SCS-CN and GIS-based approach for identifying potential water harvesting sites in the Kali Watershed, Mahi River Basin, India

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The Kali sub-watershed is situated in the semi-arid region of Gujarat, India and forms a part of the Mahi River Watershed. This watershed receives an average annual rainfall of 900 mm mainly between July and September. Due to high runoff potential, evapo-transpiration and poor infiltration, drought like situation prevails in this area from December to June almost every year. In this paper, augmentation of water resource is proposed by construction of runoff harvesting structures like check dam, percolation pond, farm pond, well and subsurface dyke. The site suitability for different water harvesting structures is determined by considering spatially varying parameters like runoff potential, slope, fracture pattern and micro-watershed area. GIS is utilised as a tool to store, analyse and integrate spatial and attribute information pertaining to runoff, slope, drainage and fracture. The runoff derived by SCS-CN method is a function of runoff potential which can be expressed in terms of runoff coefficient (ratio between the runoff and rainfall) which can be classified into three classes, viz., high ($> 40\%$), moderate ($20–40\%$) and low ($< 20\%$). In addition to IMSD, FAO specifications for water harvesting/recharging structures, parameters such as effective storage, rock mass permeability are herein considered to augment effective storage. Using the overlay and decision tree concepts in GIS, potential water harvesting sites are identified. The derived sites are field investigated for suitability and implementation. In all, the accuracy of the site selection at implementation level varies from $80–100\%$.

1. Introduction

Water is one of the most vital requirements for economic and social development. Human population of the Indian subcontinent is ever increasing thereby increasing the demand for water for domestic, agricultural and industrial use. However, the quantum of rainfall and surface water availability has remained the same; thus, resulting in over-exploitation of ground water, declining water table levels and deterioration of water quality. This calls for sustainable, alternate and decentralized approach to develop watershed at micro level so as to reduce the runoff, improve the groundwater recharge and quality. Reduction of surface runoff can be achieved by constructing suitable structures or by making changes in land management. Micro-watershed (watershed area $< 5\,km^2$) development approach calls for a detailed understanding and analysis of various rainfall-runoff model related parameters such as land use, hydraulic properties of the soil, soil moisture, slope, rainfall intensity and lithology (Prasad *et al* 1993; Yusof *et al* 2000; Cosh *et al* 2004).

In terms of spatial domains, runoff models can be classified as lumped, distributed and semi-distributed. The lumped models, assume that each sub-watershed within the watershed can be adequately represented by a weighted average representation of hydrologic parameters. A distributed basin model (or grid-based model) approach allows for a hydrologic analysis of watershed to a grid-cell

level of detail. Some salient rainfall-runoff models that are widely in practice include SCS-CN (NEH 1985), CASC2D (Downer *et al* 2002; Marsik and Waylen 2006), TOPMODEL (Beven and Kirkby 1979; Warrach *et al* 2002), HEC-1, HEC-HMS (HEC 1990, 2001), KINEROS (Woolhiser *et al* 1990), GIUH (Kumar *et al* 2007). Though each of the above models have their own merits and demerits, the Soil Conservation Service Curve Number (SCS-CN) method is simple, well acclaimed and produces better results (Stuebe and Johnston 1990; Ponce and Hawkins 1996; Michel *et al* 2005; Schneider and McCuen 2005; Mishra *et al* 2006; Sahu *et al* 2007). This method takes into account major runoff producing watershed characteristics, like soil type, land use and antecedent moisture conditions (AMCs) to estimate the loss and runoff volume (Ponce and Hawkins 1996; Mishra *et al* 2004, 2005) which can be obtained from the optical and microwave remotely sensed data. Further, spatial information on watershed parameters such as the land cover, soil, rainfall, slope and drainage network can be retrieved from Landsat, SRTM, TRMM and METEOSAT data products (Barrbera *et al* 1995; Levizzani 1999; Rabus *et al* 2003).

The Geographic Information System (GIS) has become a critical tool in hydrological modeling in view of its capacity to handle large amount of spatial and attribute data. Some of its features such as map overlay and analysis help to derive and aggregate hydrologic parameters from different sources such as soil, land cover and rainfall data (Cheng *et al* 2006; De Winnaar *et al* 2007). In recent days, an integrated study of runoff modeling, remote sensing and GIS has gained significance in targeting suitable sites for water recharging/harvesting structures (Padmavaty *et al* 1993; El-Awar *et al* 2000; Ravishankar and Mohan 2005; De Winnar *et al* 2007). These works mainly aim at prioritizing the area suitable for water harvesting by taking into consideration parameters such as runoff, physiography, environmental and socio-economic conditions. However, performance of the water harvesting/recharging structures mainly depends on geotechnical parameters like water tightness of foundation and abutments, slope, discontinuity-river channel relation and storage capacity. In this study, a decision rule based approach is proposed that incorporates hydrological, hydro-geological and geotechnical criteria for selecting sites for different structures.

2. Study area

Kali Watershed covering an area of about $200 \, \text{km}^2$ in the Godhra District of Gujarat State lies between latitudes $22°40'$N–$22°52'$N and longitudes
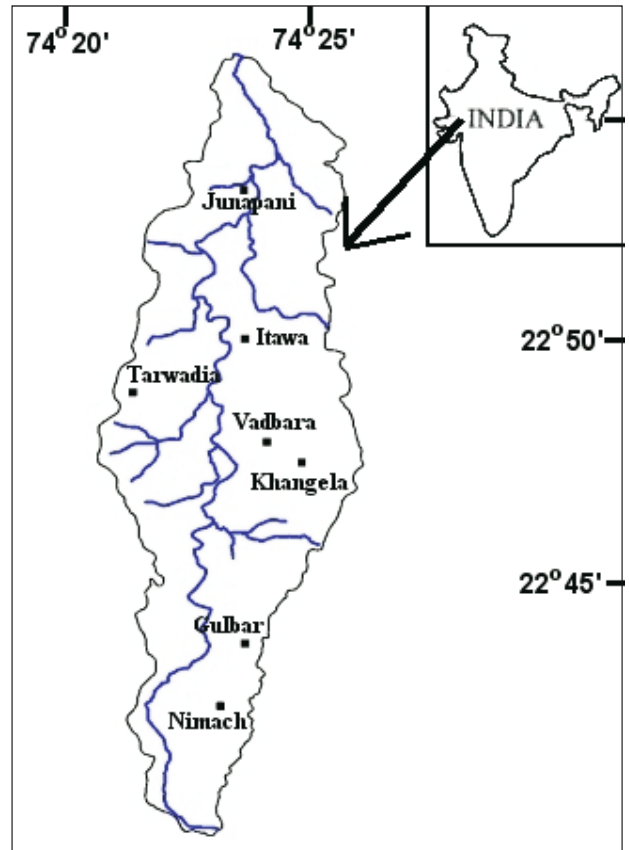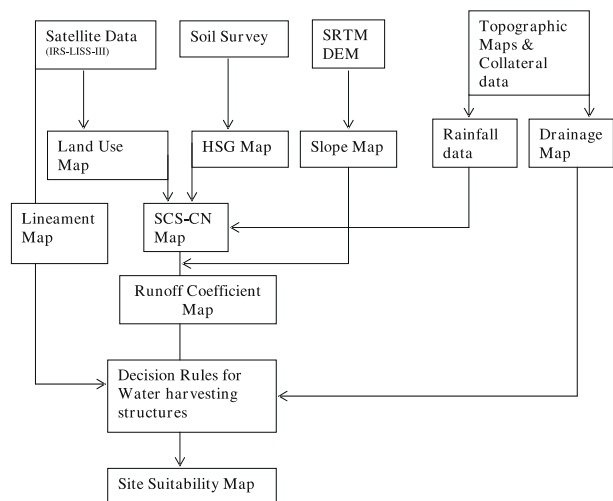

Figure 1.   Location map of Kali Watershed.

Figure 2.   Flow chart showing the adopted methodology.

$74°20'$E–$74°25'$E (figure 1). The region has been experiencing soil degradation due to inadequate forest cover, denudation of forest, uncontrolled grazing and neglect of available pasture land. The climate is semi-arid and experiences three well-defined seasons:

- hot weather from March to June,
- rainy season from July to September, and
- winter season from October to February.

The average annual rainfall is nearly 900 mm with mean maximum temperature of 40°C having high potential evapo-transpiration rate (900 mm). Soil in the region is dominantly sandy loam, loam and clay loam. Vertisol derived from basalt, phyllite and schist is also found in certain parts. Corn and wheat are the main crops cultivated in the watershed. The area comprises predominantly of hard crystalline rocks such as basalt, quartzite, phyllite, slate and schist which restrict the scope of groundwater potential to fractures and weathered zones.

3. Materials and methods

In this study, a variety of data concerned with runoff estimation such as satellite images, digital elevation model, soil map and rainfall data are used. Land use maps for the months of March and October 2004 are prepared using Indian Remote Sensing Satellite (IRS-LISS-III) data. Calibrated digital elevation model (DEM) derived from Shuttle Radar Topographic Mission (SRTM) is used to derive the slope map. Calibration of SRTM-DEM was carried out with the aid of 40 Ground Control Points (GCPs) collected using Differential Global Position System (DGPS). A second order polynomial equation was used to calibrate the DEM heights with DGPS heights and the observed Root Mean Square (RMS) error was 0.5 m. Slope map of the study area is derived from the calibrated SRTM-DEM using ERDAS imagine in-built Inverse Distance Weighted (IDW) interpolation technique. The hydrological soil group (HSG) map (1:50,000 scale) is generated with the aid of National Bureau of Soil Survey and Land Use Planning (NBSSLUP) Maps, Landsat-TM data (by image ratios and principal component analysis) and DEM. The drainage lines are digitized from the topographic sheets and subsequently updated with the aid of DEM. Flow lines are extracted from this DEM using NIH image software based on D8 algorithm. The runoff estimates for different combinations of soil group, land use classes and Antecedent Moisture Condition (AMC) classes are estimated following the procedure of 'SCS-CN method' (NEH 1985). Integration of vector coverage and collateral data is carried out using ARC/Info GIS software. Decision supports for different water harvesting/ recharge structures are made in a GIS platform. The work flow of adopted methodology is given in figure 2. Rainfall data of this ungauged watershed for the period from 1969–1994 is collected and analyzed for recurrence of storm/flood event at two-year intervals. Computation of CN variables and discharge is carried out for this event with a mean precipitation (P) of 60 mm/day. Since the

precipitation data are collected from single available station, the variations in AMC could not be accounted. Hence, AMC II is considered for the entire watershed for the given storm event.

3.1 *SCS-CN method*

The SCS-CN method explaining the water balance equation can be expressed as below (Mishra and Singh 2003):

$$P = I_a + F + Q, \tag{1}$$

$$\frac{Q}{P - I_a} = \frac{F}{S}, \tag{2}$$

$$I_a = \lambda S. \tag{3}$$

where P is the total precipitation (mm); I_a the initial abstraction (mm); F the cumulative infiltration (mm); Q the direct runoff (mm); S the potential maximum retention (mm) and λ the initial abstraction coefficient (0.2). The SCS-CN equation, as expressed below is derived from the combination of the first two equations:

$$Q = \frac{(P - I_a)^2}{P - I_a + S}, \tag{4}$$

which is valid for $P \geq I_a$. Otherwise, $Q = 0$. For a constant value of I_a (0.2S), S can be determined from the P–Q data. In practice, S is derived from a mapping equation expressed in terms of the curve number (CN):

$$S = \frac{25400}{CN} - 254. \tag{5}$$

The CN (dimensionless number ranging from 0 to 100) is determined from a table, based on land-cover, HSG, and AMC. HSG is expressed in terms of four groups (A, B, C and D), according to the soil's infiltration rate, which is obtained for a bare soil after prolonged wetting. AMC is expressed in three levels (I, II and III), according to rainfall limits for dormant and growing seasons.

Although, SCS method is originally designed for use in watersheds of 15 km^2, it has been modified for application to larger watersheds by weighing curve numbers with respect to watershed/land-cover area. In this study, the curve numbers are weighed with respect to the micro-watershed area (generally < 5 km^2) using the following equation:

$$CN_w = \frac{\sum (CN_i * A_i)}{A}, \tag{6}$$

Table 1. *Hydrological soil group and major soil types of the Kali Watershed.*

| HSG	Description	Taxonomy	Distribution (%)
A	Very shallow, somewhat excessively drained, sandy soils on valleys and gently sloping quartzite hills; moderate stoniness.	Sandy, mixed, hyperthermic Lithic Ustocherpts	1.5
B	Moderate, well drained, loamy sands on very gently sloping hills and ridges with moderate erosion; moderate stoniness.	Loamy - skeletal, mixed, hyperthermic Lithic Ustrothents	10.8
C	Shallow, well drained, clayee soils on very gently sloping basaltic plateau (with narrow valleys) with moderate stoniness; associated with shallow loamy soils with severe erosion and moderate stoniness.	Loam, mixed, hyperthermic Lithic Ustrothents	44.0
D	Moderately deep, well drained fine soils on very gently sloping basaltic plateau (with narrow valleys) with moderate erosion; associated with moderately shallow, well drained calcareous fine soils with slight erosion.	Fine, mixed hyperthemic Vertic Ustocherpts	43.7
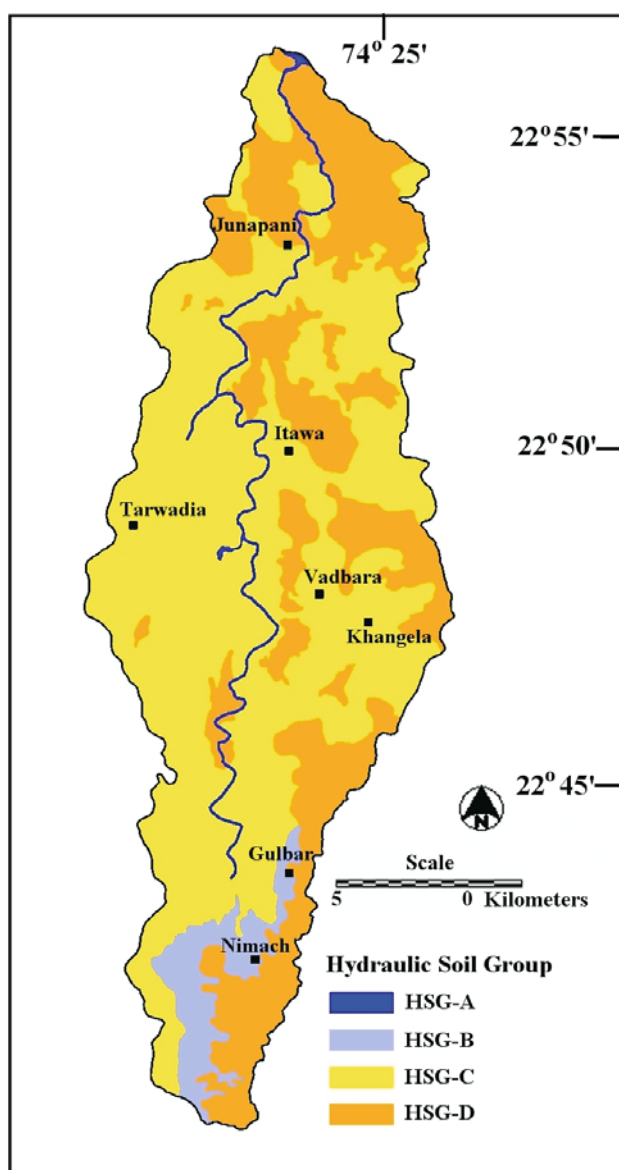
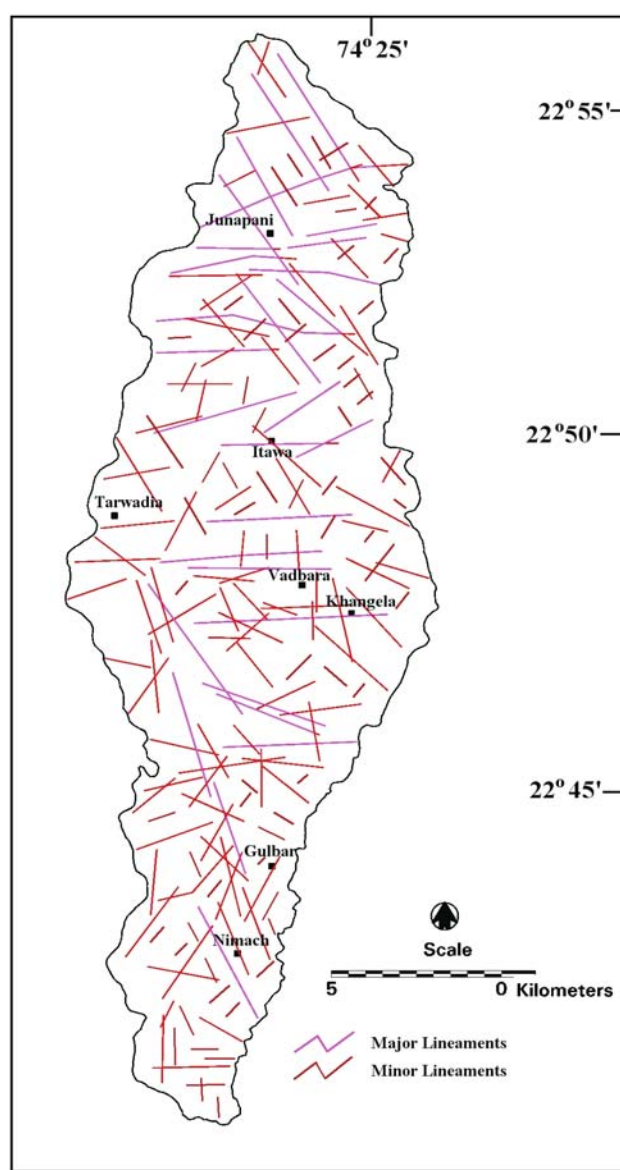Figure 3. Map showing the distribution of HSG classes in the study area.

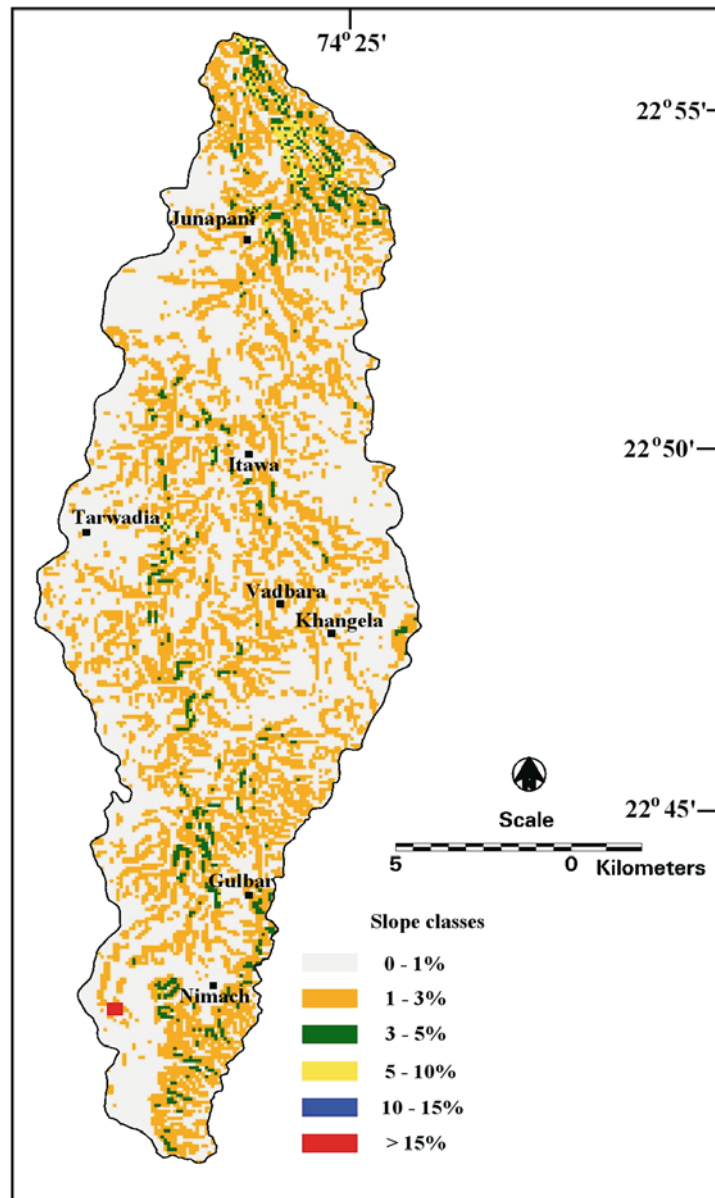Figure 4. Lineament map showing major trends of discontinuities.

Figure 5. Slope map.

where CN_w is the weighted curve number; CN_i is the curve number from 1 to any number N; A_i is the area with curve number CN_i; and A the total area of the micro-watershed.

4. Results

Spatial information on runoff coefficient, lithology, slope, drainage and fracture plays a critical role in site selection for runoff harvesting/recharging structures. Information on these primary and secondary thematic layers is given below.

4.1 *Soil*

Hydrological soil groups of the basin is determined on the basis of information from NBSSLUP map is provided in table 1 and figure 3. It is evident from the figure that the region predominantly comprises of HSG C (44%) and D (43.7%). The soil group B (10.8%) and A (1.5%) are restricted to bazada, flood plains and natural levees, which suggests high surface runoff tendency of the watershed.

4.2 *Lineament*

Fractures, rock cleavages and fault/thrust play a vital role in affecting the surface storage, ground-water recharge and base flow and consequently, the efficiency of structural measures. The above linear features (lineaments) can be measured and mapped from the toposheets and satellite images. In this study, lineament map is prepared from the satellite data following the conventional edge
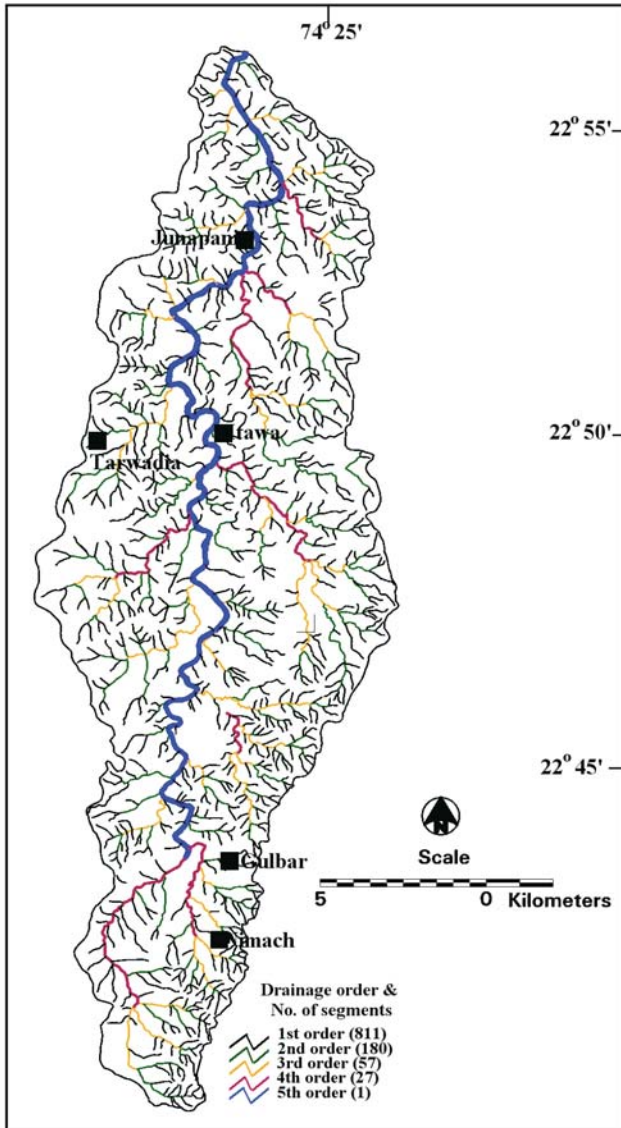
Figure 6. Drainage network map.

enhancement techniques and field checks (figure 4). In all, three predominant lineament trends bearing azimuth direction 10°, 48° and 90° trends are observed. These lineaments are classified as major (running more than 1 km) and minor (running less than 1 km) based on their length of continuity. After critical field evaluation, the major and minor lineaments are buffered (10 m and 5 m distances respectively) to represent their spatial influence in terms of leakage/seepage.

4.3 *Slope*

The slope of the area affects the runoff, recharge and movement of surface water and is one of the important parameters for site selection. The derived slope map (figure 5) is classified into seven categories such as nearly level (0–1%), very gentle (1–3%), gentle (3–5%), moderate (5–10%), strong

(10–15%), moderately steep–steep (15–35%) and very steep ($> 35\%$) as per IMSD (1995) guidelines. Since the watershed mostly comprises (85% of the total area) very gentle and moderately sloping classes, the adjustment of CN with respect to slope category is not carried out.

4.4 *Drainage network and surface water bodies*

Mapping of depression storage in the form of lakes, ponds and reservoirs using IRS LISS-IV data suggests that the surface storage is distributed throughout the watershed but more number of ponds are found in the upper reaches of the watershed, where the drainage density and pattern are mainly controlled by lithology, minor and major scale fractures (lineaments) as well as slope. Stream ordering is done for proper planning of conservation measures in terms of storage and capacity. The schematic representation of the drainage network along with stream order is given in figure 6.

4.5 *Land use*

Information on land use and pattern of their spatial distribution is one of the criteria in selecting a curve number (CN). In the present study, the IRS LISS III satellite data of two seasons (representing two cropping seasons) are used for the generation of land use categories. Supervised classification is performed employing the Bayesian Maximum Likelihood Classifier (MLC). MLC, a parametric decision rule, is a well-developed method from statistical decision theory that has been applied to the problem of classifying image data (Settle and Briggs 1987). Information collected from the Gujarat State Forest Department, Survey of India (SOI) toposheets and personal field visit to the watersheds are used to identify the signatures representing various land use classes. They are then evaluated to make sure that, there is suitable discrimination of individual classes. After obtaining a suitable grouping for satisfactory discrimination between the classes during signature evaluation, the final classification is carried out. The classification accuracy evaluated by confusion or error matrix, showed 92% and 95% accuracy for the producer and the user estimates respectively. In all, five major land use classes namely, open forest (14.8%), irrigated land (19.2%), fallow land (44.8%), barren land (19%), water bodies (1.2%) and sand (1%) are observed (figure 7).

4.6 *Runoff coefficient*

As the SCS-CN method is very sensitive to CN value, accurate determination of this parameter is
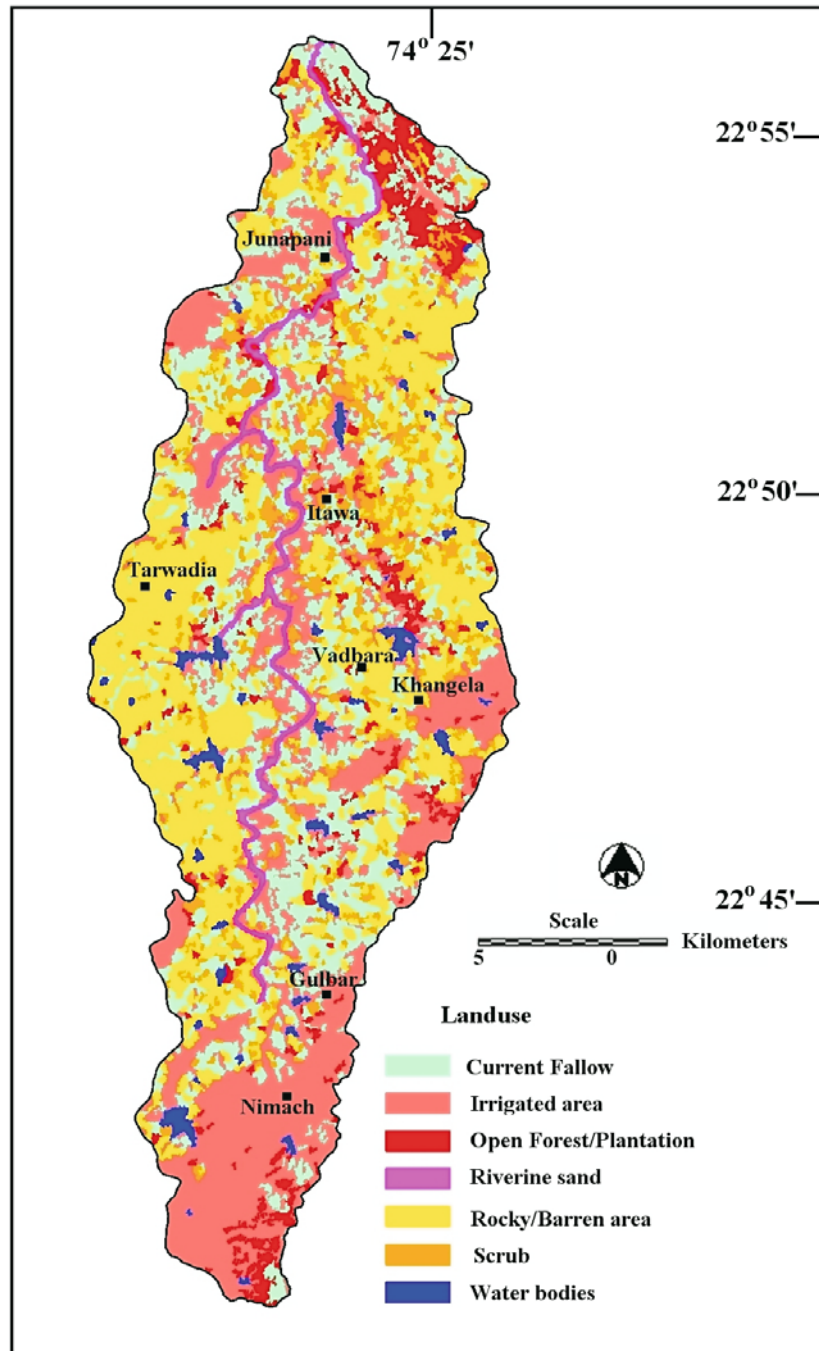
Figure 7. Land cover map.

very important. CN is again a function of HSG, land use and AMC. The AMC is determined by the total rainfall in the 5-day spell preceding a storm. As the soil moisture increases due to rainfall in the early spell, the runoff during storm event increases. In the present case, depending on the total rainfall in 5-day period, the AMC condition is classified as AMC I (< 35 mm), AMC II (35–53 mm) and AMC III (> 53 mm) (Geetha *et al* 2007). Since the rainfall data used in this work are from a single meteorological station, the

curve numbers are evaluated for AMC-II condition only. For the given mean intensity and total precipitation, the values of maximum potential retention (S) obtained from the weighted CN_w and runoff (mm/day) is estimated using equation (4). For the 60 mm/day storm event, runoff depth estimates range between 27 mm/day and 9 mm/day. Accordingly, the runoff coefficient of each HSG-land use combination (expressed as a percentage of total precipitation) is prepared in GIS. On the basis of histogram distribution (figure 8), these runoff
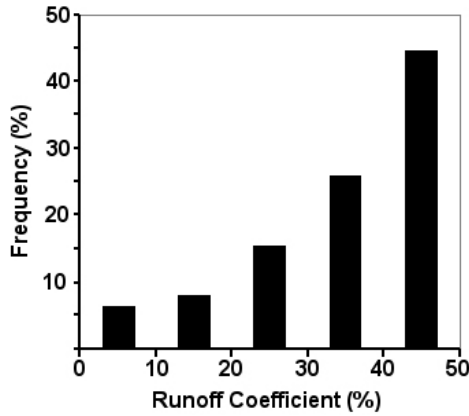
Figure 8. Histogram showing frequency distribution of different runoff coefficient classes.

coefficient classes are grouped into three broad classes such as high ($>40\%$), moderate (20–40%) and low ($<20\%$). It is evident from figure 9 that 48% of the study area falls under high runoff potential class. The moderate and low runoff coefficient classes occupy 43% and 9% of the total area respectively.

4.7 *Site suitability and site verification*

Considering the high runoff potential of the watershed, developmental structures such as farm pond, check dam, subsurface dyke and percolation tanks are suggested in the watershed for water resource development. An attempt is made to evolve a decision rule based approach for identifying the most appropriate sites for each of the proposed Water Harvesting Structures (WHS). Conventionally, factors such as watershed area, slope, land use, runoff coefficient are considered as criteria in selecting suitable sites for WHS (Padmavaty *et al* 1993; IMSD 1995; El-Awar *et al* 2000; Rao and Satish Kumar 2004; De Winnar *et al* 2007). In this work, in addition to above criteria, factors such as effective storage, foundation and abutment permeability are also considered (tables 2–4). This information is derived from maximum water level, storage area, storage volume, seepage loss, permeability of foundation and abutment following the procedures of Lund (2006) and Lee and Farmer (1990).

The effective storage for each site is arrived by adjusting the total storage for evaporation and seepage losses following the equations (7) and (8) (Lund 2006). By this technique, the evaporative and seepage losses are expressed as a fraction of total storage (S).

$$E = eab\left(\frac{3S}{ab}\right)^{2/3}, \qquad (7)$$

where E is the evaporative loss proportional to surface area of waterspread, a and b are side and longitudinal valley slopes; e is the actual evaporation; and S the storage volume.

$$D = d\left(\frac{3S}{ab}\right)^{1/3}, \qquad (8)$$

where D is the seepage loss and d is the hydraulic head.

In case of surface water storage structures, 20–35% net loss of water (due to seepage and evaporation) is considered as normal (Dahiwalkar and Singh 2006). In this study, net storage loss of over 30% is considered as unsuitable for construction of surface water storage structures like check dam. Accordingly, the computed average storage loss is grouped into three classes such as *high*, *moderate* and *low* for net storage losses $>30\%$, 15–30% and $<15\%$ respectively.

The foundation rock mass permeability is estimated based on the relationship among discontinuity spacing (S), surface opening (e) and permeability (k) for the given density and viscosity of water (Lee and Farmer 1990).

$$k = \frac{\gamma_w}{\mu}\,2\left(\frac{e^3}{12S}\right). \qquad (9)$$

In this study, permeability values of rock masses (basalt, quartzite and phyllite) with three orthogonal discontinuity sets are considered. The derived permeability values are classified into three classes such as *high* (0.5–0.1 m/day), *moderate* (0.1–0.05 m/day) and *low* (<0.05 m/day).

To implement the decision rules, an information layer is prepared by overlay of drainage network, runoff coefficient with storage attribute, slope, land use, lithology with permeability attribute and lineament maps. Suitable sites for bore well, dug well and dug-cum-bore well are determined wherever, the conditions defined in table 2 match with the attributes of the information layer. Similarly, site suitability for check dam, percolation pond, farm pond and sub-surface dyke are carried out where the defined conditions (table 3) match with the information layer. The resultant map is designated as *potential site suitability map* which comprises spatial distribution of sites suitable for various water recharging/discharging structures (figure 10). To validate the potential site suitability map and estimate the accuracy of prediction, field investigation was carried out in a small micro-watershed area near the village Khangela (figure 11). In all, 50 sites (representing all the WHS) were investigated for their suitability
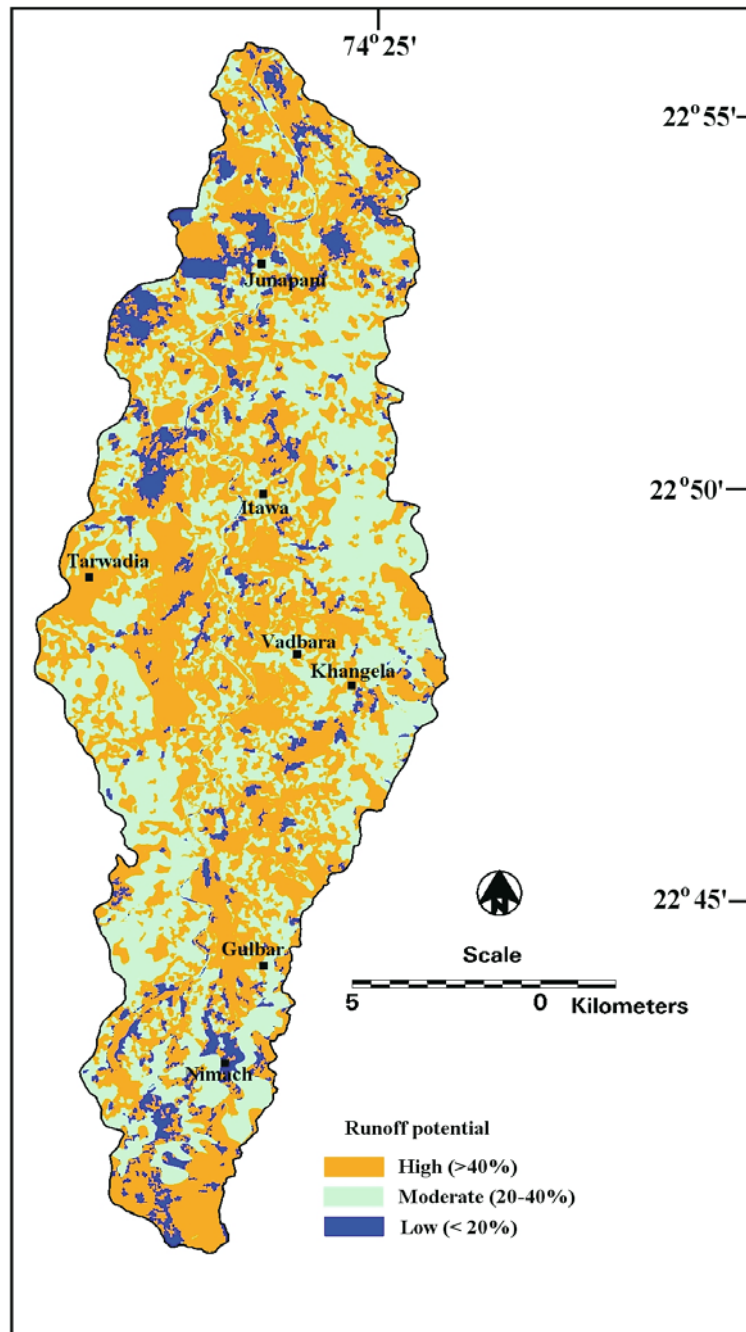
Figure 9.   Map showing the spatial distribution of different runoff coefficient classes.

and implementation. It is evident from the field study that:

- All the sites identified for farm ponds commensurate well with field conditions. This could be attributed to higher spatial frequency, smaller dimensional attributes, storage and catchment area.
- In the case of check dams, 85% of the sites are found to match with field based selection criteria. Presence of additional discontinuities (that are difficult to discern from satellite data) played

a critical role in rejecting the 15% of identified sites. These additional set of local discontinuities affect the permeability of the foundation and abutments significantly and hence, the effective storage of the reservoir. On the contrary, presence of such additional discontinuities augment infiltration and are advantageous for constructing percolation ponds. Estimated accuracy of prediction for other structures such as percolation pond and subsurface dyke are 80% and 90% respectively. In case of subsurface dykes, 10% of the sites were rejected because of additional

Table 2. *Site selection criteria for water harvesting structures.*

Bore wells

Where runoff coefficient is < 40%

Where present land use is crop land or fallow land

Where slope is 0–10%,

Where major lineament intersects

Dug-cum-bore wells

Where runoff coefficient is < 20%

Where land use is crop land or fallow or waste land

Where slope category 0–5%,

Where minor lineaments and major lineaments intersect

Dug well

Where runoff coefficient is < 20%

Where land use is crop land or fallow or waste land

Where slope category 0–3%,

Where minor lineaments intersect

discontinuities and shallow thickness of alluvium.

- Incorporation of additional parameters like effective storage, foundation-abutment permeability played a vital role in narrowing down the most appropriate sites for check dams and percolation ponds.
- Thematic layers derived from high spatial resolution satellite data may further help to increase the accuracy.

5. Discussion and conclusions

In Kali Watershed, Gujarat, India, drought like situation prevails every year due to low average annual rainfall, high runoff and evapotranspiration. This calls for proper management of

Table 3. *Site selection criteria for water harvesting/recharging structures.*

Structure	MWL* (m)	Slope (%)	Permeability	Runoff coeff.	Stream order	Watershed area (10^4m^2)	Storage loss
Farm ponds	2–2.5	0–5	Low	Medium/high	1	1–2	Moderate–low
Check dams	4–5	< 15	Low	Medium/high	1–4	25	Low
Subsurface dykes	–	0–3	High	Medium/low	>4	> 50	Low
Percolation ponds	6–7	< 10	High	Low	1–4	25–40	Moderate–high

MWL – Maximum water level.

Table 4. *Specifications for different water harvesting structures.*

| Type of structure	Applications	Required site condition	Dimensional parameters
Percolation pond	Recharge to aquifer and surface storage for restricted period. May be used for limited irrigation, livestock and domestic demand.	Permeability high, well defined broad stream channel and presence of intersecting fractures.	3–5 m high earthen bund, 5000–10000 m³ effective storage, shallow cutoff, provision for spillway, silt trap barrier in the upstream.
Check dam	Surface storage. Restricted irrigation and domestic needs.	Well defined straight stream channel with level banks, adequate catchment and rocky riverbed without any fractures.	2–4 m height of masonry structure, 5000–7000 m³ effective storage, partial treatment to foundation for leakage/seepage, provisions for overflow.
Farm pond	For livestock storage and restricted irrigation.	Narrow elongated depression with gentle slope and small catchment area.	1–2 m high elongated earthen embankment, 2000–5000 m³ storage, shallow foundation.
Subsurface dyke	To check the base flow in river and reduce evaporation losses. Mainly for domestic needs.	Straight and wide river with 2–3 m thick sandy-gravely bed material.	2–3 m deep trapezoidal cutoff foundation and impervious core wall. Storage capacity of 2000–5000 m³.
Dug well	For harvesting groundwater for domestic and livestock.	Porous and permeable rocks, high fracture density, downstream of major recharge structures.	10–12 m diameter, 18–20 m deep excavations with or without lining. Hydro fracturing/lateral drilling for augmenting the well yield.
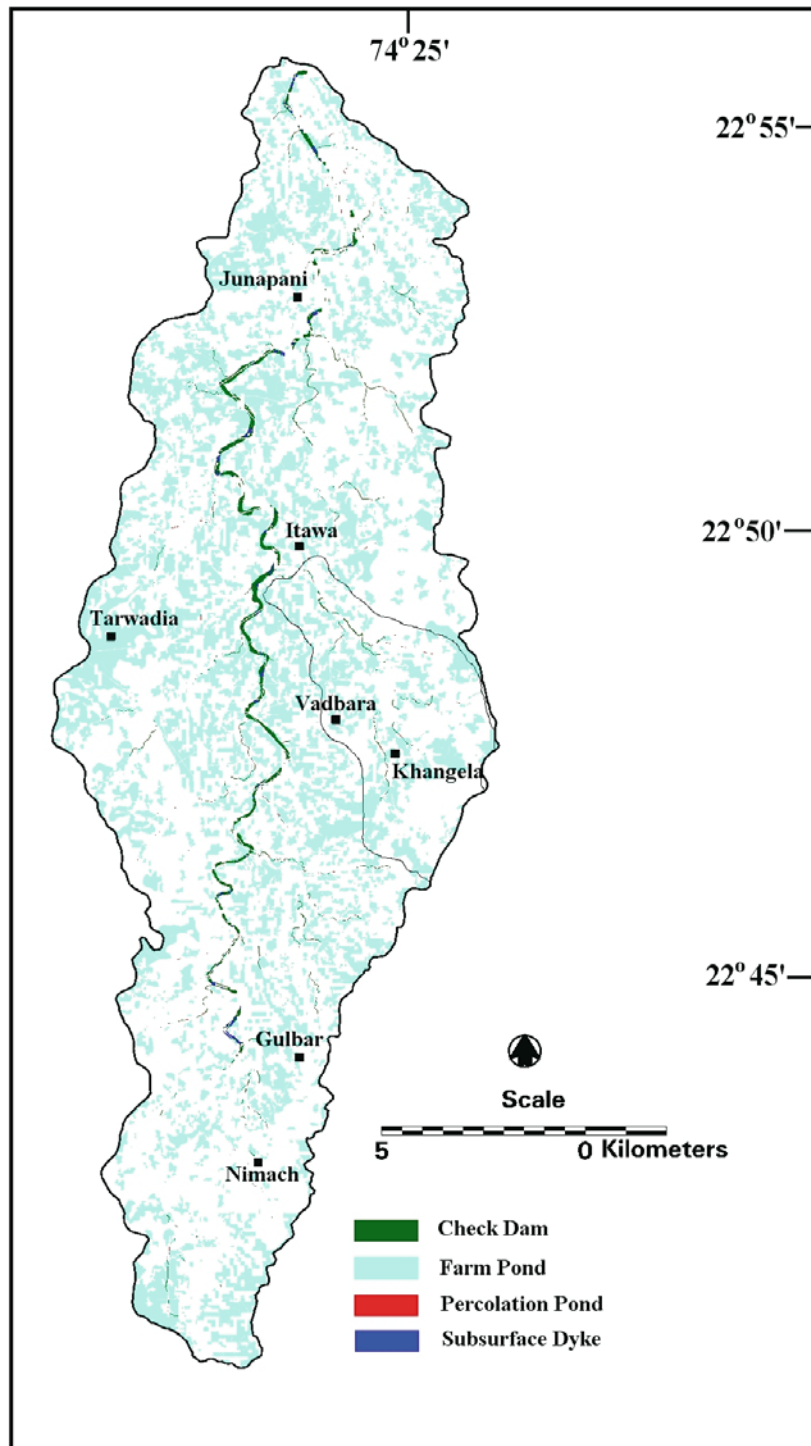
Figure 10. Potential site suitability map indicating sites for different water WHS.

surface and sub-surface water resources. In the hard rock areas like Kali Watershed, discontinuities (fractures/joints) play a vital role in groundwater recharge movement and discharge. Since the country rocks (quartzite, phyllite and basalt) have very low storitivity and transmissivity; groundwater recharge falls short of the water discharged from the aquifers. Hence, groundwater alone cannot meet the requirement of increasing demand for water. To overcome this problem, construction of surface water storage and groundwater recharge structures are proposed to augment both surface and sub-surface storage. Firstly, these activities reduce runoff velocity, thereby minimize erosion and secondly, allow the retained water to percolate and result in increased recharge. However,
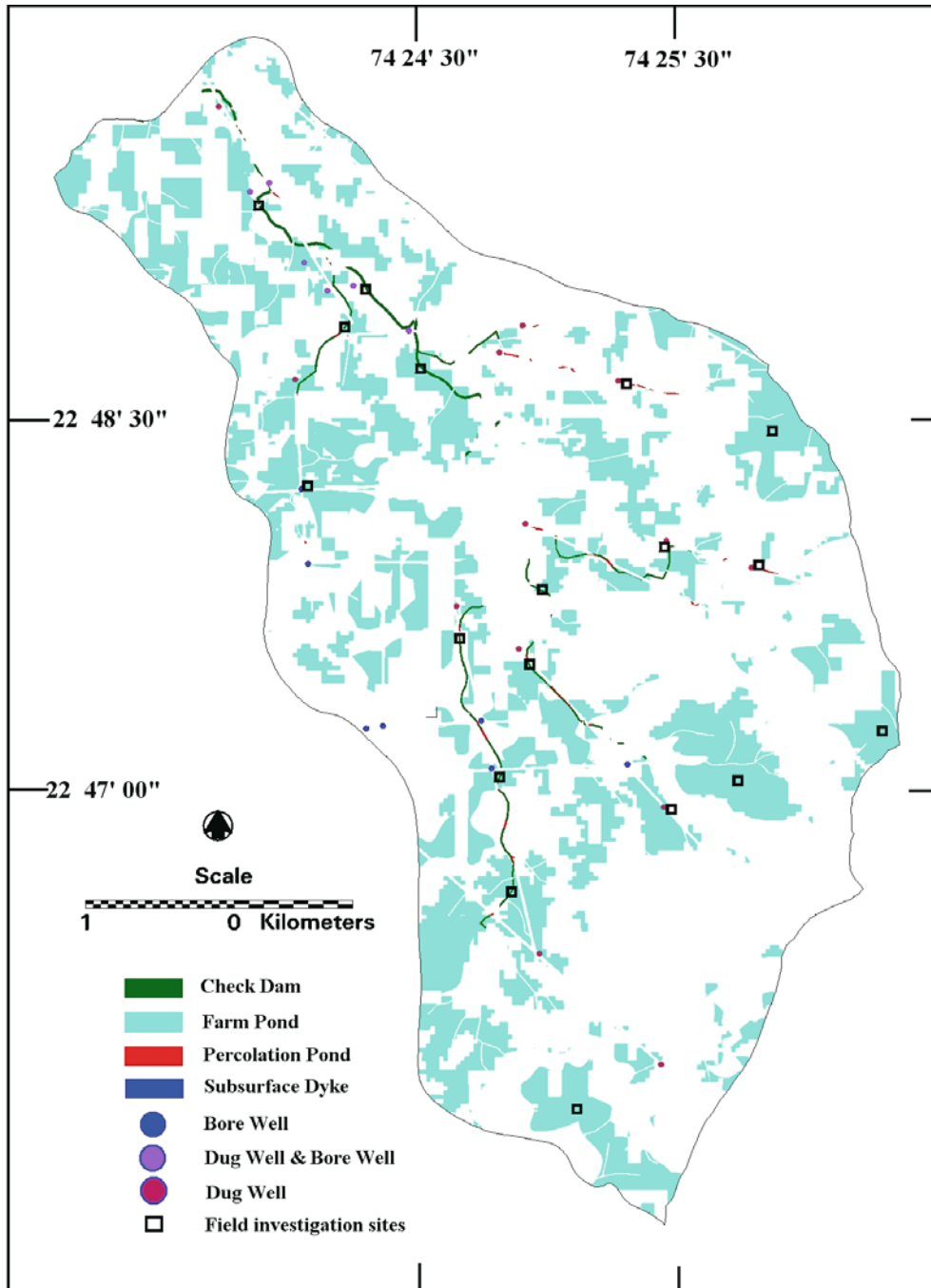
Figure 11.   Khangela watershed area indicating analytically derived and field validated sites for WHS.

efficiency and performance of these structures depend on appropriate structural design and site selection procedure (Ramakrishnan and Rao 2008).

Available literatures on site selection procedures for WHS consider slope, runoff, watershed area, drainage order and socio-economic aspects (Padmavathy *et al* 1993; IMSD 1995; Geetha *et al* 2007; De Winnaar *et al* 2007) as the main parameters. These simplified site selection criteria often result in failure/underperformance of the structures in terms of storage

and structural stability. In this study, additional parameters such as foundation-abutment permeability, effective storage are also considered as site selection criteria in addition to the above said parameters.

To appraise the suitability of selected sites for WHS construction, field investigation was carried out over a small watershed area near the Khangela village. It is evident from the field investigation that the derived potential site suitability map is fairly accurate (80–100%) and offers a good

guidance for field implementation. Such higher order of accuracy is attributed to the adopted site selection criteria. This study best exemplifies the integrated approach of remote sensing, GIS and engineering geology in water resource development.

Acknowledgements

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