Int. J. Environ. Res., 9(4):1259-1268, Autumn 2015
ISSN: 1735-6865

Identification of Potential Stormwater Recharge Zones in Dense Urban Context: A Case Study from Pune city

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Received 20 Nov. 2014; Revised 25 Feb. 2015; Accepted 9 March 2013

ABSTRACT: Anthropogenic alterations have affected urban hydrology in India and have generated a wide range of hydrological problems. Such alterations include increase in directly-connected impervious cover thus reducing natural groundwater recharge. In the past urban runoff was largely viewed as a nuisance, but within the new paradigm of sustainability, this water is recognized as a potential resource. This research paper discusses the importance of managing stormwater sustainably by recharging groundwater sources. It indicates the potential of stormwater harvesting, when properly managed, as a tool to counter depleting water sources and ever-increasing demand for water. The present study aims at developing a potential stormwater recharge zone map for a sub watershed in Pune city, India using GIS. Five classes of thematic maps have been integrated to prepare the final map. Each class is assigned a weightage depending on its influence on the recharge of stormwater. The resultant map (potential stormwater recharge zone map) thus prepared is classified into four classes: Very good, good, moderate and poor.

Key words: Sustainable stormwater management, Stormwater recharge, GIS application, Stormwater management in urban context, Stormwater management in developing countries

INTRODUCTION

The world's human population is increasing at an unprecedented rate with much of this growth taking place in urban areas. At the turn of the century, almost half the population lived in urban areas. This is expected to increase up to 60% by 2030. Major interest in the relationship between urban development and water began during 1960s when accelerating urban growth began to generate a wide range of hydrological problems (Howard and Gelo, 2002).

The covering and replacement of natural rocks, soil and vegetation by pavements, foundations, buildings and other structures has a profound impact on the hydrology of an area. It is a well known fact that natural groundwater recharge is inhibited in urban areas as impervious cover enhances runoff and limits infiltration. Urban development alters all aspects of the water cycle. The processes of urbanization exert multiple pressures on the hydrologic cycle. Specifically, increases in impervious surface result in increased hydraulic efficiency in urban catchments, and can cause substantially decreased capacity for a given landscape or region to infiltrate precipitation, with a concomitant increase in the production of runoff, shorter times of concentration or lag times and decreased recharge of water tables with a corresponding decline in base flows (Shuster *et al.*, 2005). Urban development and population growth increase water demand. Sustainability of urban water supply is one of the core issues the planners across the world are facing at present. In India this problem may get aggravated in near future mainly due to improper management of water resources, environmental degradation and rapid pace of urbanization. Concurrently, the stress on ground water system has increased tremendously resulting in steep water level declines in and around the urbanized cities.

Urban areas are characterized by extensive impervious surfaces, damaged soils and little room for green space or for stormwater management facilities leading to increase in stormwater runoff at the expense of groundwater recharge, degrading water quality and impairing aquatic habitats. According to the report of the National Disaster Management Guidelines (2010),

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urban flooding is significantly different from rural flooding because urbanization often results in greater apportionment of precipitation to runoff and compressed storm flows, which increases the flood peaks from 1.8 to 8 times and flood volumes by up to 6. Traditional engineering solutions alone cannot solve this problem and channel enlargement measures tend to transfer the problem to downstream reaches.

Developing countries suffer mainly due to the irregular and haphazard growth of cities. The priorities for economic development and investment in such cities are food, shelter, water, clothing, health and education for the rapidly growing population. The report by National Institute of Hydrology (2001) states that 'Very little attention has been paid to urban drainage because of financial limitations and because urban drainage problems constitute negative goods'.

The large scale urbanization has also resulted in increasing requirement for better and wider roads in Indian cities and towns. Most of the roads and roads constructed earlier are not provided with a proper stormwater drainage system. This has led to stagnation of water during monsoon, localized flooding, potholes and damaged roads. This coupled with increasing number of vehicles causes traffic congestions (or slow moving traffic). A lot of inconvenience and delay is now a commonly observed phenomenon particularly during monsoon season.

With increasing urbanization and degradation of receiving water quality, it has become essential to manage stormwater in a holistic, sustainable way. A variety of techniques for managing the stormwater sustainably have developed world over in the last 2-3 decades. Some of them include Low Impact Development (LID), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage system (SUDS), etc. All these techniques basically aim at source control of stormwater either by retention, detention or infiltration / groundwater recharge. The main hurdle in adopting these techniques in urbanized cities of developing countries like India is the extremely limited availability of open spaces. Apart from limited availability of space, the maintenance of these may create further problems in Indian conditions. Thus, detention or retention techniques have a limited scope, particularly in highly urbanized cities. Such problems in the adoption of sustainable stormwater systems in developing countries can be alleviated to some extent by providing techniques promoting artificial recharge of groundwater. This study aims to identify suitable sites for artificial recharge, where rainwater can be used for recharging the groundwater. In the urban environment, the selection of suitable stormwater recharge sites is of prime importance for the planners. In this regard, Geographic Information System (GIS) has been recommended as a decision making tool to facilitate the identification of potential stormwater harvesting sites during the decision making process (Mbilinyi *et al.,* 2005). GIS can serve as a screening tool for preliminary site selection as it offers a unique capability for spatial analysis of multi-source datasets with their integration (Malczewski, 2004). As it can integrate huge volumes of multi disciplinary data, both spatial and non-spatial, within the same geo referencing frame, GIS techniques are being popularly used by many researchers in water resources planning and development, delineation of land capability classes and many other areas (Chowdary *et al.,* 2009; Kinthada *et al.,* 2013).

There is extensive literature available on the use of GIS for the assessment of site suitability for stormwater harvesting in rural areas across the world. In India, potential sites for water harvesting structures have been identified within a GIS environment mostly for rural watersheds to arrive at a groundwater potential zone map (Kumar *et al.,* 2008; Singh *et al.,* 2009; Mishra *et al.,* 2010; Kaliraj *et al.,* 2013). GIS based decision support systems have been developed in South Africa for delineating suitable locations for water harvesting in numerous studies (De Winnaar *et al.,* 2007; Mbilinyi *et al.,* 2007; Kahinda *et al.,* 2008).

Analysis of potential groundwater recharge sites in dense urban areas has been rarely documented in literature. GIS was applied in identifying suitable stormwater harvesting locations in the Central Business District of Adelaide and to a portion of Melbourne City Council in Australia (Inamdar *et al.,* 2011; Shipton and Somenahalli, 2010). The focus was on developing a robust methodology for evaluating and ranking suitable stormwater harvesting sites using GIS. Recently a study regarding mapping of groundwater recharge potential zones of Allahabad city in India has been carried out (Singh *et al.,* 2014).

From the literature review conducted in this study, it was observed that GIS has rarely been applied to existing urban areas in identifying artificial recharge sites suitable for stormwater harvesting. The present study aims at developing a map for identifying potential stormwater recharge zones in a sub watershed of Pune city, India using GIS. This map would be further used to identify artificial recharge sites for various sustainable stormwater management techniques in the selected watershed, subsequently.

MATERIALS & METHODS

A case study of Pune city in India is selected for detailed analysis (Refer Fig. 1). It is the second largest city in the state of Maharashtra and the seventh largest

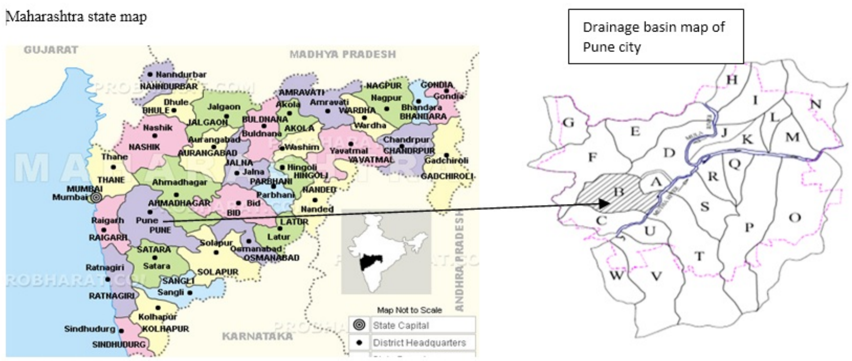

Fig. 1. Location Sketch

Fig. 2. Localized flooding

Fig. 3. Potholes and damaged roads

city in India. The current population of the city is 3.6 million and is projected to be 7.7 million in year 2041. There has been a two fold increase in built up area in less than a decade since 1999 (Desai *et al.*, 2009).

In Pune, stormwater is being managed in the traditional way by providing stormwater drains. There are 362 km length natural streams in the city which drain the runoff in Mutha river (Oak, 2010). Every year during monsoon, the roads in the city are getting damaged with increasing number of potholes and craters. The Pune Municipal Corporation has come up with an eightfold theory to explain this situation. Improper stormwater drainage is cited amongst the top 3 causes by the corporation in this regard (Pune Mirror, Aug. 6, 2013).

Increased urbanization in the city has resulted in a rising demand for water in the city. In Pune city, groundwater has emerged as an important source to meet the water requirements of various sectors. Pune's groundwater is disappearing fast due to increased use through wells and bore wells. According to Groundwater Survey and Development Authority (GSDA) report, groundwater levels in the city have dropped by more than 8.75 meters.

It is now well established that the conventional practice of urban stormwater management contributes to the degradation of receiving waterways, and it's value as potential alternative water source is being recently recognized. Consequently, this conventional practice is increasingly considered out of touch with the environmental values of society and impedes the broader pursuit of advancing more sustainable urban environments (Thomas *et al.*, 1997; Newman *et al.*, 1999; Wong *et al.*, 2000).

Pune needs a paradigm shift in the way stormwater is managed currently. One of the sustainable ways to manage stormwater in such condition would be stormwater recharge. This paper discusses the factors affecting stormwater recharge. A case study of a drainage basin in Pune city is selected for detailed analysis. The aim is to identify potential stormwater recharge zones in the selected watershed on GIS platform.

The selected Kothrud watershed (Basin 'B') in Pune city is bounded by 18º29'16.91" and 18º31'14.357"N latitudes and 73º46'51.91" and 73º50'6.84" E longitudes. The total area covered by the selected drainage basin is 11.71 sq km. A drainage map

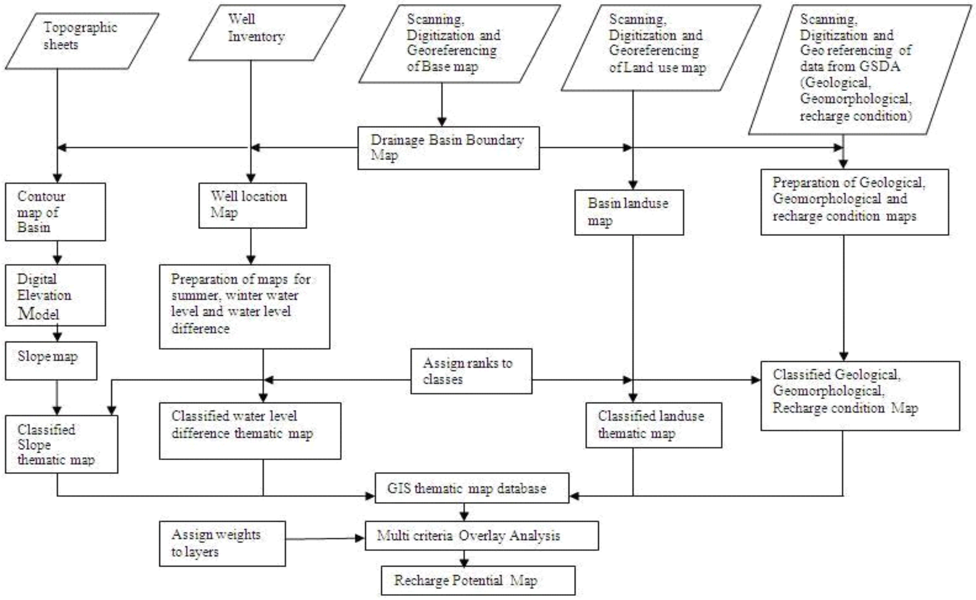

Fig. 4. Flow chart depicting methodology adopted

Table 1. Ranking for slope map

Sr. No.	Slope in Percentage	Ranking (In words)	Ranking (In numbers)
1	0 -3	Good	1
2	3 -5	Moderate	2
3	>5	Poor	3

of the study area prepared by Pune Municipal Corporation (PMC) was used as a base map for this study. This map was geo referenced using Survey of India toposheets (no. 47/F/14 and 47/F/15). The study area is one of the 23 sub watersheds of Pune city. This drainage map along with the contours was digitized and taken on GIS platform.

The selection of suitable site for artificial groundwater recharge depends on several parameters. The parameters that play an important role in site selection are geological data, geomorphological data, slope, land use/land cover, water table level fluctuation, etc. Hence, the required data for the selected catchment was collected from various sources, namely Groundwater Survey and Development Agency (GSDA) and Pune Municipal Corporation (PMC).

The methodology utilized for the present study is shown in Fig. 4. The non-spatial data like well inventory is converted into a thematic map of water level fluctuation using well locations, watershed area boundary map and GIS software. The spatial data like geomorphology, geology (Source: GSDA), land-use (Source PMC), Slope (Source: Survey of India Toposheets), etc has been digitized, geo referenced and converted into thematic maps. Each thematic map represents a parameter affecting the recharge potential

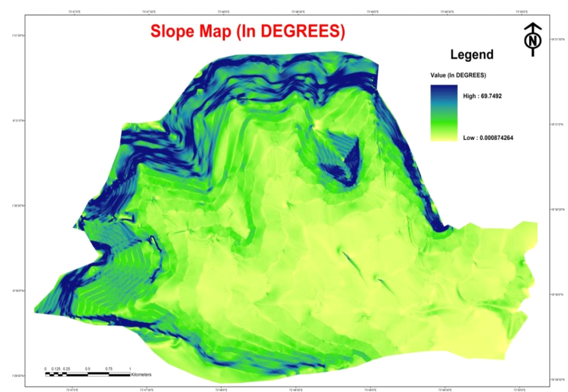

Fig. 5. Slope Map

of the selected area. These maps were classified by assigning a knowledge based ranking of one to three, one indicating highest influence and three the least. The sub classes indicate the relative influence of each on the stormwater recharge potential. Each thematic layer / map was then assigned a weight depending on its influence on stormwater recharge using expert's judgement and literature. All these classified and suitably weighted thematic maps were then integrated using GIS techniques. GIS techniques involve the integrated and conjunctive analysis of huge volumes of multi disciplinary data, both spatial and non spatial, within the same geo referencing scheme (Mishra *et al.*, 2010). Through integration of these data management technologies, potential stormwater harvesting zones can be derived. All the thematic maps were integrated in GIS environment and the polygons have been regrouped into different classes by calculating score of each, which depends on its rank

Table 2. Ranking for water level difference map

Sr. No.	Pre and post monsoon water level difference (in m)	Ranking (In words)	Ranking (In numbers)
1	4 -5	Good	1
2	2 -3	Moderate	2
3	0 -1	Poor	3

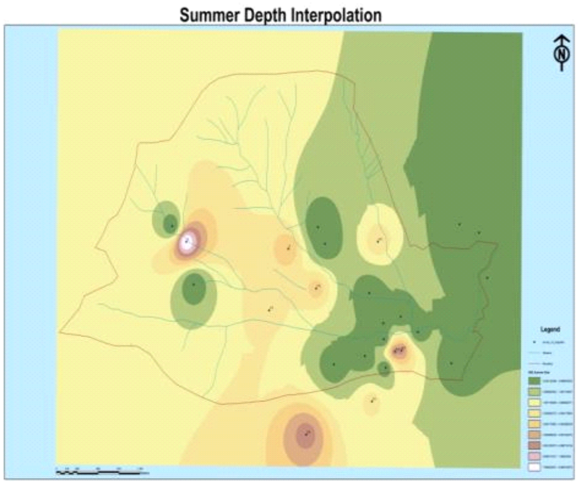

Fig. 6. Summer water level map

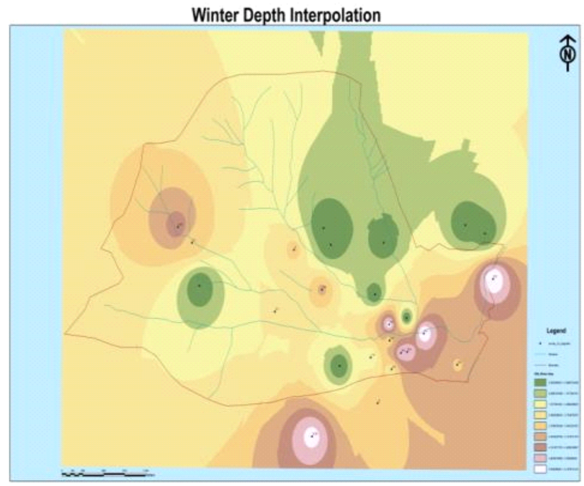

Fig. 7. Winter water level map

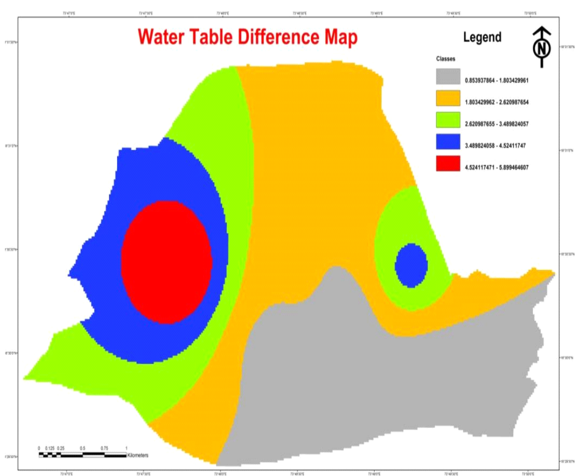

Fig. 8. Map showing pre and post monsoon water level difference

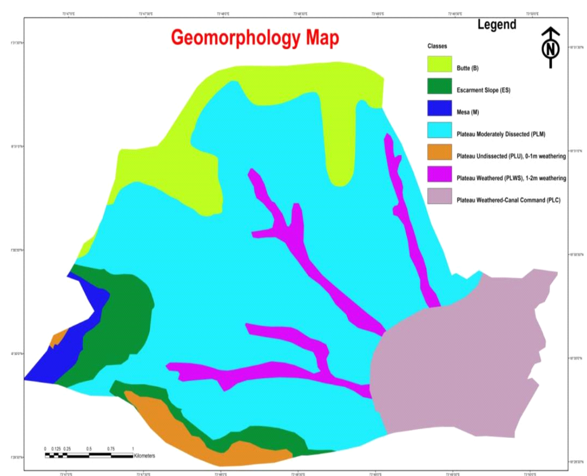

Fig. 9. Geomorphology Map

and layer weight. The average score for very good class is 18 - 22, for good 16 to 18, for moderate 12 to 16 and the other polygons having value between 8 -12 were assigned to poor category. The following methodology was adopted in the present study:

1. Bringing the spatial and non-spatial data on to a common GIS platform by digitizing and geo referencing with the help of Survey of India toposheets.

2. Preparation of various thematic maps for different parameters influencing the recharge potential.

3. Preparation of classified thematic maps by assigning knowledge based ranking of one to three to each class in the layers.

4. Assignment of appropriate weightages to all the layers based on the influence of each parameter on the recharge potential.

5. Carry out multi criteria overlay analysis by integrating all the thematic maps in GIS environment.

6. Generate potential stormwater recharge zone map for the selected drainage basin.

Table 3. Ranking for geomorphological units

Sr. No.	Geomorphologic unit	Ranking (In words)	Ranking (In numbers)
1	Weathered Plateau (1-2m)	Good	1
2	Canal Command	Good	2
3	Plateau Undissected and moderately weathered	Moderate	2
4	Mesa	Poor	3
5	Butte	Poor	3
6	Escarpment slope	Poor	3

Table 4. Ranking for recharge condition classes

Sr. No.	Description	Ranking (In words)	Ranking (In numbers)
1	Favourable zone for groundwater development	Good	1
2	Groundwater prospects good along lineaments but not suitable for large scale groundwater development	Good	1
3	Moderate yield expected	Moderate	2
4	Form runoff zone. Not suitable for groundwater development	Poor	3

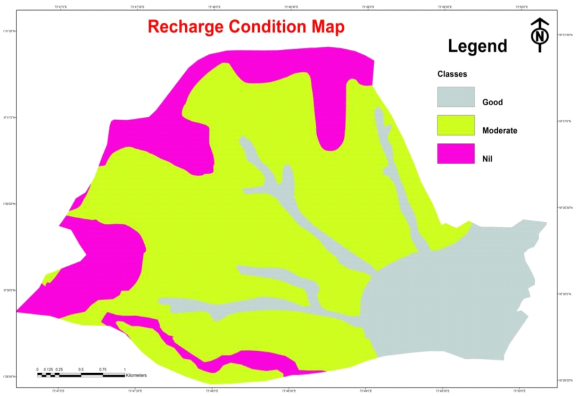

Fig. 10. Recharge condition Map

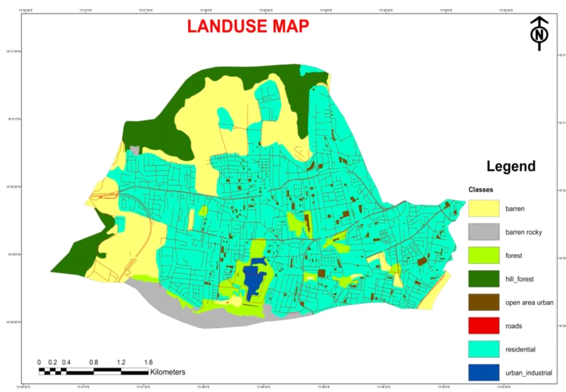

Fig. 11. Landuse Map

Slope in a given catchment has a direct effect on the runoff quantity or indirectly controls the infiltration. The Kothrud drainage basin map was scanned and first geo-referenced to the specific coordinates. The contour map was then clipped to the drainage basin (watershed) boundary map and a Digital Elevation Model (DEM) in the GIS environment was generated. The slope map was then generated from the DEM. Slope plays a key role in stormwater recharge as infiltration is inversely related to slope (Mondal *et al.*, 2009). The break in slope from steep slope to gentler slope increases the groundwater infiltration (Todd and Mays, 2005). The slope map was reclassified into three categories as good, moderate and poor by assigning ranks to percent slope values (Refer Table 1).

Well inventory of the given area was studied and the well location and pre and post monsoon water level data for those wells was extracted from it. The well locations were marked on the study area map. The summer water level ranged from 3 to 9m and winter water level was observed to be in the range of 1.4 to 7.3m. This data was used for generation of thematic maps for summer (pre-monsoon) water level, winter (post-monsoon) water level and fluctuation in the water level before and after monsoon season. The water level fluctuation data is an important factor in determining recharge potential of the area since it indicates the average water table level and recharge taking place in the selected drainage basin. The water level difference thematic map was generated using the pre and post monsoon water level maps and was classified into 3 classes as good, moderate and poor based on water level difference values (Refer Table 2).

Landforms have a different type of impact on the recharge and runoff patterns and hence should be considered independently. The runoff generation and infiltration is a dependent factor and is affected by the type of landform. Hence, geomorphology is considered

Table 5. Ranking for landuse classes

Sr. No.	Description	Ranking (In words)	Ranking (In numbers)
1	Open area	Good	1
2	Forest, Barren land, Urban residential	Moderate	2
3	Industrial, Barren rocky, Hill forest	Poor	3

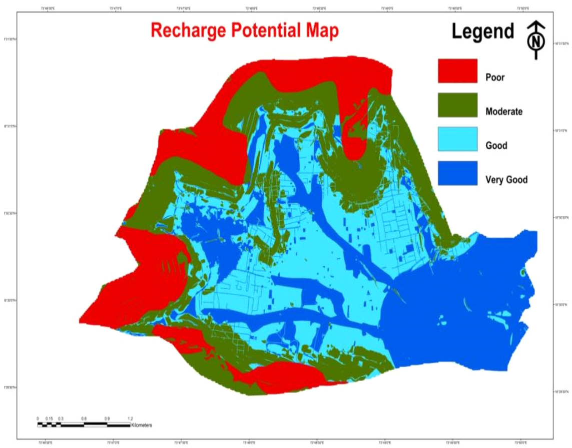

Fig. 12. Final Stormwater Recharge Zone Map

as a separate thematic layer. In a study by Sargaonkar *et al.*, (2011), Analytical Hierarchy Process (AHP) was applied for evaluating potential sites for groundwater recharge with respect to a number of criteria and the highest priority was obtained for the criteria, geomorphology.The geomorphology map of the Pune region was obtained from GSDA. This map was scanned, digitized, geo referenced using SOI toposheets and taken on GIS platform. By clipping study area boundary map, geomorphology map of the study area was generated. The study area consists of a range of landforms including butte, mesa, escarpment slope and plateau. The hilly areas express different forms. The hilly region in the study area includes a flat topped mesa, butte and hills showing rolling topography. Butte landform can be seen in the north western part of the study area. This shows poor potential for recharge. The rest of the study area is covered by plateau region with various levels of weathering. Weathered regions are considered to be good for recharge. By extraction of various classes of geomorphology, a thematic map for geomorphology was generated as per Fig. 9. The classified geomorphology thematic map / layer was obtained by assigning knowledge based ranks to the individual landform, according to its relative influence on recharge with highest value to the feature showing maximum potential for recharge as given in Table 3.

The actual recharge will also depend upon the level of weathering of the strata, available soil condition and the possibility of groundwater development. The thematic map on recharge condition indicates the recharge potential based on this aspect. The recharge condition map of Pune region was obtained from GSDA, scanned and digitized using SOI toposheets. This map was taken on GIS platform and watershed boundary map was clipped to it. This thematic map was also classified into 3 classes based on its influence on the recharge potential using the attribute data and judgement of experts from GSDA as given in Table 4.

The landuse in the selected area affects the opportunities available for recharge of stormwater. Thus the landuse map of the area was acquired from Pune Municipal Corporation (PMC), scanned, geo-referenced, digitized and clipped with study area boundary map to generate a landuse thematic map. The area was classified into various categories including residential, industrial, open, forest, barren, etc. Each category was then evaluated for its impact on the recharge potential (Refer Table 5) and the final landuse map having 3 classes (good, moderate and poor) was generated.

RESULTS & DISCUSSION

The stormwater recharge potential in a given area is affected by a number of parameters. Each parameter influences the recharge potential and the relative influence of each parameter is different. Hence, weights were assigned to each thematic layer indicating its relative importance in determining recharge potential. Since pre and post monsoon water level difference and slope are the most important parameters affecting the recharge potential, maximum weight was assigned to these two thematic layers. The rest of the thematic layers were assigned a lower weight. Each thematic layer is classified into 3 sub classes. Based on the assigned ranks for each class and the weights assigned to each layer, the total scores of the final integrated map were derived as sum or product of the weights assigned to the different layers and sub classes therein according to their suitability. All the thematic maps were converted into raster format and superimposed by weighted overlay method using spatial analyst extension of ArcGIS software. This involves a multicriteria analysis using ranks and weightages assigned to each thematic layer and their integration through GIS. The final recharge potential map was derived from this multi criteria overlay analysis incorporating all thematic layers along with their relative ranks and weights. This map is classified into 4 categories very good, good, moderate and poor based on the final scores.

Urban centers in India are facing an ironical situation with regard to water today. On one hand there is acute water scarcity and on the other, the streets are often flooded during the monsoons. Management of stormwater has become a difficult task in developing countries like India and many factors are responsible for this condition. The major factor giving rise to most of the problems is uncontrolled urban expansion resulting into inadequate infrastructure and other basic facilities. The massive urbanization in India has resulted in generation of huge quantities of stormwater which are unutilized and polluted. Although engineered infrastructure is a necessary component for drainage of urban runoff, nonstructural approaches are important complementary measures, focusing on actions to prevent and mitigate problems related to flooding, as well as those related to pollution and deterioration in environmental health conditions. In the past urban runoff was largely viewed as a nuisance, but within the new paradigm of sustainability, this water is recognized as a potential resource. According to Mr. S K Jain, former groundwater resources expert with the Ministry of Water Resources, India, road-side rainwater harvesting (RWH) has the potential to generate more than 500 billion cubic meters of additional groundwater in the country if adopted in all city roads, including national and state highways (Down to Earth, September 2010). As an alternative paradigm for more sustainable water availability, harvesting rainwater, storing it in tanks, and recharging groundwater may be put in place.

In Pune, stormwater is being managed in the traditional way by providing stormwater drains. It was observed that the existing capacity of these drains is inadequate at many places to accommodate the increasing volume of stormwater. The uncontrolled urban development has left very few open spaces to accommodate retention and detention devices. With depleting water resources, increasing water demand and flooding and water logging problems, unutilized stormwater needs to be harvested. This type of integrated study will help in designing a sustainable system for managing stormwater in urban centers.

Conventionally, decisions regarding the location and type of stormwater recharge technique could be made only after extensive ground study. This takes up a lot of time and investment. The current multi-parametric approach using GIS is holistic in nature. This will help the planners in identifying suitable site-specific stormwater recharge techniques on a regional as well as local scale, thus enabling quick decision-making for sustainable stormwater management.

CONCLUSIONS

Water management is very critical for the growth and development of any economy, more so in a developing country like India. However, this resource is now under stress, because of excessive groundwater abstraction for meeting increasing needs of growing population and very low recharge because of high percentage of impervious areas. Therefore, water resources need to be conserved, better managed and recharged to accommodate the growing needs of urbanization in a sustainable way.

The selection of suitable stormwater harvesting sites is an essential and challenging requirement. GIS and remote sensing techniques have been used to select artificial recharge sites in rural areas and derived results have been verified by ground truth field verification. Recently, this technique has been applied to urban areas and has been found to be successful there (Inamdar *et al.,* 2011).

This study demonstrates application of GIS technique in the identification of potential stormwater recharge zones in the selected Kothrud drainage basin in Pune, India. This study presents the application of this technique to urban areas for managing the stormwater sustainably. The potential stormwater recharge zone map presents the delineation of selected kothrud drainage basin into various classes. Each class indicates suitability of that zone for recharge of stormwater.

The present study focuses on an area which is from a rapidly urbanizing and growing city of India. Since most of the study area is residential, availability of rainwater from the roof-top is very high. This rainwater can be managed at source by using Low Impact Development (LID) techniques that promote recharge. This stormwater which otherwise is not managed properly creates lots of problems. In developing countries like India, conventional systems for managing stormwater are slowly being implemented. Managing stormwater sustainably is the need of the hour. This stormwater can be diverted and used for artificial recharge. Based on the potential stormwater recharge zone map generated in the present study, various techniques can be identified to harvest rooftop rainwater as well as stormwater generated from other impervious areas before it reaches the natural drains. This harvested stormwater can be either stored and utilized as an alternative source of water, or can be used to recharge groundwater. The problems in developing countries are very different from developed countries and solutions adopted there should not be blindly applied to developing countries. This type of study can be used as a decision support tool in managing stormwater sustainably in dense urban areas of developing countries.

The GIS screening tool methodology has provided a rational approach in identifying potential sites for stormwater harvesting in existing urban areas. This map along with the landuse map can be used to develop suitable techniques which promote recharge and their appropriate location for sustainable management of stormwater subsequently.

ACKNOWLEDGEMENTS

We thank Chetan Mahadik from GIS APP, Pune for his GIS related assistance.

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