during most of the year, which swells into thicker, muddy torrent for a couple of days when the rains are heavy.

Siruvani Basin is selected for this study due to the following reasons

1. It is one of the most severely degraded regions in the Western Ghats
2. Water table depletion and acute water scarcity
3. Undulated, hilly hard rock terrain with high runoff generation capacity
4. Susceptibility to land slides



Map 1 Location of the Study Area

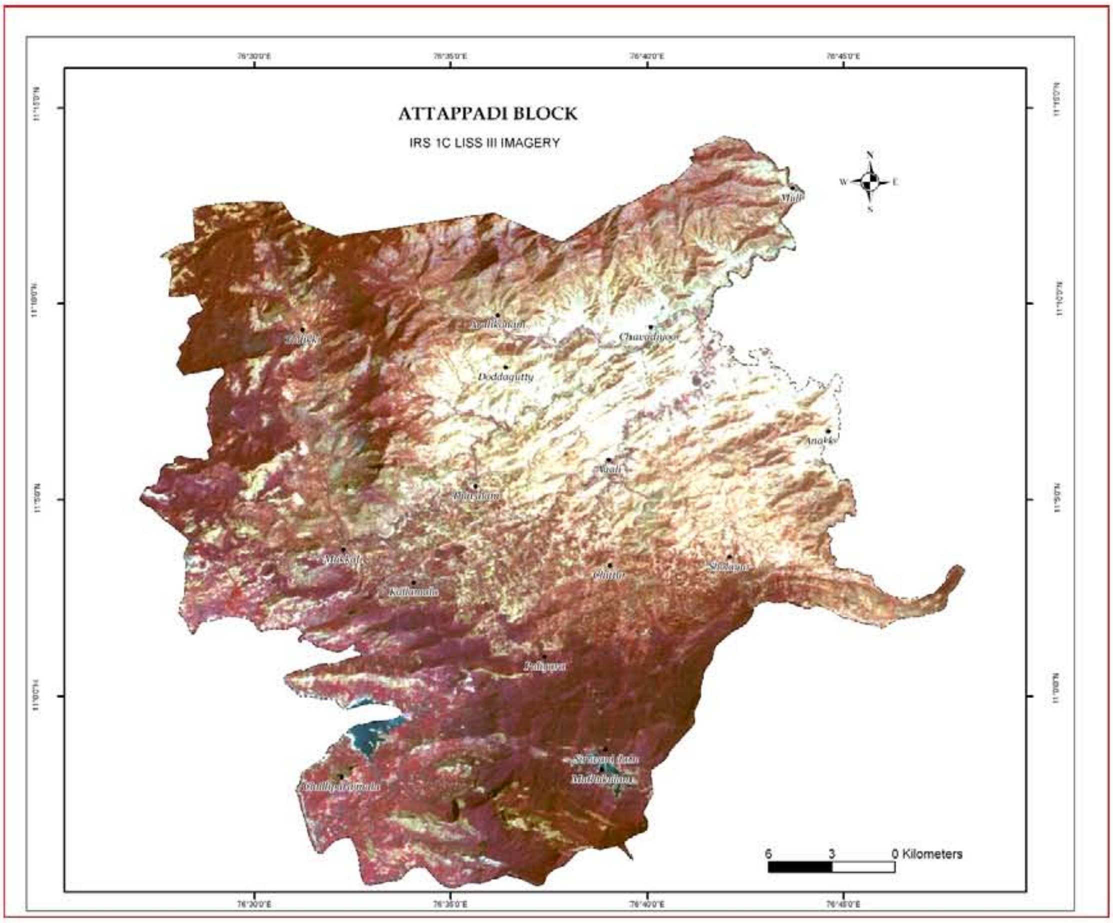


Figure 1 IRS 1C LISS III imagery of Attappadi Block

3.1.1. Climatology

a) Rainfall

The Attappadi area receives highly spatially varying rainfall from 700 to 3000 mm or more as a result of its heterogeneous topography. Due to the presence of steep and high hills in the western region of the Attappadi Block, the rainfall drastically reduces towards the eastern side resulting in a rain shadow effect and a dry climate there. The isohyetal map of rainfall of the Attappadi area (CWRDM, 1998) very clearly shows the rainfall variation in the western and eastern sides of the Attappadi Block.

b) Temperature

In the wet area, Muthikulam atmospheric temperature is less compared to Agali and Sholayur.

c) Humidity

Relative humidity is more than 70 % during most part of the year except during summer months, February to May. During summer, humidity ranges between 50% and 70%. Agali area experiences the lowest humidity through out the year.

d) Wind

Anemometer is installed only in Agali meteorological station. In July, August and September, monthly average wind velocity becomes more than 10 m/s. During the other part of the year, the wind velocity ranges between 4 to 6 m/s.

3.1.2. Topography and drainage

The terrain is undulating and slope varies from gentle to very steep. Steep slopes are located on the southern boundary of Siruvani hills. The valley portion of the central part representing the flood plain of Siruvani River has gentle to moderate slope.

Siruvani, the main river, originates from Muthikulam reserve forest and flows northward. It meets the Kodungarapallam stream and then joins the Bhavani River. The drainage pattern is generally dentritic and radial in some cases.

3.1.3. Soils

The soil series seen in Siruvani Watershed are Vattakkallumalai, Sethumadai, Edathodu, Mamana, Thavalam, Gilsi, Thekpannai, Arali and Bhavani. The soils of the area are highly eroded and less productive with textural classes varying from sandy loam to loamy sand in the upper reaches and clay to clay loam in valleys. Predominantly the soils are well drained to moderately well drained, except in valley areas which are less drained. The available water holding capacity is low in general and it ranges from 2.1 to 18 cm/100 cm soil depth. Description of various soil series associations are furnished in the Appendix 2.

3.1.4. Land use

The land use of the Siruvani Watershed can be grouped into natural vegetation (forest) and agricultural crops. The side slopes and hilltops of the major portion of hillocks located in the eastern dry area are denuded and degraded resulting in scrub or permanent fallow or barren rocky lands. These are the predominant categories of degraded lands found in the area. But the agricultural activities are intense at some portions of the western Attappadi, where sufficient rainfall is received. The natural vegetation comprises dense evergreen forest, dense deciduous forest, open evergreen forest, open deciduous forest and degraded forest. Forest tree specieses include *Tectona grandis, Dalbergia latifolia, Albizia amara, Hardiwickia binata, Cassia spp., Ipomea spp., Bauhinia spp., Bombax spp., Elaeocarpus tuburculatus, Euphoria longana, Jambosa laeta, Mangifera indica, Terminalia spp., Emtilica afficinalis, Xylia xylocarpa, Azadirachia indica, Lantana camera, Eupolorium spp.* etc. Because of low rainfall, dryland crops are generally cultivated. The main crops are ragi, chamai, tenai, makkachola, jowar, groundnut, castor, tuvarai, black gram, horse gram, cotton etc. Plantation crops like rubber, cardamom, tea, coffee etc are seen along the foot hills and coconut- banana- areca nut mixed cropping can be seen near the streams and valley fills.

3.1.5. Regional geology

The major rock types identified in the study area can be grouped into

1) Wynad schist complex and

2) Peninsular gneissic complex.

Rocks of the Wayanad schist complex occurs as layers and lenses within gneisses and include quartz biotite schist, banded iron formation and mafic/ultramafic rocks represented by pyroxenite, peridotite, talc – tremolite schist and amphibolite. Peninsular gneissic complex comprises granite hornblende gneiss and charnockite and its variants. Charnockitic rocks are confined to the area north of the Bhavani River towards Nilgiris and also to the western portions. Dolerite dykes, quartz and pegmatite veins traverse the area both in concordant and discordant fashions, which represent a later phase of basic igneous activity. All the rock types except the younger intrusive have suffered several phases of deformation and have been metamorphosed to upper amphiblolite to granulite facies. Structural studies reveal that the area has undergone polyphase deformation and metamorphism (Nair et al., 1996). The dykes of Attappadi area trend mainly in ENE-WSW, WNW-ESE and NW-SE directions and are inferred as the possible orientations of fractures developed due to the rifting of the western continental margin of India. (Sinha Roy and Radhakrishna, 1984).

3.1.6. Geomorphology

The hills from the immediate northern flank of Palghat gap covers the southern, western and northern portion of the study area and slopes towards Attappadi valley. River Bhavani flows through this valley and is controlled by the shear or fault zone. The geomorphology of the area consists of four major units. They are described below.

a) Denuded hill

Denuded hills are formed due to differential erosion and weathering. Major portion (96.33%) of the watershed falls under this denuded hills which are dissected uplands. In denuded hilly areas, groundwater potential confines along lineament and faults. The limited rainfall received in the denuded hills is not recharged *in situ* due to the steep slope of the terrain.

b) Buried pediment

Buried pediments are flat and smooth surfaces of pediment covered with shallow to moderately thick over burden of weathered bed rock. This unit has a moderate potential for groundwater development.

c) Valley fills

Valley fills are quarternary, unconsolidated sand, silt, gravel occupying narrow stretch of alluvium. Thickness of fill varies from 1 m to 6 m.

d) Intermontane valleys

These are depression between mountains or hills filled with alluvial or colluvial matter. Rainfall getting in the denuded hills reaches the lower most part, the intermontane valley, which makes it a relatively potential unit for groundwater development.

3.1.7. Groundwater Condition

Groundwater occurs in the secondary pore spaces in the crystalline rocks, the pore spaces being developed by weathering, fracturing and shearing. Most drought affected zones fall in the area underlain by hornblende gneiss. This formation is highly sheared and intruded by numerous basic dykes which controls the groundwater movement to a large extend. Groundwater occurs in biotite gneiss in the weathered zones and the voids caused by shearing. Yield of the wells in the study area were very poor and generally ranged from 200 to 300 lpm. Quality of groundwater in the area is generally satisfactory. Groundwater is tapped mostly by means of dug wells only. The use of groundwater for irrigation purpose is negligible. The tribal population mainly depends on surface water.

3.2 Geographic Information system (GIS)

A GIS integrates spatial and other kinds of information within a well defined database structure and provides software tools that can be used to manipulate and display geographical data-objects. Arc GIS 9.1 developed by ESRI was the Geographic Information System used in this study. Arc GIS 9.1 presents a comprehensive set of analysis tools that work with all the supported data formats, including geodatabase features. It also offers a completely new framework for working with these tools that combine them together in a visual modelling environment and apply scientific principles related to the study. In this study, GIS is applied to the geographical data for integration of collection, storing, retrieving, transforming and displaying spatial data for solving the planning and management problems. GIS made the data handling and analysis much easier with meaningful research outcomes. As part of the study a geodatabase ‘GWR’ was designed which contained a data set ‘Siruvani’ comprising of different feature classes. Projection of the study area was selected as WGS1984 UTM ZONE 43N. 3D analyst, spatial analyst and geostatistical analyst extension of Arc GIS was used for the analysis of the study. Spatial Analysis helps to identify trends on the data, create new relationships from the data, view complex relationships between data sets, Make better decisions. Spatial Analyst provides a rich set of tools to perform cell-based (raster) analysis. The project utilised vector, raster and TIN data structures which provided the most comprehensive modelling environment for spatial analysis.

3.3 Estimation of natural groundwater recharge

The data requirement of the soil water balance method is large. When applying this method to estimate the recharge for a catchment area, the calculation should be repeated for areas with different precipitation, evapotranspiration, crop type and soil type. In this study, a GIS methodology for estimation of ground water recharge based upon modified soil moisture balance approach was made. Using GIS, it has been possible to model the water balance in two dimensions, taking into account the spatial distribution of rainfall, evapotranspiration, soils and land use. Instead of calculating the water balance for one point, it has been calculated for every element (pixel) of the entire groundwater basin.

The following assumptions were made for reducing the complexities in the estimation of natural recharge.

1) Values of climatic parameters were assumed as uniform throughout the influencing area of each meteorological station.
2) Surface runoff potential depends on AMC, land use and HSG.
3) Evapotranspiration will be at its potential value when sufficient moisture is available in the soil. Te actual ET, in moisture deficit condition depends only on the moisture content.
4) Soil moisture storage accounted only up to the depth of root zone.
5) When ET is greater than effective rainfall, soil moisture depletion takes place in an exponential way.
6) Infiltrated water after satisfying the soil moisture deficit, is considered as contribution to ground water.
7) Total quantity of water contributed to groundwater is taken as groundwater recharge.

For estimation of ground water recharge using soil moisture balance approach, the data required are rainfall (P), Potential evapotranspiration (PET), land use map and management practices, soil map of the basin with attribute information, Water Holding Capacity (WHC), Permanent Wilting Point (PWP) and Field Capacity (FC) of soils.

3.3.1. Rainfall

Daily Rainfall from 1st July 2006 to 31st May 2007 is collected from Agali, Sholayur, and Muthikulam meteorological stations within the study area. Thiessen polygons are constructed for each meteorological station. Monthly total rainfall for all the months were calculated and added to the attribute table of these Thiessen polygons.

3.3.2. Surface runoff

Surface runoff was estimated using Soil Conservation Service (SCS) curve number method. This was done by the union of hydrological soil group map and land use map. Hydrological soil group map is generated from soil texture map. Soil texture is an important physical property which affects the infiltration rate and water holding capacity. Thirty one samples were collected from various points of the watershed such that the entire soil series groups are represented and the sampling points are located using Global Positioning System (GPS). Textural analysis was done on the collected samples. Each sample was put under any of the three groups, sand, silt and clay according to their particle size. Percentage weight of each fraction is calculated. Sampling locations are plotted and overlaid on soil series map to find which samples will come under which soil group. The percentage weight of each fraction are added as a new field in point location map and average percentage weight of each fraction for each soil series is calculated. Based on this, each soil series polygon is assigned textural classes. Hydrological soil group gives an idea about the infiltration capacity of the soil which in turn depends on the textural characteristics of the soil. Later, by assigning Curve Number for the average Antecedent Moisture Condition (AMC), based on land use and hydrological soil group in the union of texture map and land use map, Curve Number (AMC II) map is generated. AMC is found by computing the cumulative values of five day antecedent rainfall. Based on this AMC, Curve Numbers are modified. Using the modified Curve Number, runoff is calculated and represented in a map form. The procedure for the preparation of runoff map is detailed in the flow chart.

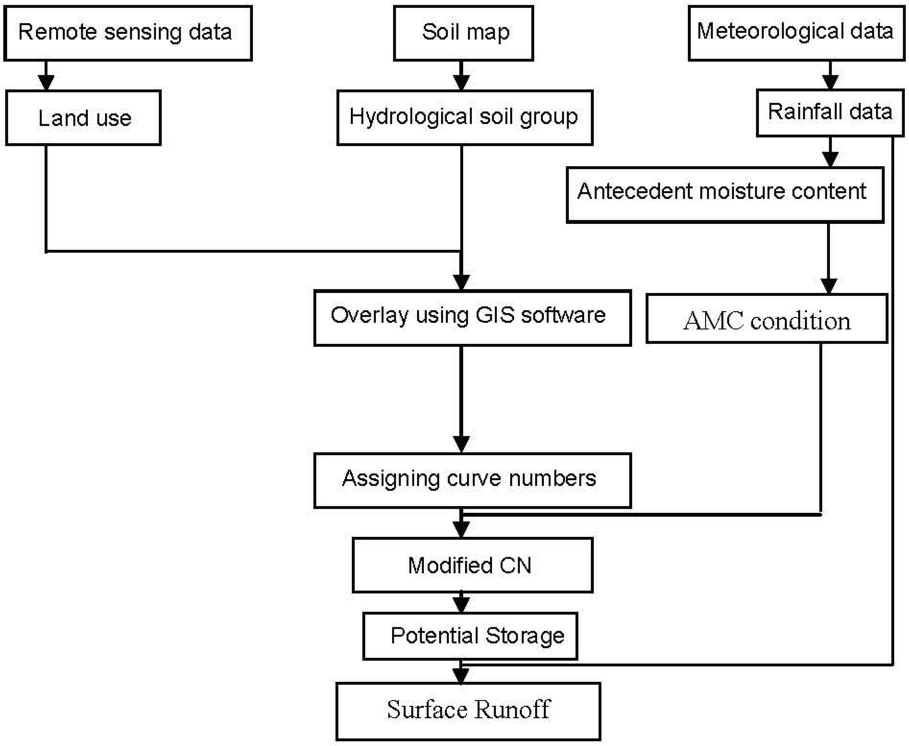


Figure 2 Flow Chart for Preparation of Surface Runoff Map

3.3.3. Potential evapotranspiration

All the climatic data required for the estimation of potential evapotranspiration through Penman method are collected from Agali, Sholayur and Muthikulam observatories located in the watershed. Thiessen polygons are constructed around each meteorological station. Monthly mean of all the climatic factors, *viz*, temperature, relative humidity, actual sunshine hours, wind velocity at 2 m height, are calculated and brought into the attribute table of the Thiessen polygons. In the land use layer of the watershed, the radiation reflection coefficient value (albedo value) is added as a field. Both the Thiessen polygons and the land use with albedo attributes are overlaid. Using the Penman evapotranspiration estimation method, the potential evapotranspiration for each Thiessen polygon and land use is calculated and the spatial and temporal distribution of PET is displayed as maps.

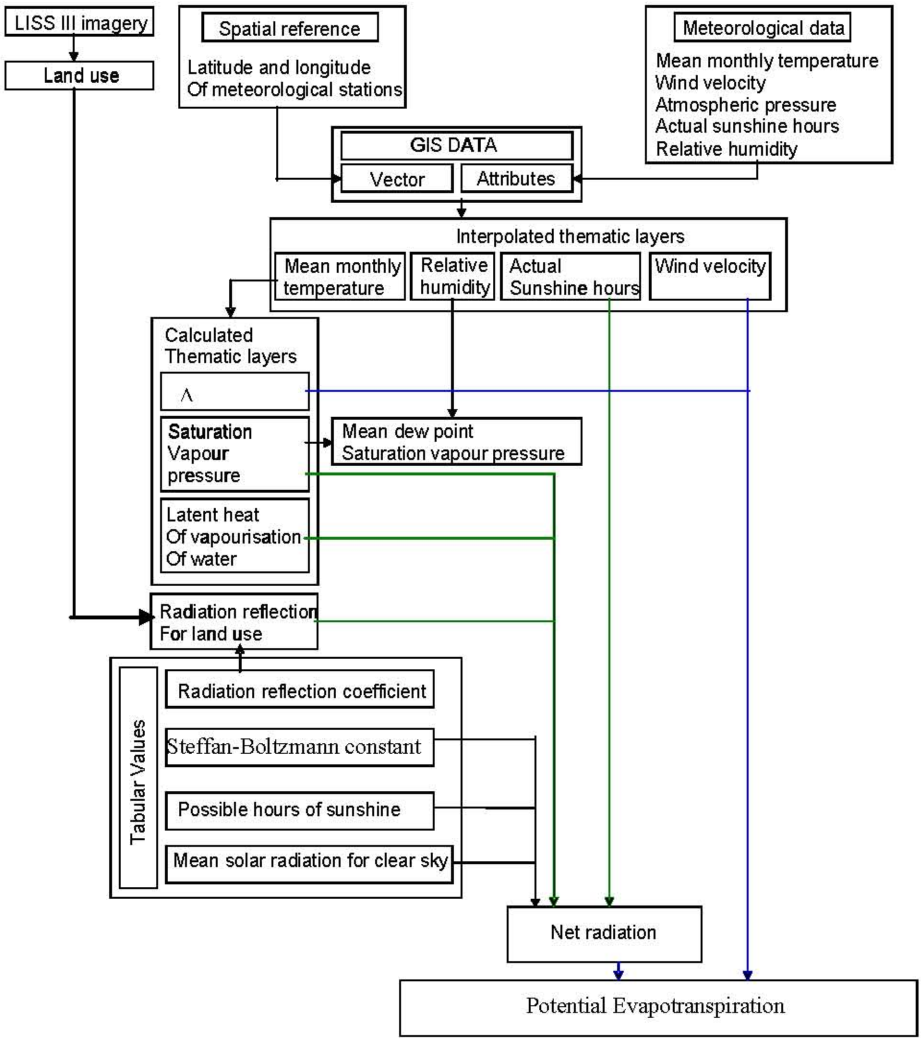


Figure 3 Flow Diagram for Generation of PET map

3.3.4. soil moisture

Soil map of the area is prepared using the soil map of the Kerala State Land Use Board. In the land use map, root depths are assigned for each land use category. The root depth of vegetation in a watershed is directly related to the amount of water available in the soil (Sen, 2005). Water holding capacities of each soil textural classes are assigned to soil map of the area and overlaid with land use layer. The attributes of root depth and water holding capacity are multiplied within the table using field calculator. The total water holding capacity of the area can be displayed as a map.

3.3.5. Water balance

The monthly total rainfall maps for the water year were rasterised. Total monthly surface runoff layers were also rasterised. Surface runoff layers for each month were deducted from the rainfall layers of the corresponding months to get the effective rainfall maps for the months. The potential evapotranspiration layers were deducted from the effective rainfall layers to get the total surface recharge for each month. Spatial and temporal distribution of surface recharge was prepared as layer. The difference in potential water holding capacity and actual water held in the soil in the previous month is deducted from the surface recharge to get the water added to groundwater flow or storage, if the surface recharge is positive. If surface recharge is negative, water is withdrawn from the soil storage. The soil moisture will deplete in an exponential manner (Dunne and Leopold, 1978). Then the moisture retained in soil after evapotranspiartion can be calculated using the formula,

$$AW = WHC \text{ X } \exp^{[APWL/WHC]}$$

Where,

AW - Moisture retained in the soil after evapotranspiration

WHC - Available Water Holding Capacity

APWL - Accumulated Potential Water Loss

APWL is zero for a month with positive surface recharge. APWL for a month with negative surface recharge is given by,

$$APWL = APWL_{previous} - \text{surface recharge}$$

While the effective rainfall is less than the potential evapotranspiration, Actual Evapotranspiration (AET) occurs will be less than PET. In this case AET is given by,

$$AET = P_{eff} + AW_{i-1} - AW_i$$

Where P_{eff} is the effective rainfall and 'i' is the sequence of months in the dry season (Donker, 1987).

3.3.6. Groundwater recharge

The excess surface recharge, after the soil moisture reaches the water holding capacity, can be considered as the recharge to the groundwater resource which is a combination of groundwater flow and groundwater storage in the aquifer. By deducting the available water holding capacity of the soil column from the sum of effective rainfall and previous month soil moisture content gives an estimate of the groundwater recharge. From June 2006, the groundwater recharges for each month were estimated within the attribute table of water balance layer. Finally these monthly recharge layers are rasterised and added in raster calculator and added to get the annual natural groundwater recharge. It is then converted to polygons and the spatial distribution of recharge was displayed in the form of a map.

3.4 Delineation of suitable sites for groundwater recharge

Delineation of suitable recharges zones is an important prerequisite for planning and implementing groundwater recharge systems. Recharge potential of a terrain depends highly on the infiltration capacity of the unsaturated zone above the aquifer, geologic and hydrogeomorphologic parameters, terrain slopes and drainage density. The highly undulating topography and steep slopes of the Western Ghats along with high intensity rainfall and accelerated deforestation makes these areas highly unstable and susceptible to slides and soil mass movements. As a hard rock terrain, its recharge potential depends largely on the hydrogeologic features. Due to its susceptibility to land slides, stability of the terrain was also separately considered so as to exclude such areas from recharge measures.

3.4.1. Delineation of potential recharge zones

Site suitability of groundwater recharge depends on various parameters like infiltration rate, geomorphology, rechargeable depth, slope, drainage density, soil texture, water holding capacity and geology. Areas having favourable combination of these parameters can be delineated as recharge suitable zones.

In hard rock areas, groundwater occurs in an unconfined condition within the fractured hard rock and its weathered mantle. The underlying lithological units do not have sufficient porosity and permeability. In hard rock terrains, the artificial recharge sutability widely depends on infiltration rate of the soil, geomorphology, geology, drainage density, lineament density, soil texture, slope and rechargeable depth of aquifer.

In weighted overlay method, the individual thematic layers are assigned weight on the basis of their relative contribution to the central theme. Classes of individual thematic layers are ranked such that most suitable classes get high rank. Weighted Index, product of weight and rank, is calculated for each feature. Areas with higher values of Weighted Index indicate the most favourable area for artificial recharge.

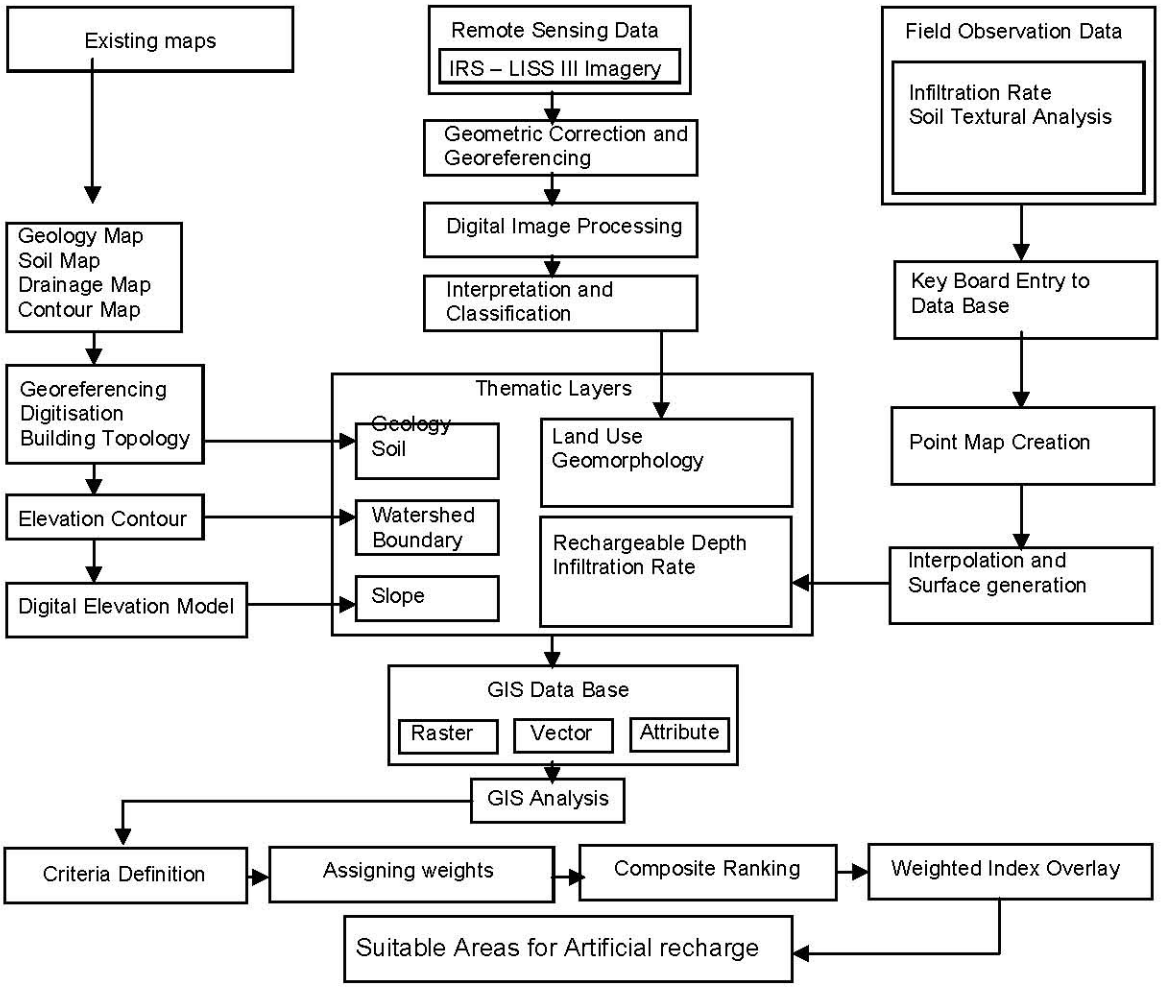


Figure 4 GIS Procedure for Delineating Potential Recharge Zones

3.4.1.1. Infiltration rate

Infiltration of water into the soil is affected by several factors like hydraulic conductivity of the soil profile, texture, porosity, vegetative cover etc. The most common method to measure the infiltration rate in soil is by using cylinder infiltrometer. Several locations are selected for infiltration rate measurement in each soil series coming in the area.

Two measurements were taken at each location and average infiltration rate was calculated. Using GPS, the latitude and longitude of the location is noted with maximum possible accuracy. Using GIS, a point map is prepared showing the locations of infiltration study, and the observed infiltration rates are added in the attribute table of each point location. This infiltration point layer is laid over the soil series layer and the average infiltration rates are added to the attribute table of each soil series polygon.

Thus, the infiltration rate layer based on the field experiment covering all soil series associations is generated.

3.4.1.2. Geology

Geology map of the Attappadi Block is georeferenced and hand digitised in Arc GIS environment. Siruvani watershed area is clipped out from the geology layer using the boundary feature class. Area of each feature is calculated using the utility tool in the tool box of Arc GIS. Geology map is prepared using this feature class. The weights and ranks for the features are assigned based on the contribution to recharge potential and are added to the attribute table of the feature class.

3.4.1.3. Geomorphology

Geomorphologic features, identified from the IRS 1C LISS III imagery for the entire Attappadi in analogue map, is georeferenced and hand digitised. Geomorphology of the study area is clipped out using the Siruvani watershed boundary feature class. Area of each features are calculated. Ranks and weights for the features based on their contribution to recharge potential are added to the attribute table.

3.4.1.4. Rechargeable depth

Thickness of the weathered formation is found out from open wells and point map of rechargeable depth is generated. Using the geostatistic tool, the interpolated surface is generated by inverse distance interpolation method and is rasterised. Rechargeable depth raster is reclassified and converted to polygon map. For each depth class the weights and ranks according to recharge potential of each category are added in the attribute table.

3.4.1.5. Slope

The elevation contours are hand-digitised from Survey of India Topographic Sheets covering the study area. The Digital Elevation Model (DEM) is generated from the elevation contour vector layer using Arc GIS 3D analyst. Slope classes are derived from the digital elevation model and reclassified. Weight and ranks are assigned to each classes of slope based on the effect on recharge potential of the terrain.

3.4.1.6. Drainage density

The drainage map prepared by hand digitising the drainage lines in the topographic sheet. Stream-orders are added to the attributes. Drainage density is the length of streams per unit area. It is usually measured in km/km^2. Using the line density tool of ArcGIS, drainage density layer is generated and reclassified. Drainage density raster is converted to polygon map. Based on the effect on the recharge potential, weight and ranks are assigned to attributes.

3.4.1.7. Weighted overlay analysis

All the parameter layers are overlaid using union tool. The index were summed up and based on the total index, resulting polygon layer is reclassified into four suitability classes, *viz,* suitable, moderately suitable, less suitable and unsuitable. Areas covered by each suitability class were calculated using the area tool. Resulting suitability clases were displayed as map.

3.4.2. Delineation of stable terrains

Landslides are caused in hilly terrains due to factors like gravity, weathering, deforestation, earthquake, heavy precipitation etc, and result in loss to property and life. Landslide is defined as “the movement of mass of rock, debris or earth down a slope”. In areas prone to landslides, the main factor is the availability of the weathered overburden that is susceptible to sliding on unstable slopes, when induced by rainfall or earthquakes. In Kerala part of the Western Ghats, several types of mass movements are occurring; these include rock falls, rock slips and debris flows. Among these, the most prevalent, recurring and disastrous is debris flows. With the onset of monsoon, all the high range districts of Kerala experiences land disturbances in the form of debris flows causing considerable damages to life and wealth. Debris flow is the swift and sudden down slope movement of highly water saturated over burden containing a varied assemblage of debris material.

Artificial recharge interventions in areas with land slide susceptibility causes water saturation of unstable land mass and debris slide and resulting in land degradation and damage. So, the land slide prone areas should be delineated and excluded from the suitable area for artificial recharge. For that, stability of slope analysis of the watershed is carried out using GIS, for delineating unstable and stable areas. The factors controlling slope stability are slope, land use, relative relief, drainage, and soil thickness.

3.4.2.1. Slope

The slope feature class already generated is reclassified for the stability analysis. Weights and ranks for each slope class are assigned and added to the attributes.

3.4.2.2. Land use

The land use map generated from the IRS 1C LISS III imagery is georeferenced and hand digitised. The areas of each land use category are calculated using the area tool in the utility tool set. Each land use classes were assigned with weight and ranks based on their land slide susceptibility. These ranks and weight are added to the attribute table by key board entry.

3.4.2.3. Drainage density

In the attribute table of drainage density feature class already prepared, new weight and ranks for the stability analysis are added based on the effect of drainage density on stability of terrain.

3.4.2.4. Relative relief

The relative relief map of the study area was prepared by overlaying a square grid with 1 km side and the highest and lowest elevation are assigned to each grid and clipped by the boundary polygon. Relative relief feature class was classified and weight and ranks were assigned to each class and were added to the attribute table.

3.4.2.5. Soil depth

Soil depth is measured using an auger at each positions of the infiltration measurement. Using the latitude and longitude, the point map is generated and the soil depth values are added to the attribute table. Using the geostatistic extension of Arc GIS, an interpolated surface is generated from the point map. It is then rasterized and reclassified to get the soil depth variation map for the entire watershed.

3.4.2.6. Weighted overlay analysis

All parametric layers prepared for the stability analysis were overlaid using the union tool. The sum of all indices were calculated and added in the attribute table as a new field. Based on this total index, the resultant layer was reclassified into four classes of stability. Stability classes were displayed as a map.

3.5 Stable and suitable areas for artificial recharge

Suitable and moderately suitable areas were taken for recharge interventions. Suitable areas have the most favourable hydrogeological condition for groundwater recharge. Moderately suitable areas may have some limiting factors and the design should be such that to mitigate the effect of that limiting factor. Unstable and highly unstable areas delineated through the stability analysis, were considered as the slide prone areas, which cannot bear moisture more than a limit. These areas were erased by overlay tools in Arc GIS 9.1 and thus the areas suitable for artificial recharge were delineated.

3.6 Sites suitable for specific recharge measures

Artificial augmentation of the recharge to groundwater storage is commenced either through increasing the infiltration opportunity time or creating a preferential flow to the deep seated aquifers. Structures or interventions for artificial recharge can be classified as rain water harvesting structures, on-stream interventions, injection recharge structures and groundwater dams. Rain pits, trenches, contour bunding, terracing etc. reduce runoff and provide more infiltration opportunity time to rain water and thus increase deep percolation. On-stream interventions like Check Dams, Vented Cross Bars, Gabion Dams, Percolation Tanks etc. create storage in the stream for the dry season and increases infiltration opportunity time. Injection method creates an artificial preferential flow to the deep seated or confined aquifer through filter shafts and wells. This method can be combined with stream interventions and gully plugs if the bed is less permeable. Groundwater dams Block the quick subsurface lateral flow in sloping highly permeable strata and store water in head water region. Most suited artificial recharge structures for Attappadi region are listed below

3.6.1. Pits and trenches

These are constructed when permeable strata are available at shallow depths. These are constructed across the slope in continuous, staggered or random manner. Pits are generally 1 – 2 m wide and 2 – 3 m deep. Trenches are 0.5 – 1 m wide, 1 – 1.5 m deep and 10 – 20 m long depending up on the availability of land and water. Many times both of them are back filled, after excavation, with filter materials. Filter material used generally are coarse sand (1.5 – 2 mm), gravels (5 – 10 mm) and boulders (5 – 20 cm). Small sized rain pits are also can be effectively recharge water if soil is permeable.

Drainage map of the area is buffered for 100 m. Resultant map of the study area is over laid on the suitable areas for artificial recharge using erasing tool. The suitable areas 100 m away from streams were obtained. These were the areas suitable for non-stream interventions. Feasible areas for pits and trenches were exhibited as a map.

3.6.2. Check dams and *nala* bunds

Check dams are constructed across small streams having gentle slope. Height of water is kept less than 2 m and excess water is allowed to flow over the head wall. Anti scouring measures should be taken in down stream side. Series of check dams can be constructed to harvest maximum runoff. The head wall can be made of concrete, masonry, gabions, or loose rocks. First or second order streams are selected for small check dams or *nala* bunds. Third and fourth order streams are suitable for masonry or concrete check dams. Catchment area for check dams should be with in 40 – 1010 ha and width of streams should be with in 5 – 15 m.

The drainage network of the study area was clipped by the stable and suitable areas for groundwater recharge. The resultant suitable streams layer is classified according to the stream order assigned to them. According to the stream order and catchment area structures were selected and exact locations were suggested. The locations for the proposed structures were exhibited as a map.

3.6.3. Subsurface dykes

It is a subsurface barrier across streams or gently sloping land which retards the subsurface flow of water and stores water in upstream. Since water is stored in subsurface, submergence of land can be avoided and evaporation loss will be very less. Narrow valleys with gentle slope, sufficient catchment area, massy basement rock at shallow depth and high rate of subsurface flow and infiltration are favourable zones for subsurface dykes. Thickly vegetated areas and areas prone to water logging and land slides are not feasible for this intervention.

The drainage network of the study area was clipped by the stable and suitable areas for recharge and overlaid on land use map and DEM. Streams in narrow valleys, not covered by dense forest with considerable catchment area can be identified for the implementation of subsurface dykes. Feasible locations were displayed in map form.

3.6.4. Recharge wells

Areas which cannot adopt spreading method due to the unavailability of fallow land and permeable layers of surface soil can be recharged with recharge tube wells. The purpose of recharge tube well is to directly feed depleted aquifers through a conduit by collecting runoff water. In this method, recharge is very fast and evaporation loss is apparently nil. It is an efficient method to recharge deep seated aquifers but the quality of runoff water is a constraint. Areas, with high fracture density, lineament density or thick weathered zone, are suitable area for this structure.

Lineament layer, hand-digitised from the lineament map of Attappadi area generated from the IRS 1C LISS III imagery, is overlaid on the stable and suitable areas for recharge. Lineaments are buffered by 50 m and the resultant layer is clipped by stable and suitable area. The feasible areas for recharge wells are represented as a map.

3.6.5. Impervious surface water harvesting and recharge

Roof water harvesting and recharging to groundwater through percolation pits are most common method among these measures. Runoff harvested from the impermeable roads and floors can also be recharged to the groundwater through percolation pits. These are mainly concentrated in the habitat area and towns. Locations feasible for this method were displayed in the map.

RESULTS AND DISCUSSION

CHAPTER IV

RESULTS AND DISCUSSION

Scientifically designed artificial recharge measures at recharge-potent sites are the requisites for reducing groundwater scarcity, in areas with low natural groundwater recharge. Using GIS software packages, it is possible to analyse the spatiotemporal variations of hydrologic as well as hydro-geologic parameters easily and efficiently.

The present study was conducted to estimate the natural groundwater recharge, to delineate the suitable area for artificial recharge and to suggest suitable interventions in Siruvani watershed. GIS analyses were carried out to study the spatial and temporal variation of climatic parameters and spatial variation of surface and subsurface terrain characteristics. The results obtained from the analysis are displayed and discussed in this chapter.

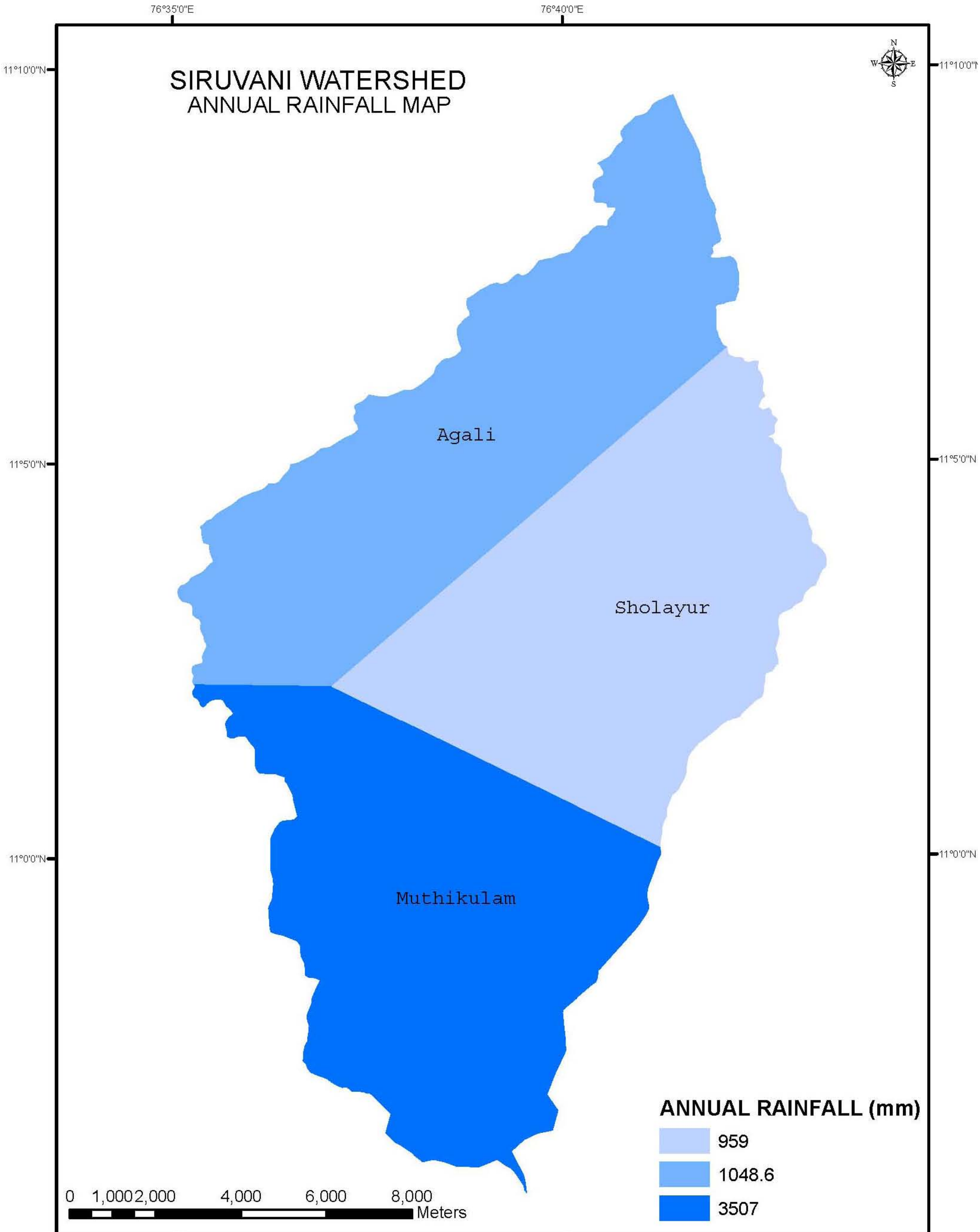
4.1. Spatiotemporal distribution of natural groundwater recharge

Considering the following parameters in a water balance model, the spatial and temporal variation of groundwater recharge in Siruvani watershed was estimated.

4.1.1. Rainfall

Rainfall maps for the months from June 2006 to May 2007 were prepared using the daily rainfall data collected from Agali, Sholayur and Muthikulam rain gauge stations. Thiessen polygons were constructed and rainfalls for each climatic zone are displayed in Figure 5. Annual rainfall map for the water year 2006-07 was generated and displayed in Map 2. Total rainfall in the Siruvani watershed was estimated as 372 Mm^3. Map 2 clearly shows the rain shadow effect in the watershed. The southern Muthikulam area gets considerable rainfall compared to Agali and Sholayur. Sholayur is the driest area with very low annual rainfall.

Agali gets more precipitation during the north-east monsoon than during south-west monsoon. Sholayur is a dry area. However during south-west monsoon, it recieves good precipitation. Muthikulam area gets both the monsoons.



Map 2 Annual Rainfall

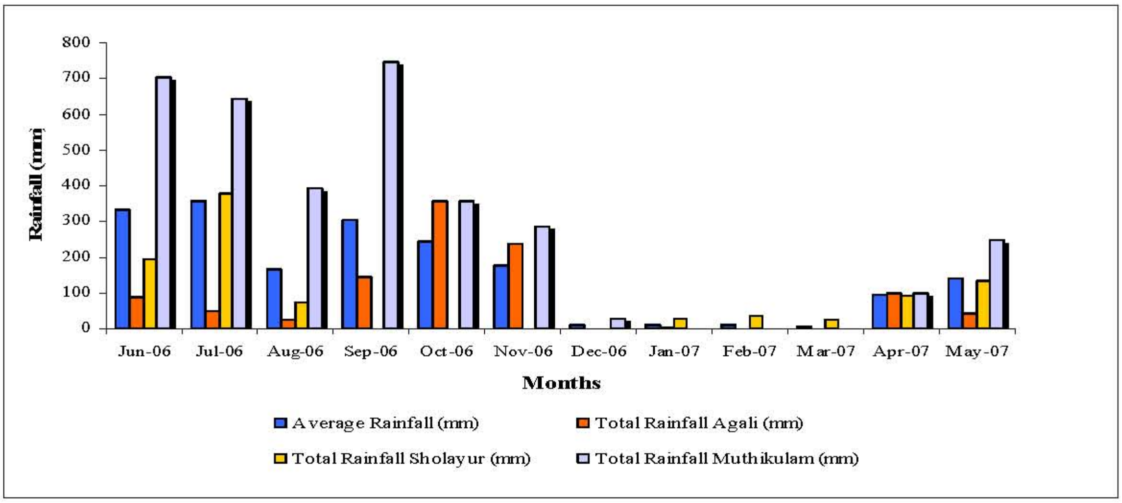


Figure 5 Monthly Rainfall in Siruvani Basin

4.1.2. Surface Runoff

Surface runoff map was generated using SCS curve number method for all the twelve months of the water year 2006-07. An annual runoff map was generated and displayed (Map 3). Annual surface runoff from the Siruvani watershed is 56 Mm^3 for the water year. On an average, 15.06 % of the obtained rainfall from the catchment is flowing out as surface runoff. In Agali area 21.39 % of the rainfall is converted to surface runoff, while it is 11.06 % and 14.2 % in Sholayur and Muthikulam respectively. Agali area is degraded and without forest covers and hence its runoff generation potential is high. Monthly estimated total surface runoffs from the catchment are given in Figure 6.

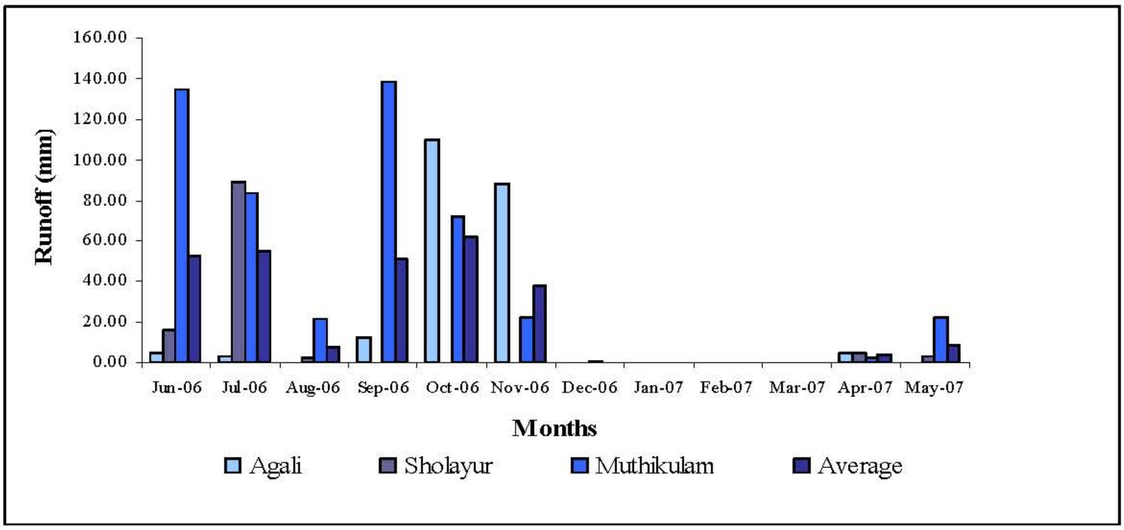
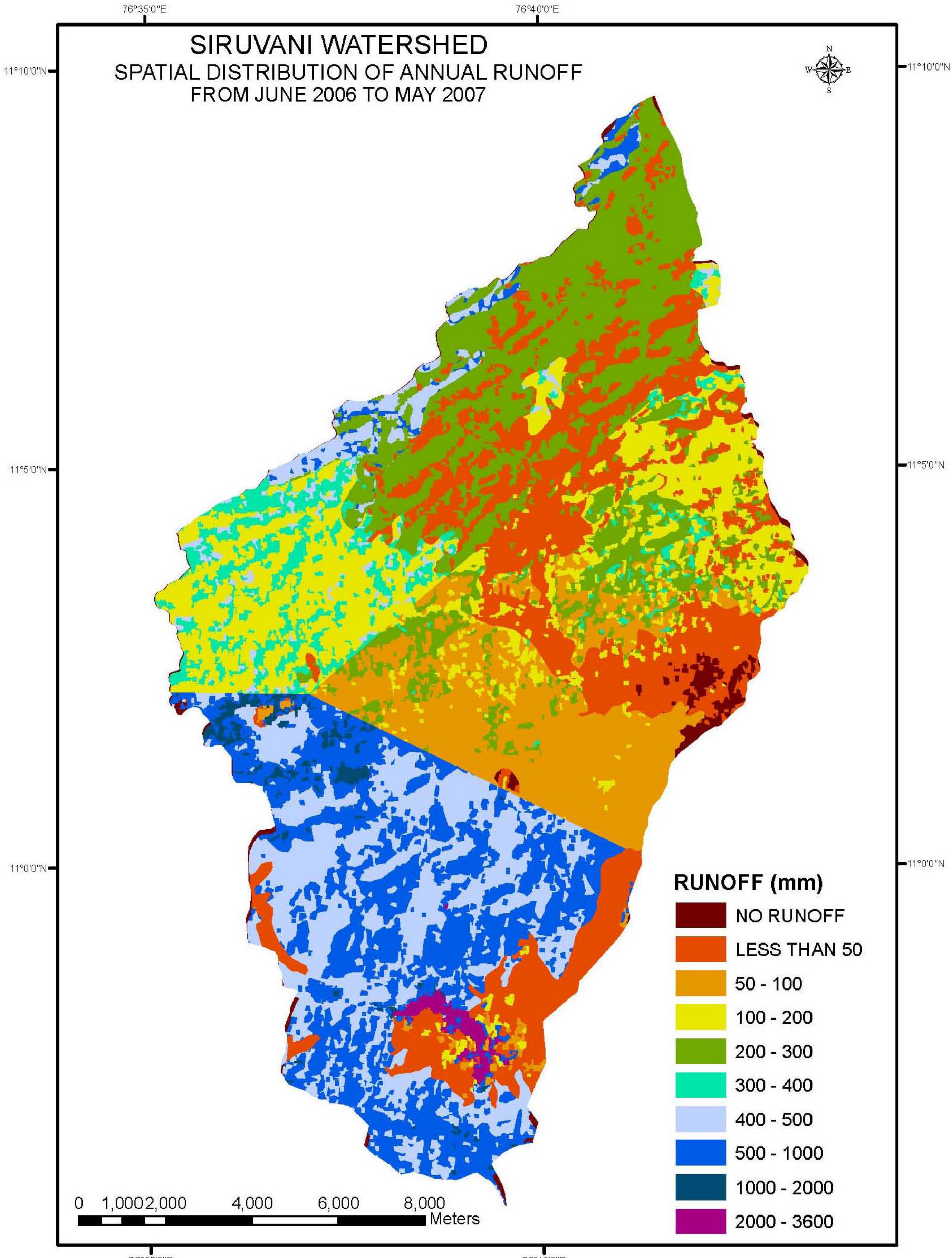


Figure 6 Estimated Surface Runoff from Siruvani Basin



Map 3 Spatial Distribution of Annual Runoff

Runoff map shows runoff depends primarily on the rainfall. As expected, high runoff was observed in months with high rainfall.

4.1.3. Potential evapotranspiration

Using the Penman method, evapotranspiration for each month were estimated and spatial variation of annual potential evapotranspiration is represented in Map 4. Total annual potential evapotranspiration from Siruvani watershed was estimated as 236.06 Mm^3. Potential evapotranspiration varies with each meteorological division, due to the climatic variation, elevation difference and land use pattern. The Muthikulam area is largely forested with high altitude. Average mean monthly temperature is low compared to Sholayur and Agali. Relative humidity is also highly varying within the watershed. The variation in annual and monthly PET is shown in Figure 7

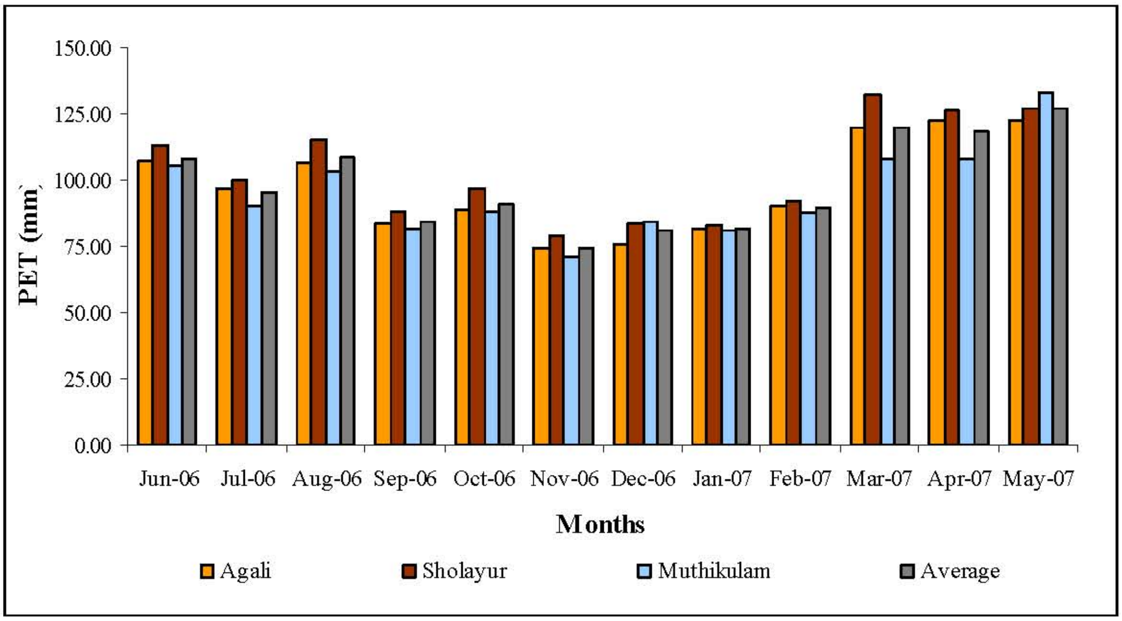
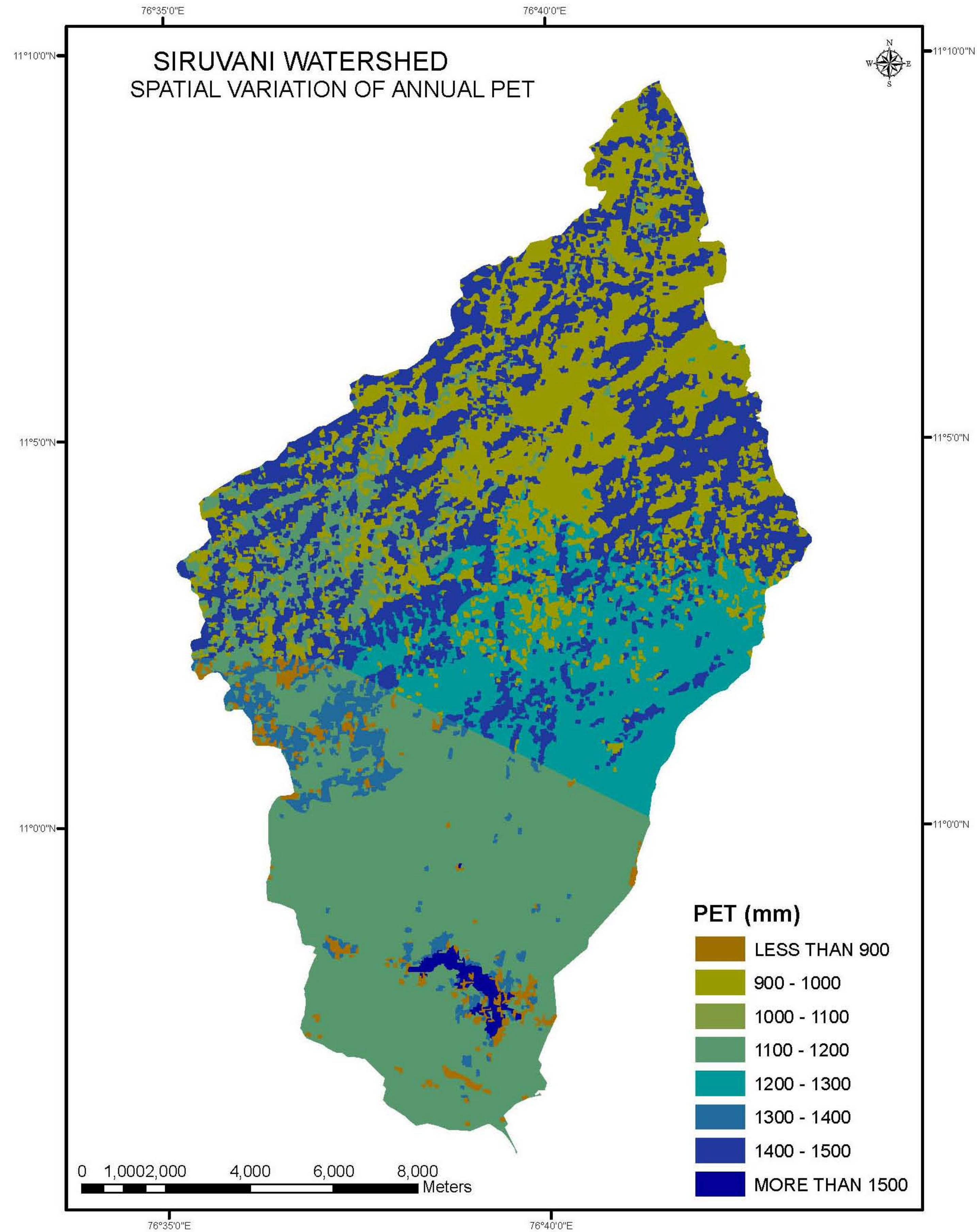


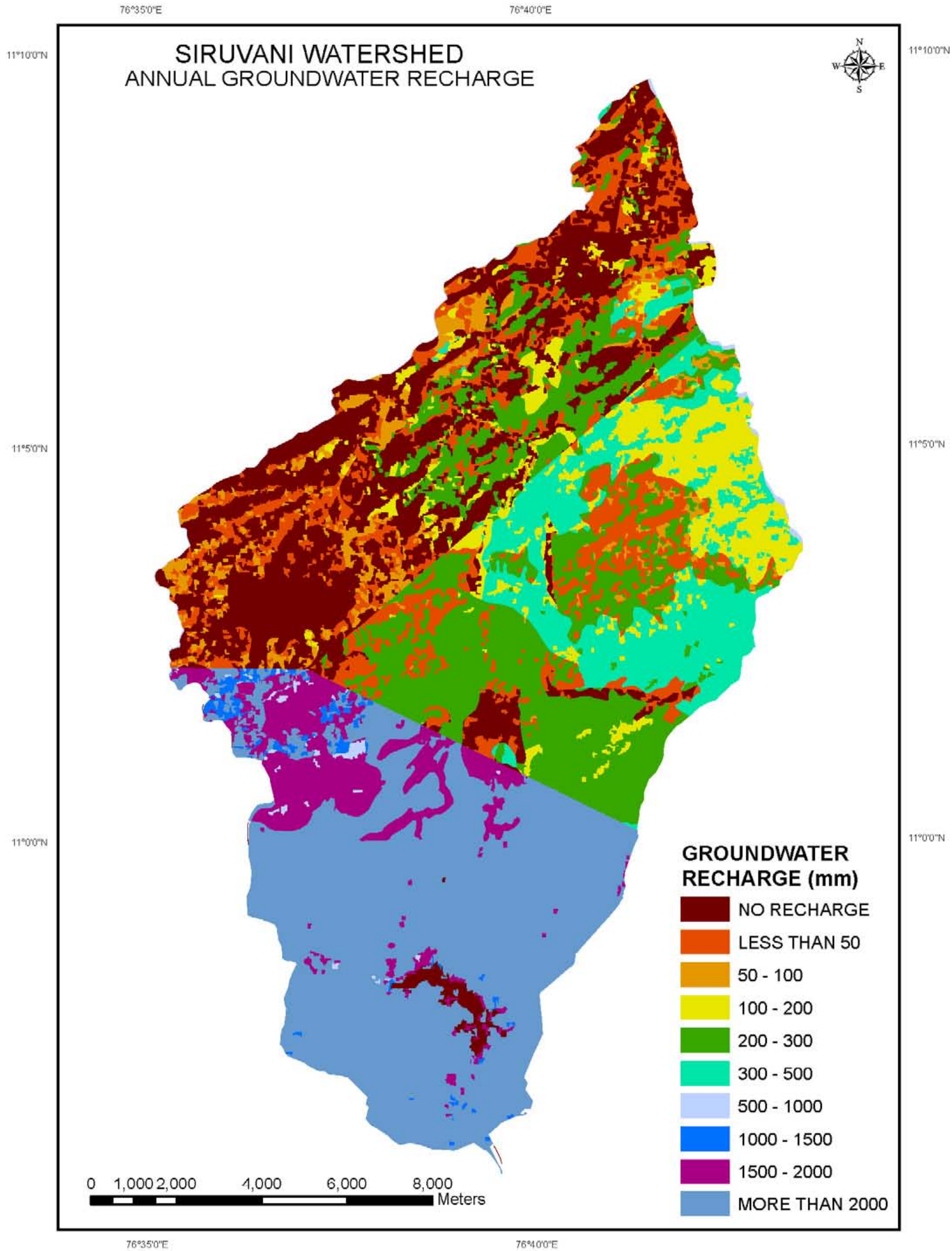
Figure 7 Estimated PET in Siruvani Basin

4.1.4. Groundwater recharge

Groundwater recharge quantities for each month are estimated using Thornthwaite water balance method. The spatial distribution of annual groundwater recharge is shown in Map 5. The total annual groundwater recharge is estimated as 158.47 Mm^3. The estimated total quantities of groundwater recharge in Siruvani watershed for each month are shown in Table 1.



Map 4 Spatial Distribution of Annual PET



Map 6 Spatial Distribution of Annual GWR

The groundwater recharge is heavy in the southern part of the Siruvani watershed. The percentage value is higher due to the fact that the groundwater recharge estimated here is actually the sum of subsurface runoff and deep percolation to groundwater. Major portion of this estimated groundwater recharge will be lost through base flow contribution to Siruvani River which is thus a perennial stream. After the groundwater detention, the excess water will reach the streams only after a lag period. Mostly this groundwater flow contributes to the runoff in the next month.

The forested Muthikulam area is getting enough rainfall and surface recharge is higher. So, there is no need of any artificial recharge measures in the forest areas of Muthikulam. And also, the surface runoff generated in water bodies is taken as 100 % of the rainfall obtained.

Table 1 Estimated Monthly Groundwater Recharge

Month	GWR (mm)				GWR (% of Rainfall)
	Agali	Sholayur	Muthikulam	Average	
Jun-06	0.00	30.66	395.44	143.68	43.53
Jul-06	0.08	180.57	468.71	216.72	60.80
Aug-06	0.55	0.75	266.78	90.71	55.09
Sep-06	0.60	0.00	526.65	178.42	59.13
Oct-06	19.46	0.00	199.28	74.06	30.41
Nov-06	42.99	0.00	193.62	80.14	45.13
Dec-06	0.00	0.00	0.00	0.00	0.00
Jan-07	0.00	0.00	0.00	0.00	0.00
Feb-07	0.00	0.00	0.00	0.00	0.00
Mar-07	0.00	0.00	0.00	0.00	0.00
Apr-07	0.00	0.00	0.00	0.00	0.00
May-07	0.00	0.02	0.07	0.03	0.02
TOTAL	63.68	211.99	2050.54	783.71	

According to this water balance model, runoff from the Siruvani reservoir will be 100 % of rainfall and groundwater recharge component will be zero, since the water balance of the reservoir is not considered.

4.1.5. Water balance for the water year 2006-07

The computation of the water balance components were carried out in Arc GIS platform and then the monthly average of these parameters are estimated. Water balance for the water year for each meteorological region were prepared and displayed in Figures 8, 9 and 10. Actual evapotranspiration for each month are calculated as per the Thornthwaite model. This model consists of the monthly

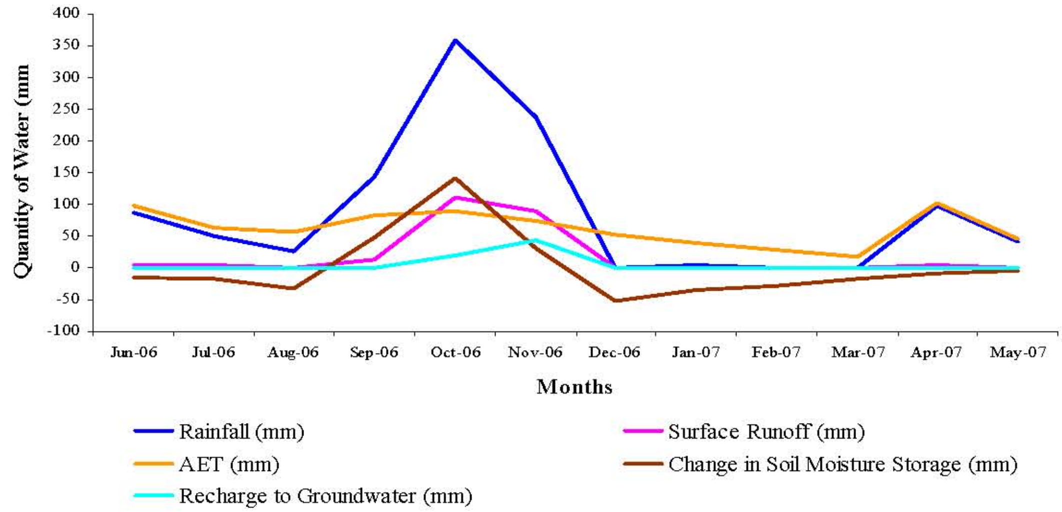


Figure 8 Estimated Water Balance of Agali Region

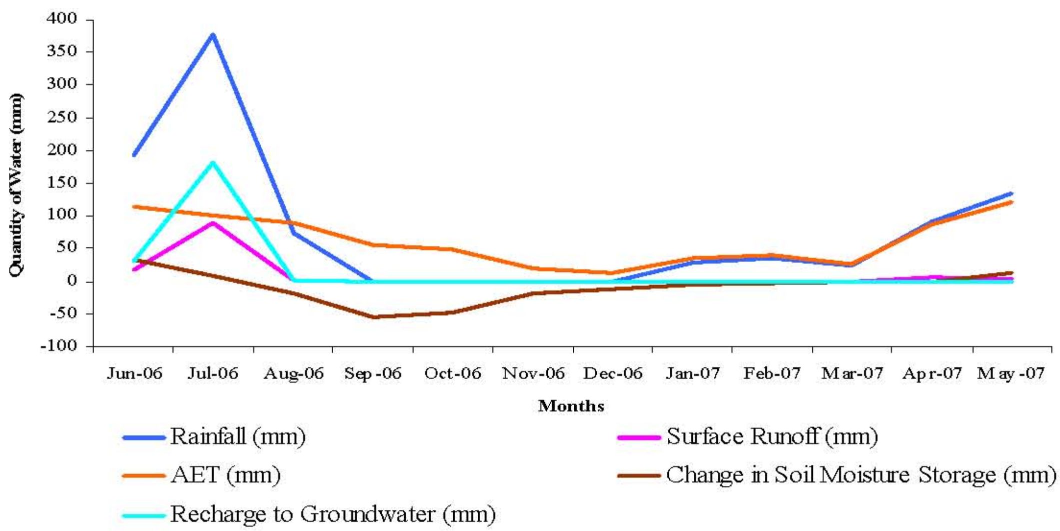


Figure 9 Estimated Water Balance of Sholayur Region

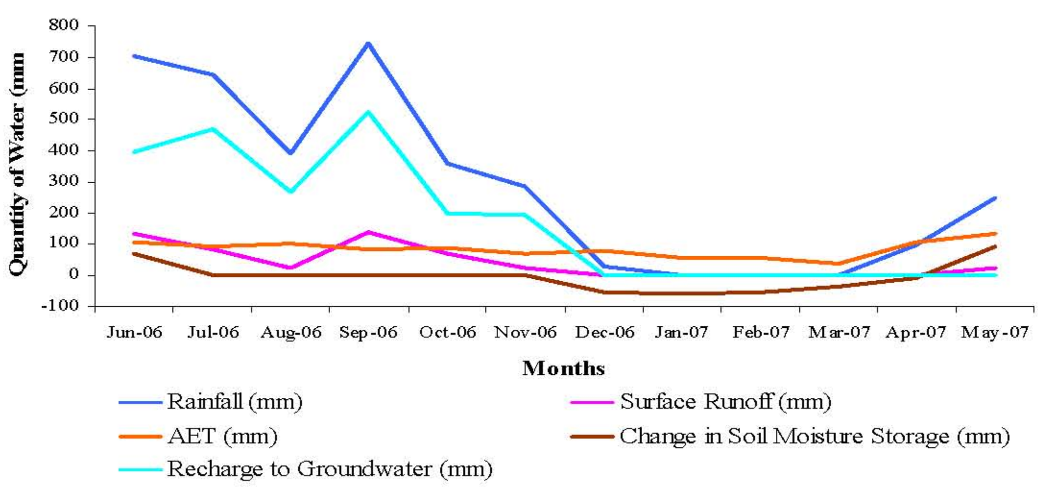


Figure 10 Estimated Water Balance of Muthikulam Region

average values of rainfall, surface runoff, actual evapotranspiration, change in soil moisture and groundwater recharge.

During January, February and March, actual evapotranspiration is found very low as the soil moisture is very low. The Agali and Sholayur regions were under drought during that period. Maximum runoff was obtained in October. The high runoff generating terrains especially Agali was getting maximum rainfall in October. Except for the four months, soil moisture storage showed negative values, since PET was always greater than effective rainfall for Agali and Sholayur regions. These regions face serious drought almost through out the year.

4.2. Delineation of suitable areas for artificial groundwater-recharge systems

By analyzing the stability and hydro-geological suitability of the terrain, the suitable and stable areas where the artificial recharge systems can be implemented without causing land slide hazard were delineated. Results obtained during the various steps of the analysis are described below.

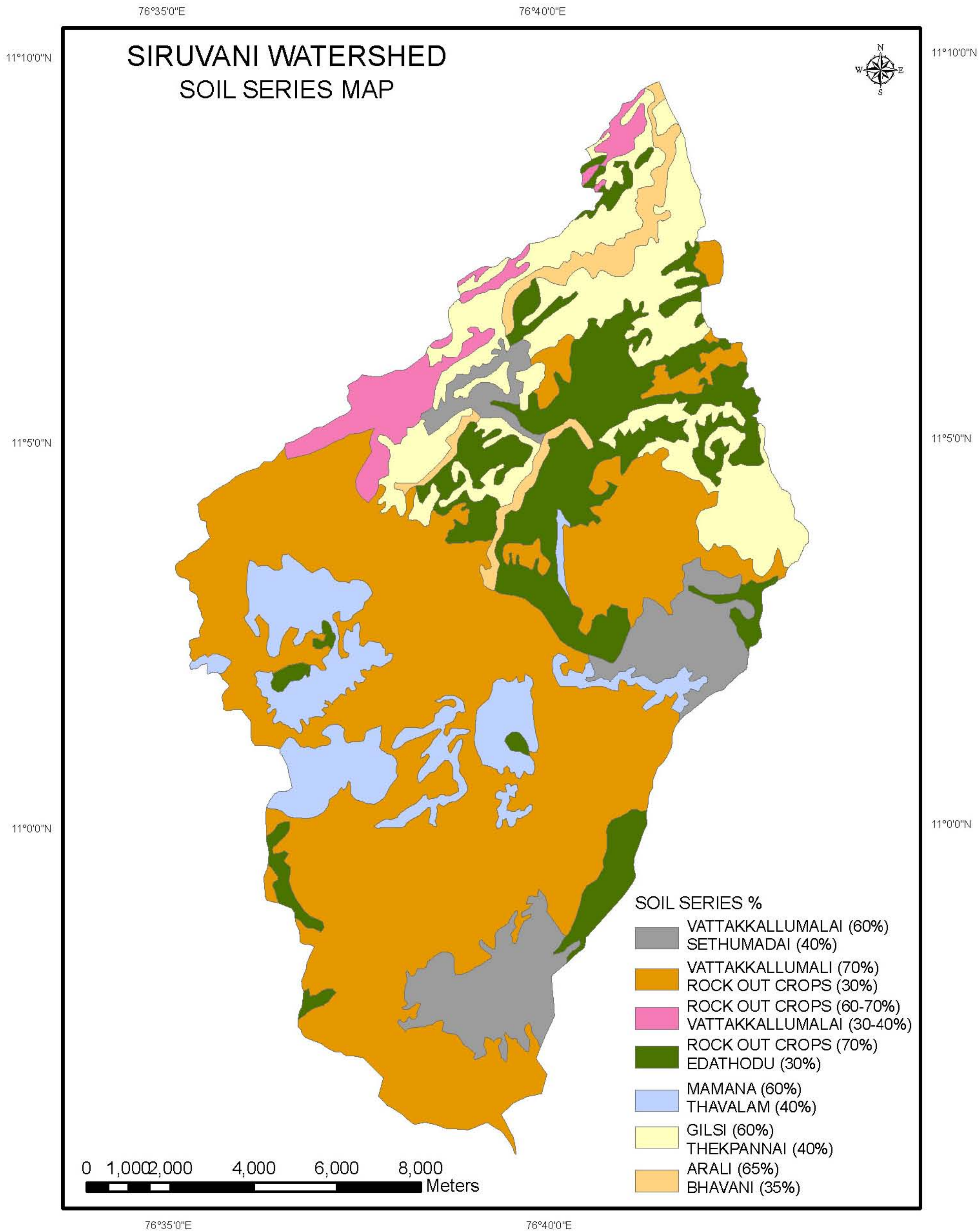
4.2.1. Delineation of potential groundwater-recharge zones

For the delineation of hydro-geologically suitable areas for groundwater recharge, the following parametric layers were digitized and suitable weights according to the contribution towards the central theme were assigned to them.

4.2.1.1. Infiltration rate

Infiltration studies were conducted at 22 locations all over the watershed using double ring infiltrometer. The measured infiltration rates are averaged inside each soil series polygon and that average values were entered as the infiltration rate of the soil series association. The observed infiltration rates are shown in the Table 2. Soil series associations of Siruvani watershed are displayed in Map 6.

Most of the soil series fall under moderately rapid infiltration. Arali – Bhavani association was found with highest infiltration capacity. Arali and Bhavani serieses are deeper well drained soils with fine loamy texture. Rock outcrops-Vattakkallumalai association was found with the least infiltration capacity, probably



Map 6 Soil Series Associations

due to the lesser soil thickness. Vattakkallumalai series is shallow and well drained. Associating with Sethumadai series, Vattakkallumalai series shows rapid infiltration rate. Elathodu series associate with rock out crops shows better infiltration. It may be due to the loamy sand texture.

Table 2 Soil Series Associations and Infiltration Rates

Sl.No.	SOIL SERIES	INFILTRATION RATE (cm/h)
1	Vattakkallumalai (60%) Sethumadai(40%)	20.80
2	Vattakkallumali (70%) Rock Outcrops (30%)	6.50
3	Rock Outcrops (60-70%) Vattakkallumalai (40-30%)	1.00
4	Rock Outcrops (70%) Elathodu (30%)	14.5
5	Mamana (60%) Thavalam (40%)	12.00
6	Gilsi (60%) Thekpannai (40%)	16.00
7	Arali (65%) Bhavani (35%)	22.80

Hydraulic conductivity of the unsaturated soil zone plays a prominent role in groundwater recharge than geology of the area. Hence, highest weight 25 is given to infiltration rate. Higher the infiltration rate, greater the recharge. So, the highest rank is given to high infiltration rate. Infiltration layer was reclassified into four classes and ranks from one to four were assigned to each class. The weights and ranks assigned to each infiltration rate class are shown in Table 3.The weights and ranks were entered to the attribute table and index was calculated within the attribute table.

Table 3 Infiltration Rate Classes with Weight and Ranks

Infiltration rate	Rank	Weight	Index
< 2	1	25	25
2-12.5	2		50
12.5-25	3		75
> 25	4		100

4.2.1.2. Geology

Geology map was vectorised and areas under each category were calculated using GIS. The obtained areas under each geologic category are exhibited in Table 4.

Table 4 Geological Units and Area Extend

Sl.No.	Geology	Area (km^2)	% Area
1	Biotite hornblende gneiss	27.78	13.88
2	Metaultramaphite	13.28	6.63
3	Hornblende biotite gneiss	15.26	7.62
4	Hornblende biotite schist	82.99	41.46
5	Pink granite gneiss	51.21	25.58
6	Garnet biotite gneiss	9.65	4.82
	Total	200.17	100.00

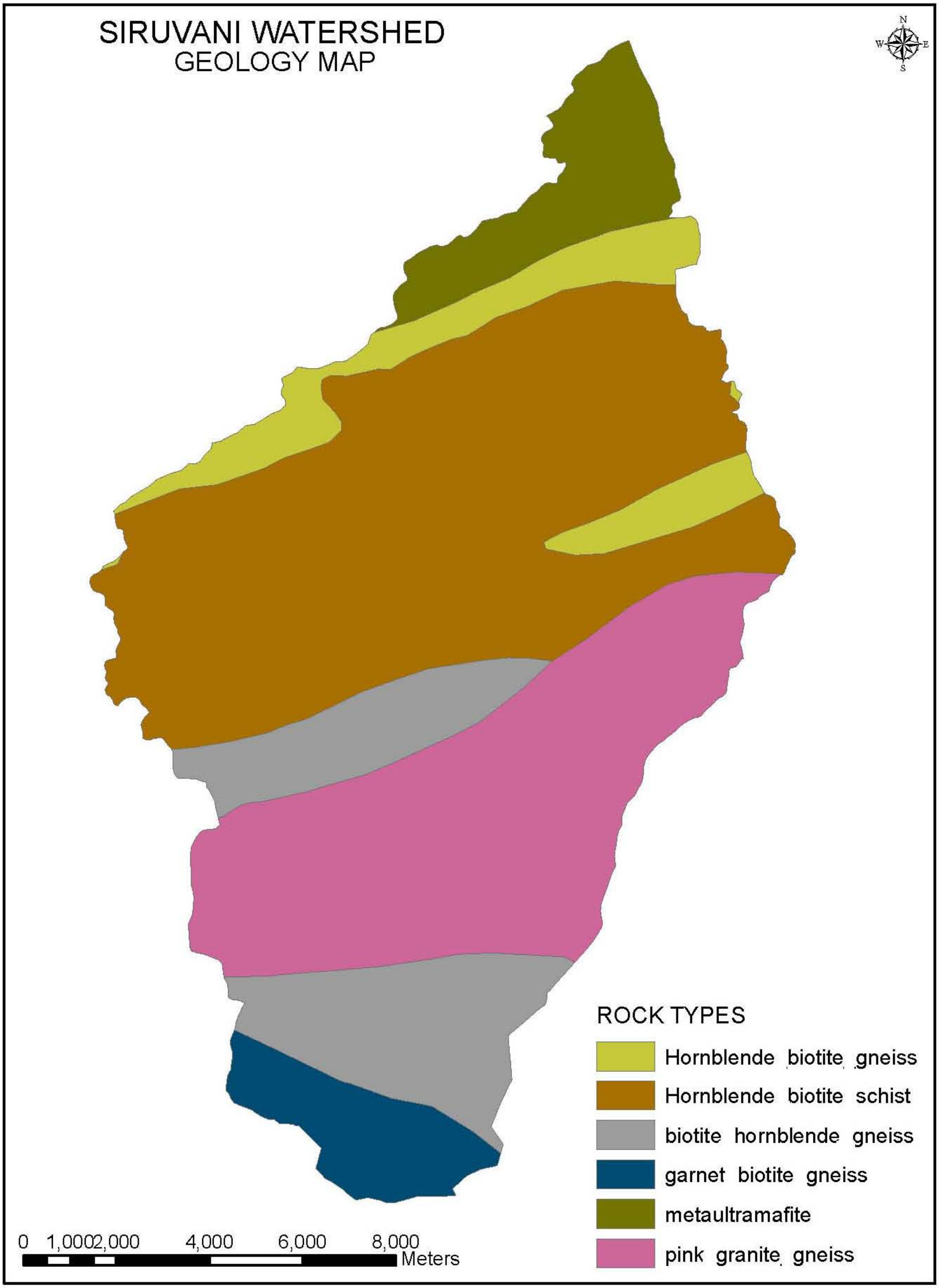
In hard rock terrains, artificial groundwater recharge potential highly depends on the underlying geology of the area. Porosity depends on the weathering processes of each geologic material. According to the weathering properties of the geologic formations, the ranks are given to each formation features. Gneisses are more susceptible to weathering. Hence the depth of weathered zone will be higher in these formations. In biotite gneisses, porosity in the weathered mantle as well as in the foliation planes gives storage space for groundwater. So, higher ranks were assigned to these formations. Metaultramaphite is having the lowest porosity hence lowest rank was assigned to it. The ranks assigned to each geologic class are listed in Table 5.

Table 5 Geologic Formations with Assigned Weight and Ranks

Geologic Formations	Rank	Weight	Index
Hornblende biotite gneiss	4		80
Hornblende biotite schist	2		40
Biotite hornblende gneiss	4	20	80
Garnet biotite gneiss	4		80
Metaultramaphite	1		20
Pink granite gneiss	3		60

4.2.1.3. Geomorphology

Geomorphology layer of the study area was digitized and areas under each geomorphologic unit were calculated using GIS. The prepared map is exhibited as



Map 7 Geology

Map 8. Geomorphologic units and their corresponding area extend are displayed in Table 6.

Table 6 Geomorphologic Units and Area Extend

Sl.No.	Geomorphology units	Area(km^2)	% Area
1	Valley fill	0.08	0.04
2	Buried pediment	5.06	2.53
3	Denuded hills	192.83	96.33
4	Intermontane valley	2.20	1.10
	Total	200.17	100.00

According to the contribution towards recharge potential of the terrain, ranks were given to each geomorphologic unit. Ranks assigned to each unit are displayed in Table 7. Geomorphology is also considered equally important as it is influencing groundwater recharge. So, weightage equal to that of geology is given to geomorphology.

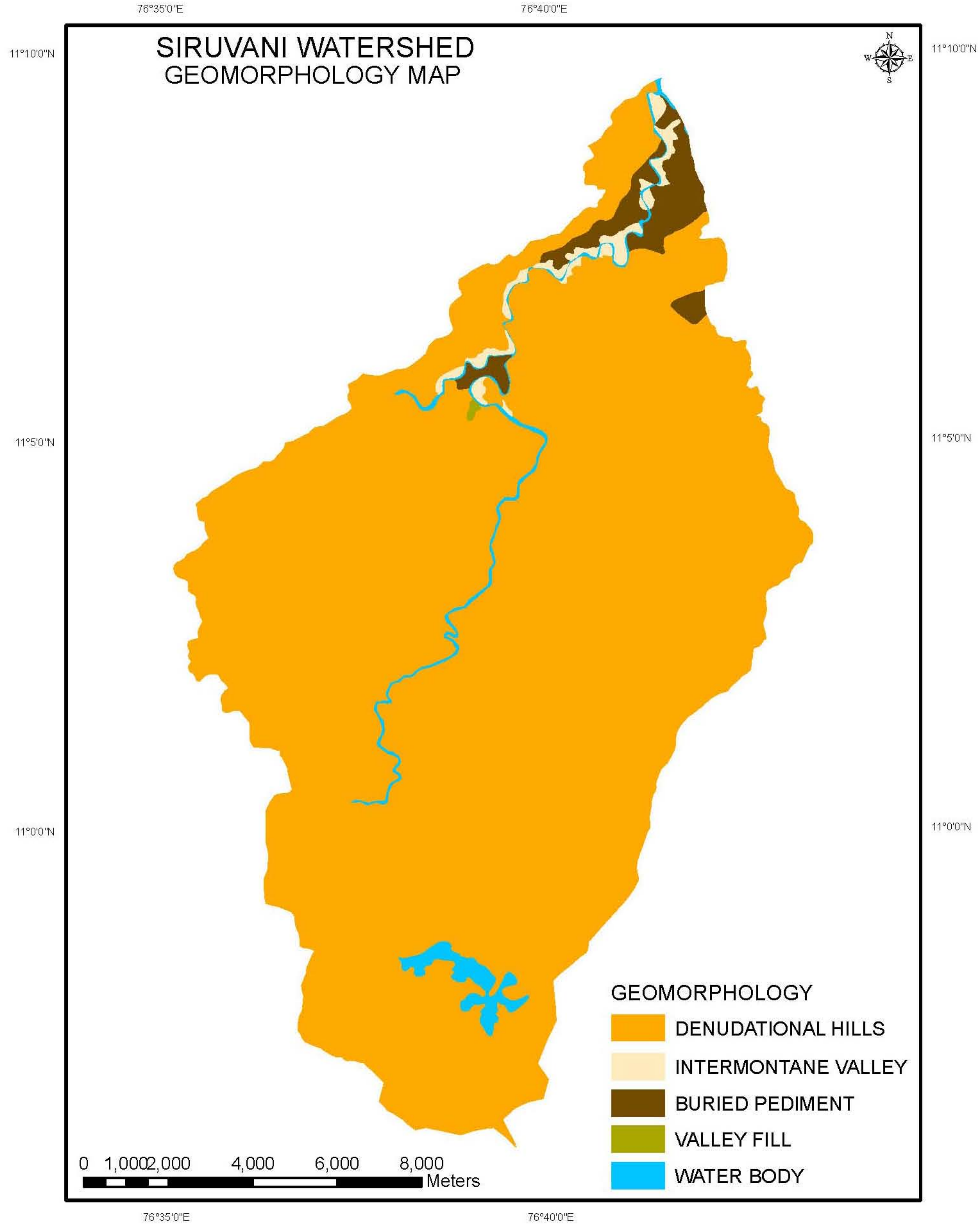
Table 7 Weight and Ranks Assigned to Geomorphologic Units

Geomorphologic units	Rank	Weight	Index
Buried pediment	3	20	60
Denuded hill	2		40
Intermontane valley	1		20
Valley fill	4		80

In denuded hills, the recharge feasibility depends largely on the underlaying geology. Buried pediment and valley fills are suitable areas for groundwater recharge.

4.2.1.4. Rechargeable depth of formation

Thickness of the weathered portion is very difficult to estimate. Well inventory can give some information about the weathered zone thickness. This may not be accurate as the wells in the study area were not dug completely into the weathered zone in most cases. The spatial variation of the weathered thickness is beyond predictions. Using the geostatistical analyst of Arc GIS, inverse distance weighed interpolation of well inventory data was done and a surface representing the weathered zone thickness was generated. Well logs and bore tests should be conducted to get more accurate information about the variation in weathered zone thickness in the watershed.



Map 8 Geomorphology

More the weathered thickness more will be storage capacity and hence more can be the groundwater recharge. So, higher ranks are assigned to higher values of rechargeable depth. Rechargeable depth plays greater role in groundwater recharge than drainage density and slope. Hence higher weightage was given to rechargeable depth than drainage density and slope. Weight and Ranks assigned are shown below.

Table 8 Weight and Ranks assigned to Rechargeable Depth Classes

Rechargeable depth (m)	Rank	Weight	Index
< 2	1		15
2-5	2	15	30
5-7	3		45
> 7	4		60

4.2.1.5. Slope

Elevation contours were digitized and digital elevation model was prepared from elevation vector using 3D analyst. From DEM, slope in degree map was generated and reclassified. Classified DEM and slope map are exhibited in Map 9 and Map 10 respectively. Slope classes and area extend are displayed in Table 9.

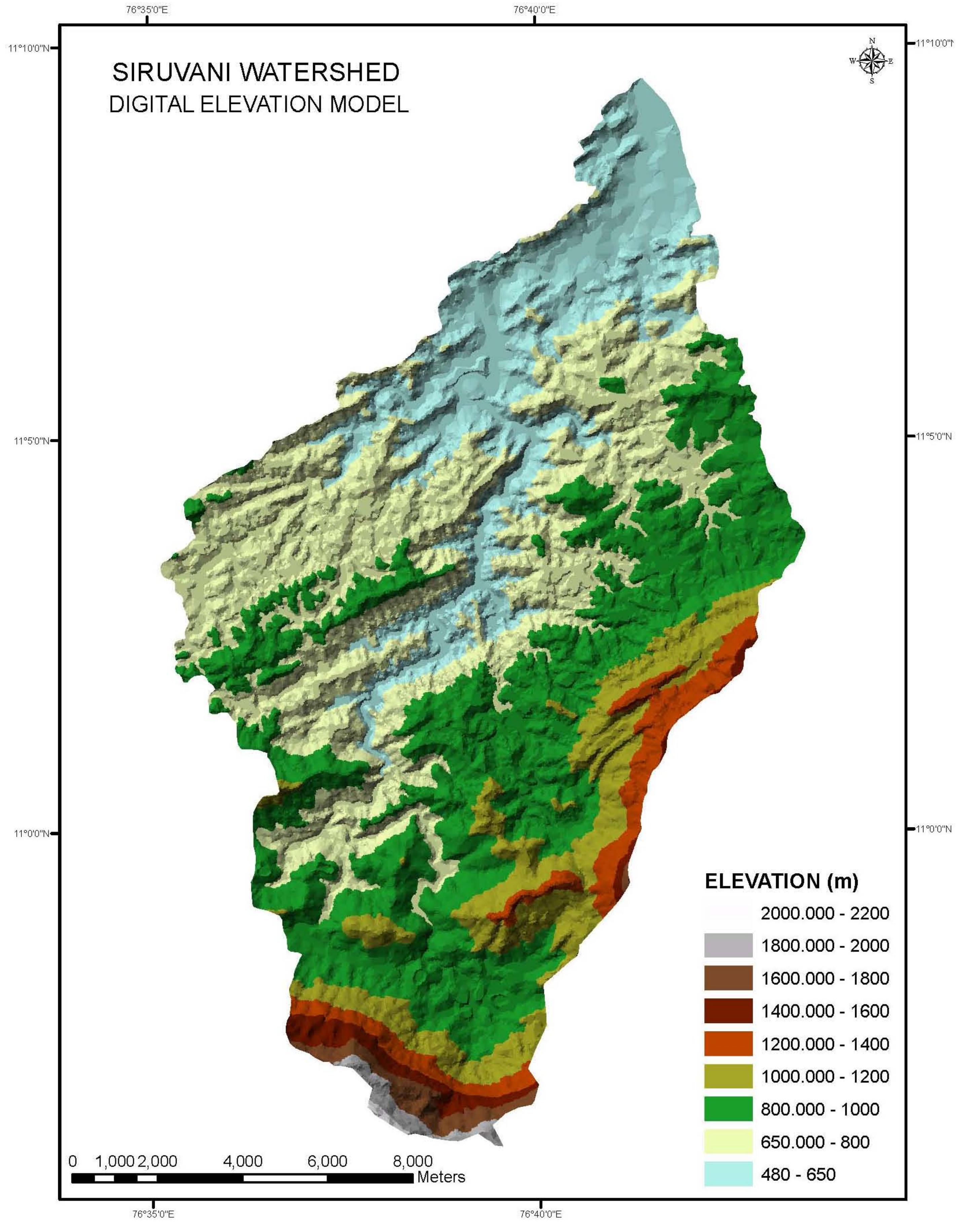
Table 9 Slope Classes and Area Extend

Sl.No.	Slope in degrees	Area (km^2)	% Area
1	>30	23.52	11.75
2	20 – 30	48.01	23.99
3	10 – 20	68.65	34.30
4	<10	59.98	29.97
Total		200.17	100.00

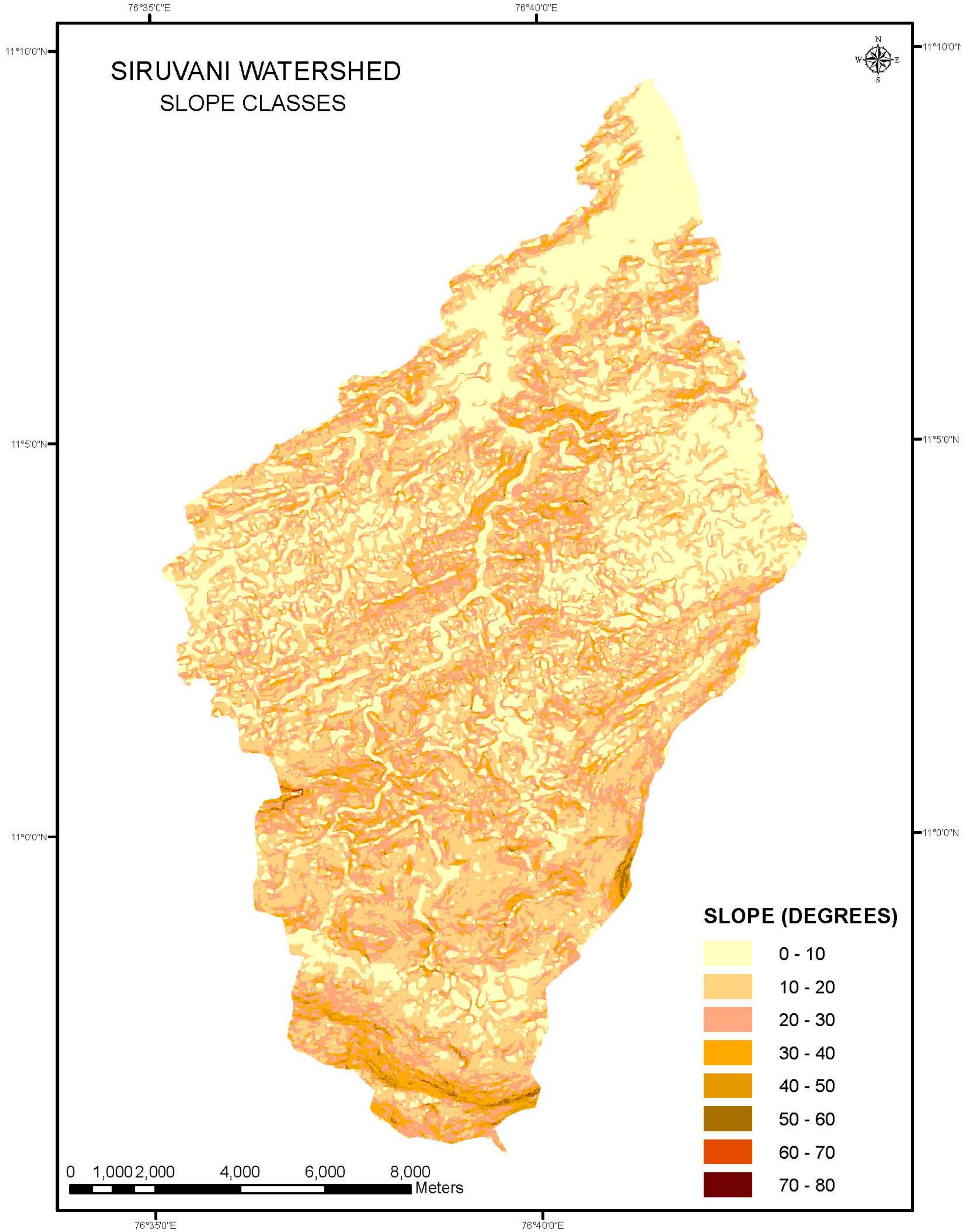
Slope reduces infiltration opportunity time, and reduces the recharge to the soil. But through interventions the effect of slope can be reduced. Hence the least weightage was given to slope. Recharge will be high in less sloping areas. High ranks were assigned to low slope classes. Slope classes and assigned ranks are shown in the Table 10.

Table 10 Weight and Ranks assigned to Slope Classes

Slope Class	Rank	Weight	Index
< 10	4		40
10-20	3	10	30
20-30	2		20
> 30	1		10



Map 9 Digital Elevation Model


76°35'0"E
76°40'0"E
11°10'0"N
11°5'0"N
11°0'0"N
SIRUVANI WATERSHED
SLOPE CLASSES
N
W
E
S
SLOPE (DEGREES)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
0 1,000 2,000 4,000 6,000 8,000
Meters

Map 10 Slope

4.2.1.6. Drainage density

Drainage lines were digitized from the drainage map of Attappadi Block prepared by AHADS; orders of streams have been given and are exhibited in Map 11. Steam orders and number of streams in each category are shown in the Table 11.

Table 11 Stream Orders and Number of Streams

Sl.No.	Stream Order	Number of Streams
1	1^{st} order	874
2	2^{nd} order	371
3	3^{rd} order	35
4	4^{th} order	10
5	5^{th} order	2
6	6^{th} order	1
Total		1293

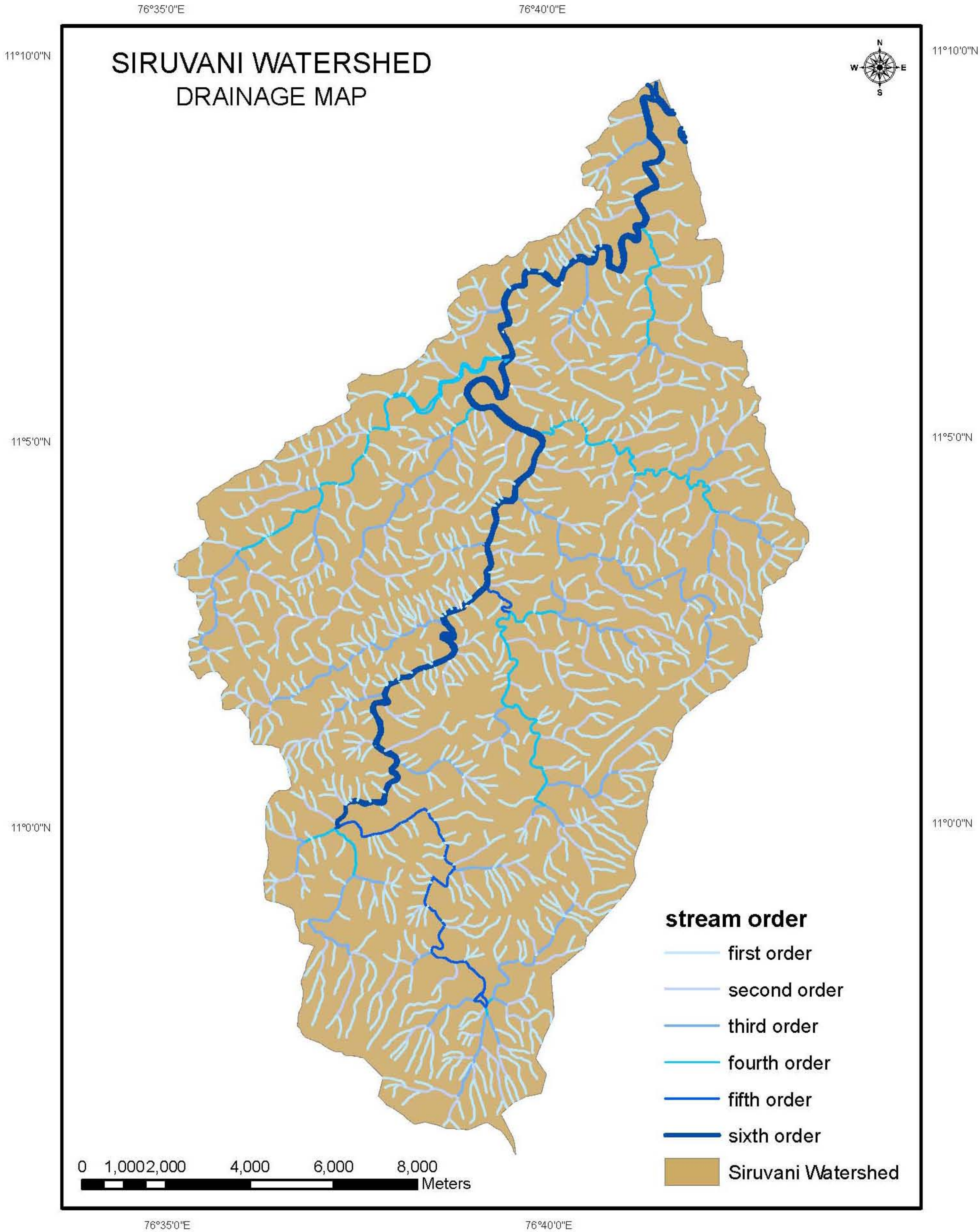
By using the line density tool of spatial analyst, drainage density of the watershed was generated and reclassified into four classes. Drainage density shows the runoff generation capacity of the terrain. More the runoff potential, less will be the recharge. So, high ranks were assigned to low drainage density classes. The ranks and classes of drainage density are shown in the Table 12.

Table 12 Weight and Ranks assigned to Drainage Density Classes

Drainage Density Class	Rank	Weight	Index
< 2	4	10	40
2-3	3		30
3-4	2		20
> 4	1		10

4.2.1.7. Potential recharge zones

By weighted overlay analysis of the above generated layers, groundwater recharge potential zones in the Siruvani watershed was delineated and it is further reclassified into four categories based on the total index after adding all the layer indices during overlay union. The gross index ranges from 100 to 400. A map showing spatial distribution of the four different potential zones for groundwater recharge has been prepared (Map 12). The classes of recharge suitability along with their area extend are shown in the Table 13.



Map 11 Drainage Network

Table 13 Suitability Zones and Area Extend

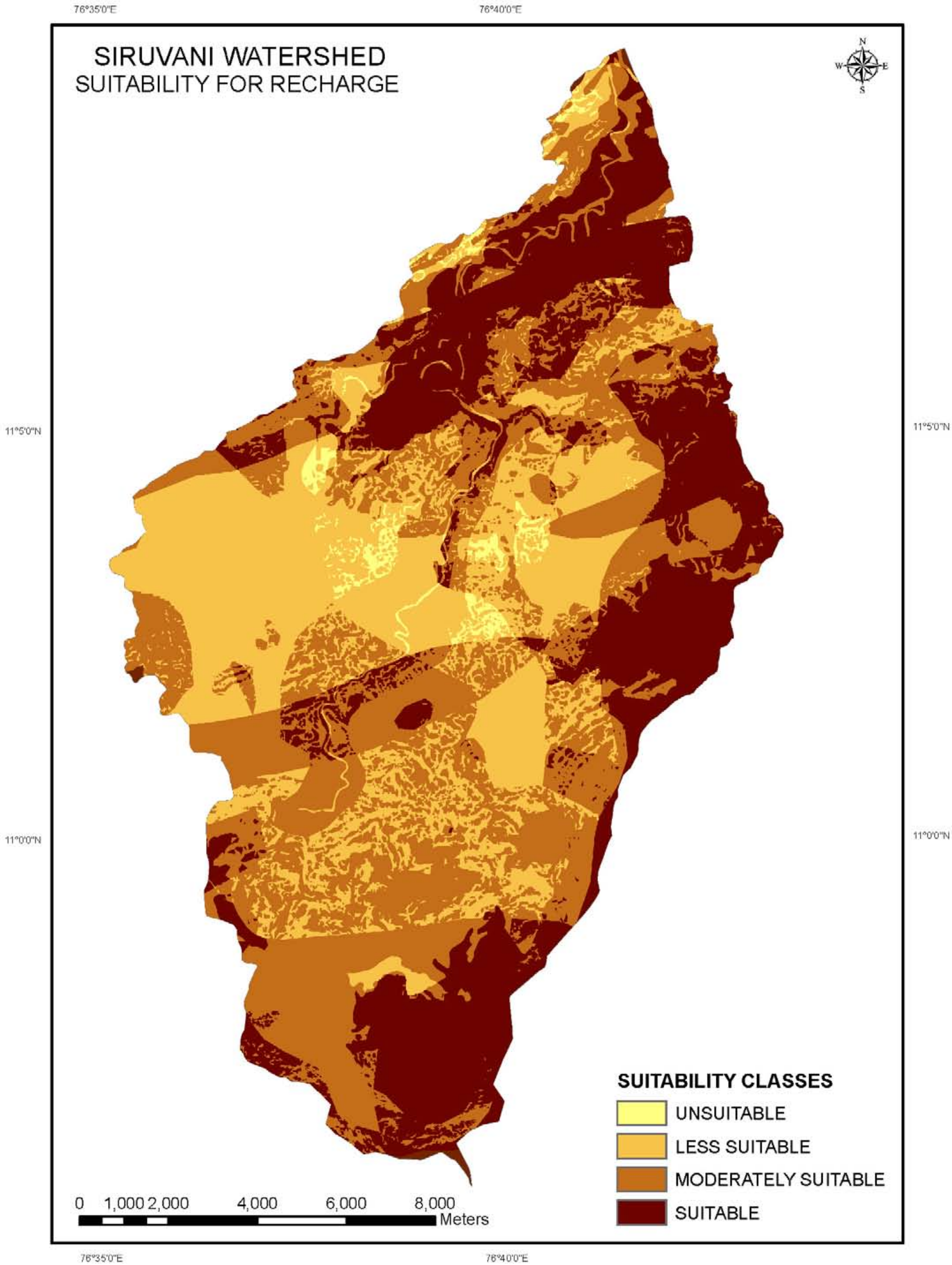
Sl.No.	Class	Area	% Area
1	Suitable	58.71	29.33
2	Moderately Suitable	79.33	39.63
3	Less Suitable	59.09	29.52
4	Unsuitable	3.04	1.52
	Total	200.17	100

Areas with gross index ranging from 100 to 175 were classified as unsuitable areas. These areas are characterised by denuded hills with low infiltration rate underlaid by metaultramaphite and schist formations. This zone could be found in the central part of the study area. Subsurface storage space for recharged water will be very low in this category. Efficiency of recharge measures will be very low in this terrain.

Less suitable zones consist of the areas with gross index between 175 and 250. These areas are characterised by less infiltration capacity. Denuded hills underlained by hornblende biotite schists and pink granite gneisses falls under this group mainly. These are seen in the central Jellippara region and western part of Sholayur of the study area. These are also not good terrains for artificial recharge.

Areas with gross index ranging from 250 to 325 were classed as moderately suitable zone. This zone spread almost the entire study area but predominantly in Muthikulam, Sholayur and Agali region. Limiting factor that makes the terrain unfavourable to recharge should be identified and designs particular to mitigate the effect of those limiting factors should be adopted. As the effect of slope in the analysis is low, moisture conservation measures can be adopted only after the stability analysis.

Suitable zone is the most suitable areas for recharge. Most of the considered parameters are favourable in these areas. Areas with gross index varying from 325 to 400 were classed as suitable zones. The suitable sites are spread in the southern most Muthikulam reserve forest area, eastern Sholayur hilly area and down stream side of Siruvani area. Due to the lower weightage adopted for slope in the analysis, suitable areas are spread over the steep terrains of the study area. Critical slope analysis for



Map 12 Suitable Areas for Groundwater Recharge

the terrain stability should be carried out to steep unstable areas from this zone. Any artificial recharge measure can be adopted in these areas if the terrain is stable.

The suitable as well as moderately suitable areas can be selected for artificial recharge measures.

4.2.2. Delineation of stable terrain for artificial recharge

Stability of terrain is an important factor to be considered in adoption of soil moisture conservation measures and land slide mitigation measures. Since the artificial groundwater recharge unstabilise the sloping terrains, the steep and unstable terrains should be removed from the hydrogeologically favourable areas for recharge. Stability of the terrain was assessed based on the slope, land use, drainage density, relative relief and soil thickness. These parameters were analysed layer by layer and overlayed to get spatial variability of terrain stability.

4.2.2.1. Slope

Slope is the main factor affecting the stability of terrain. In the absence of human interventions or geologic faults, the relative stability of a terrain is primarily controlled by local slope gradient. So, largest weight of 40 is assigned to the slope layer.

The generated slope degree map is reclassified into eight classes and weights and ranks were assigned to them. Slope map is reclassified into eight classes based on the chances of slide. Steep terrains are more susceptible to soil mass failure. Hence, higher ranks are given to higher slopes. Weights and ranks assigned to different slope classes are shown in the Table 14.

Table 14 Weight and Ranks assigned to Slope Classes for Stability Analysis

Slope in degree	Rank	Weight	Index
0 – 15	1	40	40
15 – 25	2		80
25 – 35	3		120
> 35	4		160

It is observed in Western Ghats region that debris-flows starts from 15^0 land slope onwards. Soil mass failures happen when the land slope exceeds 25^0 and severe landslides occur at slopes greater than 35^0. Thus, the terrain will be in stable condition below 15^0 land slope.

4.2.2.2. Land use

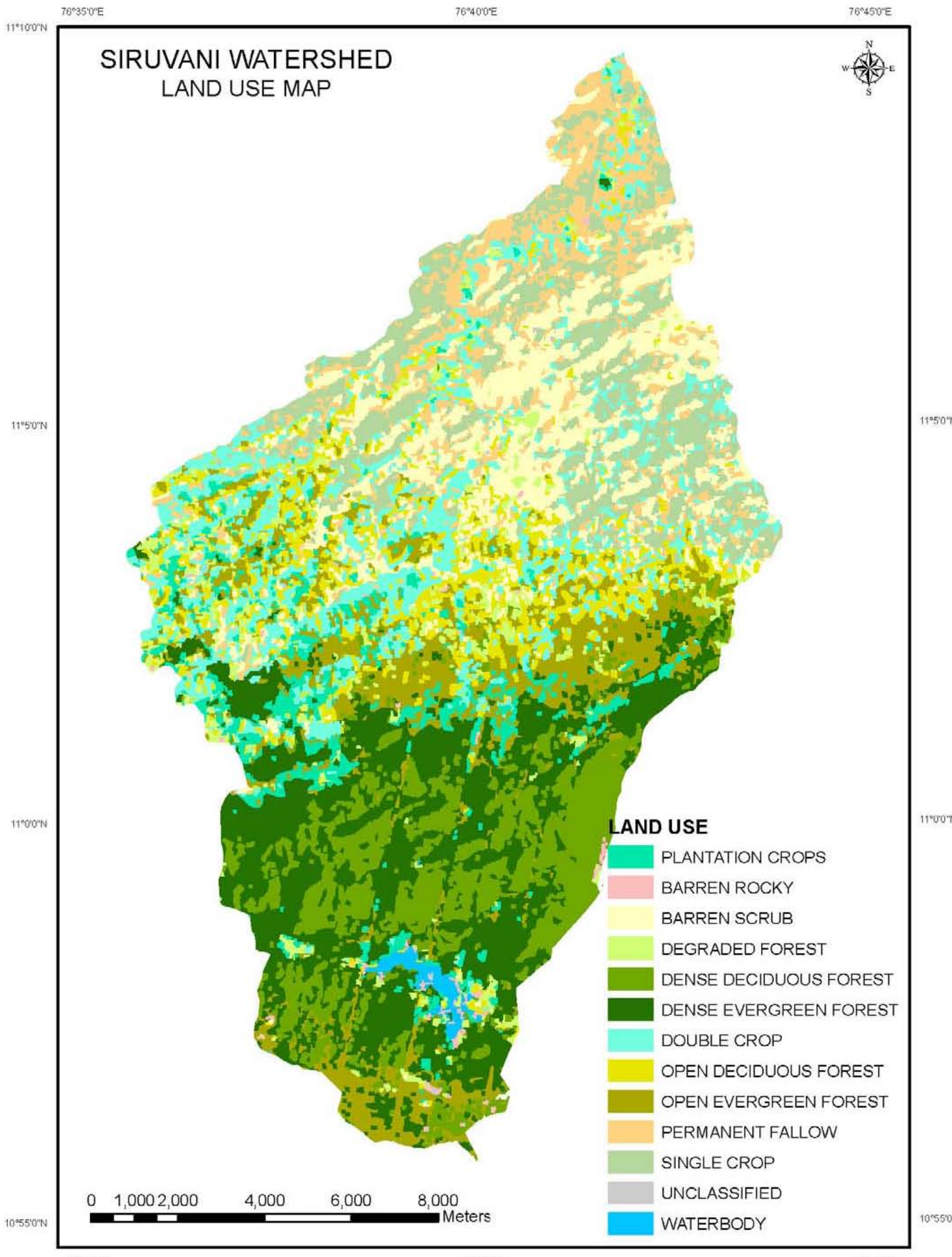
Land use map derived from the IRS 1C LISS III imagery collected from AHADS, was digitized to form the land use layer. Area covered by each land use and the percentage coverage were calculated. Different land uses and their area extends are displayed in Table 15.

The vegetative cover significantly influences the mass stability of slopes. The root anchorage of trees and plants stabilise the terrain. But, in some steep areas with high soil saturation, it acts as a surcharge over the soil mass and increases the severity of slide. In average sloped areas, it act as reinforcement to soil mass. And also, it reduces the soil moisture through evapotranspiration and makes more storage space to absorb sudden high intensity rainfalls.

Table 15 Land Use Classes of Siruvani Watershed and Area Extend

Sl.No.	LAND USE	AREA (km^2)	% AREA
1	Dense Evergreen Forest	38.47	19.22
2	Open Evergreen Forest	22.04	11.01
3	Dense Deciduous Forest	21.97	10.97
4	Open Deciduous Forest	15.06	7.52
5	Degraded Forest	7.25	3.62
6	Permanent Fallow	16.44	8.22
7	Barren Scrub	25.70	12.84
8	Barren Rocky	0.56	0.28
9	Plantation Crops	9.36	4.68
10	Single Crops	21.78	10.88
11	Double Crops	21.54	10.76
	Total	200.17	100.00

Land use map was further classified according to the root and canopy into agriculture, forest and rock out crops. Forest was again classified as dense cover, moderate cover and open cover.



Map 13 Land Use

Table 16 Weight and Ranks Assigned to Land Cover for Stability Analysis

Land Use Class	Rank	Weight	Index
Agriculture	1	30	30
Dense Cover	2		60
Moderate Cover	3		90
Open Cover	4		120

Agriculture is practiced mainly in low lying areas which are free from the threats of slides. More sloping areas are cultivated with rubber with terracing of land. So, it is considered as the least susceptible area for slides and assigned with least rank. In dense cover forest with deep and well spread root system, chances of slide depends on severity of slope. For moderate cover forests land slide susceptibility will be more than dense cover. Most susceptible land parcels are degraded forest and the areas facing deforestation. So, the open cover areas were assigned high rank.

4.2.2.3. Drainage density

Drainage density depicts directly the runoff generation nature of the terrain. A terrain with high drainage density shows high runoff potential. Low drainage density infer that soil absorbs moisture very much and is susceptible for slides, since the moisture content increases the pore water pressure and thus weakens the soil mass. So the terrain with low drainage density is more susceptible to slides and given high rank. Drainage density classes and weight and ranks assigned to them are shown in Table 17.

Table 17 Weight and Ranks Assigned to Drainage Density for Stability Analysis

Drainage Density Class	Rank	Weight	Index
< 2	4	15	90
2-3	3		60
3-4	2		45
> 4	1		15

4.2.2.4. Relative relief

Relative relief, being the difference in height between the highest and lowest points per unit area, is directly related to the degree of dissection. The areas with relative relief more than 400 are generally found susceptible to land slides.

Relative relief is closely linked with slope and so a high weightage is not needed. It is useful in understanding the morphogenesis and the intensity of section. Relative relief map was generated and reclassified. The classes were assigned with the ranks and weights. The assigned ranks and weight are displayed in the Table 18.

Table 18 Weigh and Ranks assigned to Relief Classes for Stability Analysis

Relief Class (m)	Rank	Weight	Index
< 200	1		10
200 – 400	2	10	20
400 – 600	3		30
> 600	4		40

4.2.2.5. Soil depth

The overburden thickness is an important criterion in the natural stability of slopes. For a flat terrain soil thickness will not make harm. But in steep lands, the high soil thickness makes the slides severe. Most of the slides are confined to the upper soil horizon without affecting the basements. The soil thickness of the region varies from 0.5 m to 5 m. Soil thickness is reclassified into four groups. The weight and ranks assigned are displayed in the Table 19.

Table 19 Weight and Ranks Assigned to Soil Depth Classes for Stability Analysis

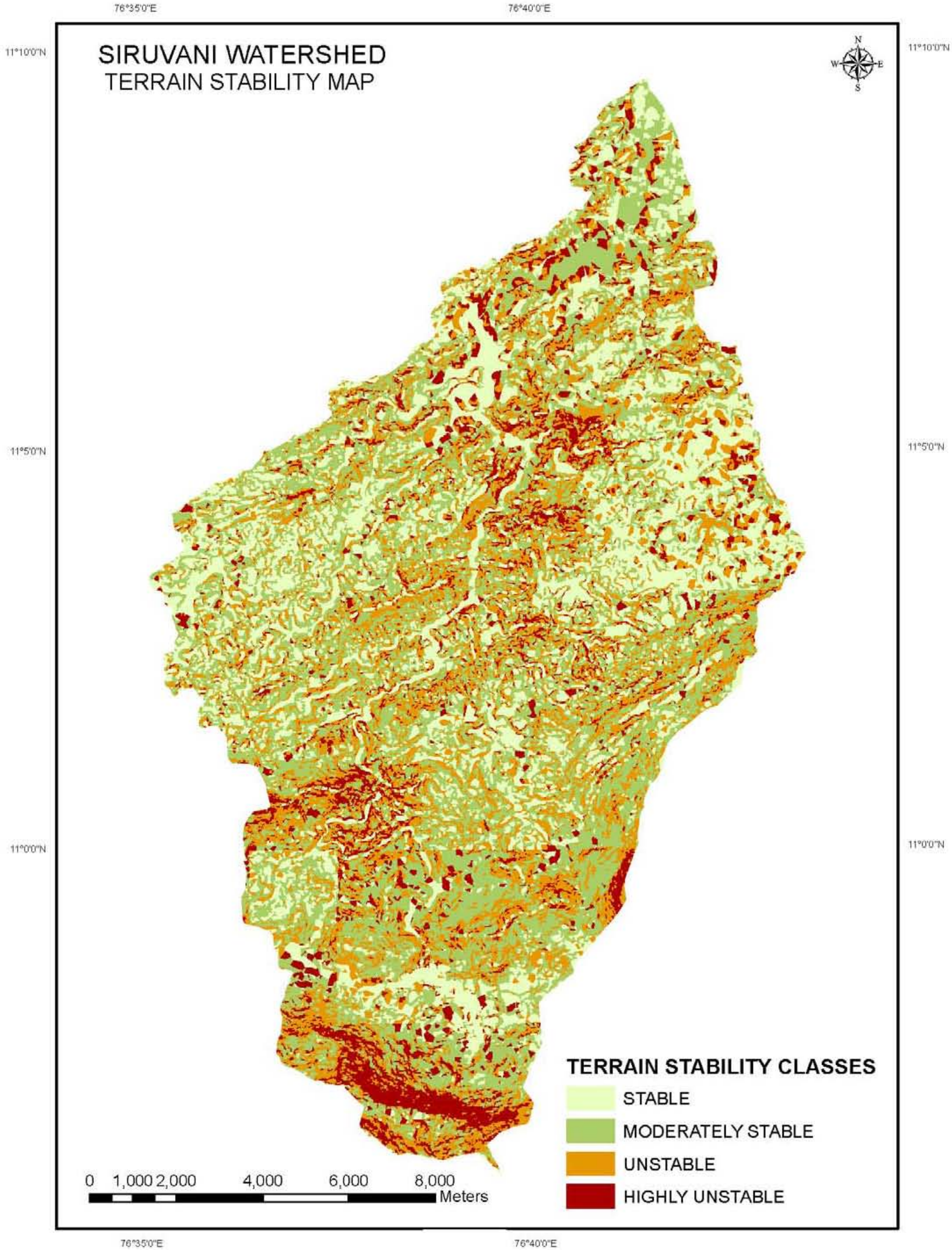
Soil Depth (m)	Rank	Weight	Index
< 1	1		5
1 – 2	2	5	10
2 – 3	3		15
> 3	4		20

4.2.2.6. Stability of the terrain

Through overlay analysis of the above said parameters, the stability map of the study area has been prepared (Map 14). It is classified into four classes based on the gross index after the overlay. The classes and their area extend are shown in the Table 20.

Table 20 Stability Zones and Area Extend

Sl.No.	Class	Area	% Area
1	Stable	56.65	28.30
2	Moderately Stable	71.34	35.64
3	Unstable	51.10	25.53
4	Highly Unstable	21.08	10.53
	Total	200.17	100.00



Map 14 Terrain Stability

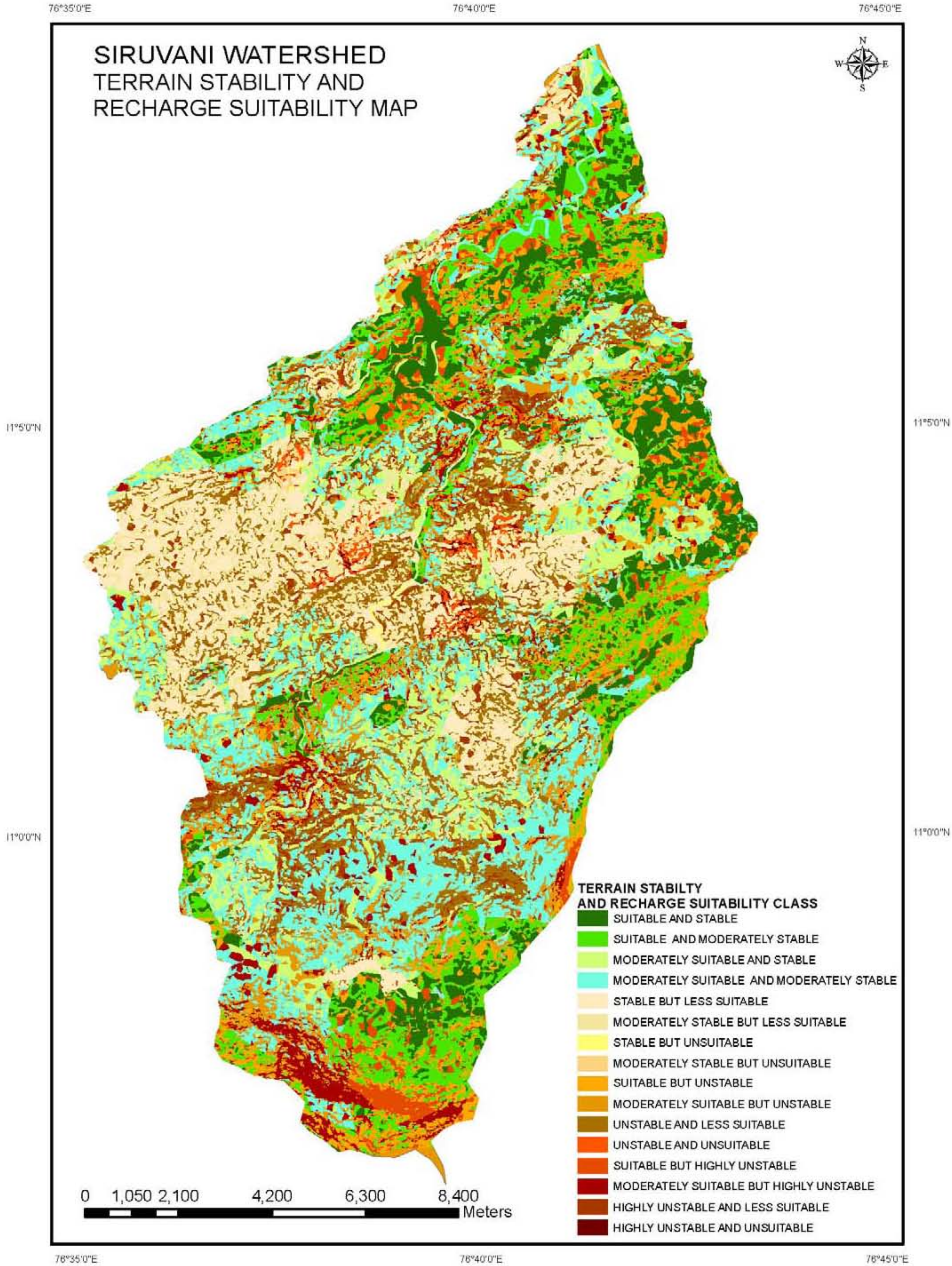
Highly unstable zones are mostly characterised by steep slopes. The gross index value ranges from 300 to 360. The highly unstable areas are mostly with open cover land use. Areas with high slope and high relative relief and containing degraded forests, permanent fallow, barren lands and some open forest, fall under unstable category. Areas with degraded natural vegetation in high slope areas are most favourable for mass movements. Mitigation measures like regeneration of natural vegetation, reforestation and slope stabilising using various artificial means should be adopted. If healing measures are not taken, these areas could soon be deteriorated to critical category. Structures are not feasible here. Measures which raise the soil moisture content should be avoided in these terrains.

Moderately stable zones mainly occupy the areas with moderate slope. It includes agricultural plantation, open forests and some dense forests. These areas are stable now and future land use activities should be carefully planned. Forests reinforce the soil mass with well established root system. So in these areas, terrain is much stable and resistant to mass movements. If natural drainage is interrupted and slope is modified unscientifically, land slides could be triggered in this zone. Improper land use practices and development activities could also destabilise many slopes falling within this zone.

Stable zones are the low lying areas of the watershed and are well distributed in the study area. Here relative relief and slopes are very low making this zone very stable and resistant to any mass movements. This zone consists of agricultural crops as well as forest.

4.2.3. Stable and potential recharge areas

For augmenting groundwater, the areas with land slide susceptibility should be excluded, since the moisture increment will trigger soil mass failures in unstable terrains. The results of the stability and suitability analysis are overlayed to get the stable and suitable sites for implementation of artificial groundwater recharge structures. After the analysis, sixteen classes were obtained according to the recharge potential and land slide susceptibility. The classes and their area coverage are exhibited in the Table 21.



Map 15 Stable and Suitable areas

Stable and suitable, moderately stable and suitable, stable and moderately suitable, and moderately stable and moderately suitable zones cane be selected for artificial groundwater recharge. In stable and suitable zone, any groundwater recharge systems adapted to the terrain features can be adopted. While taking the moderately stable zones, care should be given to adopt stabilising measures to keep terrain stable even when the soil mass is saturated with water. Design of the artificial recharge system should be carefully made if the terrain is moderately suitable for recharge, taking into account the limiting parameter of the recharge suitability.

Highly unstable, unstable, less suitable and unsuitable terrains could better be avoided from the artificial recharge.

Table 21 Combined Suitability and Stability Zones and Area Extend

Sl.No.	Class	Area	% Area
1	Stable and Suitable	19.94	9.96
2	Moderately Stable and Suitable	19.77	9.88
3	Unstable and Suitable	12.63	6.31
4	Highly Unstable and Suitable	6.37	3.18
5	Stable and Moderately Suitable	20.56	10.27
6	Moderately Stable and Moderately Suitable	33.37	16.67
7	Unstable and Moderately Suitable	16.90	8.44
8	Highly Unstable and Moderately Suitable	8.49	4.24
9	Stable and Less Suitable	15.95	7.97
10	Moderately Stable and Less Suitable	17.54	8.76
11	Unstable and Less Suitable	19.85	9.92
12	Highly Unstable and Less Suitable	5.75	2.87
13	Stable and Unsuitable	0.20	0.10
14	Moderately Stable and Unsuitable	0.66	0.33
15	Unstable and unsuitable	1.72	0.86
16	Highly Unstable and Unsuitable	0.46	0.23
	Total	200.17	100.00

4.3. Sites suitable for specific recharge structures

Specific recharge measures need specific site selection for the maximum effectiveness of recharge. The study area being a hard rock terrain, most effective interventions for augmenting the groundwater resource could be gully plugs, *nala* bunds, check dams, subsurface dykes, recharge wells etc. methods like pits, trenches, recharging of the excess runoff from hard surfaces like roads and roof tops are also possible in this area. The specific areas best suited for these recharge measures are delineated and displayed.

4.3.1. Pits and trenches

Pits and trenches are suitable in non-stream areas where overland flow is high. These areas were delineated and displayed in the Map 16. Total area suitable for pits and trenches was found to be 28.7 km^2. There is no need of artificial recharge measures in the forested areas since considerable groundwater recharge is occurring there. The degraded forest areas can be treated with pits and trenches. Lands of plantation crops can be treated with rain pits, crescent shaped terraces and basins. Five hundred pits can be provided in one hectare of land.

4.3.2. Check dams and nala bunds

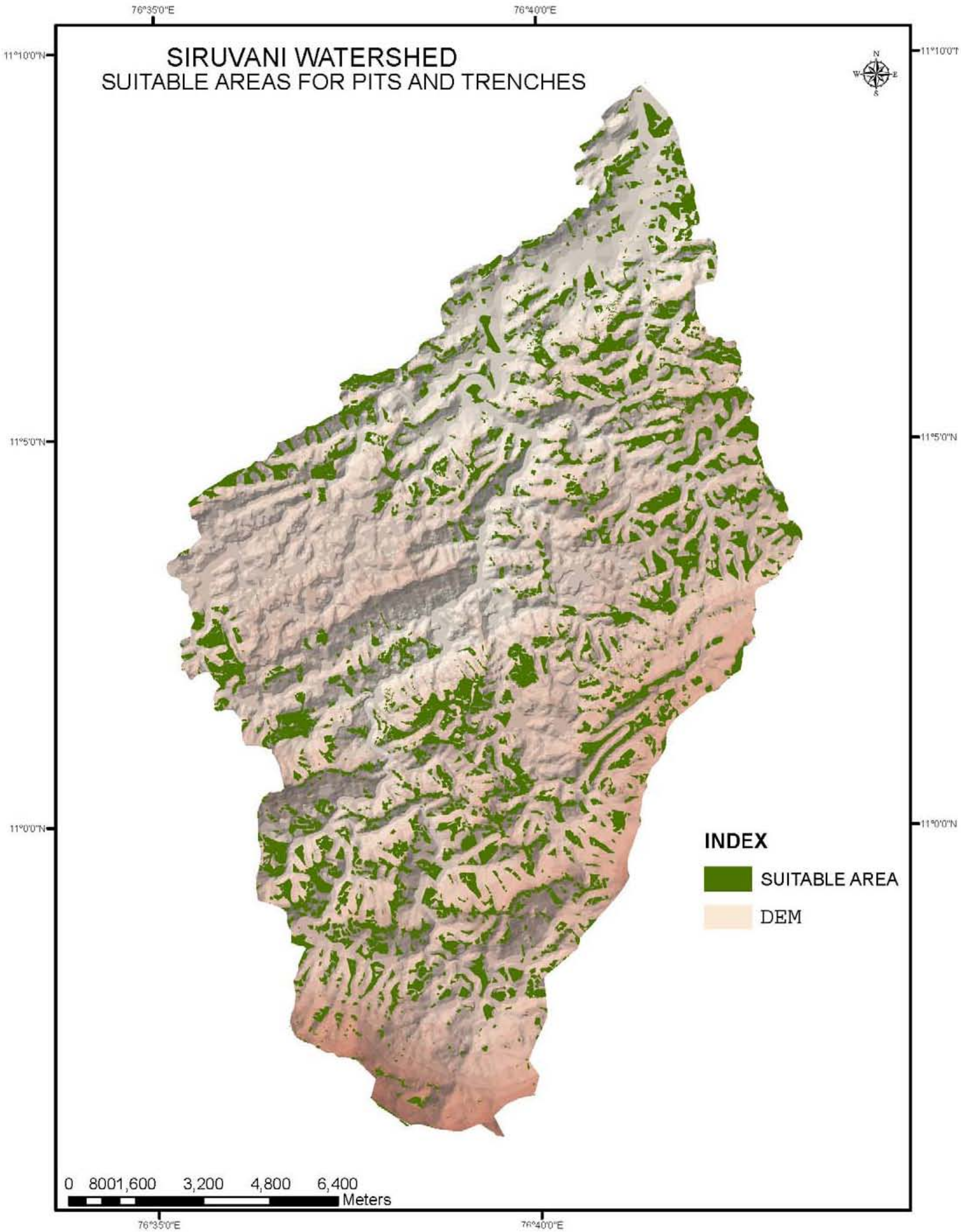
Possible locations for the *nala* bunds and check dams were found by overlaying the streams over stable and moderately stable potential areas. The Map 17 shows the suitable locations for check dams and *nala* bunds. *Nala* bunds using loose rocks can be introduced in the first order and low discharge second order streams. Recharge from third and fourth order streams can be effectively improved by introducing gabion check dams. Masonry or concrete check dams are required in fifth and sixth order streams.

4.3.3. Subsurface dykes

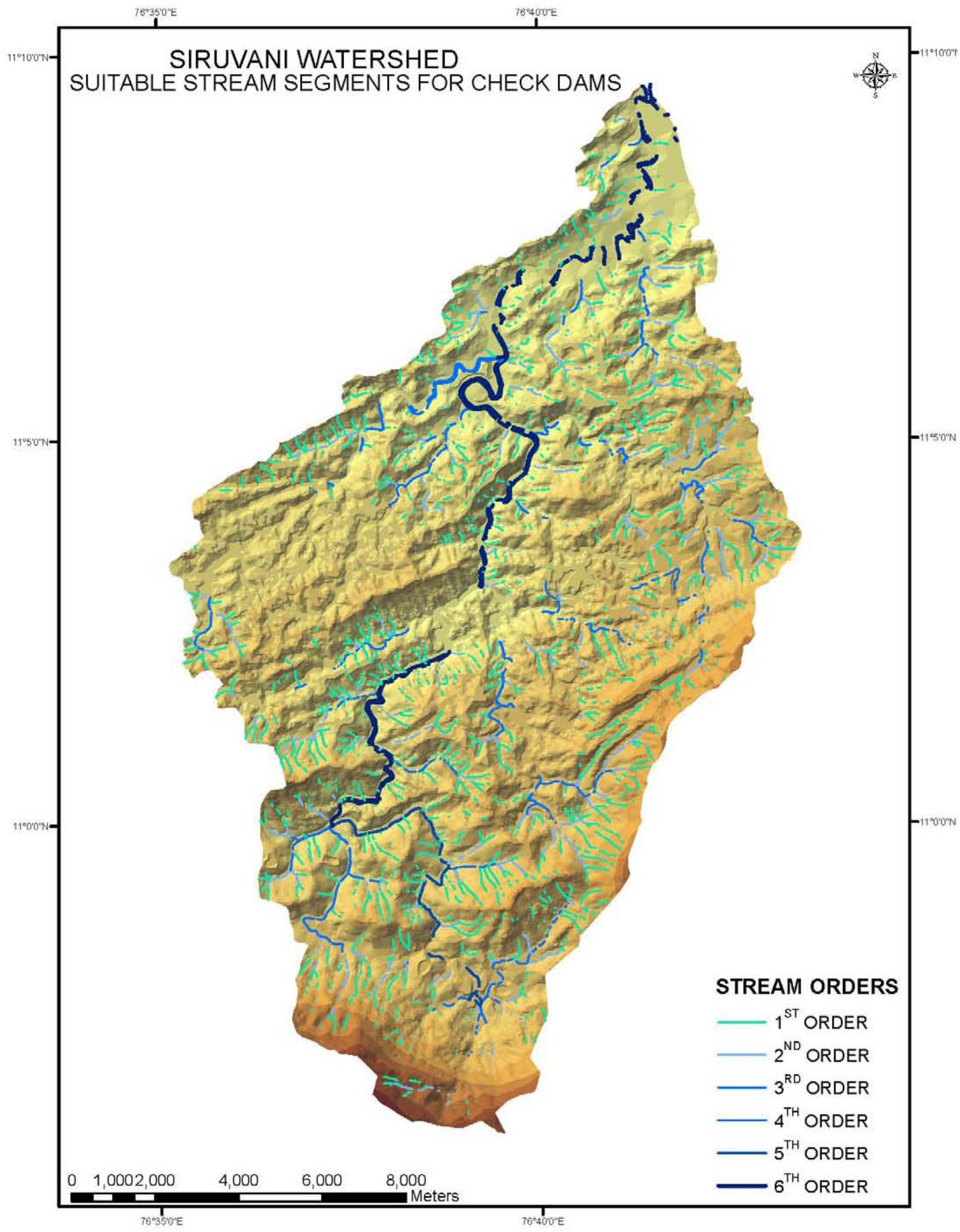
Most suitable locations for sub surface dykes are found by overlaying the streams and stable and moderately stable potential areas over DEM. Map 18 shows the suitable sites for the construction of sub surface dykes. Here also, dense forest areas were excluded from the interventions. Series of dykes will increase the amount of water that can be stored in subsurface and reduce sub surface runoff loss.

4.3.4. Recharge wells

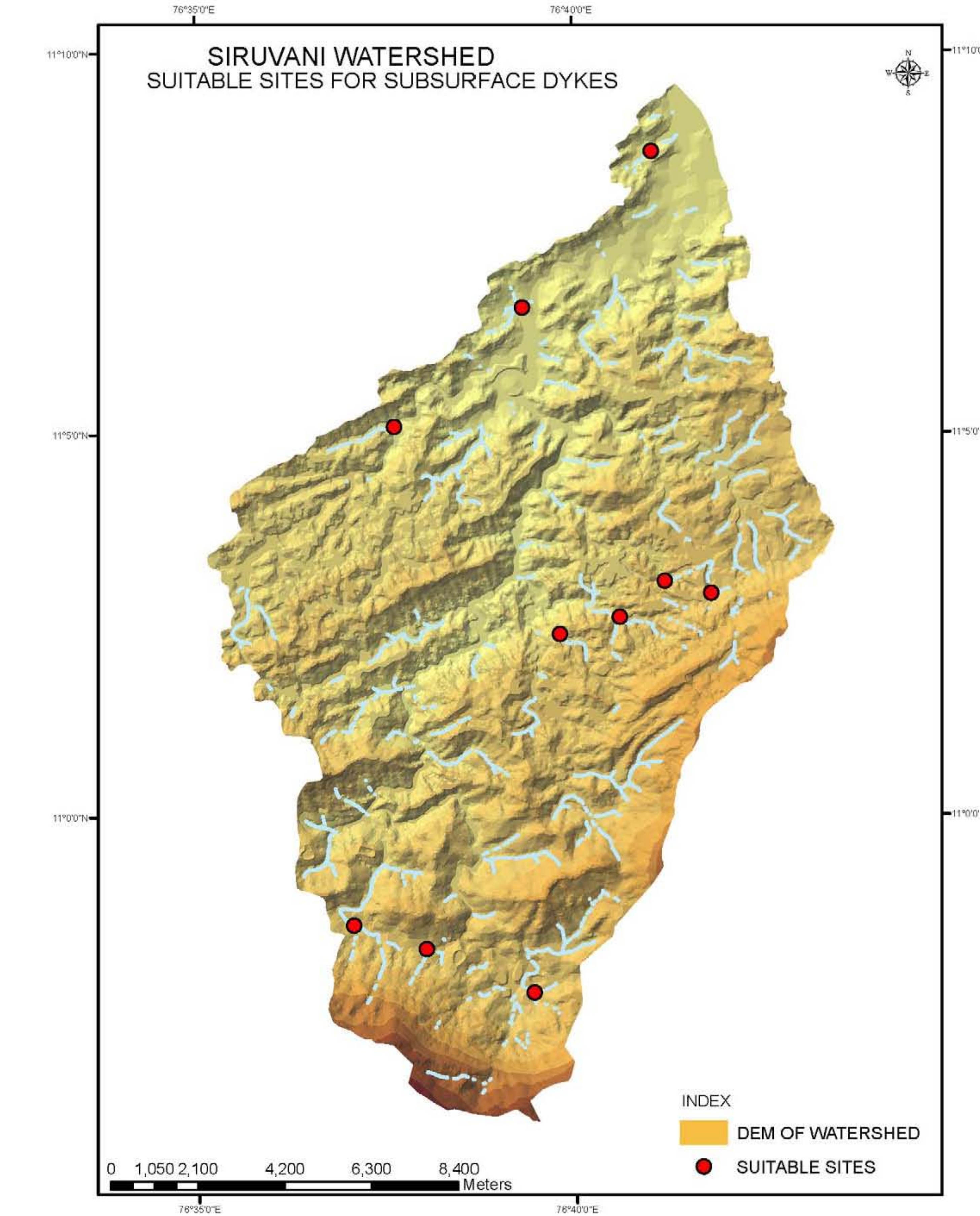
Sites for the installation of recharge wells were found by overlaying the lineament map over the stable and moderately stable potential sites. Suitable site for recharge wells are displayed in Map 19. As direct injection of water to the aquifer is taking



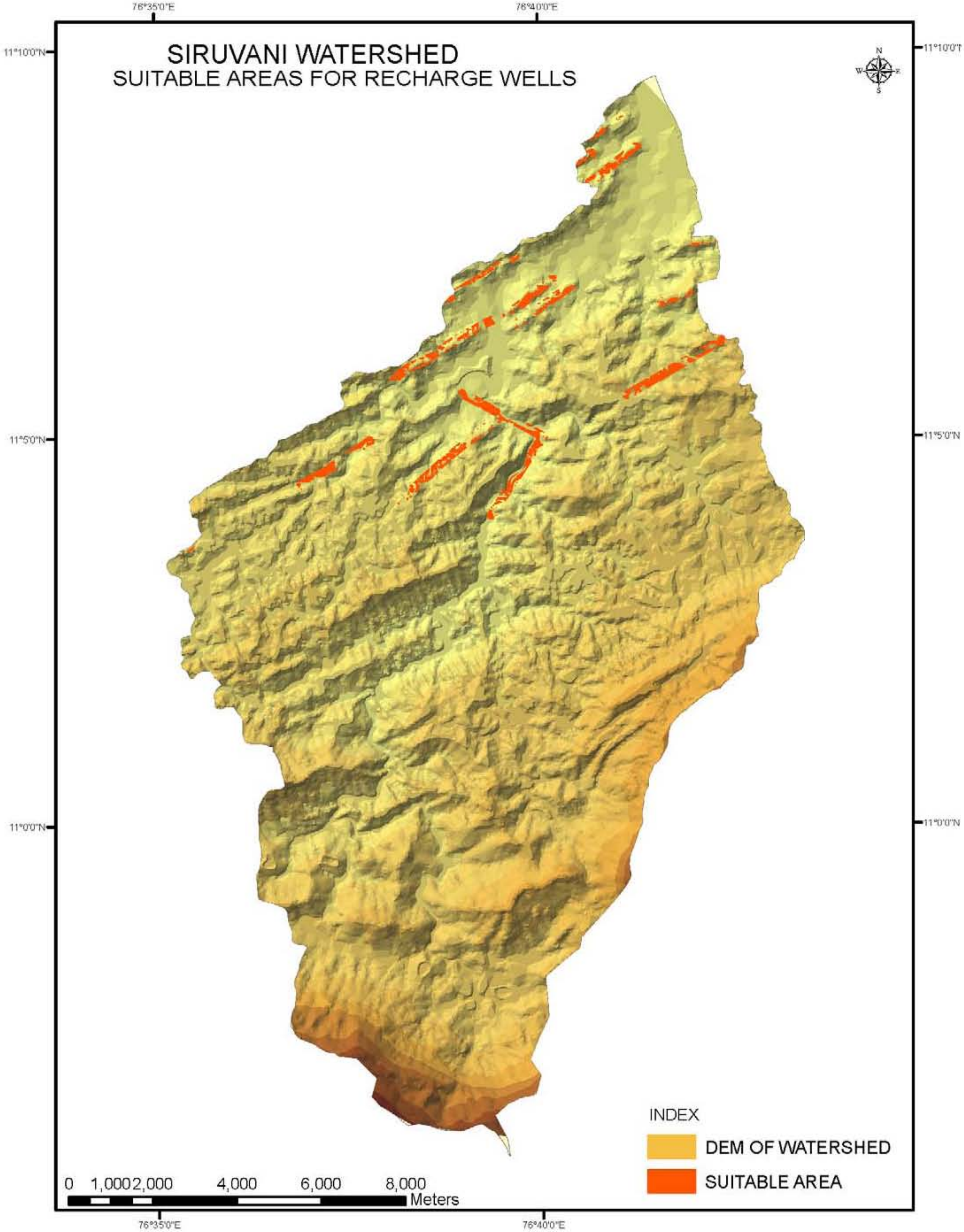
Map 16 Suitable Areas for Pits and Trenches



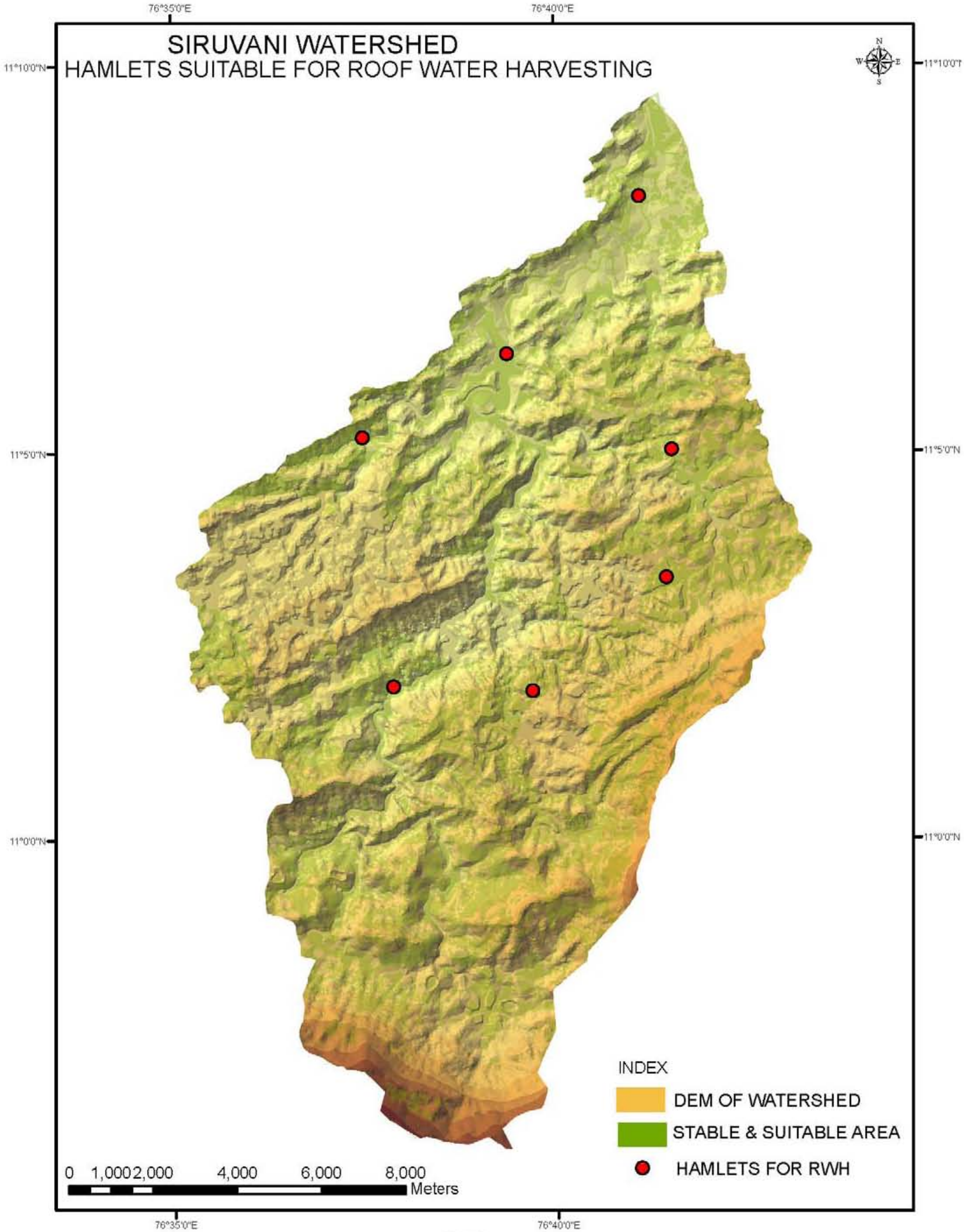
Map 17 Suitable Streams for Check Dams



Map 18 Suitable Locations for Subsurface Dykes



Map 19 Suitable Areas for Recharge Wells



Map 20 Suitable Locations for Roof Water Harvesting

place in this case, care should be taken with regard to the quality of runoff. Areas where enough abandoned dug wells are available are more suitable for this measure.

4.3.5. Impervious surface water harvesting and recharge

By overlaying roads, towns and human habitats, the suitable areas for hard surface water harvesting and recharging structures were delineated. The roof tops of town area and tribal hamlets were selected for impervious water harvesting, storing and recharging. Overflow from the ferro-cement storage tanks were diverted to a percolation pit filled with filter media. The sites are displayed in Map 20.

SUMMARY AND CONCLUSION

CHAPTER V

SUMMARY AND CONCLUSIONS

Declining trend of ground water resources is a severe problem faced by most part of the world. The imbalance between the discharge and recharge and consequent degradation of groundwater calls for new sustainable approaches for groundwater basin management in which groundwater recharge is considered as an important step. For sustainability of the groundwater resources, the extraction from the aquifer should be kept less than or equal to the recharge into it. Natural recharge potential of terrains varies with their hydrogeological and topographical features as well as climatological factors. So, artificial recharge to aquifer is essential in places where, the natural groundwater recharge is less due to various terrain features. Artificial recharging is the planned human activity of augmenting the amount of available groundwater through interventions designed to increase the natural replenishment of aquifers through percolation of surface water. The major requirements of an artificial groundwater recharge system are the availability of non-committed runoff, hydrogeologically and topographically favourable recharge area and site specific design of artificial recharge structures.

Kerala state is typical with highly undulated terrain and heavy rainfall. Due to this typical physiography, rainwater recharging to the subsurface storage is very less. As a consequence, most of the area in high ranges faces severe drought in summer season. This situation calls for an efficient management practice for a sustainable groundwater basin development. Groundwater recharge is found essential for the safe development of groundwater resource. At the same time, most of the areas in Western Ghats are susceptible for land slides and debris movement due to high slope and high intensity rainfall. Delineation of potential areas for groundwater recharge along with terrain stability analysis is essential for designing artificial recharge systems in Western Ghats.

The utility of remote sensing and Geographic Information System have well proved in the suitable site selection and estimating the spatiotemporal distribution of geographical and climatic parameters. The capability of remote sensing and GIS to capture, store, retrieve, analyse and display geographically referenced data for generating the spatiotemporal distribution of natural groundwater recharge in a watershed was utilised in this study to find out the suitable areas for artificial recharge without the danger of land slides and to select site specific recharge methods.

Siruvani watershed in Attappadi Block was selected for the study due to its highly undulating topography, susceptibility to slides, climate variation, water scarcity and degradation through severe erosion. Base line maps obtained from various agencies were digitised and brought to Arc GIS platform for further analysis.

Thornthwaite - Mather water balance method was used for the estimation of groundwater recharge. Daily precipitation data obtained from Agali, Sholayur and Muthikulam meteorological stations within the watershed were brought into Arc GIS in the form of a point map. Theissen polygons were constructed to get the spatial distribution of rainfall. The runoff potential of the terrain was estimated using SCS curve number method. Overlaying the soil map and land use map, the curve numbers corresponding to the average antecedent moisture condition (AMC II) were assigned according to land use and hydrological soil group. Actual antecedent moisture condition was determined from the past five day rainfall. Actual curve numbers for these actual AMC were calculated and assigned to find the runoff. Runoff for the twelve months from June-06 to may-07 and the total runoff for the water year were found out and displayed as maps. The total annual runoff from the catchment having a geographical area 200 km^2 was found as 56Mm^3. Potential evapotranspiration (PET) was estimated using the Penman equation. Various meteorological data were assigned to the Theissen polygons and PET was determined for each climatic and land use polygon. Annual PET was estimated as 236 Mm^3 for the whole basin. According to the available water holding capacity of the soils, soil moisture variation and storage was also estimated. Substituting these parameters in the water balance model, the groundwater recharge was estimated. The annual natural groundwater recharge in the watershed was estimated as 58 Mm^3 including the subsurface runoff and groundwater storage. The spatiotemporal distribution of natural groundwater recharge is displayed as maps. It is found that in the neighbourhood area of Muthikulam meteorological station, natural groundwater recharge component is very high. But a major portion of the deep percolated water eventually turns out as base flow to the river Siruvani and keeps it perennial.

For delineating the hydrogeologically favourable areas for artificial recharge, parameters including infiltration capacity of the soil, geology, geomorphology, drainage density, slope, rechargeable depth are considered. Polygon feature layers of each parameter are created through hand digitising of existing maps and incorporating results from the field experiments. According to the extend of contribution to the central theme, ranks were assigned to the classes of each parameter and weights were assigned to each parameter itself. Through overlay analysis, union of these parametric layers were formed and reclassified according to the weighted index of polygons. Entire area of watershed was classified into four classes viz, suitable, moderately suitable, less suitable and unsuitable. It is found that in Siruvani watershed, 59 km^2 area is suitable and 79 km^2 area is moderately suitable for groundwater recharging.

To avoid the areas prone to land slides, stability analysis of the terrain was carried out. The considered parameters influencing the stability of the terrain are land use, drainage density, slope and relative relief. Polygon feature layers were prepared for all the parameters and weights and ranks were assigned based on the quantum of contribution to the central theme. Overlay analysis was done for delineating the landslide prone areas. The watershed area was classified into four classes viz, stable, moderately stable, unstable and highly unstable. By overlaying the suitable sites and stability layers, areas suitable for artificial recharge structures were delineated. 57 km^2 area was classified as stable terrain, 71 km^2 area was classified as moderately stable. Highly unstable and unstable areas were excluded from the hydrogeologically favourable areas using overlay tools. Total area suitable for artificial recharge was estimated as 94 km^2.

The study area is underlained by hard rock. The efficient recharge structures for hard rock terrains are *nala* bunds, check dams, recharge wells, subsurface dykes and other soil and water conservation structures like pits, trenches, bunds and terraces. By overlaying suitable and stable areas and drainage network over the digital terrain model, sites suitable for these artificial recharge methods were identified and their spatial locations were displayed in maps.

The following conclusions were extracted from the study

1. Siruvani watershed experiences high rainfall variability. Hence any groundwater recharge measures should consider the rainfall spatial distribution.
2. The forested area of the watershed has very high natural recharge capacity. As a result all the streams draining from that area are perennial. No substantial recharge interventions required there; however subsurface dyke can be constructed.
3. Artificial recharge suitability analysis shown that about 30 % of the area is suitable and 40 % is moderately suitable.
4. Stability analysis shown that unstable areas are very considerable with a geographical spread of 35 % of the total area out of which 10 % is highly unstable with frequent landslide problems.
5. Study reveals the combination of suitability and stability analysis, which will be of great utility to the planners in decision making.
6. Suitable interventions for this area are pits and trenches, recharge wells, impervious surface water harvesting, *nala* bunds, check dams and subsurface dykes.
7. Remote Sensing and GIS methodology adopted is effective in generating the spatiotemporal distribution of natural groundwater recharge potential of terrain, in suggesting suitable areas for groundwater recharge systems and in locating the appropriate groundwater recharge measures in these suitable areas.

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GROUNDWATER AUGMENTATION PLAN FOR A DEGRADED WESTERN GHAT TERRAIN USING REMOTE SENSING AND GIS

By

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ABSTRACT OF THE THESIS

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ABSTRACT

The safe development of groundwater resource primarily depends upon the groundwater recharge. Artificial groundwater recharge is essential in terrains with low natural groundwater recharge. Availability of non-committed runoff, hydrogeologically favourable area for recharge and site specific design of artificial recharge structures are the major requirements of an artificial groundwater recharge system. A quantitative evaluation of spatial and temporal distribution of groundwater recharge is a prerequisite for operating groundwater resource management system in an optimal manner. While enjoying a humid tropic climate with heavy rainfall, Kerala also faces acute shortage of fresh water during the summer season, especially in the high range areas. In this study, an effort is taken to prepare a groundwater augmentation plan for a highly degraded Western Ghats terrain, the Siruvani sub basin of Bhavani river basin. Plan includes the evaluation of spatiotemporal distribution of natural groundwater recharge, delineation of land slide resistant hydro-geologically suitable areas for artificial recharge and to suggest specific recharge structures adapted to the terrain characters.

Using Thornthwaite–Mather water balance method, the spatiotemporal distribution of groundwater recharge was prepared and natural groundwater recharge in the watershed was estimated. Penman method and NRCS curve number methods were employed for generating the water balance parameters. Monthly natural recharge varies from 0 to 44 Mm^3. the total annual natural recharge was found as 158 Mm^3. By analysing the infiltration rate, geology, geomorphology, rechargeable depth, slope and drainage density, land use, relative relief, soil depth etc., hydrogeologically potential areas for groundwater recharge systems and land slide prone areas were delineated through GIS weighted overlay analysis. Land slide prone areas were excluded from potential recharge areas. 46.78% of total area was found to be favourable for artificial recharge. The most suitable recharge structures suitable for the hard rock hilly terrains viz, check dams, subsurface dykes, recharge wells, runoff harvesting structures are suggested and suitable locations for the specific recharge measures were delineated.

APPENDICES

APPENDIX 1

Monthly Average Climatic Data

Agali station

Month	Rainfall (mm)	Relative humidity	Maximum temperature (^{0}C)	minimum temperature (^{0}C)	Sun shine hours	Wind velocity (m/s)
Jun-06	87.50	77.68	36.61	22.78	8.54	4.91
Jul-06	50.80	77.46	26.79	22.63	5.10	18.68
Aug-06	25.10	76.84	28.08	21.96	6.61	16.86
Sep-06	144.10	83.41	27.65	21.35	3.67	14.25
Oct-06	359.00	80.59	30.38	21.61	4.80	7.30
Nov-06	236.70	84.61	29.74	19.87	4.43	4.11
Dec-06	0.00	73.38	27.68	16.60	6.96	5.34
Jan-07	4.60	68.58	28.73	15.52	7.85	4.80
Feb-07	0.00	62.67	30.48	16.26	9.34	4.47
Mar-07	0.00	54.61	33.10	19.85	9.25	5.37
Apr-07	98.60	63.67	33.83	21.95	8.21	5.62
May-07	42.20	66.84	30.20	23.30	8.48	10.36

Sholayur station

Month	Rainfall	Relative humidity	maximum temperature (^{0}C)	minimum temperature (^{0}C)
Jun-06	193.00	82.25	28.70	19.58
Jul-06	378.00	83.20	28.00	19.00
Aug-06	73.00	80.87	27.80	18.87
Sep-06	0.00	80.90	25.77	16.83
Oct-06	0.00	80.91	26.33	16.29
Nov-06	0.00	84.00	27.15	17.55
Dec-06	0.00	79.39	25.84	15.84
Jan-07	28.00	79.88	27.70	22.23
Feb-07	35.00	79.70	28.35	18.35
Mar-07	25.00	80.77	28.65	18.58
Apr-07	92.00	81.60	30.03	19.73
May-07	135.00	83.10	31.30	21.90

Muthikulam station

Month	Rainfall (mm)	Maximum Temperature (^{0}C)	Minimum Temperature (^{0}C)	Relative humidity
Jun-06	704.00	27.60	18.60	84.20
Jul-06	643.00	27.00	17.60	85.30
Aug-06	392.00	26.20	21.50	82.10
Sep-06	747.00	25.30	19.70	82.32
Oct-06	359.00	25.80	22.00	83.00
Nov-06	287.00	26.10	18.50	86.00
Dec-06	28.00	25.30	17.70	82.00
Jan-07	0.00	26.32	16.08	82.25
Feb-07	0.00	27.92	14.88	82.30
Mar-07	0.00	28.50	15.70	84.00
Apr-07	99.00	29.86	16.74	83.00
May-07	248.00	30.24	17.96	81.00

APPENDIX 2

Description of soil series

Soil series	Description of soils
Vattakkallumalai	Shallow, moderately well drained, fine loamy soils occurring in moderate to steep slopes with sandy loam surfaces.
Sethumadai	Moderately deep, moderately well drained fine loamy soils occurring in moderate to steep slopes with clay loam surfaces
Edathodu	Very shallow, well drained, soils occurring on moderate to steep slopes with loamy sand surface
Mamana	Very deep, moderately well drained, fine soils occurring in moderately steeply sloping lands with clay surface
Tthavalam	Very deep, moderately well drained, fine soils occurring in moderately steeply sloping land with clayey surface.
Gilsi	Moderately deep, well drained, fine loamy soils occurring on gently gentle to moderate slope with gravelly clay loam.
Thekpannai	Shallow, moderately well drained, fine loamy soils occurring in moderate to steep slopes with gravelly sandy loam surfaces
Arali	Very deep, moderately well drained, fine loamy soils occurring in gentle slopes with clay loam surface
Bhavani	Very deep, moderately well drained, fine loamy soils occurring in gentle slopes with sandy clay loam surface

APPENDIX 3

Infiltration study sample

Serial No.	SI 12
Location	Kuravanpady
Date	03-07-2007
Description	Site along a valley
	Soil depth is about 3m
	Thickly vegetated valley

local time	interval (minutes)	cumulative time (minutes)	intake (cm)	intake in cm/h
1125	0	0	0	0
1127	2	2	1.5	45
1129	2	4	1.3	39
1131	2	6	1.3	39
1133	2	8	1.2	36
1135	2	10	1.2	36
1140	5	15	2.5	30
1145	5	20	2.4	28.8
1150	5	25	2.2	26.4
1155	5	30	2.1	25.2
1200	5	35	1.9	22.8
1215	15	50	5.3	21.2
1230	15	65	4.7	18.8
1245	15	80	4.7	18.8
100	15	95	4.7	18.8
115	15	110	4.7	18.8

Basic infiltration rate is taken as 18.8 cm/hour

APPENDIX 4

Available Water Holding Capacities of Different Soil Series Associations

Sl.No.	SOIL SERIES	AWC mm/m
1	Vattakkallumalai (60%) Sethumadai(40%)	38.6
2	Vattakkallumali (70%) Rock Outcrops (30%)	21
3	Rock Outcrops (60-70%) Vattakkallumalai (40-30%)	21
4	Rock Outcrops (70%) Elathodu (30%)	25
5	Mamana (60%) Thavalam (40%)	178.4
6	Gilsi (60%) Thekpannai (40%)	32
7	Arali (65%) Bhavani (35%)	150.4

APPENDIX 5

Curve Numbers adopted for Runoff Estimation

Land use	Hydrologic Soil Group			
	A	B	C	D
Row crops	72	81	88	91
Plantation Crops	39	61	74	80
Barren Rocky	74	84	90	92
Barren Scrub	35	63	75	80
Dense Evergreen Forest	25	55	70	77
Dense Deciduous Forest	27	57	73	80
Open Evergreen Forest	28	58	74	83
Open Deciduous Forest	29	60	77	86
Degraded Forest	31	63	81	89
Permanent Fallow	77	86	91	94
Water Bodies	100	100	100	100

APPENDIX 6

Tabular values for Potential Evapotranspiaration

Mean Solar Radiation for Cloudless Skies (Jensen *et. al.*, 1990)

Month	Degrees North Latitude					
	0	10	20	30	40	50
	Mean Solar Radiation MJ/m^2d					
Jan	28.18	25.25	21.65	17.46	12.27	6.7
Feb.	29.18	26.63	25	21.65	17.04	11.43
Mar.	30.02	29.43	28.18	25.96	22.9	18.55
Apr.	28.47	29.6	31.14	29.85	28.34	25.83
may	26.92	29.6	31.4	32.11	32.11	30.98
Jun.	26.25	29.31	31.82	33.2	33.49	33.08
Jul.	26.27	29.46	31.53	32.66	32.66	31.53
Aug.	27.76	28.76	31.14	30.44	29.18	26.67
Sep.	29.6	29.6	28.47	26.67	23.73	20.1
Oct.	29.6	28.05	25.83	22.48	18.42	13.52
Nov.	28.47	25.83	22.48	18.3	13.52	8.08
Dec.	26.8	24.41	20.5	16.04	10.76	5.44

Mean Monthly Values of Possible Sun shine Hours (Subramanya)

North Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0^o	12.1	12.1	12	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
10^o	11.6	11.8	12	12.4	12.6	12.7	12.6	12.4	12.9	11.9	11.7	11.5
20^o	11.1	11.5	12	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
30^o	10.4	11.1	12	12.9	13.7	14.1	13.9	13.2	12.4	11.5	10.6	10.2
40^o	9.6	10.7	12	13.2	14.4	15	14.7	13.8	12.5	11.2	10	9.4
50^o	8.6	10.1	12	13.8	15.4	16.4	16	14.5	12.7	10.8	9.1	8.1

Radiation Reflection Coefficient for Various Land Uses

Surface	Range of albedo values
Close ground crops	0.15 - 0.25
Bare lands	0.05 - 0.45
Water surface	0.05
Forest area	0.05-0.12