Integrated remote sensing and geographical information system based approach towards groundwater development in hard-rock terrain

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Abstract

In an effort to maintain the water table condition in balance, artificial recharge schemes are being implemented in various parts of the world. The selection of sites for artificial recharge is a very important task in recharge studies. Occurrence and movement of groundwater in the hard-rock terrain are controlled by secondary porosities developed through weathering and fracturing. Groundwater occurs in the weathered residuum under unconfined condition and circulate through fractures and fissures below. Here the aquifers are characteristically discontinuous. Presence buried pediments, alluvial fan or bajadas, palaeochannels offer good source of water.

Present study aims in siting artificial recharge structures in the chronically drought prone hard-rock (mainly Precambrian granite gneiss) terrain of the river basin named Sali of Bankura district of eastern India where the average annual rainfall is 1200mm. In this investigation, integrated remote sensing and GIS techniques have been used. Various pertinent information like lithology, structure, landcover/landuse, aerial aspects of drainage basins, paleochannels, and other pertinent landforms have been extracted from visual interpretation of IRS IB Satellite data, Survey of India (SOI) topographical sheet aided by field checks. Depth of weathered residuum, water table conditions, rainfall data have also been considered. All the thematic information layers have been digitized and analyzed in GIS environment and the produced composite maps show suitable sites for construction of artificial recharge structures.

Key words: *Hard-rock, Water table condition, Artificial recharge, Site selection, Remote sensing, GIS, Composite map(s).*

Introduction

Application of remote sensing technique in groundwater studies has been used for more that two decades. In the hydrogeological study, mainly visual interpretation of satellite imagery is in use. However, satellite data must be used in conjunction with available ancillary information in application of remote sensing to groundwater hydrology. Apart from updating the hydogeomorphological and structural information in the geological maps, vegetal cover can be mapped and such information can be utilized to estimate water budgets even in different seasons.

The concept of integrating remote sensing and GIS is comparatively new. Blending of the two techniques has been proved to be an efficient tool in groundwater studies (Gustafsson, 1993; Saraf and Jain, 1994; Krishnamurthy and Srinivas 1995, Krishnamurthy *et. al.* 1996). Occurrence of groundwater in hard-rock terrain is confined to jointed, fractured and weathered portions. In India, about 65 per cent of the total geographical area is covered by hard-rock formations. Therefore, an efficient management of surface water resources and groundwater development is required in such formations. Remote sensing data provide accurate spatial information and it can be economically utilized over conventional techniques of groundwater studies.

GIS technique involves integrated and conjunctive analysis of huge volumes of multi-disciplinary data, both spatial and non-spatial, within the same geo-referencing scheme. Through integration of these two spatial data management technologies groundwater development by water harvesting and artificial recharge can be well organised. Aquifer recharge occurs in nature by natural precipitation, seepage from canals and reservoirs and return flow from irrigation. The geomorphic features like alluvial fans, buried pediment, old stream channels and the deep-seated interconnected fractures are the indicators of subsurface water accumulation. These features are the natural recharge sites due to their high permeability and water holding capacity. Moreover, it is clear that higher the permeability lower the drainage density and higher the drainage density higher the surface run off .It has been observed that the terrain transmissibility is inversely proportionate to the square of drainage density (Omar, 1990). Das and Kader (1996) observed that combined effect of drainage density (01.15-14.76km/sq km), stream frequency (0.95-12.11), bifurcation ration (2-10) and granitic lithology favours high surface run off and low infiltration. The National Remote Sensing Agency, Govt. of India (1989-1990) under the auspices of the National Technology Mission for Drinking Water and with the active collaboration of state departments has prepared hydrogeomorphological maps (scale 1:2,50,000) for the whole of India, utilizing landsat TM/IRS imageries (Reddy, 1999). The identification of lineaments has immense importance in hard-rock hydrogeology as they can identify rock fractures that localize ground water (Das, 1990). The hydrogeologists usually infer subsurface hydrological condition through surface indicators, such as aerial geological features, linear structures and vegetal cover. Most of the geological linear features are assumed to be the zone of fractured bed rocks and the position of porous and permeable strata where enhanced well yields can be expected.

Data integration and composite map generation may be performed through GIS technique (scale 1:50,000). Delineation of pertinent area (open deep-seated fractures, weathered residuum, alluvial fans, old channel courses or the channel fills etc.) in the composite map is one of the most desired task for ground water development, construction of artificial recharge structure and for surface water storage (Geomorphic lows with impermeable layer) augmentation by water impounding structures. This sort of integrated study is usually undertaken watershed wise.

The present investigation demonstrate the capabilities of IRS-LI SS-II (Linear Imaging Self-scanning Sensor) in hydrogeological studies through preparing hydrogeomorphological, lineament, drainage and other relevant thematic maps. IRS-LI SS-II operates in the visible-NIR spectral range of the electromagnetic spectrum and has a spatial resolution of 36.25 m.

Considerations

The type of artificial recharge system that can be developed at any site is controlled to a large degree, by the geologic and hydrologic conditions. Site selection criteria in addition to economic consideration, should include the following:

i) Source of recharge water
ii) Chemical, physical and biological characteristics of recharge water
iii) Availability of a geological formation suitable for artificial recharge
iv) Thickness and permeability of the material overlying the geological formation considered suitable for recharge
v) Proximity of the potential recharge site to the cone of depression of an appropriate well
vi) Water level differences between the aquifer and the recharge site

In the present study, attempt has been made involving the factors like lineaments, geomorphic features related to groundwater occurrence (hydrogeomorphic features), hydrogeological landuse and drainage density to select artificial recharge sites in the upper catchment area of Sali river basin Bankura district, West Bengal, eastern India.

The followings are the objectives of the present investigation:

i) To develop integrated remote sensing and GIS techniques in hydrogeological investigation emphasizing recharge site selection
ii) To create a digital data base

The study area

The study area has been chosen as it represents a typical hard-rock area comprising mostly granite gneiss. It is situated in a part of Bankura district, West Bengal, India and bounded by longitude $87^{O}5'$ to $87^{O}10'$ E and latitude $23^{O}20'$ to $23^{O}28'$ N. The area is drained by the tributaries of Sali river (a sub-basin of Damodar river). The average annual rainfall is 1210 mm. Relief of the terrain ranges from 80 m to 150 m. The area comprises single agricultural crop and is drought prone due to considerable surface run-off of rainwater.

Methodology

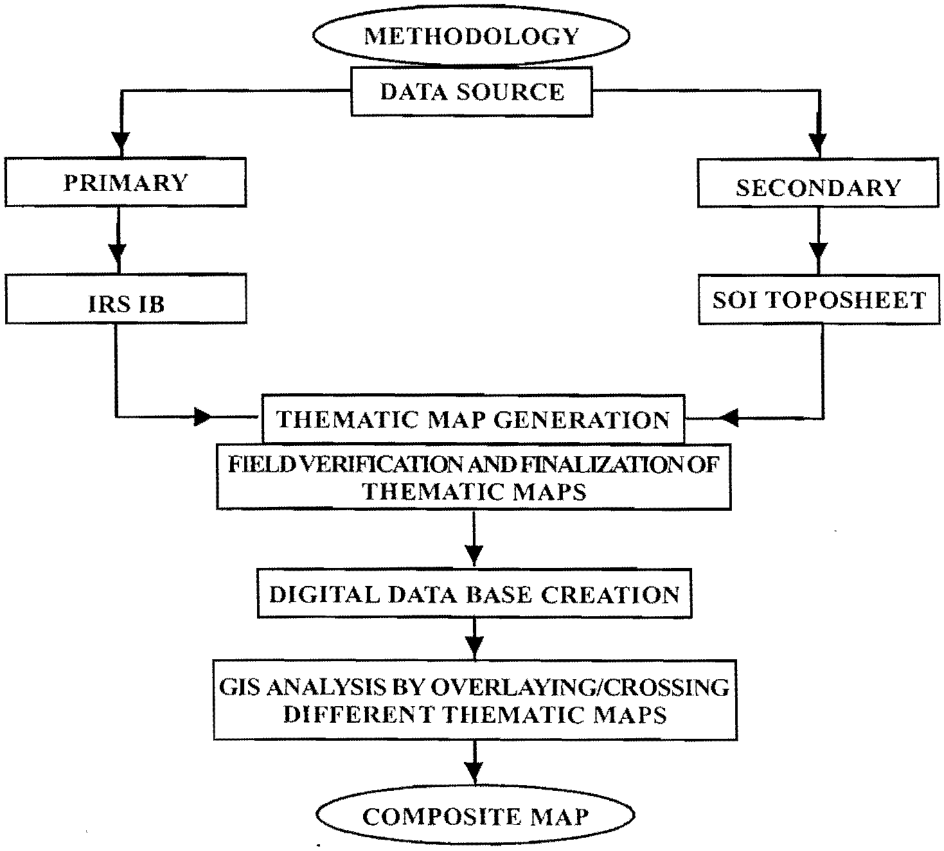
The methodology adopted in the present study involves several steps (mentioned below) and it has been explained schematically in the Figure 1.

(a) Preparation of thematic maps, viz.
(b) Geomorphology
(c) Lineaments
(d) Drainage
(e) Landcover/Landuse of the area

Using IRS-IB Liss-II standard FCC data on 1:50,000 scale, of November 1996 (P-19, R-51), SOI topographical sheets (73 M/3, M/7 surveyed 1971-72) as base maps aided by field checks.

(a) Preparation of maps using collateral data derived from field and laboratory processing. This data sets are:
(b) Depth of weathered zone (obtained through well inventory process)
(c) Geomorphic features (extracted by visual interpretation of satellite data aided by field checks)
(d) Drainage density (derived from measurements and analysis of 3^{rd} order sub-basins)
(e) Lineament density (derived from grid analysis)
(f) Digitization of all the themes using ARC/INFO GIS software package
(g) Overlay analysis of different thematic layers and outputs show areas and sites suitable for artificial recharge
(h) Digital elevation model (DEM) has been generated from elevation contours at 20 m intervals using a linear interpolation method

Figure 1. Flow chart showing data flow and GIS analysis operation followed in the present study



Digitization has been performed in the ARC/INFO environment and subsequently files were exported to ILWIS 2.1 environment. All the segment files were polygonised and rasterized for analysis purpose. Crossed thematic product has been overlaid on segment maps for easy understanding and better visual interpretation. Drainage texture analysis has been performed on the basis of 3^{rd} order sub-basins. Stream ordering has been performed according to Strahler (1952).

Geologic and landform condition of the area

The area is having an undulating micro relief with highs and lows. The maximum elevation is found to be of 154 m (spot height) above msl. A small portion of the study area is covered by alluvium and rest is covered by fairly thick weathered profile of granite gneiss and laterite. Hard-rock of the region has been traversed by network of oriented fractures and often includes pegmatitic dyke that are genetically related to preferred boundaries of Bengal basin (Dasgupta and Sikdar, 1992). The basement gneiss and schist are much weathered at the surface and are generally mantled by a soil cover. Thickness of this soil cover varies from place to place. The rocks show foliation and well-defined joints. Foliation dip is 40-50^{O} NE. The four sets of joints are ENE-WSW, ESE-WNW, SE-NW and SSW-NNE. The common spacing of joints is about 2 m and vertical joints are widely spaced. Extensive lateritization has taken place mainly at the water devides. Some times valley fills contain relicts of laterite. The depth of the valley varies from a few meters to several meters. Geomorphologically the area exhibits stepped sequence of three terraces of which oldest is capped mainly by laterite and to some extent by brown sticky clay with kankar. Repeated cycles of oxidized silt, grey to brown clay, coarse to fine grained brown sand occur below the laterite and clay kankar capping. The laterite capping forms a hard protective cover, which is very much resistant to chemical and mechanical alterations.

Drainage analysis

The Sali (a 4th order river), ephemeral tributary of the Damodar river, originated from the western part of the study area and flows in WNW-ESE direction along its coarse length of 73.6 KM. The channel Sali reveals the structural control over drainage development. The overall drainage pattern is rectangular. The area comprises mostly agricultural land of single cropping. The undulatory side of the Sali river basin forms the soil cover from 2-5 m thick. Morphometrical study of 3rd order drainage basin has been performed with the help of SOI topographical sheets (scale 1:50,000), however, updating the information of minor to major streams has been performed with the help of IRS IB satellite data (scale 1:50,000) of November 1996. Post monsoon data offers a good understanding about the drainage conditions. Third order sub-basins have been studied in context of their large dimensions, which facilitate recognition of lithology, structure and nature of sediments. Drainage density theme has got one of the most influential impact in deriving the result to locate the artificial recharge sites. High to moderate drainage density values are favourable for run-off and does not encourage natural recharge and due to this reason composite layer products with other pertinent thematic information mentioned earlier show suitable sites for groundwater recharge. In the present study, drainage density values have been classified into three categories. Drainage density less than 1.5 Km/sq. km is the low drainage density value, from 1.5 Km/sq. Km to 2 Km/sq. Km are the medium drainage density values and drainage densities over 2 Km/sq. Km are the high drainage density values.

Hydrogeomorphological condition

The channel fill sediments and pediments with considerable thickness (>20 m) and weathered materials of granite gneissic rock are potentially good aquifers. In the study area the main hydrogeomorphic features are channel fills and buried pediment of moderate thickness (somewhere it exceeds 20 m of thickness). The SE part of the Sali river exhibits a gentle gradient and is covered with sands of moderate thickness (10-20 m). Areal extension of flood plain deposit is very limited but traces of old river channels ubiquitously present in the study area. The deep seated interconnecting fractures are good reservoirs of groundwater though the fractures or the joint systems of compact nature do not hold water. Amongst various landuse/landcover types, channel fill and agricultural field are potentially good area for siting artificial recharge structures. Coincidence of channel fill and deep seated lineament make good reservoir for groundwater accumulation.

GIS Analysis

When a wide range of mono-disciplinary resource maps are available, the users must seek ways in which the available information can be combined to give an integrated over-view, or a reclassification or generation as needed (Burrouh, 1990). The criteria for any analysis is dependent on the objective and also the data sets. In the present study, all the thematic maps have been developed on the basis of hydrogeomorphology and other surface geological expression of a potential aquifer. Cross analysis has been performed between lineament density raster map with hydrogeomorphology raster map and the product (Figure 2) shows suitable sites for construction of artificial recharge structures and this has been overlaid by channel fill and lineament segment maps and the final out put (Figure 3) shows the sites for artificial recharge. High drainage density raster map has been crossed with land cover map and the product (Figure 4) shows the suitable sites for construction of artificial recharge structures. Medium drainage density rasterer map has been crossed with landcover map to get an idea about the distribution (Figure 5) of artificial recharge sites under this condition. Drainage pattern has been overlaid on digital elevation model (DEM) (Figure 6) of the study area to get an idea about the three dimesional configuration of the same. Three dimensional perspective model is useful in understanding the role of surface water reservoirs and their topographic locations in controlling groundwater condition.

Figure 2. Map shows the suitable area for artificial recharge in the channel fill land cover and high lineament concentration

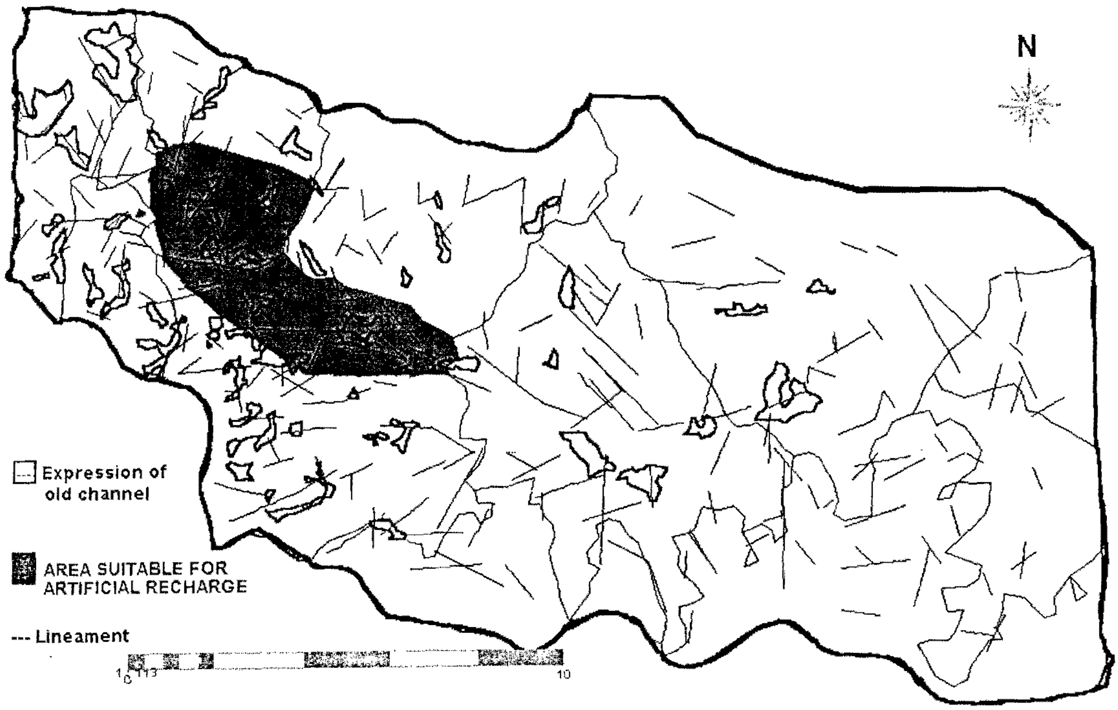


Figure 3. Map shows the suitable sites in the intersections of lineaments and channel fill land cover

Figure 4. Map shows the suitable areas of artificial recharge in the high drainage density and channel fill land cover (after Das, 2002)

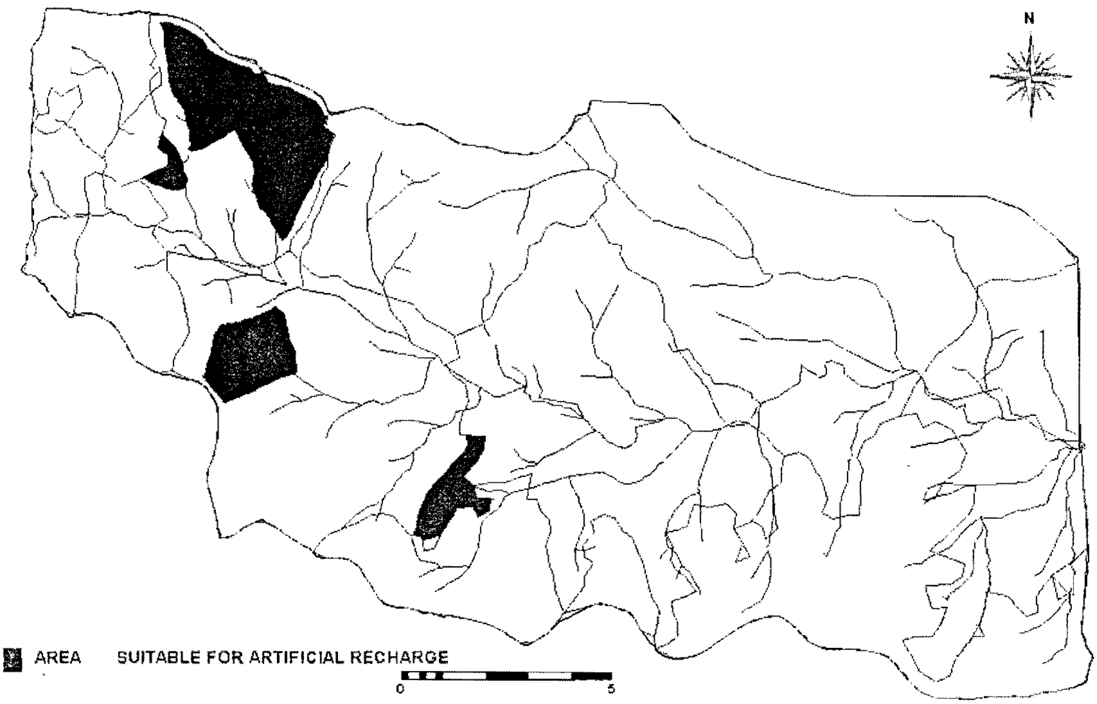


Figure 5. Map shows the. moderately suitable areas of artificial recharge in the medium drainage density and channel fill land cover

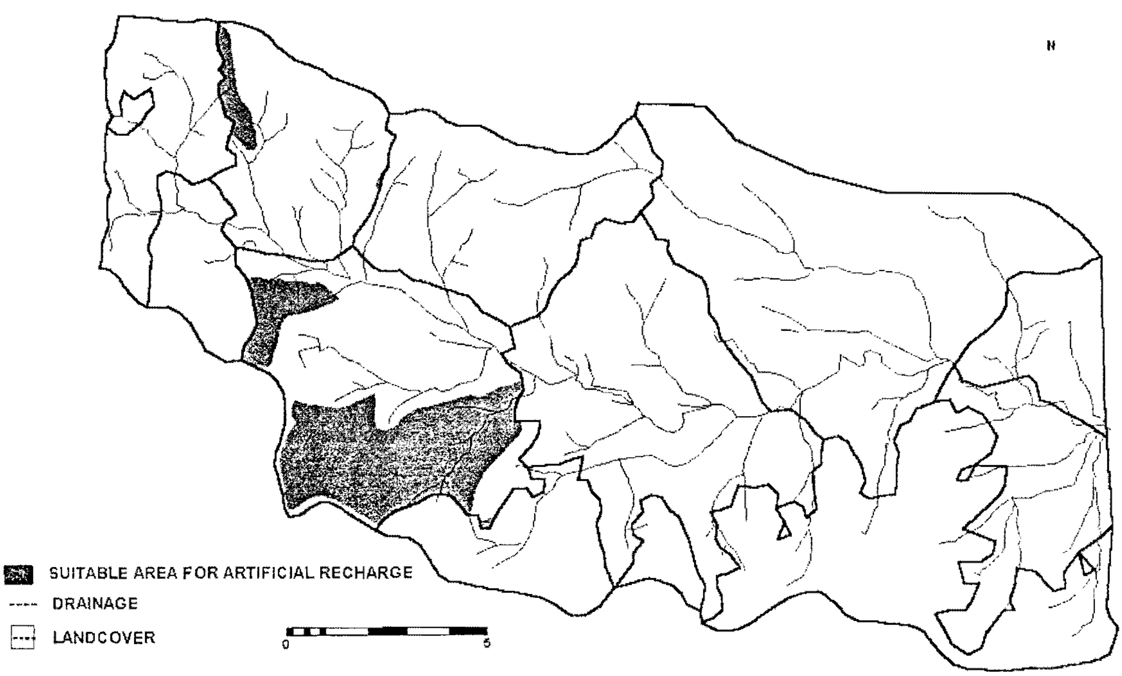
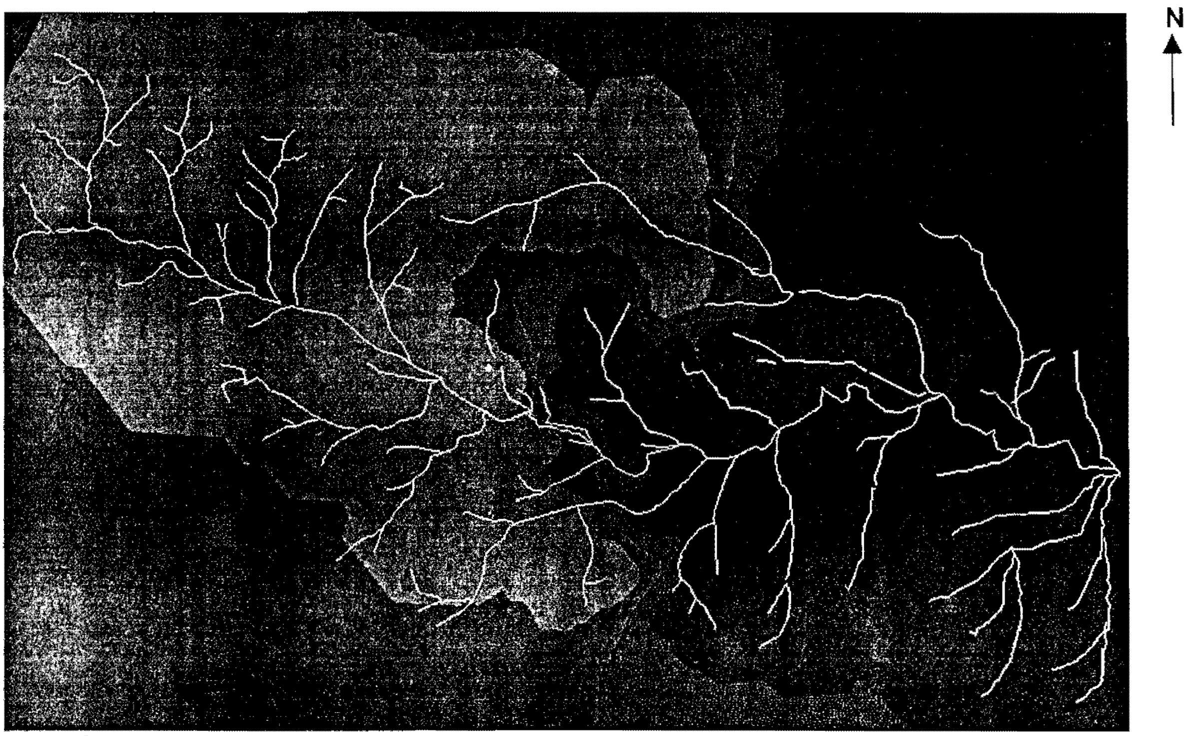


Figure 6. Drainage network super imposed over the DEM of the study area. Lighter tones in the DEM depict higher ground, whereas darker tones indicate lower ground



Discussion

In the study area, the channel fill sediments, pediments with moderate thickness (>20 m) and weathered materials of the country rock have the potentiality to be good aquifer. Though in the present investigation the main hydrogeomorphic features are channel fills (or the palaeochannels), and buried pediments (some where it exceeds 20 m of thickness), the drainage density and lineament density are highly determining factors in locating artificial recharge sites. High to medium drainage density are favourable for surface run-off and does not encourage natural recharge and due to this reason, overlay analysis of drainage density theme with other relevant thematic layer(s), reveals suitable sites for groundwater recharge. The deep-seated interconnecting fractures and joints (lineaments) are potentially good sub-surface reservoir. However, fractures and joints systems of compact nature can not accumulate water. Numerous land use and land cover types have been grouped into seven hydrogeological land use classes to avoid complexities during analysis. Channel fills and agricultural land cover/use areas are suitable for construction of recharge structures. Satellite image interpretation and subsequent field checks reveal that the cultivated area is mainly along the palaeochannel courses. Intersections of channel fills area and deep-seated lineaments offer to be potential reservoir. Though the area under study has got a gentle slope, the influence of slope factor is not adequate enough to be considered in the recharge site selection process.

Conclusion

The detailed information provided by the composite maps(s) has been proved to be very much useful in narrowing down the target points for selecting artificial recharge sites. Thus, the digital database created aiming towards site selection purpose will go long way for planning, development and management of groundwater. Apart from direct benefits, spatial data management techniques have clearly demonstrated their usefulness in understanding the factors responsible for maintaining the hydrological cycle, i.e. the vegetal cover, surface water bodies, lithotypes and landform. Supply of groundwater even in the dry months is very much essential for sustainable development. It is true that satellite alone cannot provide information regarding confined aquifers, then geophysical and drilling data have to be consulted for acquiring sub-surface information and decisions file shall be created through overlay by GIS technique. Evolution and implementation of well thought, long term national policies and creation of a positive international atmosphere alone can lead such development across the world enabling entire human kind to share the benefits of satellite remote sensing and GIS.

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