विश्लेषणात्मक पदानुक्रम प्रक्रिया के द्वारा वर्षा जल संग्रहण संरचनाओं का लक्ष्यीकरण और प्रारूपण

Analytic Hierarchy Process for Targeting and Designing Rainwater Harvesting Structures

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DIVISION OF AGRICULTURAL ENGINEERING

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Analytic Hierarchy Process for Targeting and Designing Rainwater Harvesting Structures

A Thesis

By

Kishor Pandurang Gavhane

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This is to certify that the thesis entitled, "**Analytic Hierarchy Process for Targeting and Designing Rainwater Harvesting Structures**", submitted to the faculty of the Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** in **AGRICULTURAL ENGINEERING** is a record of *bonafide* research work carried out by **Mr. Kishor Pandurang Gavhane** under my guidance and supervision, and no part of this thesis has been submitted for any other degree or diploma.

It is further certified that all the assistance and help availed during the course of investigation as well as all sources of information have been duly acknowledged by him.

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"Acknowledge all of your small victories and people who play a part in it. They will add up to something great."

"The best and safest thing to keep a balance in your life is to acknowledge the great powers around us and in us". So, it is essential that I acknowledge the great powers, who paved the way on which I have walked so far. Any accomplishment requires the effect of many people along with the sincere guidance of experienced persons and blessings of **Almighty**.

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(Kishor)

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ALOS	Advanced Land Observing Satellite
AMC	Antecedent Moisture Condition
ASAR	Arid and Semi-Arid Region
ASTER	Advanced Spaceborne and Thermal Emission Reflection Radiometer
ArcGIS	Aeronautical Reconnaissance Coverage Geographical Information System
AVNIR-2	Advanced Visible and Near Infrared Radiometer type 2
AW3D	ALOS World 3D
CI	Consistency Index
CR	Consistency Ratio
CN	Curve Number
CGWB	Central Ground Water Board
DEM	Digital Elevation Model
ERDAS	Earth Resource Data Analysis System
ESA	European Space Agency
FCC	False Colour Composite
FAO	Food and Agricultural Organization
GDP	Gross Domestic Product
GPS	Global Positioning System
GIS	Geographic Information System
GDP	Gross Domestic Product
HSG	Hydrologic Soil Group
IARI	Indian Agricultural Research Institute
IMAGINE	Imagine making a generation in our natural excellent
JAXA	Japan Aerospace Exploration Agency
km	Kilometer

km^2	Square kilometer
LULC	Land use / land cover
Mm^3	Million cubic meters
NIR	Near Infrared
NRCS	Natural Resource Conservation Service
NRCS-CN	Natural Resource Conservation Service-Curve Number
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PRISM	Panchromatic Remote-sensing Instrument is suitable for Stereo Mapping
RCI	Random Consistency Index
RWHS	Rain Water Harvesting Structures
RS	Remote Sensing
SWAT	Soil and Water Assessment Tool
SWIR	Short-wave infrared
SCS	Soil Conservation Service
SRTM	Shuttle Radar Topography Mission
USA	United States of America
USDA	United States Department of Agriculture
WHS	Water Harvesting Structures
WLC	Weighted Linear Combination

Chapter 1

INTRODUCTION

Water is an essential commodity for sustaining all life forms. It is used in many different ways such as drinking, domestic, agriculture and food production, industrial, power generation and recreational use, etc. It has been reported that out of 2.5% global fresh water availability, only 1% is available for human consumption (Oki et al., 2006; Hoekstra, 2009). The world's need for water is growing twice as fast as the population (FAO, 2015). Water use has been increasing worldwide by about 1% per year since the 1980s, driven by a combination of population growth, socio-economic development and changing consumption patterns (United Nations, 2019).

The global water demand has increased manifolds in recent past due to the exponential rise in human population over the last few decades. According to the most recent report by the United Nations; the global water demand is expected to continue increasing at a rate of 1 % until 2050, accounting for an increase of 20 to 30% above the current level of water use, mainly due to rising demand in the industrial and domestic sectors. Further, the water stress levels will continue to increase far more than 2 billion people who live in countries experiencing high water stress, and about 4 billion people those experience severe water scarcity during at least one month of the year, as demand for water grows and the effects of climate change intensify (United Nations, 2019).

Population and economic growth due to Climate Change may lead to the severe water shortage across a big part of Asia (Chen et al., 2016). Several countries including India in the world (limited largely to Asia and Africa) will be the most adversely affected with a possibility of reduction in Gross Domestic Product (GDP) up to 6 % or more. On the contrary, India can actually add 1% to its GDP because of efficient water management (World Bank, 2016). India will be in water stress zone by the year 2025 and water scare zone by 2050 (Anonymous, 2002). As the population of our country is increasing rapidly, thereby the demand of water for domestic, agricultural and industrial use is also increasing. Over- utilization of ground water, declining water table levels and deterioration of water quality will make the problem more complex. Uncertainty of rainfall may lead to scarcity or varying availability of surface water resources. The impact of water scarcity is different for each economy, depending less on how climate change affects water, but more on how the country manages its water resources (World Bank, 2016).

Rainfall distribution in India is not uniform. The temporal and spatial variability of rainfall is very high because of monsoon climate and land-mountain topography. Most of the rainfall approximately 80 % of total annual rainfall is received within three monsoon months and rest 20 % in nine dry months. The unpredictable rainfall patterns may lead to serious soil moisture deficit problems in the agriculture field. These problems affect the crop production and increasing food risk (Wu et al., 2018). To get maximum production, it is necessary to ensure water supply throughout the year and this can be achieved by constructing water harvesting structures in order to harvest runoff generated by the rainfall. This captured runoff will be used in non-rainy season during critical growth stages and prolonged dry spells of crops as supplemental irrigation.

Arid and semi-arid regions in general and Rajasthan state of India in particular; are constantly affected by water scarcity for various purposes because of spatio- temporal rainfall distribution. Rajasthan receives low and variable rainfalls and thereby is prone to droughts. Under the Koppen climate classification, the greater part of Rajasthan falls under Hot Desert and remaining portions of the state falls under hot Semi-Arid. The climate in the state of Rajasthan is semi-arid to arid with scanty to moderate average annual rainfall distribution ranging from less than 100 mm in *Barmer* and *Jaisalmer* bordering Pakistan to more than 900 mm in *Banswara* and *Jhalawar*. In the south eastern part of Rajasthan, rainfall is as high as 1000 mm.

However, in the eastern Rajasthan where we intended to take up the present study, the average annual rainfall was 640 mm with average number of 35 rainy days. The temperature profile featured hot temperatures over the year with extreme temperatures in both summer and winter resulting into high atmospheric water demand. The *Gambhir* River watershed in *Bharatpur* and *Karauli* districts of Rajasthan (India) is located between 26° 36′ 0.8″ N to 26° 57′ 35″ North latitudes and 77° 0′ 2″ E to 77° 16′ 54″ E longitudes. Most of the surveyed Rainwater Harvesting Structures (RWHS) in the study area (Check Dams, Anicuts, *Khadins* and Ponds etc.) were found in dilapidated conditions; silted or dried up. The ground water recharge has reduced while pumping (draft) steadily increased resulting in to sharp depletion in the water table requiring creation of new RWHS vis-à-vis repair and maintenance of the existing ones. As some excess runoff is available in the selected watershed for harvesting and future utilization requiring appropriate planning and designing of the suitable RWHS using modern tools and techniques.

In order to mitigate the adverse effects of incessant droughts; Rain Water Harvesting (RWH) and its efficient utilization is a time-tested mechanism which should be practiced on large scale wherever the possibilities exist. To increase the availability of water for crop and livestock production, inhabitants of dry areas have constructed and developed several techniques for harvesting rainwater. Plant production can be increased significantly in drought prone areas by concentrating the rainfall/runoff in parts of the area using water harvesting structures (Prinz, 1996, Samra et al., 2002). A sustainable water resources management in the agriculture sector is vital for food crisis that acts as a catalyst for socio-economic development of the country (Ramakrishnan et al., 2008).

RWH is basically an age-old technology but gaining popularity on watershed basis in a new way because every watershed is unique in character as well as the availability of rainfall varies spatially and temporally (Rao et al., 2003). Hence, reduction of surface runoff and its storage can be achieved by constructing suitable RWHS or by making suitable changes in land management practices for in-situ soil moisture conservation (Mkiramwinyi et al., 2006). The main role of RWH is to increase the amount of available water by capturing rainwater in one area for local use or for transfer to another area. There are several benefits of RWH, such as to control excessive runoff, flood in the downstream catchment, and to improve soil moisture and for soil conservation (Ammar et al., 2016; Li et al., 2018). Water harvesting structures act not only like surface water reserves but also the ground water recharging systems which will be extremely useful for the conservation of precious natural resource like soil and water that are depleting day by day at alarming rate.

RWHS are one of the important components of watershed development which not only collects and stores water but can also be utilized to recharge the ground water (Ahmad and Verma, 2017). RWH has been practiced in many areas as a practical solution for reducing water shortage, and to maximize water quality. In addition, it is a measure to address climate change effects on precipitation variability (Barron, 2009; Ndiritu et al., 2011). The RWH technology, if designed, adopted and implemented efficiently, shall not only boost the production and productivity of rainfed agriculture but also provide much required groundwater recharge and resilience to climate changes (Mwenge et al., 2008).

Identification of potential sites for RWHS is an important step towards maximizing water availability and land productivity in the semi-arid areas. The identification of suitable sites and technical design are the two key factors behind the success story of RWH systems (Al-Adamat et al., 2010). However, selection of appropriate sites for different RWH technologies on a large scale presents a great challenge, since the necessary terrain, slope, soil, biophysical, socio-economic and hydro-meteorological data are often lacking (Mbilinyi et al., 2007) due to poor data monitoring infrastructure. Field surveys are the most common method for determining suitable site for RWH structures for small areas but selection of appropriate site in larger areas is a great challenge. Also, it requires lot of survey and point data of temporal and spatial variation which is time consuming and costly task. Pacheco and Campos (2016) reviewed different methodologies for establishing the economic feasibility of RWH systems and reported that many more variables need to be included in the final solution.

Many researchers have developed and applied various techniques and criteria to identify suitable site for RWH structures. The accurate determination of the location and types of rainwater harvesting interventions through a land suitability assessment is key to successful implementation. However, adequate information about land resources is needed. Unfortunately, the arid and semi-arid areas suffer from a scarcity of detailed soil information and preparation of this data is often costly and time consuming (Al-Shamiri, 2012). All methods and tools used in previous research studies related to site selection for RWHS have some limitations but Geographic Information Systems for collating the huge spatial information/Remote Sensing (GIS/RS) tools for collecting the synoptic views and data for large areas in one go; in association with Multi-criteria Decision Tools, Optimization Techniques and Analytical Hierarchical Procedures (AHP) are some of the t new and most modern decision tools for identification of their suitable types, appropriates sites, sizing and capacity etc. required for designing and construction. GISs and RS can meet the challenges of missing data required for the selection of potential sites for RWH, especially in arid and semi-arid regions (Adham et al., 2018). GIS is a tool that reduces time and cost of the site selection and provides a digital data bank for future monitoring program of the selected sites. Further, GIS plays a key role in maintaining data and analyzing optimal locations. These techniques enable us to perform watershed analysis in shorter time and in a cost-effective manner. The main research gap as identified in the field surveys was non-scientific siting and sizing of RWHS which needed attention and therefore, the present study was initiated with the major objectives:

1. To estimate surface runoff potential of a watershed using NRCS-CN method and Geospatial techniques.
2. To select most appropriate sites for different types of Rainwater Harvesting Structures (RWHS) using Analytic Hierarchy Process (AHP).
3. Design of different types of Rainwater Harvesting Structures (RWHS).

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Chapter 2

REVIEW OF LITERATURE

Methodology for designing Rain Water Harvesting Structures (RWHS) has transformed from the most primitive nature to highly advanced one; based on the advent of new tools and techniques of data collection (GPS assisted field surveys using Total Stations, Remote Sensing, Drones), Data analysis (GIS and Soft Computing Tools like Genetic Algorithm, Multi Criteria Decision Making Tools (MCDs)) including Analytical Hierarchical Programming, Artificial Neural Network and other Hybrid Models involving ANN and Wavelets/ Baysian Algorithms/ Ant Algorithm and others. These techniques being highly advanced and complex in nature are data intensive which is the major bottleneck in their application particularly in Indian watersheds which are not so well equipped as for as the data collection is concerned. This section contains the most recent and comprehensive reviews of the past works done by various researchers on the above lines in a sequential manner in order to clearly bring out the research gaps which have been attempted to be abridged through the present research work.

2.1 Estimation of Surface Runoff Potential using NRCS-CN Method

Runoff is an essential hydrologic variable which is required for the management of the water resources. It helps in planning of soil and water conservation measures to be taken in a watershed. The rainfall-runoff processes depend on various factors like storm characteristics, watershed characteristics, edaphic characteristics and initial losses due to Land Use and Land Cover (LULC) etc. which vary with space and time. There are various methods and models for estimating runoff from a given area, but their applicability depends on the data availability. The NRCS-CN method developed by the United States Department of Agriculture (USDA)-Soil Conservation Services (1972), is most widely used. It is a stable conceptual model relatively easy to use, requiring minimum data, gives adequate result and is widely adopted in USA and many other countries for computation of direct runoff (Subramanya, 2016). This method was developed in 1954 and documented in 1956 in Section 4 of the National Engineering Handbook (NEH-4) which is published by the Soil Conservation Services, United States Department of Agriculture. The method undergone changes in 1964, 1971, 1972, 1985 and 1993. The NRCS-CN was developed by several early investigators including Mockus (1949), Sherman (1949), Andrews (1954) and Ogrosky (1956). The main reason for its wide adoption lies in the fact that it considers most of the runoff producing watershed characteristics like soil type, antecedent moisture content, surface condition and land use/cover (Mishra et al*.,* 2003). Although, NRCS-CN method is originally designed for use in watersheds of size less than 15 km^2, it has been modified for application to larger watersheds by weighing curve numbers with respect to land use/cover of area under study (Ramakrishnan *et al.*, 2008).

Perrone and Madramootoo (1998), used Antecedent Precipitation Index for selecting appropriate curve numbers to predict surface runoff and peak flow at the outlet of the St. Esprit watershed located near Montreal, Canada. These curve numbers were used as an input to the AGNPS model. The study indicated that the AGNPS model performed best for the rainfall events between June, 1^{st} and November, 1^{st}. It was found that the simulations of surface runoff were enhanced considerably with the use of antecedent precipitation index as compared to the three antecedent moisture conditions in the SCS curve number method. Mishra et al. (1999), devised the modified Soil Conservation Service-Curve Number (SCS-CN) method. They compared the existing SCS-CN method propounded by Mockus (1964) method, the method of Fogel and Duckstein (1969) with its modified form. They proposed some modifications using data collected from five watersheds. The study revealed that the modified form of SCS-CN method was more accurate than the existing method.

Melesse et al. (2002), conducted a study to estimate storm runoff depth of the S65A sub-basin of the Kissimmee River Basin in south Florida using NRCS-CN method, RS and GIS. Using the NRCS 1972 National Engineering Handbook (NEH 4) guidelines, the curve numbers were calculated for each grid cell based on the information of soil and land cover. The spatially distributed runoff depth was calculated from 190.5 mm of rainfall. It showed that about 1 %, 0.7% and 2% of the sub-basin's land use has runoff depths greater than 180 mm for 1980, 1990 and 2000 land use; respectively. They concluded that the land use changes determined from Landsat images are useful in studying the runoff response of the basin.

Nayak and Jaiswal (2003), performed Rainfall-Runoff Modelling for Bebas River of Madhya Pradesh using Satellite data, RS and GIS. They used ILWIS 2.2 GIS for storing, processing and computing weighted average rainfall and runoff curve numbers of each sub-basin. It was found that the value of seasonal correlation coefficient is in between 0.92 to 0.94.

While Mishra et al. (2003), once again tried to modify the original Soil Conservation Service Curve Number (SCS-CN) technique by considering the antecedent moisture and the static portion of infiltration and altered the same to perform more efficiently. They proposed a basic spreadsheet methodology for determining maximum potential retention (S) by using preceding 5-days rainfall amount. The modified form of SCS-CN technique was found to perform well on the similar data sets as used in the National Engineering Handbook (SCS, 1971). Further, Mishra and Singh, (2004), developed a criterion to test the validity of the existing Soil Conservation Service Curve Number (SCS-CN) method. According to the developed criterion, when the potential maximum retention is less than or equal to twice the total rainfall amount, the existing SCS-CN method is observed to be valid. They evaluated this criterion using the data of two watersheds. This technique was expanded for predicting rainfall-excess rates and infiltration by separating the capillary infiltration from steady infiltration. The expanded SCS-CN method was tested using 55 sets of laboratory infiltration data on soils varying from Plainfield sand to yellow light clay. The study revealed that observed and computed infiltration and rainfall-excess rates were found to be in close agreement.

Later Mishra and Singh (2006), further studied a variation of curve number data as prescribed in the National Engineering Hand Book–Section 4 (NEH-4) of the Soil Conservation Service (SCS) with AMC condition and soil type. NEH-4 tables were condensed using volumetric concept which involves soil, water and air. The daily rainfall-runoff data from four Indian watersheds exhibited a power relation between the potential maximum retention or CN and the 5-day antecedent rainfall amount. Including this power function, the SCS-CN method was modified. This modification also eliminates the problem of sudden jumps from one AMC level to the other. It was found that the runoff values calculated using the modified method and the existing SCS-CN method utilizing the NEH-4 AMC criteria gave similar results.

Seungwoo and Taeil (2007), examined the utility of SCS curve number method for irrigated paddy field. The measured rainfall and runoff data of the level-terraced paddy fields was used to compute the CN values. The CN values were estimated from the maximum potential retention at probabilities of 10, 50, and 90 per cent, from a fitted lognormal distribution. The CN values for three AMC conditions, AMC I, AMC II and AMC III were found to be 67, 82, and 91, respectively. The depths of flooding and the heights of check gates were also examined to compute the hydrologic characteristics for paddy fields. From the field data the flooding depth was observed to be a major factor affecting retention storage. The study found that the flooding depth in paddy fields corresponding 10, 50 and 90 per cent probabilities were observed to be equivalent to AMC I, II, and III respectively.

Patil et al. (2008), developed a GIS interface using the Visual Basic for Applications programming language to compute the surface runoff by adopting NRCS-CN method and its three modified forms. It is found that, altogether, the modified CN I method gave best results in all three AMC situations, whereas the modified CN III method performed well for AMC I and AMC II conditions. The original NRCS-CN performed satisfactorily for all the AMC conditions with a marginal difference of R^2 (0.89 to 0.75) and E values (0.82 to 0.84). Altogether, it was observed that the ungauged watersheds like Banha watershed would give accurate estimation of surface runoff if modified CN I method is used. They also emphasized on the need to test the developed interface under different watershed conditions to check the foretell ability of modified CN methods for estimating surface runoff from ungauged watersheds.

Shadeed and Almasri (2010), developed a GIS-based SCS-CN approach to calculate the composite curve number of West Bank catchments of Palestine. Soil and land use maps were intersected using GIS techniques to generate new and smaller polygons associated with Hydrologic Soil Groups (HSGs) and LULCs. The curve number and runoff volume were computed from the built database using the field calculator**.** CN I for AMC I was used in assessing the predicted runoff volumes for the four events as the region falls in arid to semi-arid climate. The simulated runoff values for the four events were found to be slightly more than the observed ones. Runoff depth deviations values obtained with the present approach range between 7% and 20%. By considering all the rainfall events, the accuracy of the proposed approach in estimating direct surface runoff was found to be about 85%. They recommended that the initial abstraction formula used by the SCS-CN method should be investigated and its applicability in dry conditions should be verified.

Laura et al. (2011), used Soil Conservation Service Curve Number method (SCS-CN) for computing surface runoff from Rosia Poieni mining area of Romania. ArcGIS 9.2 software was used for storing and managing spatial information. ArcCN-Runoff tool, an extension of ArcGIS software, was used for computing the curve number map of the study area. Using soil and land use/land cover information, curve numbers and runoff maps were developed. In the same year Xiao et al. (2011), also examined the applicability of SCS-CN methodology in Liudaogou watershed having high spatial heterogeneity. They investigated that the most appropriate value of I_a/S for a given watershed was 0.22 which slightly improved the SCS-SN model performance. It was also observed that the runoff for the modified I_a/S values was increased gradually up to the rainfall amount of 50 mm. Above this limit the runoff volume was increased gradually.

Soulis and Valiantzas (2013), used rainfall-runoff information of heterogeneous watershed to compute SCS-CN parameters. The correlation was established between the calculated CN values and rainfall depth. This correlation was used to know the spatial variation of CN values in the watershed considering its specific characteristics. The proposed methodology could provide information on CN and its spatial variability. GIS was used to store and analyze spatial data and RS data. The developed methodology was capable to estimate the CN values for different soil and land use practices in heterogenous watersheds. The method was validated in small experimental watershed situated in Greece.

Patil and Mali (2013), assessed the potential of rooftop RWH in Pirwadi village located in Kolhapur district of Maharashtra using geospatial techniques. Rooftop area of various houses and buildings were calculated using ArcGIS and Google image of the study area. Runoff coefficient for different types of roofs were computed using Randey's coefficient of runoff index. Gould and Nissen formula (1999), were used to determine the potential of rooftop RWH for various types of roofs. It was found that the total potential of rooftop RWH in the study area was more than the total annual cooking and drinking requirements of the community in the given area and it is recommended to go for RWH to overcome the problems of water scarcity in villages. Bansode and Patil (2014), conducted a study to estimate the surface runoff using SCS-CN method and geospatial techniques. They stated that runoff computation is required to determine and forecast its effects on different parts of watershed. The correlation coefficient between rainfall and runoff on daily, monthly and yearly basis was found to be 0.73, 0.97 and 0.99 respectively for the rainfall data of 10 years. The study found that RS and GIS techniques can be useful to tackle the problem in conventional methods of runoff computation.

Muthu and Santhi (2015), used SCS-CN method integrated with GIS to depict the surface runoff depth from Thiruporur block of Kancheepuram district, Tamil Nadu. Rainfall data of seven rain-gauge stations was used for the period 2004-2014. The rainfall runoff maps of Thiruporur Block are created in ArcGIS 10.2 using Inverse Distance Weight interpolation and the seasonal runoff depth maps were generated. The runoff depth is more in the inner part of the Thiruporur block for all the seasons, where water harvesting structures could be installed. The calculated surface runoff is used to plan for proper water and land management practices in the study area.

Ningaraju et al. (2016), estimated runoff of an un-gauged Kharadya milli watershed in Mandya district of Karnataka over the area of 23.95 km^2 by using SCS-CN method and GIS tool. The average annual rainfall of the watershed was 749 mm from 2003 to 2013 while runoff varied between 35.47 mm to 240.16 mm. Integration of RS and GIS tool was very useful for obtaining land use details of the study area. Study area had gravelly clay soil and cultivable crop land with the proportion of 58.63 % and 39.49 %, respectively. The study revealed that estimation of runoff from the un-gauged watersheds for better watershed management and conservation purposes can be achieved by using SCS-CN method and GIS tool.

Satheeshkumar et al. (2017), worked out surface runoff potential of Pappiredipatti watershed, Tamil Nadu using SCS-CN method employed with RS and GIS. The curve numbers for AMC I, AMC II and AMC III were 85.92, 72.8 and 93.46 respectively. The average annual runoff and average Runoff volume for the duration of fifteen years were 181.7 mm and 32,682,501 Mm^3 respectively. It was observed that the rainfall-runoff relationship showed a good correlation coefficient of 0.84.

Rawat and Singh (2017), derived surface runoff from ungauged Jhagrabaria watershed of Allahabad district, Uttar Pradesh using SCS-CN method, Earth Observation data sets and GIS. This investigation revealed that the watershed produces an average annual runoff volume of 14 years as 3.58 × 106 m^3 from an average annual rainfall, 110.77 cm of 14 years. The average annual surface runoff and runoff coefficient of 14 years was 23.83 cm and 0.22; respectively. The correlation analysis suggests that the strong correlation as R^2 (0.91) was observed between satellite drive rainfall and runoff from SCS-CN method. The developed rainfall–runoff model for the study area will be helpful to understand the watershed and its runoff flow behaviour.

Raju et al. (2018), computed surface runoff from Mandavi river basin of Rayalaseema region in Andhra Pradesh using RS and GIS techniques. The weighted CN is resolute based on AMC-II with a combination of HSGs and land use/land cover categories. The weighted curve number (CN) was calculated for AMC II (Antecedent Moisture Condition) with the combination of hydrologic soil groups and land use and land cover classes. The curve numbers for the study area showed 52.292 (CNII) for normal condition, 31.506(CNI) for dry condition and 71.583 (CNIII) for wet condition. The annual rainfall-runoff relationship for the period 1995 to 2014 showed overall increase in runoff with the rainfall in the study area.

Pathak et al. (2018), employed NRCS-CN method coupled with RS and GIS to study the effect of urbanization on runoff potential of Haridwar city belonging to Uttarakhand state of India. They noticed that urbanization area is increased 13.4 % for 2001 to 2010 and 38.4 % for 2010 to 2015 for which the weighted CN comes out to be 68.5, 67.4 and 68.6 for 2001, 2010 and 2015; respectively. Further, they noticed that runoff primarily depends upon the rainfall which has affected due to climate change. They emphasized the need to monitor and design storage tanks or to implement low impact development techniques to store storm water and to downgrade the pressure from freshwater resources.

2.2 Selection of suitable site for RWHS using RS and GIS

Identification of suitable sites for (RWHS) is an important step for maximizing water availability and land productivity in the semi-arid areas. The most common method for determining potential site for RWHS for small area is field surveys but there is great challenge for selecting suitable site in larger areas. Also, it demands lot of survey and collection of point data of temporal and spatial variation. Such method consumes more time and it involves intensive labour which is costly task. Hence, many investigators have used remote sensing (RS) and geographical information systems (GIS) to locate suitable sites for different RWH systems (Ramakrishnan et al., 2008; Chowdary et al., 2009; Srivastava et al., 2007; Shanwad et al., 2011).

The RS and GISs are especially suited to meet the data requirements for selecting suitable locations for RWH in Arid and Semi-Arid regions as most of the areas are ungauged. RS and GIS increase the accuracy and precision of run-off prediction (Silveira et al., 2000; Terzoudi et al., 2007; Shi et al., 2009; Raghuwanshi, 2010; Suresh et al., 2013) which finally helps in identifying potential locations for RWHS in cost-effective manner for better management of water resources of the region. The review related to identification of potential site for RWHS is presented in the following section. Accordingly, Gupta et al. (1997), estimated the rainwater harvesting potential for a semi-arid area of Rajasthan state, India using geographic information system (GIS) and remote sensing. The SCS runoff curve number model was used to compute the annual runoff potential for each basin. The basin six was found suitable for locating maximum number of structures as it showed the maximum runoff potential and largest drainage network among all six basins. Due to change in the amount of the annual runoff volume and the drainage network, the number of proposed structures was reduced in case of other basins.

Oweis et al. (1998), developed a methodology for selecting suitable sites and methods of water harvesting in the dry areas of West Asia and North Africa using geographical information system and remotely sensed data. Landsat thematic mapper scene is processed in ERDAS Imagine software. The classified land use image was superimposed with slope image generated from digital elevation model. The results showed that about 12% of the total area to be unsuitable for any type of water harvesting. Out of the total suitable area, 24% area was favourable for macro-catchment and 4% area for micro-catchment water harvesting systems. Remaining area was favourable for both the methods. They suggested that implementation of further data levels will help to locate the water harvesting areas more precisely according to the suitability for each water harvesting method. The developed methodology was expected to be suitable for other arid regions of similar characteristics.

Murthy et al. (2003), conducted a study to demarcate groundwater potential zones in Vamsadhara river basin located in Srikakulam district of Andhra Pradesh. Different thematic maps including drainage, hydrogeomorphology, rainfall, land use, soils, and slope map were digitized and geo-rectified using ground control points. Weight factor was assigned to each thematic map and all the map layers were overlaid to generate a composite map. The groundwater potential zones were located by summing the weight factor for each layer. The study revealed that integrating various thematic maps will give more accurate results than considering only single characteristic to select groundwater potential zones. Winnar et al., (2007) represented a strategy to identify potential runoff harvesting sites at the Potshini catchment of South Africa using geographic information system (GIS). Various factors were combined to identify most suitable site for rainwater harvesting. Based on GIS analysis it was found that about 17% percent of area has a high surface runoff generating potential. The study revealed that supplementing information of runoff that is an essential for locating runoff-generating areas and identifying areas of catchment where surface runoff is generated is a vital step in promoting runoff harvesting technologies.

Kahinda et al. (2008), developed a Rainwater Harvesting Suitability Model (RSM) with the help of Model Builder, an extension of ArcView 3.3. The developed model can create physical, potential and suitability maps. They demonstrated a methodology to locate site for in-field and ex-field (RWH) structures in South Africa. By integrating physical, ecological and socio-economic factors in Model Builder that enables a weighted overlay of datasets, suitability maps for both in-field and ex-field type of RWH structures were developed. The RSM consist of physical, ecological and vulnerability sub-models from which the physical, the ecological and the vulnerability maps were derived respectively. The study revealed that 30% area for in-field RWH and 25% area for ex-field RWH were highly suitable.

Ramakrishnan et al. (2009), proposed a methodology for site selection of different RWH structures like check dam, percolation pond, farm pond, well and subsurface dyke in semi-arid Kali watershed of Gujarat based on spatially varying parameters like runoff potential, slope, fracture pattern and micro-watershed area using RS and GIS. Factors such as effective storage, foundation and abutment permeability are also considered as a site selection criterion in addition to IMSD and

FAO guidelines. The sites for water harvesting structures were located with the help of overlay and decision tree concepts in GIS. A field investigation was performed in small watershed area to confirm the suitability of selected sites. It was found that the proposed potential sites were fairly accurate (80–100%).

Elewa et al. (2012), demonstrated a procedure to find the surface water potential and determining the effective RWH areas in Sinai Peninsula of Egypt. The nine thematic maps comprising of volume of annual flood, lineaments frequency density, drainage frequency density, maximum flow distance, basin area, basin slope, basin length, average overland flow distance and soil infiltration were used as input layers in Weighted Spatial Probability Model (WSPM). The surface runoff potential was calculated from Finkel and the SCS-CN runoff models. The WSPM divided the whole area into four classes of potential RWH area including high potential RWH area (5.74-12.0 %) and low potential RWH area (23.64-29.85 %). Most of the area consist of moderate potential RWH area (64.35-64.40 %).

Kadam et al. (2012), conducted a study in order to locate potential site for RWH structures in upper Karha watershed in Pune district of Maharashtra. SCS-CN method integrated with GIS was used to compute the surface runoff potential of the watershed. Various thematic layers were integrated based on priority in GIS environment using intersection tool. Different RWH structures were selected using Integrated Mission for Sustainable Development (IMSD) guidelines. The results indicated that about 84 % of the total area was suitable for construction of different RWH structures.

Tumbo et al. (2013), developed a GIS based Decision Support System (DSS) for identifying potential sites for RWH techniques. The main focus of the study was to determine the suitability level of the factors that are most important for locating RWH sites. It was found that suitability levels of factors differ for different type of RWH techniques. The locations of existing RWH structures were compared with that obtained from an ArcView based DSS for evaluating the applicability of developed suitability levels. Ndiva was found suitable in clay soils with steep slope (18°-30°), stone terraces in sandy clay loam soils with moderately steep slopes (10°-18°), bench terraces in clay or silt clay soils with 5°-18° slopes and boda in slit clay or clay soils with 2°-5° slopes. The results indicated that 81.4 % RWH structures were located in very high and high suitability levels.

Prasad et al. (2014), conducted a study to locate suitable sites for RWH structures using GIS and Multi Criteria Evaluation (MSE) technique. The SCS-CN method is used to compute runoff depth of the watershed. Equal weightage was allocated to different thematic layers while integrating. The soil, slope, LULC and stream order maps were integrated using Weighted Overlay function in GIS platform. The resulted map showed suitable locations for constructing water harvesting structures like check dam, storage tank, stop dams and percolation tank. It was found that 12 sites for storage tanks, 16 for percolation tanks, 13 for stop dams and 15 for check dams were suitable for construction.

Mahmoud et al. (2015), identified potential areas for RWH in United Kingdom by developing site suitability maps using GIS assisted Decision Support System (DSS) and RS. The DSS combined various thematic maps including slope, rainfall surplus, soil texture, land use/land cover and curve number. IDRISI software was used to assign weights to each layer. The suitable areas of water harvesting were identified by integrating above thematic layers and weighted overlay process using model builder of ArcGIS 10.1. The model classified. The study divided entire area into five classes based on their suitability for RWH. It was found that 18.95 % area had excellent and 27.25 % area had good suitability for RWH out of total area. The study recommended to construct RWH structures in eastern and western parts of UK in future as these areas will be more prone to water scarcity in future.

Naseef and Thomas (2016), conducted a study to locate the potential sites for RWH structures using RS and GIS. Surface runoff was predicted using hydrologic modelling in SWAT. Land use map, Runoff potential map, Soil map, Permeability map, Stream order map and Slope maps were prepared and overlaid in GIS platform using 'Intersect' tool in ArcGIS to identify suitable sites for RWH structures. The selection of type of RWH structure suitable for given location was selected using Integrated Mission for Sustainable Development (IMSD) guidelines. The study revealed that 37% of the total area was suitable for check dams, 7.07% area for farm ponds, 4.27% area for percolation ponds and only 1.91% area was suitable for subsurface dykes. It was concluded that most of the area was suitable for constructing check dams whereas subsurface dykes were least suitable.

Rejani et al. (2017), used GIS to find the potential locations for constructing various types of RWH structures in three stages. Thematic maps of drainage lines, slope, soil characteristics, stream orders an LULC were integrated in GIS platform. Then various stages were applied to optimize the location of RWH structures. The first stages comprise of finding the potential location of different type of RWH structures based on soil texture, LULC, slope and rainfall characteristics. Optimal number of sites for RWH structures were computed in second stage based on slope, horizontal interval and vertical interval between the structures. The obtained locations were further improved by considering the extra runoff available after fulfilling the existing soil and water conservation and RWH structures. Suitable sites for 74 farm ponds, 25 rock fill dams and 5 check dams were located. The obtained sites were validated by using Google Earth and collected ground truth data. It was also suggested to increase the capacity of existing farm ponds so as to capture maximum runoff.

Ahmad and Verma (2017), conducted a study to locate suitable site for RWH structures using GIS, RS and Multi Criteria Decision Making technique. Various raster layers were created in GIS environment based on physical characteristics of watershed. Multi-criteria decision making technique was used to give percentage importance to different layers. It was found that runoff was most important parameter (55%) followed by slope (10%) and stream order (10%). Weighted overlay analysis showed that three sites were highly suitable, seven sites were moderately suitable and ten were least suitable for the given watershed.

Lohar et al. (2018), carried out site suitability investigation for locating different types of soil and water conservation structures in Chinnar watershed of Tamil Nadu. The study developed different thematic layers like drainage density, soil texture, slope, runoff, land use, lineament and geomorphology using GIS and RS data. Different thematic layers were integrated using weighted overlay analysis in ArcGIS 10.1. The lower weight was assigned to the factor that is not suitable and higher weight was assigned to the factor which is highly suitable for the given soil and water conservation structure. The summed score classified the total area into four suitability classes. Results of the study revealed that about 34 percent area was moderately suitable, and only 0.8 percent area was highly suitable for locating soil and water conservation structures.

Mugo and Odera (2018), presented an approach to select potential sites for RWH structures using geospatial techniques in Kiambu County, Kenya. The SCS-CN model was used for runoff estimation. Weights were assigned to different thematic layers such as rainfall, soil texture, drainage density, slope, land use/cover and lineaments density using weighted overlay analysis. The total area was classified into five classes namely most suitable, suitable, moderately suitable, less suitable and not suitable areas. The RWH structures like contour bunds, contour ridges, bench terraces, percolation tanks and check dams were allocated to sites nearby villages. It was found that 14 contour bunds, 8 contour ridges, 10 bench terraces, 9 percolation tanks and 14 check dams were suitable for the given area.

Haile and Suryabhagavan (2019), developed RWH site suitability model to locate potential zones of RWH in Arsi Zone of Central Ethiopia using AHP and Fuzzy modelling. The Fuzzy Extent Analysis was used to identify more influential criteria. Various thematic layers were integrated using Weighted Linear Combination of fuzzy suitability index values to generate five suitability classes. The results indicated that 57% of the total area was suitable for RWH and check dams were suitable for most parts of the area. The developed model can be used in other similar areas to ensure water availability. The study recommended that ground validation and socio-economic factors should be considered before implementation so as to increase the effectiveness of RWH.

2.3 Design of Rainwater Harvesting Structures

Srivastava et al. (2007), developed a WINDOWS based menu-driven software 'SODEPT' for design of Percolation tank. The input data was long term daily rainfall and evaporation data, seepage rate of the tank bed which is a function of textural characteristics and hydraulic conductivity, area of catchment, hydrological complex characteristics defined by curve numbers, area available for construction of the tank (length and width) for excavated type of the percolation tank or width of the gully and slope of the drainage way for impounded type of the tank, and cost of the earthwork for different depths and lead. The output was capacity of the tank for most economic recharge per unit investment, total recharge during the year, recharge during monsoon and recharge during post monsoon months and expected storage level at the end of the monsoon.

Ward et al. (2008), evaluated the design of two newly built RWH systems using continuous simulation modelling approach. It was found that tank designed using simple approach have substantially more capacity than that designed using simulation model. The study emphasized the importance of catchment size which was neglected in commonly used methods. It was also found by financial analysis that rooftop RWH systems in big commercial buildings were more economically viable than smaller buildings. The study recommended to go for simulation models rather than using simple single calculation methods for designing rooftop RWH systems. At the same time Matos et al. (2014), computed the size of storage tank based on amount of water available from a commercial building nearby using Ripple method. Thirteen scenarios of non-potable uses were considered using Ripple method to find the best solution. It was found that only 2,11 and 13 scenarios were optimistic to given condition compared to others. Scenario 2 (rainwater only for pavement washing and irrigation with a storage volume of 11 m^3) was selected as best solution to the building considering the location, construction and mainly the costs with storage tank having volume of 1163 m^3. The study showed that the use of stored rainwater in pavement washing and garden irrigation is the best configuration for RWH system for the given building.

Chiu *et al.* (2015), developed GIS-simulation-based design system (GSBDS) for systematic and cost-effective design of RWH structures on a city scale. The developed GSBDS can address both temporal and spatial variation of rainfall. A case study of eight communities in the Taipei metropolitan area of Taiwan were carried out. The rainfall data base, energy-saving investigation, water balance model, spatial technologies and economic feasibility analysis were integrated in GSDBS. The study showed that when both water and energy-savings are considered then the scheme will be feasible based on optimal design. The study revealed that RWH not only saves water but can be an alternate renewable energy source to rapid urbanization.

Yazdi *et al.* (2018), developed a simulation-based optimization model to determine size, shape and the number of check dams for flood mitigation. HEC-HMS model was used to simulate watershed rainfall-runoff process considering various check dam designs. The model was coupled with a multi-objective evolutionary algorithm, called non-dominated sorting differential evolution (NSDE), to find the trade-off solutions considering three objective functions: 1) minimizing the investment cost, 2) minimizing the flood peak discharge and 3) maximizing the time to peak discharge. The proposed model was applied to a mountainous watershed in Iran and (near) optimal strategies, including the suitable number of check dams in each sub-watershed, and optimal dam size (e.g. optimal height, bottom width and side angles) in each sub-watershed were obtained. The results showed that cost-effective designs can decrease peak discharge up to 53%, 54 and 54% corresponding to 2-yr, 5-yr and 10-yr flood return period scenarios, respectively. In addition, the check dams can also increase the time to peak for up to 88%, 81 and 77%, corresponding to 2-yr, 5-yr and 10-yr flood scenarios, respectively.

Vema *et al.* (2018), suggested a method for getting the optimal size of check dams by considering the objectives of increasing the amount of water in the watershed and ensuring certain amount of flow in the downstream areas. The study found that the amount of moisture in the watershed was increased due to the construction of check dams constructed using traditional method and simulation-optimization model approach. The check dam size obtained from simulation-optimization model resulted in increased flows in downstream reaches compared to the size of check dam obtained from the traditional method. Also, the sizes obtained from the developed framework showed that there are no significant dry spells during the growing period. The developed approach can be helpful in suggesting optimal size of the check dam for effective and sustainable watershed management.

2.4 Critique of the Review of Literature

Efforts were made to present only the most relevant reviews pertaining to the different objectives of the study. Efforts were also made to incorporate the works reported till most recent past i.e. up to 2018 and to discard very old and primitive works. However, the highly diverse nature of the factors affecting the rainfall and runoff phenomenon is one of the most discussed and researched topic revolving around which is a large chunk of research globally and nationally. It is unlikely that all such works could be referred to; but as far as possible the concerted efforts were made to go through majority of the studies as per the availability of records in most of the databases like CERA etc. In this pursuit it is likely that some important works might have been left out. This review is only limited in this aspect which is due to the access to the literature and availability of very many journals belonging to the field of agricultural engineering.

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Chapter 3

MATERIAL AND METHODS

Objectives of the present research work were finalized based on the research gaps identified in a rigorous exercise that followed a detailed review of the works done by the past workers in India and abroad. It was observed that a scientific methodology incorporating morphometric, hydrologic, edaphic, geo-political and socioeconomic criteria was the need of hour for siting and sizing of RWHS which were either already abandoned or neglected due to no water availability round the year resulting from faulty operation/design. Further, since water availability is a perennial problem in the *Gambhir* River watershed; which does receive a reasonably good amount of rainfall and could be harvested in the structures; that will not only help in quick recharging of the ground water but also help in arresting the resources degradation. As the deep submersible pump technology has proliferated in the entire country; backed with free energy in form of electric supply, with no or minimal restrictions on the ground water draft, all the traditional surface water bodies get dried up with the advent of summer season. Rainfall abrasions make the condition of the surface as well as ground waters even worse as the surface water bodies; so vital for recharging the ground water, are facing a serious neglect of upkeep and maintenance. The procedures and methodologies followed in this research have been described in detail in the following sections.

3.1 Study area

The *Gambhir* River watershed (study area) lies in *Karauli* and *Bharatpur* districts in the eastern Rajasthan in the foothills of one of the oldest mountain ranges of *Aravallis*. *Gambhir* River also known as *Utangan* River is the only River that passes through the study area. The salient features of the study area are being discussed in the following sections;

3.1.1 Location

The research area extends between 26° 36′ 0.8″ N to 26° 57′ 35″ North latitudes and 77° 0′ 2″ E to 77° 16′ 54″ E longitudes. The present watershed occupies an area of 602.24 km^2. The watershed drains into *Gambhir* River. This River originates in the hills near *Hindaun* city of *Karauli* district. It provides water to

Keoladeo National Park, *Ghana* Bird Sanctuary located in *Bharapur*, Rajasthan. It has three tributaries namely *Sea, Kher* and *Parbati*. The River after passing Rajasthan and Uttar Pradesh (U.P.) finally joins Yamuna River near *Rahauli* in U.P. The location of the *Gambhir* River watershed is shown in Fig. 3.1.

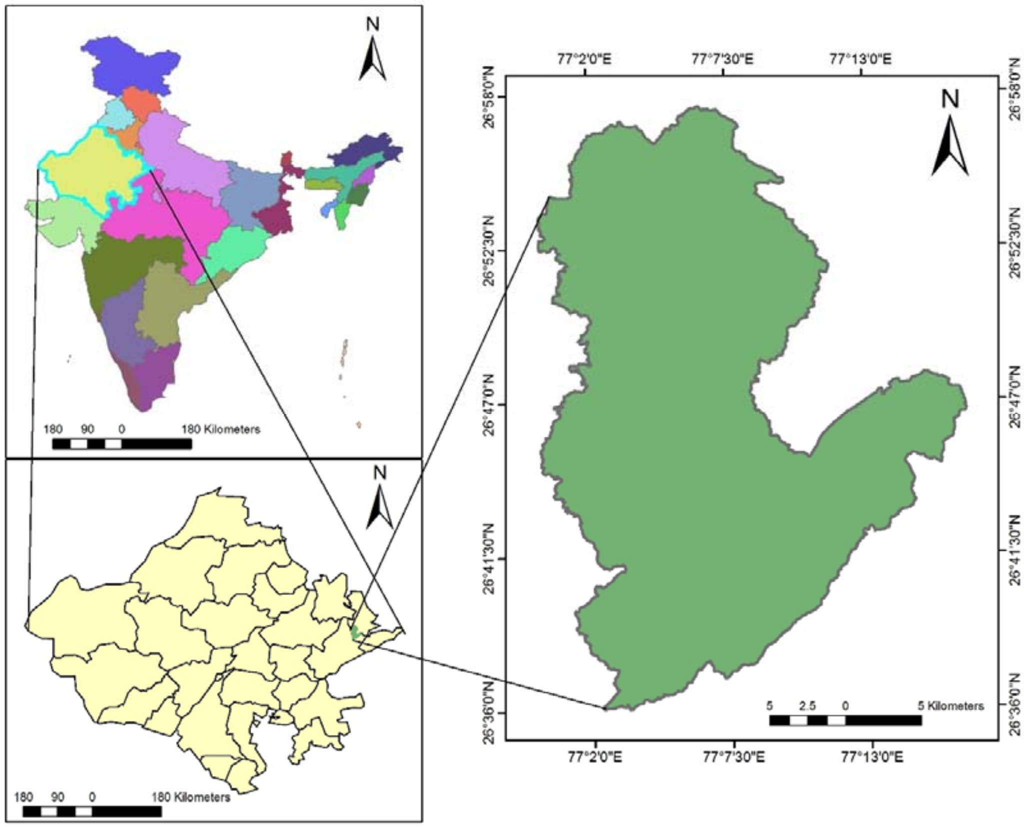

Fig. 3.1 Location of the *Gambhir* River watershed**.**

3.1.2 Rainfall and Climate

Rainfall in this area is inconsistent in nature which varies with space as well as time. The total annual potential evapotranspiration is 1502.6 mm. Nearly 85% of the total rainfall occurs in monsoon months from June to September. The *Gambhir* River watershed receives poor and irregular rainfall leading to severe water scarcity especially in post monsoon season. The *Gambhir* River watershed experiences very hot summers and very cold winters. Temperature in summer varies from 25°C to 45°C and in winter it is from 5°C to 23°C. The area experiences high potential evapotranspiration rates, especially during May and June. Thus, the climate of the *Gambhir* River watershed is semi-arid. The elevation of the watershed varies from

400 to 600 m above mean sea level (CGWB, 2017). The variation in the temperature is very substantial.

Due to water scarcity and edaphic conditions the main crop widely grown in the area is Mustard which requires less or little water. Occasionally, the saline patches of perched aquifers are also found in the *Gambhir* River watershed. Rabi and Kharif are the two main cropping seasons. The main crops are Mustard, Wheat and Bajra but some other crops like Chickpea, Pigeon pea, Mung bean and Sorghum are cultivated in some part of the watershed. Mixed cropping system is also very commonly being practiced in the watershed. Those farmers who have facility of water in their fields cultivate cash crops. However, the rainfed area is mainly single cropped. Most of the area relies on rainfall and ground water pumping from tube wells for irrigation.

3.1.3 Problem of water scarcity

Rajasthan is India's largest state with nearly 11 % of the country's land but access to only 2 % of the national water resources. More than half of the state is under severe water crisis and sustainable solution to this problem is the main challenge before scientists and planners (Anonymous, 2018). *Karauli* and *Bharatpur* districts of the state are facing serious problems of water scarcity especially in non-monsoon months. Most of the water bodies in the area like *Check dams, Anicuts, Ponds* etc. have been filled with silt. No one takes care of these water bodies. There is no provision of ground water recharge facility in the area. Increasing population is putting tremendous pressure on the vital water resource. As a result, tube wells are used in large numbers that are pumped indiscriminately without making ample provisions for ground water recharge. Due to this, water level goes down every year and whole area comes under dark zone. The depth to water table fluctuated from 5 to 34.06 m during pre-monsoon and 3 to 34.06 m during post-monsoon seasons in the year 2014. Detailed examination of long-term water level data for the last ten years (2005-2014) shows that the groundwater level of *Hindaun* tehsil, which lies in the *Gambhir* River watershed, is decreasing by 0.14 m per year which is highest among the five tehsils of *Karauli* district. (CGWB, 2017). Currently, the entire *Gambhir* River watershed faces the problem of drinking water from March to June every year. Hence, the water is provided for drinking purpose to villages and animals during these months through tankers.

3.1.4 Data collection

The data required for the present study were obtained from Water Resources Department, Rajasthan, Food and Agricultural Organization, satellite data from Advanced Land Observing Satellite (ALOS) of Japan Aerospace Exploration agency (JAXA) and Sentinel satellite data of European Space Agency. Brief details about data and its collection are summarized as follows:

3.1.5 Rainfall data

The daily rainfall data of 11 years (2007-2017) of four rain gauge stations located nearby the *Gambhir* River watershed were acquired from Water Resources Department, Jaipur, Rajasthan. This data was used for computing designed rainfall, designed runoff and to prepare rainfall and runoff maps of the *Gambhir* River watershed.

3.1.6 Soil data

Soil map of the world was downloaded from Harmonized World Soil Database v 1.2 of FAO website (http://www.fao.org) having scale of 1:5,000,000. The data was used to prepare soil map and Hydrologic Soil Cover Complex or Soil Group maps of the *Gambhir* River watershed.

3.1.7 Satellite data

The ALOS data comprising of Digital Elevation Model (DEM) of the *Gambhir* River watershed was downloaded from (https://www.eorc.jaxa.jp). This data was used to delineate the watershed and sub-watersheds, generate its drainage network and for preparing stream order map, drainage density map and slope map of the *Gambhir* River watershed. The Sentinal-2A satellite data was downloaded from (https://scihub.copernicus.eu). It was used for preparing Land use map of the *Gambhir* River watershed.

3.1.7.1 Advanced Land Observing Satellite (ALOS) data

The ALOS was launched on January 24, 2006 from the Tanegashima Space Centre by JAXA through a launch vehicle H-IIA. It is the largest satellite ever for Japan. An optical sensor on board of ALOS, Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM), was operated from 2006 to 2011. Using PRISM stereo image pairs with a resolution of 2.5 m to generate a global DEM between latitudes 80° N and 80° S (Takaku and Tadono, 2009), JAXA generated 1° × 1° tiles of 1 arc sec (~30 m) DEMs by resampling the 5 m ALOS DEMs, and released these products to the public in 2016 (Tadono et al., 2016). As a commercial product, AW3D (ALOS World 3D) offers up to 0.15 arc-second (5 m) resolution within 80° North and 80° South latitude range. For non-commercial purposes, the resolution level of 1 arc-sec (30 m) is publicly available as JAXA product AW3D30. This data set is distributed in terms of 1° x 1° geographic latitude and longitude tile. The revisit time of the satellite is 46 days and it completes one cycle in 2 days. The dataset has been compiled with images acquired by the Advanced Land Observing Satellite "DAICHI" (ALOS). The dataset is published based on the DSM dataset (5-meter mesh version) of the "World 3D Topographic Data", which is the most precise global-scale elevation data at this time, and its elevation precision is also at a world-leading level as a 30-meter mesh version. The satellite sensor had three remote-sensing instruments.

The Panchromatic Remote-sensing Instrument is suitable for Stereo Mapping (PRISM) and also for developing the Digital Elevation Models (DEMs). The Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) for precise land coverage observation, and the Phased Array type L-band Synthetic Aperture Radar (PALSAR) for day-and-night and all-weather land observations that enabled precise land coverage observation and can collect enough data by itself on scale of 1:25,000 without relying on points of reference on the ground. The PRISM has only one (Panchromatic) band with wavelength of 0.52 to 0.77 μm with spatial resolution of 2.5 m. The AVNIR-2 has four bands with spatial resolution of 10 m, as follows:

1. Band 1: 0.42 to 0.50 μm
2. Band 2: 0.52 to 0.60 μm
3. Band 3: 0.61 to 0.69 μm
4. Band 4: 0.76 to 0.89 μm

3.1.7.2 Sentinal-2A data

Sentinel-2A satellite was launched on June 23, 2015 from the spaceport in Kourou, French Guiana. It is the first optical Earth observation satellite in the European Copernicus programme and was developed and built under the industrial leadership of Airbus Defense and Space for the European Space Agency (ESA). It is a sun-synchronous satellite. To achieve frequent revisits and high mission availability, two identical Sentinel-2 satellites (Sentinel-2A and Sentinel-2B) in the same orbit, operate together, 180° apart for optimal coverage and data delivery. The revisit frequency of each single satellite is 10 days and when they are operated combinedly the revisit time is 5 days. The satellites are equipped with the Multispectral Imager instrument that offers high-resolution optical imagery. It has multi-spectral data with 13 bands in the visible, near infrared, and short-wave infrared part of the spectrum. It acquires imagery at high spatial resolution ranging from 10 m to 60 m. It has four bands at 10 meters, six bands at 20 meters and three bands at 60 meters spatial resolution. Sentinel-2A provides more details in NIR band range and SWIR band range, which is helpful for land cover classifications in precision agriculture and forest monitoring applications among many others. The characteristic features if this satellite is given in Table 3.1.

Table 3.1 Specification of bands of Sentinal-2A satellite.

Bands	Wavelength	Bandwidth	Resolution
Band 1 – Coastal aerosol	442.7	21	60
Band 2 – Blue	492.4	66	10
Band 3 – Green	559.8	36	10
Band 4 – Red	664.6	31	10
Band 5 – Vegetation red edge	704.1	15	20
Band 6 – Vegetation red edge	740.5	15	20
Band 7 – Vegetation red edge	782.8	20	20
Band 8 – NIR	832.8	106	10
Band 8A – Narrow NIR	864.7	21	20
Band 9 – Water vapour	945.1	20	60
Band 10 – SWIR – Cirrus	1373.5	31	60
Band 11 – SWIR	1613.7	91	20
Band 12 – SWIR	2202.4	175	20

Source: Copernicus Open Access Hub (https://scihub.copernicus.eu/).

3.1.8 Softwares

Mainly three software's Arc-GIS 10.3, ERDAS-IMAGINE 2015 and MS-Office were used for creation, pre-processing and analysis of the collected data. Arc-GIS 10.3 software was used for storing and editing spatial data as well as hydrologic, geographic, spatial and overlay analysis, mapping etc. ERDAS IMAGINE 2015 software was used for image processing and pre-processing of satellite data. For documentation and performing other operations including matrix calculation, MS-Office software was used.

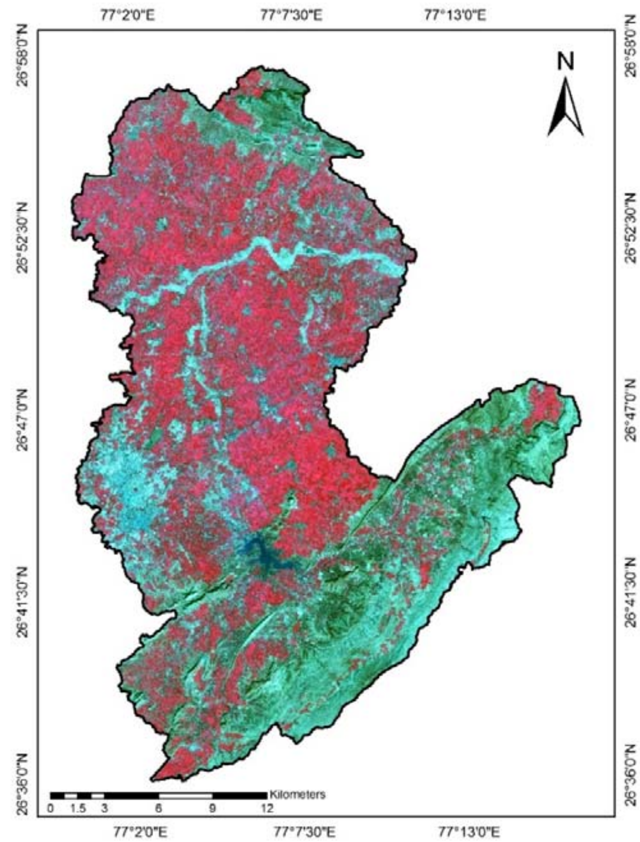

Fig 3.2 False Colour Composite (FCC) image of the *Gambhir* River watershed.

3.2 Methodology for preparing different thematic maps

Various techniques and methodologies were adopted for preparing different thematic maps for this study. The methodology adopted for achieving the objectives is described in detail in the following sub-section.

3.2.1 Delineation of watershed boundary

The watershed has been delineated using Arc-SWAT tool from DEM of the *Gambhir* River watershed. After setting up the project, following steps were followed for delineating watershed from DEM in Arc-GIS.

3.2.1.1 Digital Elevation Model (DEM)

A DEM is defined as any digital representation of the continuous variation of relief over space (Burrough, 1986), where relief refers to the height of the earth's surface with respect to datum considered. A 30 m resolution DEM of ALOS acquired from (https://www.eorc.jaxa.jp) is used in the present study. It generates more accurate River network even in areas of high topography and high relief and its effective resolution is also good and far better than the SRTM (Shuttle Radar Topography Mission) or ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEMs (Boulton, 2018). The elevation of *Gambhir* River watershed varies from 196 m to 394 m above means sea level. The DEM of *Gambhir* River watershed is shown in Fig. 3.3 below:

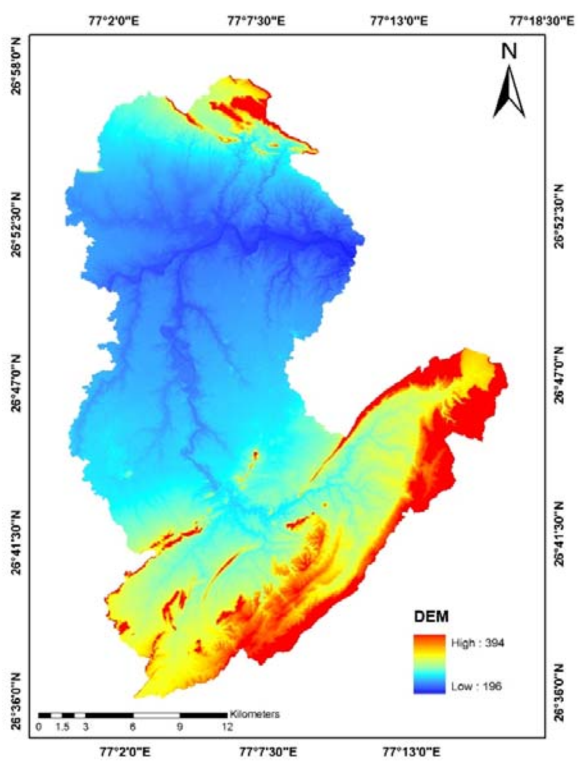

Fig. 3.3 Digital Elevation Model (DEM) of the *Gambhir* River watershed.

3.2.1.2 Sink fill

Almost every DEM has sink area that stands in the way of flow routing. These sinks can be caused by systematic data error like limitation of resolution as a source of systematic data error or natural landform like Karst topography. These sinks should be filled otherwise generated drainage network may be discontinuous. The fill tool does this by raising depression cells to the elevation of nearest neighbourhood cells connected to the depressed cell (Jenson and Domingue 1988).

3.2.1.3 Flow direction mapping

The direction of flow from every cell in the raster is determined by flow direction tool of ArcGIS 10.3. The most commonly used method is Deterministic 8 (D8) algorithm (Jenson and Domingue, 1988). The data used for a flow direction calculation is elevation value. Direction of flow is determined by direction of steepest slope from central cell to one of the eight neighbourhood cells. When a direction of steepest descent is found, the output cell is coded with the value representing that direction.

3.2.1.4 Flow accumulation

Flow accumulation is a process based on the data of flow direction that assign every cell with a value equals to number of cells flow into it (O'Callaghan and Mark, 1984). The Flow accumulation tool calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster. Cells with a high flow accumulation are areas of concentrated flow and may be used to identify stream channels.

3.2.1.5 Drainage network identification

The drainage channels are defined as cells with accumulated flow exceeding a user-defined threshold (O'Callaghan and Mark, 1984). Stream networks can be delineated from a digital elevation model (DEM) using the output from the Flow Accumulation Tool. Flow accumulation in its simplest form is the number of upslope cells that flow into each cell. By applying a threshold value to the results of the Flow Accumulation Tool, a stream network can be generated. After setting the threshold value of sub-basin, then the user can delineate the stream network and outlets through clicking the button.

3.2.1.6 Watershed delineation

A watershed is the upslope area from which runoff resulting from rainfall flow past a common outlet. Outlet location is selected from the generated drainage network which defines the boundary of watershed. This gives the required delineated watershed.

3.3 Estimation of surface runoff potential

The surface runoff potential of the *Gambhir* River watershed was estimated using NRCS-CN method as described below:

3.3.1 NRCS-CN method

The NRCS-CN method, formerly known as SCS-CN method was developed in 1954 and documented in 1956 in Section 4 of the National Engineering Handbook (NEH-4) which is published by the Soil Conservation Services, United States Department of Agriculture. The method estimates direct runoff based on different combinations of Hydrologic soil group, Antecedent Moisture Condition (AMC) and land use classes. It is also known as Hydrologic Soil Cover Complex method. For drainage basins where no runoff has been measured, the Curve Number method can be used to estimate the depth of direct runoff from the rainfall depth, given an index describing runoff response characteristics. The main reason for its success is that it accounts many of the factors affecting runoff generation including soil type, land use and treatments, surface condition, and antecedent moisture condition, incorporating them in a single CN parameter. This method is based on the water balance equation of the rainfall in a known interval of time, which is given as,

Mass inflow – Mass outflow = Change in mass storage …(3.1)

$$P - Q = I_a + F \quad \ldots(3.2)$$

$$P = I_a + F + Q \quad \ldots(3.3)$$

where,

P = Total precipitation,

I_a = Initial abstraction (surface storage, interception and infiltration),

S = potential maximum retention,

F = Cumulative infiltration; and

Q = Direct surface runoff.

This method is based on two fundamental hypotheses.

1. According to first hypothesis, the ratio of actual infiltration (F) to potential maximum retention (S) is equal to the ratio of actual runoff (Q) to maximum runoff (P- I_a) are equal.

$$\frac{Q}{P - \mathrm{Ia}} = \frac{F}{S} \quad \ldots(3.4)$$

2. The second hypothesis is that the amount of initial abstraction (I_a) is some fraction of the potential maximum retention (S)

$$I_a = \lambda S \quad \text{… (3.5)}$$

The initial abstraction accounts for the short-term losses, such as interception, surface storage and initial infiltration. Parameter λ is frequently viewed as a regional parameter dependent on geologic and climatic factors (Bosznay, 1989). The existing SCS-CN method assumes λ to be equal to 0.2 for practical applications. Many other studies carried out in the United States and other countries report λ to vary in the range of 0 - 0.3 Combining Eq. 3.2 and 3.3, and solving for Q, the popular form of SCS-CN method is obtained as:

$$Q = \frac{[P - Ia]^2}{(P - Ia + S)}, \text{ for } P > I_a \quad \text{… (3.6)}$$

$$Q = 0, \text{ for } P \leq Ia \quad \text{…(3.7)}$$

for λ = 0.2 S, above equation becomes,

$$Q = \frac{[P - 0.2S]^2}{P + 0.8S} \quad \text{…(3.8)}$$

Eq. 3.8 has been modified for Indian conditions (Subramanya, 2008), where λ=0.1 is applicable for black soils under AMC (antecedent moisture condition) types II and III. While the value of λ equal to 0.3 is valid for black soils under AMC-I condition and valid for all other soils under three AMC conditions. The retention capacity (S) of the watershed can be predicted in terms of a dimensionless parameter curve number:

$$S = \frac{25400}{CN} - 254 \quad \text{…(3.9)}$$

where, S is in mm.

3.3.2 Curve Number (CN)

Curve number is the dimensionless number and is very useful for rainfall-runoff modeling. CN has a range of $0 \leq CN \leq 100$. Impervious surfaces and water bodies have CN = 100 and for an infinitely abstracting catchment CN = 0. Although CN theoretically varies from 0 to 100, the practical design values of CN lie in the range of 40-90 (Mishra *et al*., 2003). CN depends upon Hydrologic Soil Group, Antecedent Moisture Content and Land use/land cover.

3.3.3 Soil type

In the determination of CN, the Hydrological Soil Cover Complex classification is adopted. Soil properties greatly influence the amount of runoff. For hydrologic analysis of watershed, the hydrologic properties of soil or a group of soils are essential factors (Suresh R. 1996). Hydrologic modeling is based on hydrological soil properties like soil type, soil depth, infiltration rate etc. There are four HSGs (A, B, C and D) which are given in Table provided by NRCS. Following is a brief description of four classes.

3.3.4 Antecedent moisture condition (AMC)

Antecedent Moisture Condition (AMC) is defined as the wetness index of soil. It refers to the moisture content present in the soil at the beginning of the rainfall runoff event under consideration. It is determined by total rainfall prior to the commencement of rainfall event (SCS, 1986). There are three antecedent soil-moisture conditions (I, II and III) according to different soil conditions and rainfall limits for dormant and growing seasons (Table 3.2).

Table 3.2 Hydrologic Soil Group classification.

S. No.	HSG	Description	Infiltration (mm/h)
1.	A	Soil having high infiltration rates, deep, well to excessively drained sand or gravels with low runoff potential when thoroughly wetted.	>7.62
2.	B	Soils having moderate infiltration rates, moderately deep to deep, moderately drained soil with fine to moderately coarse structure and moderate runoff potential when thoroughly wetted.	3.81-7.62
3.	C	Soils in this group have moderately high run-off potential when thoroughly wet. Water transmission through the soil is somewhat restricted. Group C soils have high runoff potential	1.27-3.81
4.	D	Soils having low infiltration rates, shallow over an impervious layer or clay pan, very slowly drained and high run-off.	0.0-1.27

Source: SCS, 1954, 2004; Subramanya, 2013

AMC I: Dry watershed with little or no preceding 5 days rainfall. indicates the lowest runoff potential because the soils are dry enough but not to the wilting point and satisfactory cultivation has taken place,

AMC II: Average soil moisture condition with appreciable rainfall in preceding 5-days. It represents average runoff producing potential under average moisture condition.

AMC-III: high soil moisture with considerable rainfall in preceding 5 days. It has the highest runoff generating potential due to low infiltration rate and wetness of the soil.

Table 3.3 Classification of Antecedent Moisture.

S. No.	**Previous 5 days rainfall in mm**		
	AMC class	**Dormant season**	**Growing season**
1	I	<12.7	<35.6
2	II	12.7 – 27.9	35.6 – 53.3
3	III	>27.9	>53.3

Source: SCS, 1954, 2004; Subramanya, 2013.

There are tables relating the value of CN to land use or cover, to treatment or practice, to hydrological condition, and to hydrological soil group. Together, these four categories are called the Hydrological Soil-Cover Complex. The relationship between the CN value and the various Hydrological Soil-Cover Complexes is usually given for average conditions, i.e. Antecedent Soil Moisture Condition Class II. The CN_{II} values for the hydrologic soil-cover complexes observed in *Gambhir* River watershed are presented in table 3.4.

Table 3.4 Curve number values for different land use classes.

S. No.	**Land use**	**AMC**	**Hydrologic soil group**	
			C	D
1	Water Body	II	100	100
2	Open Forest	II	60	64
3	Scrub land	II	64	67
4	Built-up	II	91	93
5	Agriculture	II	76	79

The weighted CN_{II} was calculated using following formula:

$$CN_{II} = \frac{\sum_{i=1}^{N} CNi \times Ai}{\sum_{i=1}^{N} \quad Ai} \qquad \ldots(3.10)$$

Where,

Ai = area for i[th] land use.

i = the number of different lands uses present in the watershed.

CNi = curve number for i[th] land use.

Following equations are used in the cases of AMC-I and AMC-III (Chow et al., 1998):

$$CN(I) = \frac{CN(II)}{2.281 - 0.0128\, CN\,(II)} \qquad \ldots(3.11)$$

$$CN(III) = \frac{CN(II)}{0.427 + 0.00573\, CN\,(II)} \qquad \ldots.(3.12)$$

3.3.5 Land use/Land cover

Land use/Land cover is one of the most important thematic inputs in any study as it provides the present status of land utilization and its pattern. Land use refers to man's activities and various uses which are carried out on land, whereas land cover refers to natural vegetation, water bodies, rock/soil, artificial cover and others resulting due to land transformations. Some of the LULC classes of the *Gambhir* River watershed shown in the following Plate 3.1.

3.4 Preparation of different thematic maps

Various thematic layers required for accomplishing first objective are described in the following sections.

3.4.1 Land use/Land cover map

Sentinal-2A satellite data of high resolution was used for the present study. LULC classification using Sentinal-2A data gives more accurate results than Landsat-8 data (Marangoz et al., 2017; Carrasco et al., 2019). Land use/Land cover map was prepared from satellite imagery captured on 10[th] January, 2019 by Sentinal-2A satellite having spatial resolution of 10 m. Two satellite images were downloaded from (https://scihub.copernicus.eu/). ERDAS IMAGINE 2015 software was used to for image processing which includes layer stacking, mosaicking sub setting the scene to *Gambhir* River watershed, creating signature files and supervised image classification.

a. Scrub land b. Open forest

c. Water body d. Crop land

Plate 3.1 Land use/Land cover classes in the *Gambhir* River watershed.

3.4.1.1 Layer stacking

The downloaded satellite imagery; the raw image is generally provided with a collection of individual separate bands in tiff format. Each band is in grey scale consisting of black and white colour. The colour image which is formed by combining Red, Green Blue bands is the output of the layer stacking procedure. The layer stacking of the raw image was performed by combining Red, Green Blue and Near-infrared bands of 10 m spatial resolution using layer stack tool in the raster module of ERDAS IMAGINE 2015.

3.4.1.2 Mosaicking

Mosaicking is a method of combining multiple images of the same scene into a larger uniform image so that the boundaries between the original images are not seen. As the *Gambhir* River watershed falls within two tiles, mosaicking was necessary to get one uniform image for the whole area. Mosaicking was performed in MosaicPro module of ERDAS IMAGINE 2015.

3.4.1.3 Sub-setting the image

To accomplish the subset image two things are necessary, namely the Area of Interest (AOI) boundary file and the main satellite image should be geo-referenced and both are required to be in the same co-ordinate system**.** It removes data outside the area of interest reducing the file size and improving the processing time for many operations. It was done by using subset and chip option in raster module.

3.4.1.4 Image enhancement

Image enhancement is the procedure of improving the quality and the information content of original data before processing (Haldar, 2013). The visual appearance of the satellite imagery was improved using spatial enhancement menu in ERDAS IMAGINE 2015.

3.4.1.5 Supervised classification

The image classification process involves translating the pixel values in a satellite image into meaningful categories. Unlike unsupervised classification, supervised classification requires that the user should have prior knowledge of *Gambhir* River watershed, which often enhances the accuracy of classification (Yiqiang *et al.,* 2010). In supervised classification, a signature file is required to be created by user which is subsequently used for final classification. Every object has its own spectral reflectance. Based on the spectral reflectance, samples of known land use type were specified by drawing polygons in sufficient numbers called training areas. These polygons were finally merged to represent particular land cover class. This procedure was followed for each class to create the signature file for the whole area. The computer algorithm classified the entire image using Maximum likelihood classifier.

3.4.2 Rainfall map

Daily rainfall data of 2007-2017 was used for preparing rainfall map. The mean annual rainfall of the *Gambhir* River watershed was computed using Theissen polygon method using the rainfall data of four nearby stations. The spatial variability rainfall maps of the *Gambhir* River watershed were prepared by using Inverse Distance Weighing (IDW) method in Arc-GIS. This method is based on the assumption that features which are nearer to one another are more alike than that those which are at greater distance. It makes use of the values measured at the neighboring locations to estimate the value of an unmeasured location. (Mair and Fares, 2010). The weights used for averaging are inversely proportional to distance between the measured and unmeasured values. The equation 3.13 was used:

$$Z(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \quad \ldots(3.13)$$

where,

$Z(S_0)$ = predicted values at S_0,

N = number of the sample points,

λi = weight assigned; and

$Z(Si)$ = the measured precipitation at Si.

The weight λi was computed as:

$$\lambda_i = \frac{d_{i0}^{-p}}{\sum_{i=1}^{N} d_{i0}^{-p}} \quad \ldots(3.14)$$

Table 3.5 Locations of rain gauge stations.

Stations	Latitude	Longitude	District
Hindon	26.9000	77.2833	Karauli
Mandrayal	26.7166	77.0166	Karauli
Bayana	26.2666	26.2666	Bharatpur
Bhusavar	27.1500	77.5333	Bharatpur

3.4.3 Soil map

The soil map of the world in digital format at a scale of 1:5,000,000 was downloaded from Harmonized World Soil Database v 1.2 of FAO (Food and Agriculture Organization) website (http://www.fao.org). The soil map of the *Gambhir* River watershed was prepared from this map using Arc-GIS. The soil map provides information on different soil properties like percentage of sand, silt and clay of different soil layers along with soil depth, soil texture, hydrologic soil group, etc.

3.4.4 Hydrologic soil group (HSG) map

Soil map of the *Gambhir* River watershed was reclassified into the two hydrologic soil groups on the basis of soil texture and infiltration characteristics. After that final HSG map of the *Gambhir* River watershed was prepared using Arc GIS software.

3.4.5 Hydrometer analysis

Soil samples have been collected during field survey and these were analysed for soil texture determination using hydrometer method. The results obtained are presented in (Appendix-I).

3.4.6 Generation of Curve Number (CN) map

Curve number map of the *Gambhir* River watershed was prepared by spatially joining the thematic layers of Hydrologic Soil Group and Land use/Land cover map in ArcGIS environment. The resulting map gives polygons of each land use/land cover class associated with specific soil type. Suitable curve number values based on each land use/land cover class were assigned to hydrologic soil groups using the standard table furnished by SCS, USDA. Field calculator tool was used to calculate area of each polygon and weighted curve number is then computed using equation 3.10. The obtained value is for AMC condition II**.** Daily rainfall data from 2007-2017 were analysed for specifying the AMC conditions based on cumulative rainfall of previous five days using excel sheet. After the determination of curve numbers for different AMC, potential maximum retention (S) for each AMC was estimated using equation. Given the spatial variability maps of CN and S, the surface runoff potential of different polygons and the entire area was determined using the equation (3.8) and raster calculator in ArcGIS environment. From the equations given above, CN values for AMC I and III were computed.

3.5 Selection of most appropriate sites for different types of RWHS using Analytic Hierarchy Process (AHP)

For selecting the most appropriate sites, six criteria were considered namely, Rainfall, Slope, Runoff, LULC, Soil and Drainage density based on data availability.

Plate 3.2 Field visit to *Gambhir* River watershed for data collection and surveys.

a. Hydrogen Peroxide treatment b. Preparation of Calgon solution

c. Mechanical stirrer d. Final solution before Hydrometer reading

Plate 3.3 Hydrometer analysis for soil texture determination.

Thematic maps of these criteria were prepared and a suitable weightage is given to each layer using AHP**.**

3.5.1 Preparation of Various thematic maps

The procedure for preparing various thematic layers required for accomplishing second objective are described in the following sections.

3.5.1.1 Watershed slope map

Slope is an important parameter for site selection of water harvesting structures. The runoff, recharge, and movement of surface water depend on the slope of the area. Slope map was generated from DEM. It was done by Surface option from Spatial Analyst Tools. The slope map of the *Gambhir* River watershed has been classified into five classes: (a) nearly level (0 to 3 %), (b) gentle (3 to 5 %), (c) moderately gentle (5 to 10 %), (d) steep (10 to 15 %), and (e) very steep (>15 %).

3.5.1.2 Stream order map

Stream order map can be prepared from DEM. The Strahler's stream ordering system was adopted for stream ordering (Singh, 1992). The Stream order map was also used for selecting sites for water conservation structures It is done by choosing "Hydrology" option from 'Spatial Analyst Tools'. To start with, the DEM should be geo-referenced and transferred to projected coordinate system. Then Flow direction map of the area is determined. Then Flow accumulation of the area is then prepared by eliminating the values which are below five hundred in flow accumulation map. This Flow accumulation and flow direction maps are used to generate stream network. After generating the stream network, identify the stream order of each sub basin.

3.5.1.3 Drainage density map

Drainage density is the ratio of total length of streams of all orders to the total area of drainage basin (Horton, 1932). The drainage network of the *Gambhir* River watershed is required to be prepared as stated earlier. After the drainage network has been generated, the drainage density map was prepared by using line density function of Spatial Analyst Tools in ArcGIS 10.3.

3.6 Multi-Criteria Decision Analysis (MCDA) using Analytic Hierarchy Process (AHP)

Human beings are required to make decisions at various levels. Decision making, for which we gather most of our information, has become a mathematical science today (Figuera et al., 2005). Psychological studies have found that human beings make biases while making decisions (Kahneman, 2011). In view of these biases and increasing complexity of present-day problems, there was a need to go for a methodology which is easy to comprehend and use, making effective and safe decisions. There are various methods of decision-making but most of them need human expertise in specific areas such as operations research, economics and probability. However, a methodology was required that could be used in a more natural way by decision-makers (Mu and Pereyra-Rojas, 2017). AHP satisfies all these requirements, it has been adopted and used by many organizations all over the world in solving many decision-making problems.

Analytic Hierarchy Process (AHP) was developed by Saaty, 1980 . The AHP is an effective method for solving complex decision-making problems and may assist the decision maker to fix priorities and make the best decision based on it. By reducing complex decisions to a series of pairwise comparisons, and then analysing the results, the AHP helps to both subjective and objective feature of a decision. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the bias in the decision-making process. Since the comparisons are made through subjective or personal perception, some amount of inconsistency may occur. To ensure that the perceptions are consistent, the consistency was verified by determining the consistency ratio, included to measure the degree of consistency among the pairwise comparisons of various criteria's which is considered as one of the most significant advantages of the AHP (Emrouznejad and Ho, 2017).

The AHP integrates and coverts input in the form of spatial data to output in the form of decision. The qualitative data of different themes and features is transformed into quantitative data by forming a pairwise comparison matrix using Saaty's scale (Saaty, 1980). The scale used to assign the judgement values weree given in the Table 3.5.

Table 3.6a Scale for pairwise comparison (Saaty, 2008).

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Equal to moderate importance	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate to strong importance	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong to very strong importance	
7	Very strong importance	An activity is favoured very strongly over another, its dominance demonstrated in practice
8	Very strong to extremely strong importance	
9.	Extremely strong importance	The evidence favouring one activity over another is of the highest possible order of affirmation

The basic procedure consists of setting up the goal, considering and analysing the factors or criteria's that affect the final decision and assigning judgement to different criteria's using Saaty's scale. To check the consistency of assigned weights, the Consistency Ratio (CR) as suggested by Saaty (1980) was computed using equation 3.15:

$$CR = \frac{CI}{RCI} \qquad \ldots(3.15)$$

Where,

CI = Consistency Index

RCI = Random Consistency Index

The Consistency Index (CI) is given by the equation 3.16:

$$CI = \frac{\lambda max - n}{n-1} \qquad \ldots(3.16)$$

Where, λ_{max} is principal eigenvalue and n is the number of criteria. Random Index is an estimation of the average value of Consistency Index obtained from a large enough randomly generated matrices of size *n* (Table 3.6).

Table 3.6b The values of RCI for different order of matrix.

No. of Criteria	1	2	3	4	5	6	7	8	9	10
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.46

The computed value of CR should be less than 10% to ensure consistency in decision making otherwise the assigned weights should be re-evaluated to maintain the consistency. If CR is less than 10%, the judgements are consistent which can be considered suitable for AHP analysis (Saaty, 1980).

3.6.1 Procedure of AHP analysis

The detailed procedure for computing the weights of criterion is presented below:

- Form A pairwise comparison matrix given as,

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

- The sum of the values of each column of pairwise comparison matrix is given as,

$$SC_{ij} = \sum_{i=1}^{n} C_{ij}$$

Form a normalised comparison matrix is calculated by dividing each entry in a column by its column total,

$$X_{ij} = \frac{C_{ij}}{\sum_{i=1}^{n} C_{ij}} = \begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix}$$

Where,

$$C_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

- Compute the sum of each row and divide it by number of criteria to give criteria weights

$$W_{ij} = \frac{\sum_{i=1}^{n} X_{ij}}{n} \begin{bmatrix} W_{11} \\ W_{12} \\ W_{13} \end{bmatrix}$$

- Multiply the criterion weights obtained with the original pairwise comparison matrix to get weighted sum value. Divide the weighted sum value with corresponding criterion weight to get the Consistency Vector as,

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} * \begin{bmatrix} W_{11} \\ W_{21} \\ W_{31} \end{bmatrix} = \begin{bmatrix} Cv_{11} \\ Cv_{21} \\ Cv_{31} \end{bmatrix}$$

This is obtained by,

$$Cv_{11} = \frac{1}{W_{11}} [C_{11}W_{11} + \quad C_{12}W_{21} \quad C_{13}W_{31}]$$
$$Cv_{21} = \frac{1}{W_{21}} [C_{21}W_{11} + \quad C_{22}W_{21} \quad C_{23}W_{31}]$$
$$Cv_{31} = \frac{1}{W_{31}} [C_{31}W_{11} + \quad C_{32}W_{21} \quad C_{33}W_{31}]$$

- Find the value of λ_{max} by averaging the values of Consistency Vector.

$$\lambda = \sum_{i=1}^{n} Cv_{ij}$$

- Find the Consistency Index using the equation 3.16.
- Select the value of Random consistency index from table 3.6 based on number of criteria.
- Finally compute the Consistency Ratio using equation 3.15
- If the Consistency Ratio < 0.10, then our judgements are consistent and there is no biasness in our decision making. If it is more than 0.10, then repeat the procedure again by altering comparison values in pairwise comparison matrix.

The aim of the present study was to identify the most suitable site for RWHS. Six different criteria's consisting of Runoff, Rainfall, Land use/land cover, Soil, Slope and Drainage density were considered for this analysis using AHP. Each of these criteria were having sub-criteria. e.g., land use consisted forest, cropland, scrubland, water bodies and built-up areas. Firstly, ranks were given to the sub-criteria's and then main criterion using Saaty's scale from 1 to 9 to form a pairwise comparison matrix and subsequently weights were finalized.

3.6.2 Identification of potential rainwater harvesting zones

All the thematic maps i.e., Land use/land cover map Runoff map, Slope map Rainfall map, Soil map, and Drainage density map were considered for preparation of RWH potential zone map. Relative weights were assigned to all these criteria including sub-criteria of each these based on expert opinion by constructing pairwise comparison matrix using AHP. Each thematic layer was reclassified based to the weights assigned to sub-criteria of each main criteria. These thematic layers were integrated in ArcGIS environment based on weights of each main criteria using Weighted Linear Combination (WLC) method which gives a Water Harvesting Potential Index (RWHPI). The weight of each criterion obtained by AHP analysis was multiplied by the reclassified map to yield Rainwater Harvesting Potential Zone map using following expression (equation 3.17):

RWHPI = (Rainfall map*Rlw) + (Runoff map*Rfw) + (LULC map* LULCw) + (Slope map*Sw) + (Soil Texture *STw) + (Drainage density map*Ddw)

…(3.17)

Where; w = the weight of each criterion.

Based on expert's opinion three types of RWHS i.e., Farm Pond, Percolation tank and Check dams were suggested for the *Gambhir* River watershed. Besides the overall suitability map for RWHS, site suitability analysis for three different types of RWHS were also carried out using Boolean logic approach in ArcGIS environment. Suitability criteria for these structures were adopted from literature (Ramakrishna *et al.,* 2009 Chowdary *et al.,* 2009; Agarwal *et al.*, 2013; Kadam *et al.,* 2012; Krois and Schulte 2014; Rais and Javed 2014; Jha *et al.,* 2014) and it is presented in the Table 3.7.

3.6.3 Farm ponds

Farm ponds are suitable in agricultural lands on the lower elevation with soils of preferably low permeability to reduce seepage losses and to store maximum amount runoff. In soils of low to high permeability, ponds should be lined with suitable lining material. Unlined farm ponds facilitate groundwater recharge. Farm ponds store the runoff during monsoon season which can be used for irrigating the crops or to supply drinking water to animals and human beings. Government of India provides assistance to the farmers community through different schemes as follows: National Horticulture Mission (NHM), National Mission for Sustainable Agriculture (NMSA) sub-schemes under Mission for Integrated Development of Horticulture (MIDH) provides an assistance of 20 Lakh rupees per unit of RCC lining / 500-micron plastic lining-based community farm pond of size (100 m x 100 m x 3 m) for command area of 10 ha. For an individual farmer, to construct a farm pond of size 20 m x 20 m x 3 m with RCC lining / 300-micron plastic lining, a subsidy of 50 % of total cost or Rs.75000 per beneficiary for plain areas having command area of 2-hectare. National Mission on Oilseeds and Oil Palm (NMOOP) scheme provides an assistance of Rs.40,000 for lining of new farm ponds to reduce percolation losses.

Table 3.7 Criteria used for identification of suitable zones/ site for RWHS.

Structure	Slope (%)	Stream order	Hydrologic soil group	LULC	Runoff potential	Perme-ability
Farm pond	0–5 %	1-2	B	Agriculture	Moderate/ High	Low
Percolation Tank	<10 %	1-4	A	Scrub land / Waste land	Moderate/ Low	Low
Check dam	<15 %	3-4	C	River stream near cultivated land	Moderate/ high	High

3.6.4 Percolation tank

Percolation tank helps in augmenting groundwater. These are generally constructed on streams and bigger gullies in order to impound a part of the run-off water. Percolation tank is an artificially created surface water body, submerging in its reservoir highly permeable land areas, so that the surface run-off is made to percolate and recharge the ground water storage. The percolation tank should have adequate catchment area. The hydrogeological condition of site for percolation tank is of utmost importance. The purpose of percolation tank is to conserve the surface run-off and diverts the maximum possible surface water to the ground water storage. Thus, the water accumulated in the tank after monsoon should percolate at the earliest, without much evaporation losses.

3.6.5 Check dams

Check dams are constructed across small streams having gentle slope and feasible in hard rock as well as alluvial formations. The site selected for check dam should have sufficient thickness of permeable bed or weathered formation to facilitate recharge of stored water within short span of time. Check dams are used as multipurpose structure with an aim to trap the silt, to store water as small tanks and also to utilize the water for agricultural purposes. In alluvial as well as hard rock areas, dug wells which have either gone dry or the water levels have declined considerably can be recharge through Recharge-cum-Discharge wells. In the area of moderate or gentle slopes, fast flowing water can be intercepted before it attains the erosive velocity by putting contour bunds across the slope following contour lines in the area.

3.7 Detailed analysis for selected micro-watershed

There were 59 micro-watersheds in the *Gambhir* River watershed. The point locations of different types of RWHS can be given based on the stream order criteria but the selected locations should be verified through ground truthing. Because of the time limitations, we have selected a micro-watershed number-36 (MW-36). The suitable locations of the farm pond, percolation pond and check dam suggested based on the suitability maps by precisely looking at the surface, simultaneously using DEM, flow direction and flow accumulation maps and ground truthing was also done.

3.8 Design of rainwater harvesting structures

The locations of the three different types of RWHS were randomly selected and the catchment area of these structures were computed using DEM. The catchment area of given location is worked out with from DEM the help of ArcGIS using spatial analyst tool. Steps followed to compute the catchment area of a particular RWHS are described below:

1. Add a DEM of the *Gambhir* River watershed and create a new shapefile. Add a point on the location of RWHS whose catchment area is to be determined.
2. Use fill function to fill all the sink areas in DEM.
3. Compute flow direction and flow accumulation data using Spatial analyst toolbox.
4. Use snap pour point tool and give the required input data as computed above to make sure that the selected point has highest accumulated flow.
5. Finally, use 'Watershed' tool to delineate the required catchment area of the structure.

The detailed hydrologic and hydraulic design of the selected structures were computed using standard design procedures.

3.8.1 Design of farm pond

Design of farm pond can be accomplished by two ways viz.;

1. Demand based
2. Water availability based

In demand-based method, it is required to have an information about the cropping pattern of the area, irrigation water requirement of different crops, total population and water requirement of human beings as well as animals. The design dimensions of the pond is then computed by using standard formulas to meet these requirements. For water supply purpose, the farm pond should meet the drinking water requirement of the whole village on yearly basis. Detailed surveys are required to collect such information. Due to time constraint, the first method is beyond the scope of this study. So, we have decided to go for design of farm pond based on the amount of runoff generated from the given catchment of the pond i.e., water availability-based design. In supply-based method, design dimensions of the farm pond depend on the amount of runoff that can be captured. Detailed steps for doing the same has been given in following sub-section.

3.8.1.1 Rainfall data analysis

Rainfall is one of the most important hydrological input parameters for the design of farm ponds. Its distribution varies temporally as well as spatially in semi-arid areas of the country. There are several methods for selecting a suitable probability distribution function. Weibull's probability distribution is commonly used for it is simple and easy to use in such field conditions. Using Weibull's method, a rainfall with 75% probability was selected as a design rainfall for the present study. The design of dugout farm pond comprises of determining the specifications for capacity of pond, shape of pond, depth, top & bottom widths, side slopes, inlet and outlet.

3.8.1.2 Catchment area

The catchment area of farm pond of given location is worked out with from DEM the help of ArcGIS using spatial analyst tool.

3.8.1.3 Designed capacity of the farm pond

The capacity of the dugout pond depends on the amount of inflow that can be expected in a given period purpose for which stored water is to be used. The storage losses such as evaporation and seepage and amount of silt also affect the storage capacity of pond.

3.8.1.4 Designed dimensions of the farm pond

The dimensions to be selected for a pond depend on the required storage capacity. Of the three dimensions of a pond, the most important is depth the selection of dimensions for excavated pond depends on the required capacity, soil type, purpose and type of machine available for pond construction. The size of a pond should be relative to the size of the catchment area contributing surface runoff to the site.

3.8.1.5 Designed depth and side slope of the farm pond

Depth of farm pond is the most important dimension among the other. As the *Gambhir* River watershed comes under semi-arid region, evaporation losses are more which can be reduced by increasing the depth to reduce the surface area for same volume of water stored in pond. However, as the depth increased seepage loss would also increase. Seepage loss can be controlled by compacting or providing lining with suitable material. The side slopes of the pond depend the types of soil at the excavation site. Generally, side slopes not steeper than the nature angle of repose of the excavated soil are selected. Depth of farm pond is taken as 4 meter and side slope as 1.5:1. After determining various dimensions, volume of excavation is computed by using Prismoidal formula as given below:

$$V = \frac{A+4B+C}{6} X\ D \qquad ...(3.18)$$

where,

V = volume of excavation (m^3),
A = area of excavation at the ground surface (m^3),
B = area of excavation at the mid- depth point (m^3),
C = area of the excavation at the bottom of pond (m^3); and
D = average depth of the pond (m).

3.8.1.6 Design of inlet channel

The inlet was designed as chute spillway for conducting the runoff into the pond in a controlled manner. The entry section was designed as a rectangular broad crested weir. The minimum size of inlet should be 1 m x 1 m in section and the length should be maintained as per the site condition. The silt trap of size 5 m x 5 m x 1 m is provided to check the incoming silt.

3.8.2 Design of the check dam

The catchment area of check dam of given location was worked out with the help of ArcGIS from DEM by using spatial analyst tool. The check dam was designed as a drop spillway**.** The standard design procedure was adopted based on established literature (Suresh, 1993; Sharda et al., 2016). Step by step procedure followed is given in the following section:

a) Computation of peak discharge

Peak rate of runoff is computed was computed by various methods. Most commonly used method is Rational formula. Due to non-availability of data Dickens formula is used to compute peak discharge. It is given by following formula;

$$Q = CA^{3/4} \qquad ...(3.19)$$

Where, Q is the peak rate of runoff (m^3/s), C is constant whose value for Northern India is 6 and A is the cathment area in km^2.

a) Select an arbitrary value of 'L', and substitute in following formula to compute the value of 'h'

$$\mathbf{Q = \frac{1.711 LH^{3/4}}{(1.1 + 0.01F)}} \qquad ...(3.20)$$

where, Q = peak discharge (m^3/s).
F = net drop from the top of the transverse sill to the crest (m).

Compute h/F ratio for each set of combination of L and h values. Select that combination in which $h/F \geq 0.5$ and $L/h \geq 2.0$ (Sharda *et al.*, 2016)

b) Minimum length of head wall extension (E) is given by following equation:

$$E = (3h + 0.6) \text{ or } 15F \qquad \ldots(3.21)$$

Greater value from these equations is adopted

c) Length of Apron (L_h) is computed by using the following equation:

$$L_h = F\left(2.28\frac{h}{F} + 0.52\right) \qquad \ldots(3.22)$$

d) Height of wing wall and side wall at junction (J) is determined by using the following equations:

$$J = 2h \text{ or } \left[F + h + s - \frac{(L_h + 0.10)}{2}\right] \qquad \ldots(3.23)$$

The higher value is taken as the height of wing wall and side wall at the junction.

e) Height of transverse sill. It is given by

$$h_i = \frac{h}{3} \qquad \ldots(3.24)$$

g) Height of longitudinal sill

$$S = \frac{h}{4}$$

h) The parameter M and K are calculated by the following equations;

$$M = 2(F + 1.33\,h - J) \qquad \ldots(3.25)$$

$$K = (L_h + 0.1) - M \qquad \ldots(3.26)$$

3.8.3 Design of dugout ponds for ground water recharge

The design dugout pond is carried out using the same methodology adopted for design of farm pond (dugout type). The only difference between them is that this pond is solely used for recharging and augmenting groundwater whereas the farm pond is provided with lining to control seepage losses and the stored water in it is re-utilized for various purposes.

The materials and methods as described above were utilised for fulfilling the objectives of this study as proposed in Chapter 1. Many assumptions and criteria were adopted from the standard protocols and a few were suitably modified for the edaphic, climatic and socio-economic conditions of the *Gambhir* River watershed. Results obtained from the above analysis are presented and discussed objective wise in details in the Chapter 4 (Results and Discussions).

***

RESULTS

Location and capacity of the RWHS are the two most vital aspects of designing procedure for successful harnessing of water (surface as well as subsurface flows) for future utilization. The appropriate hydrologic, hydraulic and structural design (i.e. type, numbers, size, dimensions of the structure and the strength of materials) aspects are other main considerations for appropriateness of the design of RWHS. As propounded in the Chapter 1, a novel methodology was developed, an innovative technique for deciding the location, size and type of structures based on available databases using AHP, RS and GIS supported with Boolean logic. The present study was based on the application of Multi-Criteria Decision Making and Geo-spatial Technologies for identification of potential sites for RWHS in the *Gambhir* River watershed spread in two districts namely; *Bharatpur* and *Karauli*, in semi-arid, *Rajasthan* state of India. This chapter deals with the quantified results obtained following different analysis of various input data; thematic layers prepared from RS data, RWH potential zoning and site selection for RWHS following a comprehensive site selection criterion. Further, discussions leading towards drawing meaningful conclusions are also done simultaneously at appropriate places in this chapter.

4.1 Estimation of surface runoff potential using NRCS-CN method

The runoff potential of the *Gambhir* River watershed was computed using NRCS-CN method based on 11 years rainfall data (2007-2017) of four nearby stations and RS data in ArcGIS environment. For this purpose, two thematic layers i.e., Land use/Land cover map and Hydrologic Soil Group map were combined spatially in ArcGIS environment to develop the Hydrologic Soil Cover Complex map. Suitable CN values were assigned to pixels based on the generated Hydrologic Soil Cover Complex map. Curve number map corresponding to Antecedent Moisture Content (AMC) II condition was prepared using the generated Hydrologic Soil Cover Complex map. From the spatially varied rainfall map and CN map using the NRCS-CN runoff formula as given in the equation 3.8 and 3.9 spatially varied runoff map of the *Gambhir* River watershed was prepared.

4.1.1 Land use/Land cover map

The land use of the *Gambhir* River watershed was classified into five different classes namely (i) Agriculture (ii) Scrub land (iii) Open forest (iv) Built-up area; and (v) Water body. The spatial map of the *Gambhir* River watershed depicting different LULC classes in the *Gambhir* River watershed is given in Fig. 4.1. The areal extent of different LULC is shown in the Fig. 4.2.

Agricultural lands occupied majority of the area in the watershed (58%). It covers around 350.41 km^2 area. Water bodies occupied an area of about 4.73 km^2 (1 %). Scrub land occupies an area of 167.25 km^2 (28%). With majority of area under scrub land lying in the southern part of the watershed. Forests dominated the northern and southern part the *Gambhir* River watershed having total coverage of 45.23 km^2. Built-up areas were estimated about 34.64 km^2.

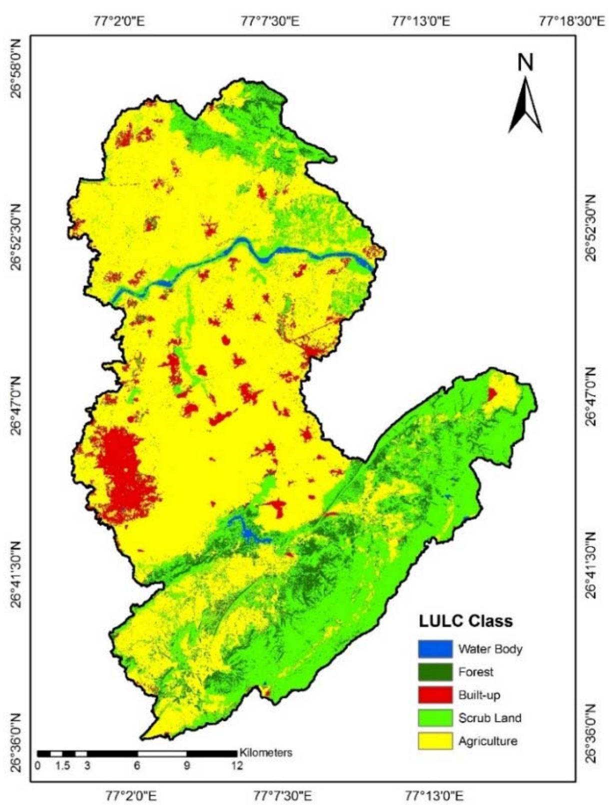

Fig. 4.1 Spatial map of the *Gambhir* River watershed depicting different LULC classes.

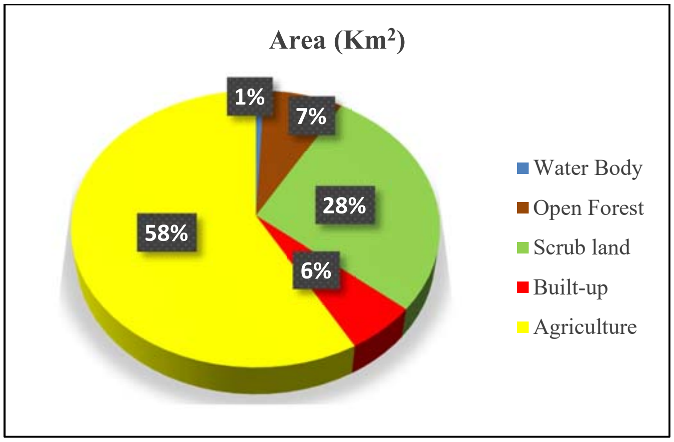

Fig. 4.2 Areal expanse of different LULC classes in the watershed.

The forest area in the watershed was not very dense and the vegetation in scrub land was also scanty due to poor survival rate without ample water. This fact is evident as the area under water bodies is only 1 % of the total geographical area. Majority of the water bodies remain dry for substantial period of the year during post monsoon season. Also, as the LULC map is based on the satellite imagery acquired on 10th January which corresponds to cloud free rainless period the area under water bodies was not pronounced.

4.1.2 Soil map

Loam and clay loam types of soil are found to be the major soil textural classes in the *Gambhir* River watershed (Fig. 4.3). Loamy soil is the dominating soil class covering 79.34 % portion with an area of 477.86 km^2 of the total area in northern and central portions of the *Gambhir* River watershed. Clay loam soil is found in southern part of the *Gambhir* River watershed occupying area of 124.40 km^2 (20.66 %) (Table 4.1). The laboratory analysis of collected soil samples from the different locations in the watershed confirmed the soil types as given by the FAO harmonized world soil database with minor abrasions.

4.1.3 Hydrologic Soil Group (HSG) map

Two hydrologic soil groups 'C' and 'D' occur in the *Gambhir* River watershed as depicted in Fig. 4.3. This map has been derived from the soil map of the *Gambhir* River watershed. Most of the *Gambhir* River watershed is having HSG 'C' whereas only small portion consist HSG 'D' located on South-eastern part of the area. The runoff producing characteristics of hydrologic soil group D is higher as compared to the runoff producing characteristics of soils of hydrologic soil group C. Thus, based on the hydrologic soil group map the watershed has moderate capabilities for producing runoff that can be harvested in the RWHS if their location and size could be optimized well.

Table 4.1 Properties of soil classes in the *Gambhir* River watershed.

Soil property	Loam	Clay loam
Sand	41	38
Silt	37	29
Clay	22	33
Bulk density	1.5	1.1
Hydrologic soil group	C	D
Area (km^2)	477.87	124.39
% Area	79.35	20.65

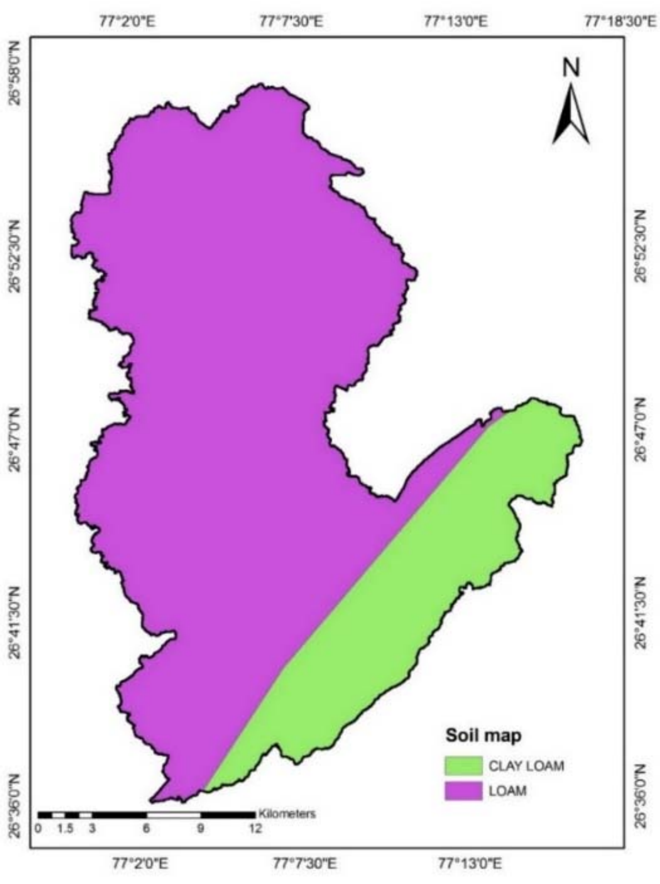

Fig. 4.3 Soil map of the *Gambhir* River watershed.

4.1.4 Curve Number (CN) map

The computation of weighted curve number in general is a tedious task. Often the data of area under each land use class may not be accurate. This can be done more easily and accurately using RS and GIS techniques. The curve number map for the *Gambhir* River watershed was prepared by using curve number values for AMC II condition as shown in Fig. 4.4. A sizeable area belonging to agriculture has the CN of 79 mainly due to being void of any vegetation. However, the rocky and barren terrains without forest cover has shown a high CN between 90-100. The weighted curve number for the *Gambhir* River watershed computed using field calculator tool in ArcGIS was found to be 80.25. Accordingly, CN value for AMC I and AMC III condition computed using equations (3.7) and (3.8) was found to be 64 and 90.49; respectively.

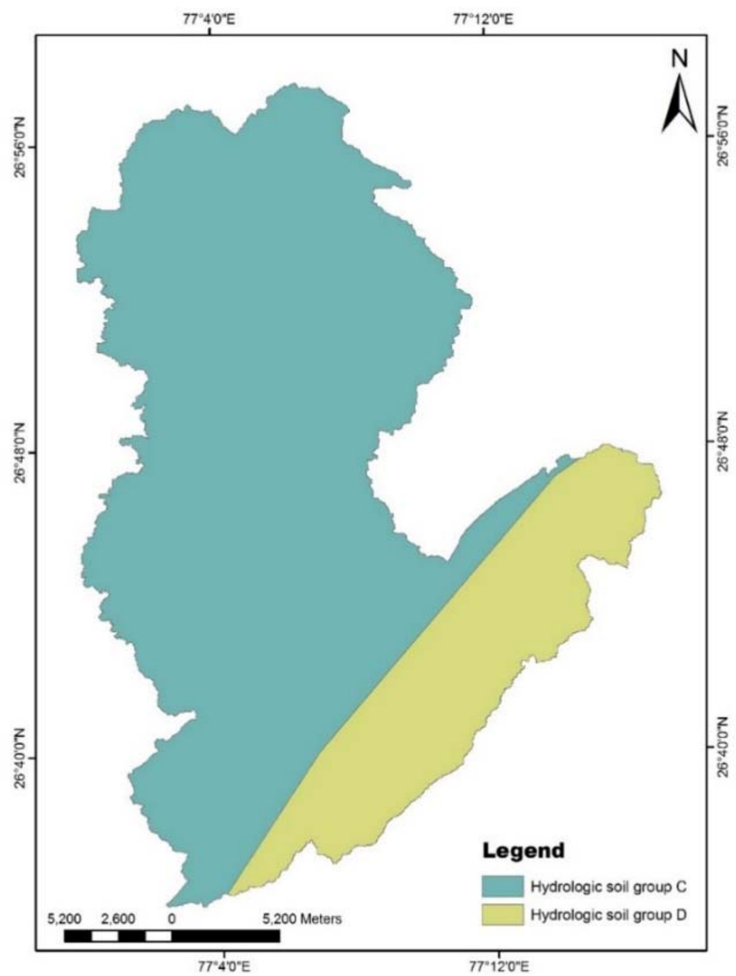

Fig. 4.4 HSG map of the *Gambhir* River watershed.

The estimated curve number for agricultural lands as 79 is indicative of high runoff generation capacity while a weighted CN value of 80.25 for AMC II condition suggest that the watershed has good potential of runoff generation. Based on AMC III (wet condition) it is expected that the runoff in the rainy season will be higher compared to the other seasons.

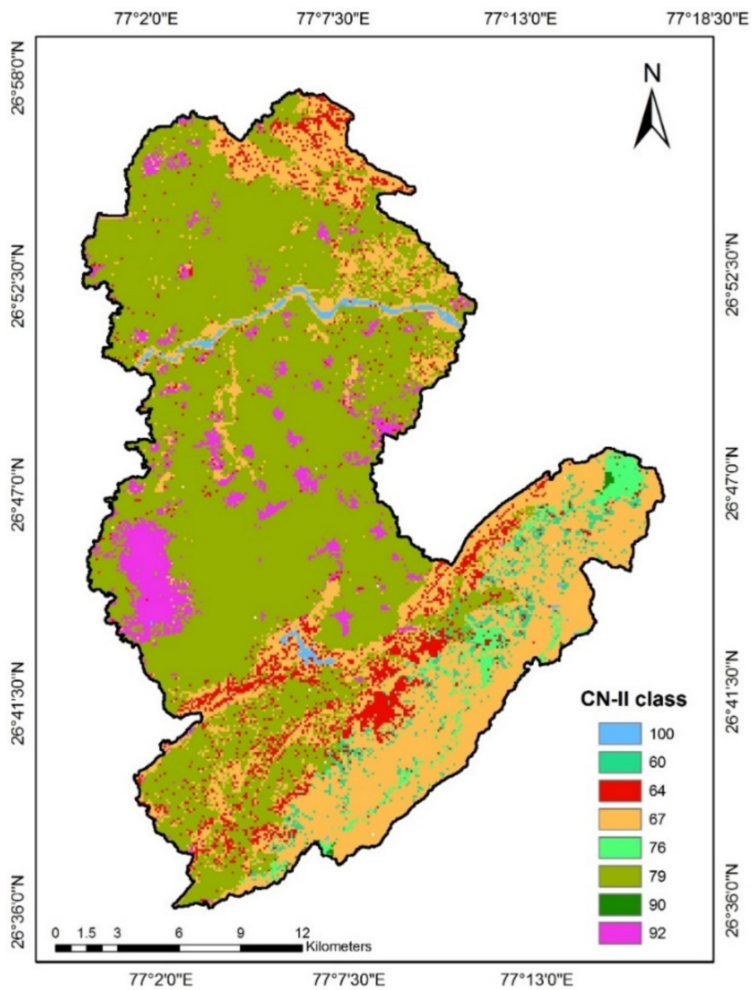

Fig. 4.5 Curve Number (CN) map of the *Gambhir* River watershed.

4.1.5 Rainfall analysis

Time series daily rainfall data from 2007-2017 of four rain gauge stations located nearby the *Gambhir* River watershed, were analysed for mean monthly and mean annual rainfall. The mean monthly rainfall of rain gauge stations are shown in the Table 4.2. The *Hindaun* station located inside the *Gambhir* River watershed (others located outside) showed a decreasing rainfall trend as shown in Fig 4.6. Most of the rainfall (about 91%) occurs in the months of June, July, August and September. July and August months. Approximately, 60% of the total rainfall occurs in July and August months. The mean monthly rainfall in August month was highest (226 mm) followed by July month. However, out of 11 years the watershed has received below average rainfall in 5 years indicating the serious deficit in the water availability which warrants that the runoff in the years of good rainfall must be conserved and stored in appropriately designed RWHS. It was also observed that in a year of highest rainfall (2016) rainy days were (34) less than the highest number of rainy days observed (46). The rainy days also showed a decreasing trend over the period of 11 years. The Theissen polygon map of the *Gambhir* River watershed is presented in Fig. 4.8. Polygon areas influenced by different stations are described in Table 4.4. It was found that 3 out 4 stations considered influence the mean annual rainfall with Hindaun station having more influence than the other two. The mean annual rainfall of the *Gambhir* River watershed was found to be 640 mm.

Table 4.2 Mean monthly rainfall of rain gauge stations.

Month	Mean monthly rainfall in mm					
	Hindaun	**Mandrayal**	**Bhusavar**	**Bayana**	**Mean**	**SD**
Jan	9	16	11	17	14	4
Feb	7	9	2	13	8	5
Mar	18	11	15	17	15	3
Apr	2	3	3	8	4	3
May	8	10	6	10	8	2
Jun	93	122	62	97	93	25
Jul	173	229	163	212	194	31
Aug	226	225	154	210	204	34
Sep	93	63	131	96	96	28
Oct	9	20	9	20	15	6
Nov	2	12	5	12	8	5
Dec	1	3	0	0	1	1

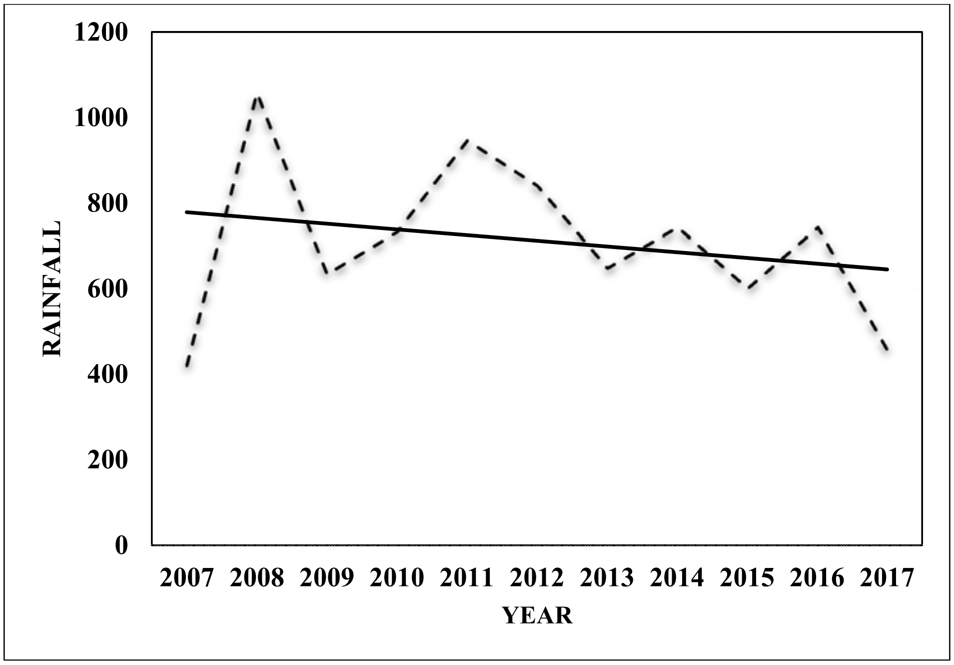

Fig. 4.6 Temporal variations in the annual rainfall of *Hindaun* meteorological gauging station.

Table 4.3 Mean annual rainfall of the rain gauge stations.

Annual and mean annual rainfall in mm				
Year	**Hindaun**	**Mandrayal**	**Bhusavar**	**Bayana**
2007	523	376	289	421
2008	811	1178	662	1059
2009	419	744	344	635
2010	420	748	515.6	733
2011	737	690	694	947
2012	833	824	753	841
2013	825	933	513	649
2014	824	561	527	744
2015	359	724	632	602
2016	842	826	735	744
2017	463	339	491	454
Mean	**641**	**722**	**560**	**712**
SD	**201**	**238**	**152**	**192**

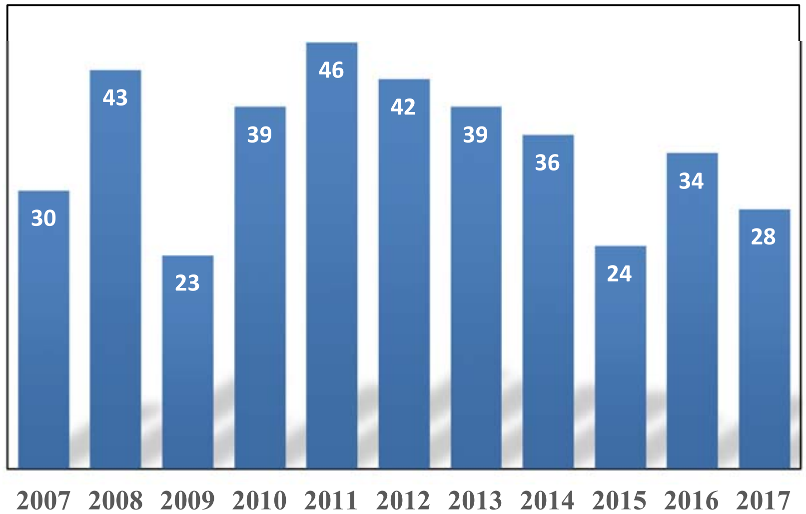

Fig. 4.7 Annual rainfall days in the *Gambhir* River watershed.

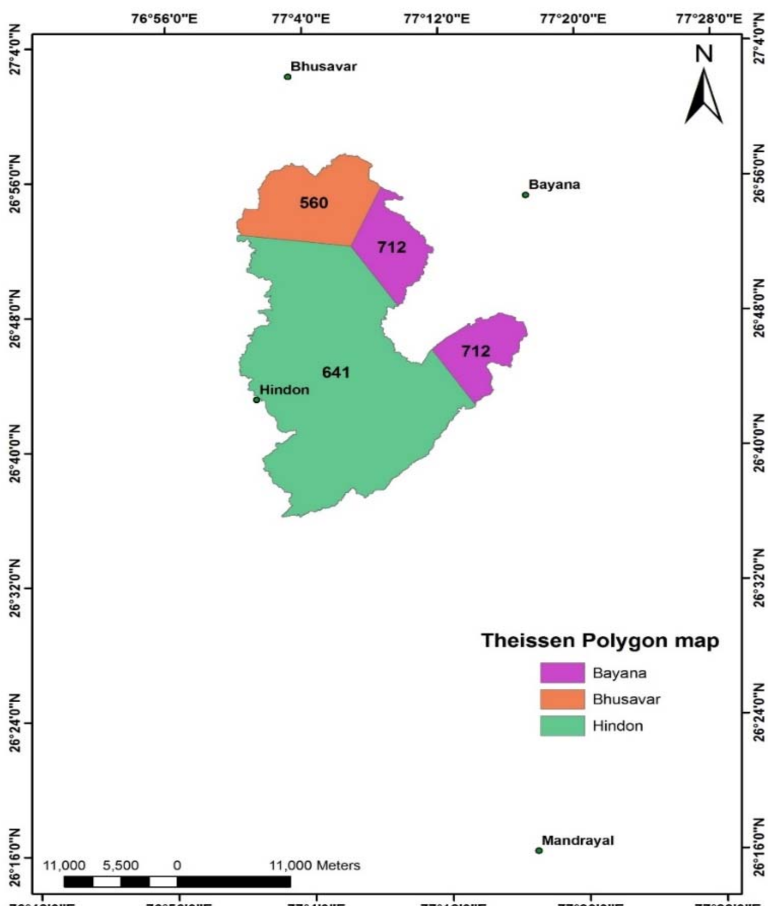

Fig. 4.8 Theissen polygon map of the *Gambhir* River watershed.

Table 4.4 Polygon areas influenced by different stations.

Station	Mean Annual Rainfall (mm)	Area of Polygon (Km^2)	Weighted Depth of Rainfall
Bayana	712	99.81	71071.84
Hindaun	641	408.46	261822.86
Bhusavar	560	93.99	52634.4
Total		**602.26**	**385529.1**

For determining AMC conditions, the rainfall data from 2007-2017 were analysed based on cumulative rainfall amount of five days. Using NRCS-CN method, daily runoff depth for 11 years was computed using Micro-soft Excel sheet. A sample data is presented in Appendix VII**.** The mean annual runoff was found to be 190 mm.

Table 4.5 Computed annual runoff and runoff coefficient values.

Year	Annual rainfall	Runoff depth (mm)	Runoff coefficient
2007	523	127	0.24
2008	811	195	0.24
2009	419	126	0.30
2010	420	159	0.38
2011	737	190	0.26
2012	833	269	0.32
2013	825	296	0.36
2014	824	285	0.35
2015	359	131	0.36
2016	842	358	0.42
2017	463	143	0.31
Mean	**641**	**190**	**0.32**
SD	**192**	**78**	**0.06**

4.1.6 Spatial rainfall depth map

The spatial rainfall map of the *Gambhir* River watershed as depicted in Fig. 4.9 shows the spatial variability of rainfall depth over the *Gambhir* River watershed. The rainfall depth varies from 586 mm to 688 mm. Most of the eastern part receives higher rainfall as compared to other parts of the watershed. The rainfall regions of the area can be classified into three groups namely high rainfall, moderate rainfall and low rainfall regions respectively. About 123.24 km^2 area receives high rainfall (649-686 mm) while, 213.74 km^2 area comprise of lower rainfall region receiving 586-534 mm. Most of the area comprise of moderate rainfall region with rainfall of 634-649 mm.

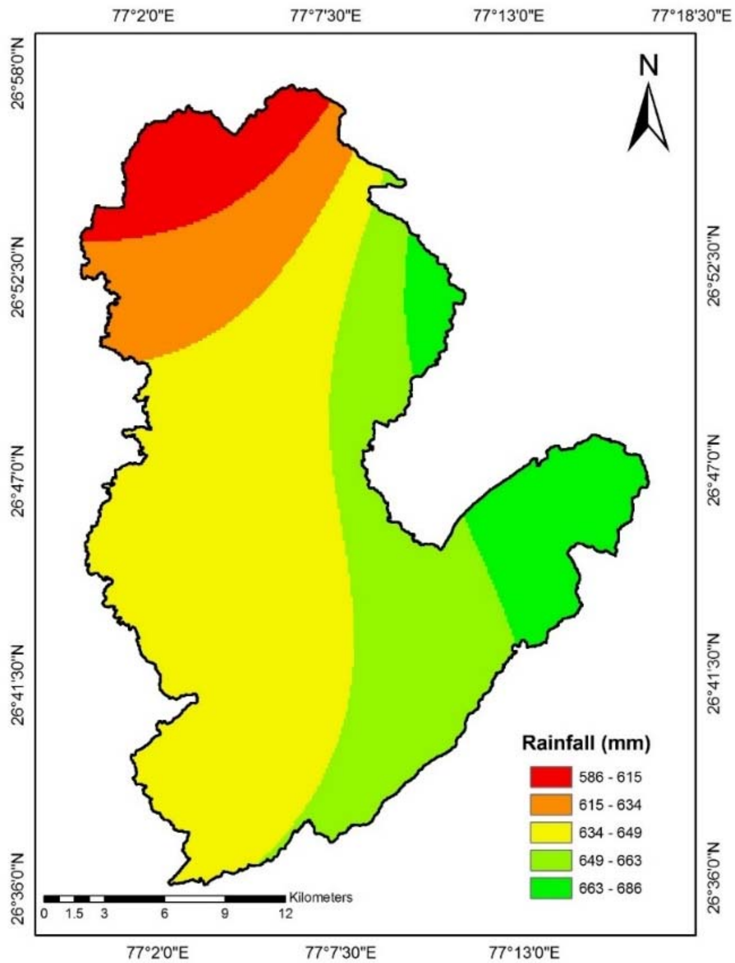

Fig. 4.9 Spatially distributed mean rainfall depth map of the *Gambhir* River watershed.

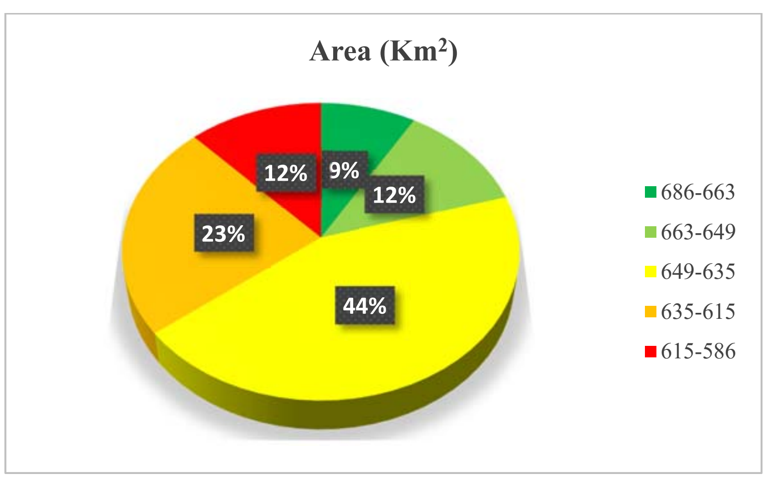

Fig. 4.10 Areal distribution of rainfall in *Gambhir* River watershed.

4.1.7 Runoff potential map

The runoff potential map of the *Gambhir* River watershed as depicted in Fig. 4.11 shows the spatial variability of runoff depth over the *Gambhir* River watershed. The runoff depth varies from 136 to 321 mm. Most of the eastern part has higher runoff potential as this region receives more rainfall compared to others. Portions of high runoff potential throughout the area are built up areas where infiltration is lower showing more runoff depth. Approximately, 109.61 km^2 of the total area has highest runoff potential (284-321 mm) whereas, 28.11 km^2 area has lowest runoff potential. Most of the lower runoff potential area are located on western part of the *Gambhir* River watershed. Medium runoff potential (210-247 mm) region covers 96.44 km^2 area. The areal distribution of runoff is shown in Fig. 4.12.

4.2 Selection of most appropriate sites for different types of RWHS using Analytic Hierarchy Process (AHP)

For selecting the most appropriate sites, six criteria were considered namely, Rainfall, Slope, Runoff, LULC, Soil and Drainage density based on data availability.

4.2.1 Preparation of various thematic maps

Various thematic layers required for accomplishing second objective are described in the following sections.

4.2.1.1 Slope map

Slope is an important parameter that affects the runoff as the movement of surface water depends on slope of the *Gambhir* River watershed. The slope (in percentage) of the *Gambhir* River watershed varies from 0 – 84 %. The slope map of the *Gambhir* River watershed can be classified into five classes: (a) nearly level (0 to 3 %), (b) gentle slope (3 to 5 %), (c) moderately gentle slope (5 to 10 %), (d) steep (10 to 15 %), and (e) very steep (>15 %).

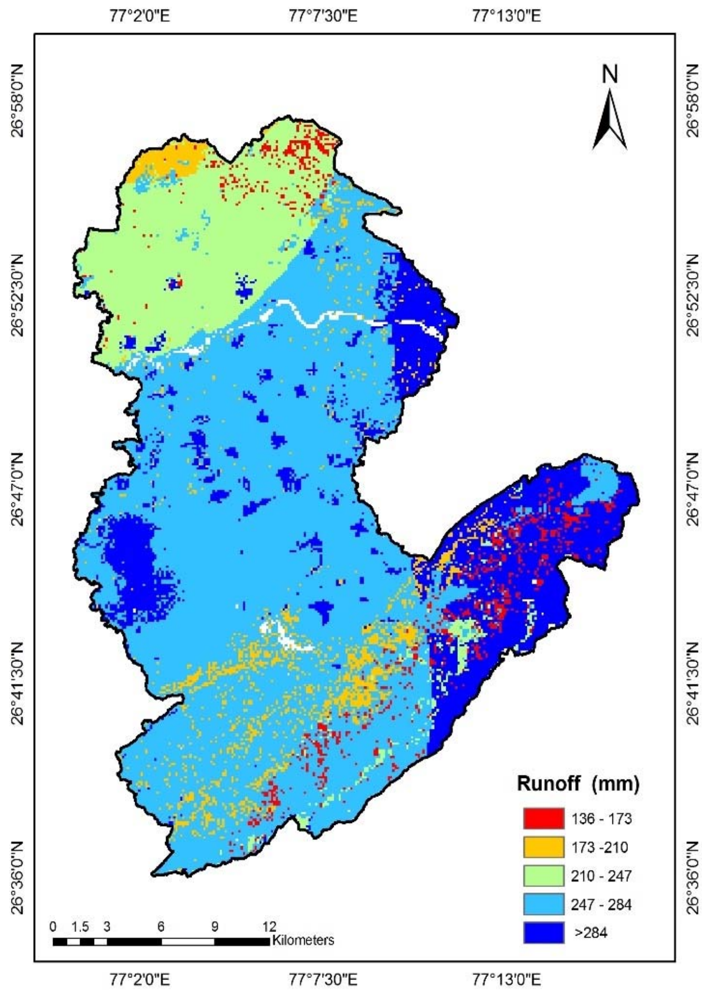

Fig. 4.11 Spatially distributed runoff map of the *Gambhir* River watershed.

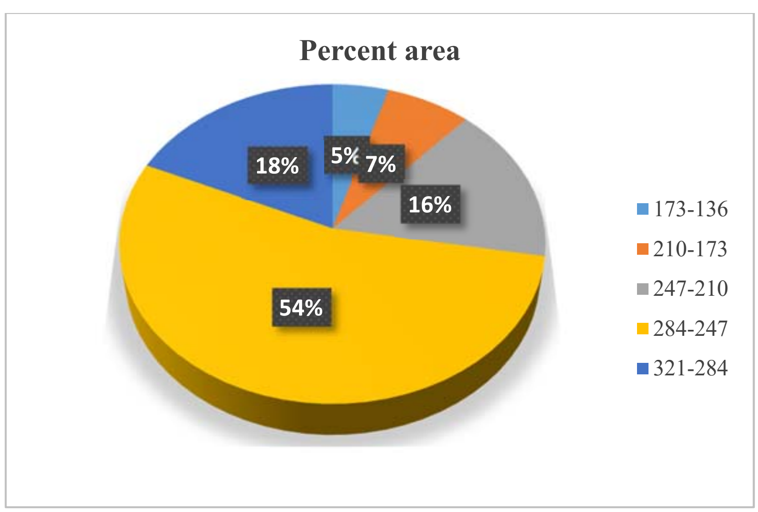

Fig. 4.12 Areal distribution of runoff in *Gambhir* River watershed.

Slopes up to 5 % i.e., ‘nearly level’ to ‘gentle’ slopes are considered as the most suitable for citing RWHS. These classes cover an area of about 455.30 km^2 and 66.76 km^2 respectively. The ‘moderately gentle’ and ‘steep’ slopes occupies an area of 66.76 km^2 and 13.56 km^2 respectively. Area under ‘very steep’ class is found to be 20.09 km^2. Most of the area lies under nearly level class whereas ‘very steep’ class occupies only 3.34 % of the total area is unsuitable for locating RWHS (Fig. 4.13 and Fig. 4.14). As per the slope conditions of the watershed almost a large area is suitable for construction of RWHS especially the farm ponds that are highly required for storing water for irrigation purposes. However, some percolation structures would help in faster augmentation of the ground water due to artificial ground water recharge so that the draw down in the tube wells remain in permissible limits while pumping. Efforts should be made by the watershed beneficiaries to collect as much water as possible by creation of different types of structures wherever feasible so that all the water should be conserved in the watershed that will make it resources sustainable.

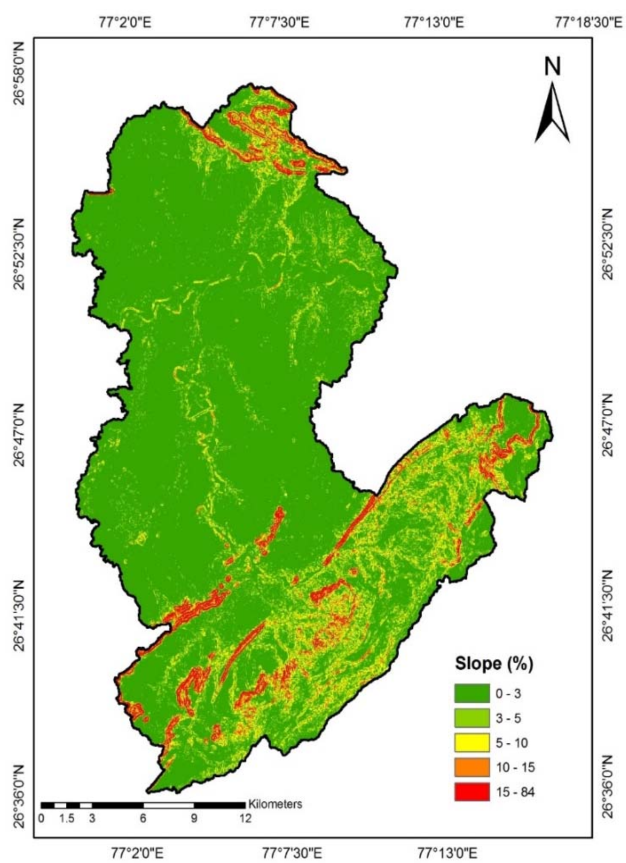

Fig 4.13 Slope map of the *Gambhir* River watershed.

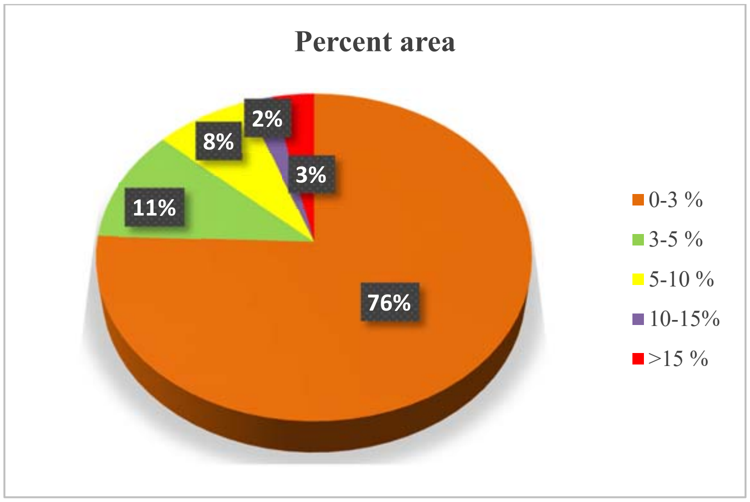

Fig. 4.14 Areal distribution of slope classes.

4.2.1.2 Stream order map

The stream order map of the *Gambhir* River watershed is presented on Fig.4.15. The trunk order of the *Gambhir* River watershed was found to be five with stream length of 33.89 km. Approximately 49.38 % of the total drainage network consist of first order streams. The second and third order streams covers drainage lengths of 134.16 (26.69 %) and 68.64 (13.66 %) respectively. The second and third order streams are important from the point of view of RWH. The fifth order stream covers more length (6.74 %) than fourth order stream (3.44 %). The length wise distribution of stream orders is given in Table 4.6. The number of streams of orders 1 through 5 was 183, 31, 11, 3 and 1.

Table 4.6 Length wise distribution of stream orders.

Stream Order	Number of Streams	Stream length (km)	Percent length
1	183	248.19	49.38
2	31	134.16	26.69
3	11	68.64	13.66
4	3	17.28	3.44
5	1	33.89	6.74

4.2.1.3 Drainage density map

Drainage density of the *Gambhir* River watershed varies from 0 to 2.74 km/ km^2 (Fig.4.16) with mean density of 0.82 km/ km^2 and standard deviation of 0.52.

Drainage density can be grouped into five classes. (a) very low (0-0.5 km/km^2), (b) low (0.5-1 km/km^2), (c) moderate (1-1.5 km/km^2), (d) high (1.5 to 2 km/km^2) and e) very high (2-2.7 km/km^2). Drainage density of very low to low category is dominant in the *Gambhir* River watershed covering an area of about 376.97 km^2 whereas drainage of very high category occupies a small portion of 6.46 km^2 the *Gambhir* River watershed. Moderate and high drainage density classes occupy about 157.32 km^{2}and 61.38 km^2 respectively (Fig. 4.17). High drainage density is indicative of either high rainfall resulting into bisected watersheds or a highly erosible soil base which results in to severely eroded land mass. As the soil of the present watershed belongs to the loam and clay loam the second fact holds good due to which one can conclude that the watershed has high erosion potential as well.

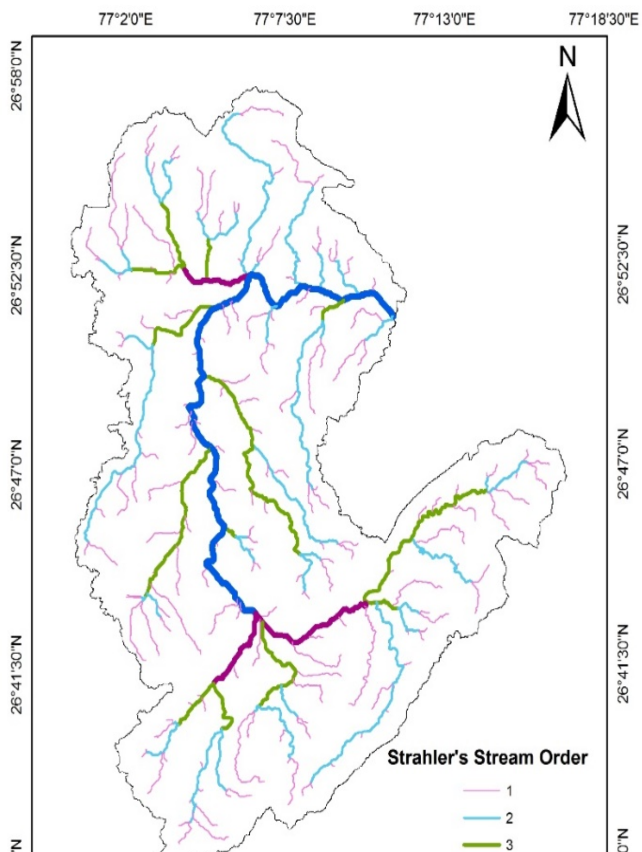

Fig. 4.15 Stream order map of the *Gambhir* River watershed.

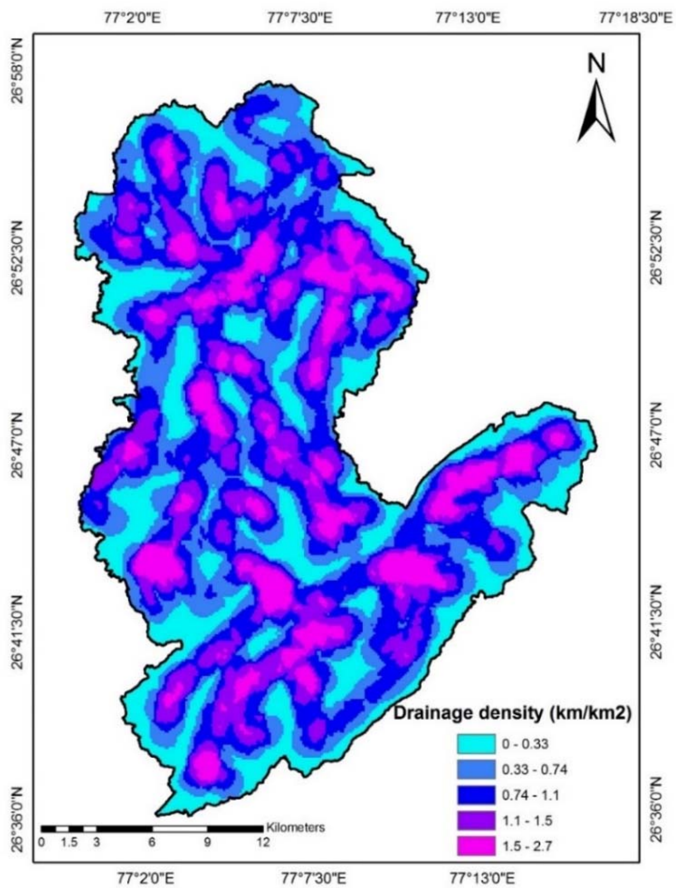

Fig. 4.16 Drainage density map of the *Gambhir* River watershed.

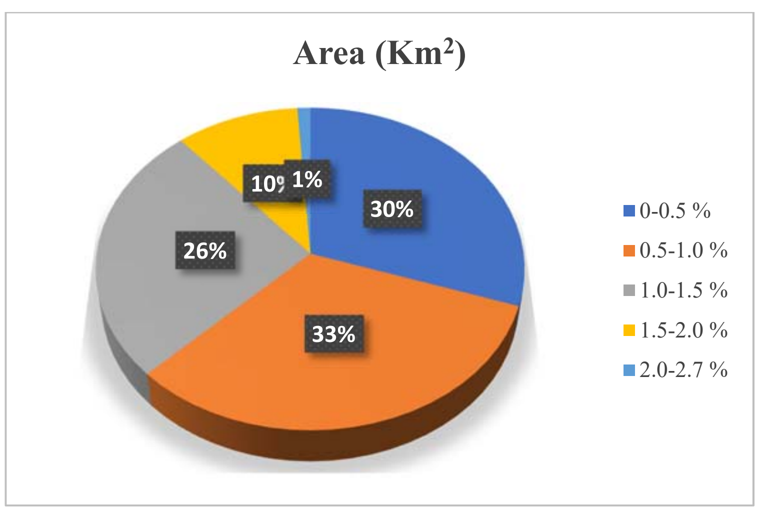

Fig. 4.17 Areal distribution of Drainage density classes.

4.2.2 Use of AHP for determining criteria weights

For selecting suitable site for RWHS all criteria are not equally important. Whereas, this depends on the type of RWHS to be designed. Thus, for one type of RWHS the most important criteria may be the least important one for designing the percolation structures. Therefore, it is required to assign different weights to different criterion. The AHP is used to assign weights to each criterion based on expert's opinion. The overall site suitability map was prepared considering six criteria. Priority has been given by comparing two criteria at a time using Saaty's scale as explained in detail in the section 3.5 in Chapter 3. The pairwise comparison matrix and their resulting weights area described in the following section. For each of these matrices the consistency ratio is less than 0.1, giving a confirmation that the resulting criteria weights are consistent.

4.2.2.1 Land use/Land cover (LULC)

Five LULC classes were identified in the *Gambhir* River watershed. For pairwise comparison, open forest and built-up area have been given a lowest priority. Accordingly, ranks were assigned to each class using Saaty's scale. After normalising the pairwise comparison matrix and checking the consistency, weights for each criterion were finalised for different RWHS. Weights for farm pond construction for each LULC class are shown in Table 4.7. Agricultural lands have highest weightage while built-up areas have least weightage. Scrub lands have got higher weightage than open forest class (Fig. 4.18).

Table 4.7 Pairwise comparison matrix for LULC classes.

Rank	**9**	**8**	**5**	**3**	**1**
LULC Class	**Agriculture**	**Scrub land**	**Open forest**	**Water body**	**Built-up**
Agriculture	1.00	3.00	4.00	5.00	8.00
Scrub land	0.50	1.00	2.00	4.00	6.00
Open forest	0.25	0.50	1.00	2.00	4.00
Water body	0.20	0.25	0.50	1.00	2.00
Built-up	0.13	0.17	0.25	0.50	1.00

Table 4.8 Normalized pairwise comparison matrix for LULC classes.

LULC Class	Agriculture	Scrub land	Open forest	Water body	Built-up	Criteria weight
Agriculture	0.48	0.61	0.52	0.40	0.38	0.48
Scrub land	0.24	0.20	0.26	0.32	0.29	0.26
Open forest	0.12	0.10	0.13	0.16	0.19	0.14
Water body	0.10	0.05	0.06	0.08	0.10	0.08
Built-up	0.06	0.03	0.03	0.04	0.05	0.04

Consistency Index = 0.0088
Random index = 1.12
Consistency ratio = 0.0079

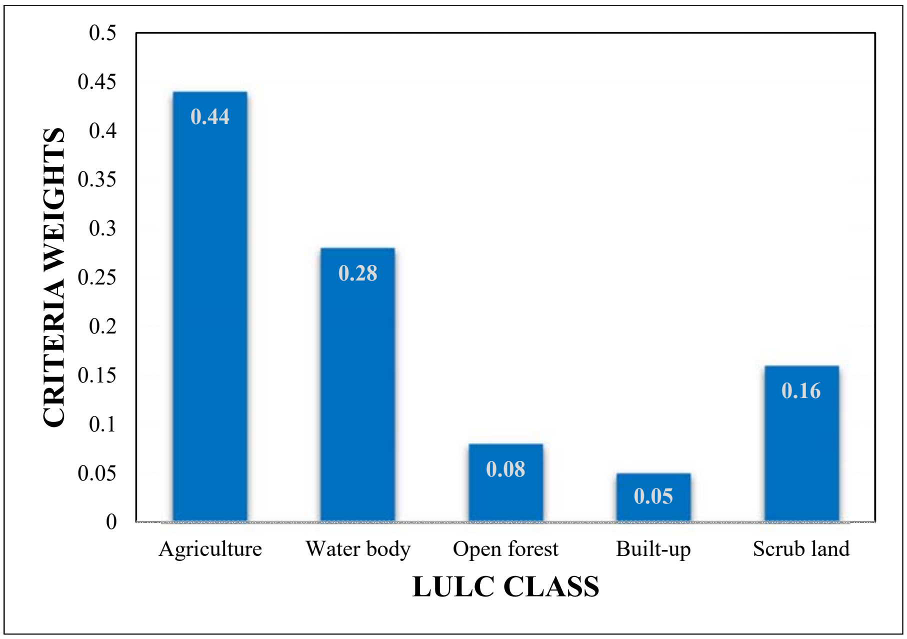

Fig. 4.18 Criteria weights for each LULC class.

4.2.2.2 Slope

The slope map has been classified into five classes. Generally, rainwater harvesting structures are not suitable for slopes more than 5% because of uneven runoff distribution and large amount of earthwork required (Critchley *et al.,* 1991). Therefore, higher weightage is given to these classes and a pairwise comparison matrix is formed as shown in Table 4.9. Normalized pairwise comparison matrix for slope classes is given in Table 4.10. Criteria weights are confirmed after checking the consistency, are shown in Fig. 4.19. The slope class of 0-3 % has got higher weightage amongst all classes whereas slope class of more than 15% got lower weightage.

4.2.2.3 Drainage density

Higher drainage density class has given more priority than those having lesser drainage density. The resulting pairwise comparison matrix is shown in Table 4.11. Normalized pairwise comparison matrix for drainage density classes is given in Table 4.12. The weights calculated after checking the consistency are shown in Fig. 4.20. Drainage density greater than 2 km/km^2 got the highest weightage by than other classes whereas drainage density up to 0.5 km/km^2 got least weightage.

Table 4.9 Pairwise comparison matrix for slope classes.

Rank	**9**	**7**	**6**	**5**	**1**
Slope	**0-3 %**	**3-5 %**	**5-10 %**	**10-15 %**	**>15 %**
0-3 %	1.00	3.00	4.00	6.00	8.00
3-5 %	0.33	1.00	2.00	5.00	7.00
5-10 %	0.25	0.50	1.00	3.00	6.00
10-15%	0.17	0.20	0.33	1.00	4.00
>15 %	0.13	0.14	0.17	0.25	1.00

Table 4.10 Normalized pairwise comparison matrix for slope classes.

Slope	**0-3 %**	**3-5 %**	**5-10 %**	**10-15 %**	**>15 %**	**Criteria Weights**
0-3 %	0.53	0.62	0.53	0.39	0.31	0.48
3-5 %	0.18	0.21	0.27	0.33	0.27	0.25
5-10 %	0.13	0.10	0.13	0.20	0.23	0.16
10-15%	0.09	0.04	0.04	0.07	0.15	0.08
>15 %	0.07	0.03	0.02	0.02	0.04	0.03

Consistency Index = 0.0711
Random index = 1.12
Consistency ratio = 0.0635

Table 4.11 Pairwise comparison matrix for drainage density classes.

Rank	**9**	**7**	**6**	**5**	**1**
Drainage density	**>2**	**2-1.5**	**1.5-1**	**1-0.5**	**0.5-0**
>2	1.00	2.00	6.00	7.00	8.00
2-1.5	0.50	1.00	4.00	2.00	6.00
1.5-1	0.17	0.25	1.00	3.00	4.00
1-0.5	0.14	0.50	0.33	1.00	2.00
0.5-0	0.13	0.17	0.25	0.50	1.00

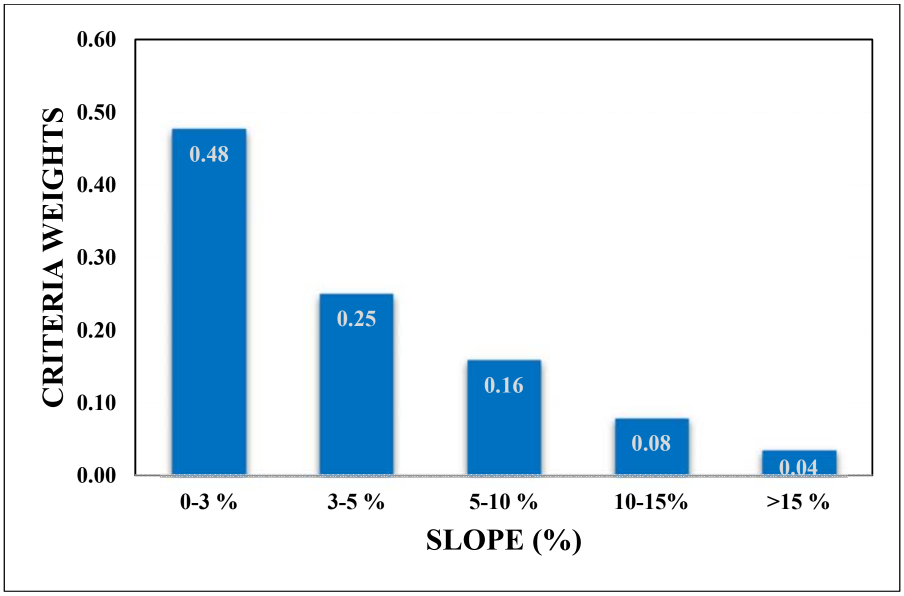

Fig. 4.19 Criteria weights for each slope class.

Table 4.12 Normalized pairwise comparison matrix for drainage density classes.

Drainage density	>2 %	2-1.5 %	1.5-1 %	1-0.5 %	0.5-0 %	Criteria Weights
>2 %	0.52	0.51	0.52	0.52	0.38	0.49
2-1.5 %	0.26	0.26	0.35	0.15	0.29	0.26
1.5-1 %	0.09	0.06	0.09	0.22	0.19	0.13
1-0.5 %	0.07	0.13	0.03	0.07	0.10	0.08
0.5-0 %	0.06	0.04	0.02	0.04	0.05	0.04

Consistency Index = 0.0791
Random index = 1.12
Consistency ratio = 0.0706

4.2.2.4 Rainfall

The areas which receive higher rainfall are preferred over those receiving lesser rainfall. Because in higher rainfall areas there is more possibility of generation of higher runoff. A pairwise comparison matrix is formed as shown in Table 4.13 by giving more rank to higher rainfall classes. The weights of each class are shown in Fig. 4.21. Higher rainfall classes have got more weights than lower rainfall classes. Normalized pairwise comparison matrix for rainfall classes is given in Table 4.14.

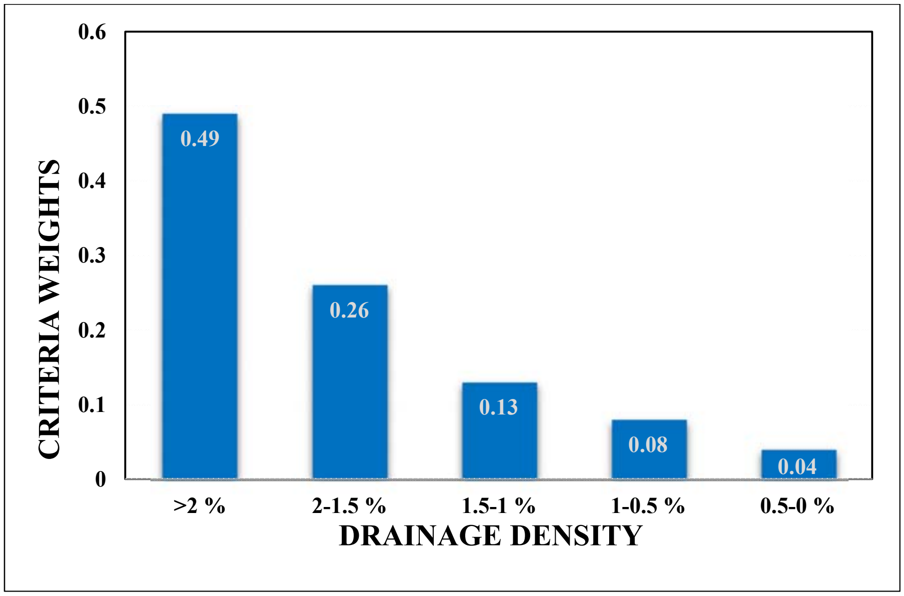

Fig. 4.20 Criteria weights for each drainage density class.

Table 4.13 Pairwise comparison matrix for rainfall classes.

Rank	**9**	**7**	**6**	**5**	**4**
Rainfall	**686-663**	**662-649**	**648-635**	**634-615**	**614-586**
686-663	1	2	3	4	5
662-649	0.5	1	3	4	5
648-635	0.33	0.33	1	3	4
634-615	0.25	0.25	0.33	1	2
614-586	0.2	0.2	0.25	0.5	1

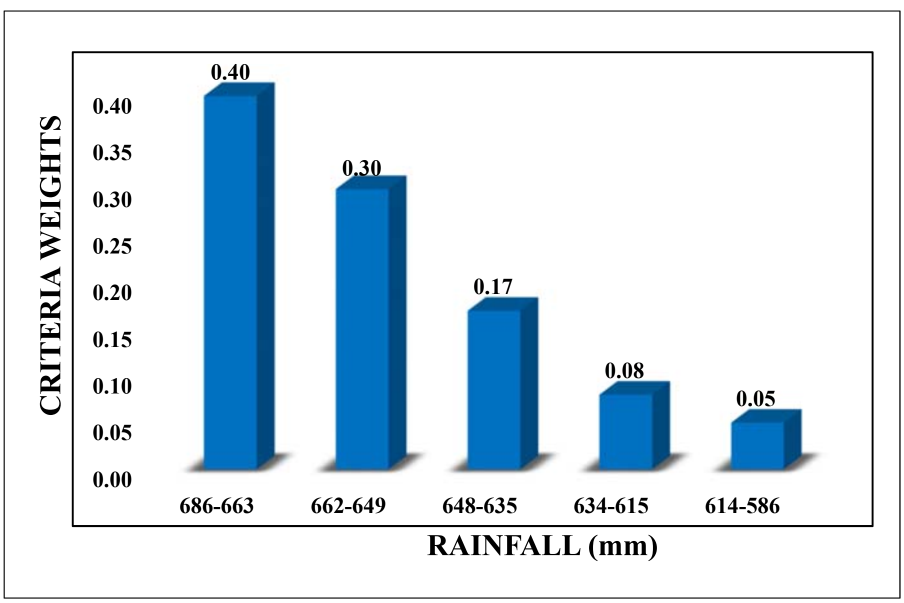

Fig. 4.21 Criteria weights for each rainfall classes.

Table 4.14 Normalized pairwise comparison matrix for rainfall classes.

Rainfall	686-663	662-649	648-635	634-615	614-586	Criteria weights
686-663	0.44	0.53	0.40	0.32	0.29	0.40
662-649	0.22	0.26	0.40	0.32	0.29	0.30
648-635	0.15	0.09	0.13	0.24	0.24	0.17
634-615	0.11	0.07	0.04	0.08	0.12	0.08
614-586	0.09	0.05	0.03	0.04	0.06	0.05

Consistency Index = 0.0502
Random index = 1.12
Consistency ratio = 0.0448

4.2.2.5 Runoff depth

Higher runoff producing areas have been given more priority than lower runoff producing areas. Considering this a pairwise comparison matrix is formed as shown in Table 4.15. Criteria weights after checking the consistency are shown in Fig. 4.22. The class having runoff of 321-284 mm has got the higher weightage (0.45) compared to last three classes, while runoff of 284-247 has got slightly lesser weightage (0.34) than the first class. Normalized pairwise comparison matrix for runoff classes is given in Table 4.16. Normalized weights obtained for various sub-classes are summarized in Table 4.17.

Table 4.15 Pairwise comparison matrix for runoff classes.

Rank	9	7	4	3	2
Runoff	**321-284**	**284-247**	**247-210**	**210-173**	**173-136**
321-284	1.00	2.00	5.00	8.00	7.00
284-247	0.50	1.00	6.00	7.00	6.00
247-210	0.20	0.17	1.00	3.00	4.00
210-173	0.13	0.14	0.33	1.00	2.00
173-136	0.14	0.17	0.25	0.50	1.00

Table 4.16 Normalized pairwise comparison matrix for runoff classes.

Runoff	321-284	284-247	247-210	210-173	173-136	Criteria Weights
321-284	0.51	0.58	0.40	0.41	0.35	0.45
284-247	0.25	0.29	0.48	0.36	0.30	0.34
247-210	0.10	0.05	0.08	0.15	0.20	0.12
210-173	0.06	0.04	0.03	0.05	0.10	0.06
173-136	0.07	0.05	0.02	0.03	0.05	0.04

Consistency Index = 0.0766
Random index = 1.12
Consistency ratio = 0.0684

4.2.3 Overall site suitability map

For preparing the overall site suitability map, six criteria namely LULC, Soil, Slope, Rainfall, Runoff, Drainage density were considered based on data availability. Thematic layers of these criteria were reclassified by giving weights as computed in the above section. These layers were overlaid by giving weights computed using AHP. The weights after checking the consistency are shown in Fig. 4.23. The pairwise comparison matrix and Normalized pairwise comparison matrix of these criteria are shown in Tables 4.18 and 4.19; respectively.

Table 4.17 Normalized weights obtained for various sub-classes.

	Sub-class	Assigned Weight	Normalized Weight
Runoff (mm)	321-284	9	0.45
	284-247	7	0.34
	247-210	4	0.12
	210-173	3	0.06
	173-136	2	0.04
Rainfall (mm)	563-624	9	0.40
	501-562	7	0.30
	476-500	6	0.17
	475-451	5	0.08
	450-421	4	0.05
Slope (%)	0-3	9	0.48
	3-5	7	0.25
	5-10	6	0.16
	10-15	5	0.08
	>15	1	0.03
LULC	Agriculture	9	0.44
	Scrub land	8	0.28
	Open forest	5	0.16
	Water body	3	0.08
	Built-up	1	0.05
Soil Texture	Loam	9	0.66
	Clay-Loam	7	0.34
Drainage density (km/km^2)	2.75-1.54	9	0.49
	1.53-1.13	7	0.26
	1.12-0.75	6	0.13
	0.74-0.34	5	0.08
	0.33-0	1	0.04

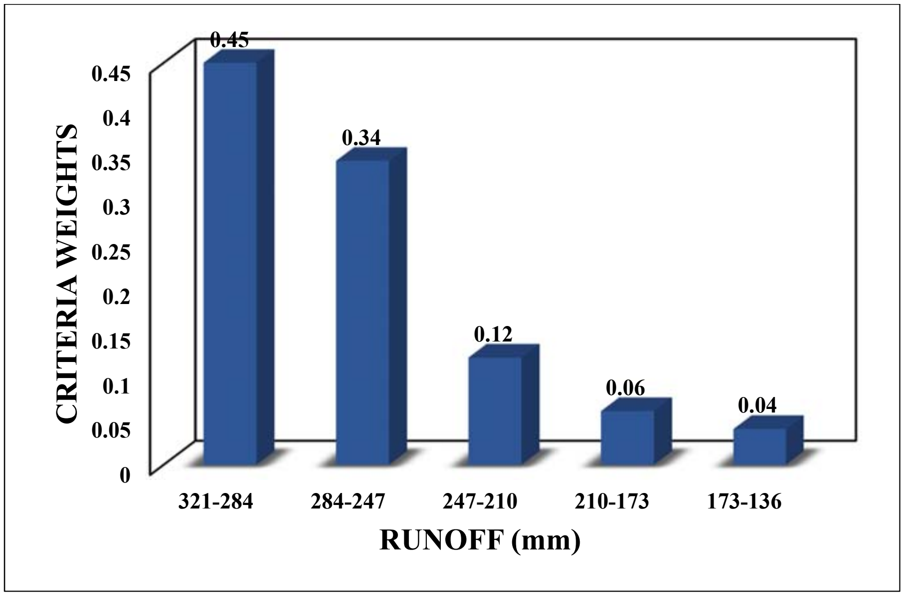

Fig. 4.22 Criteria weights for each runoff classes.

The six criteria layers were overlaid using Weighted Linear Combination (WLC) assigning the obtained weights as shown in Fig.4.23. The resulting map is shown in Fig. 4.24. The map has been divided into five sub-classes namely, i) Very highly suitable, ii) Highly suitable, iii) Moderately suitable, iv) Least suitable and v) Not suitable. The areal distribution of these classes is shown in Fig.4.25. It was found that about 75.54 km^2 area was very highly suitable whereas 109.18 km^2 area was least suitable for construction of RWHS. Moderately suitable class covers most of the area (259.21 km^2) in the watershed. About 43.77 km^2 area was not suitable at all for constructing any type of RWHS.

Table 4.18 Pairwise comparison matrix for different criteria.

Rank	**9**	**8**	**7**	**6**	**4**	**3**
Main Criteria	**Runoff depth**	**Rainfall**	**Slope**	**LULC**	**Soil texture**	**Drainage density**
Runoff depth	1.00	2.00	4.00	5.00	6.00	8.00
Rainfall	0.50	1.00	3.00	4.00	5.00	7.00
Slope	0.25	0.33	1.00	3.00	4.00	6.00
LULC	0.20	0.25	0.33	1.00	3.00	5.00
Soil texture	0.17	0.20	0.25	0.33	1.00	4.00
Drainage Density	0.13	0.14	0.17	0.20	0.25	1.00

Table 4.19 Normalized pairwise comparison matrix for different criteria.

Main Criteria	Runoff depth	Rainfall	Slope	LULC	Soil texture	Drainage density
Runoff depth	0.45	0.51	0.46	0.37	0.31	0.26
Rainfall	0.22	0.25	0.34	0.30	0.26	0.23
Slope	0.11	0.08	0.11	0.22	0.21	0.19
LULC	0.09	0.06	0.04	0.07	0.16	0.16
Soil texture	0.07	0.05	0.03	0.02	0.05	0.13
Drainage density	0.06	0.04	0.02	0.01	0.01	0.03

Consistency Index = 0.0934

Random index = 1.24

Consistency ratio = 0.0754

Table 4.20 Normalized weights of the main criteria for identification of suitable zones for RWHS.

Sr. No.	Thematic Layer	Assigned Weight	Normalized weight
1.	Runoff depth	9	0.26
2.	Rainfall	8	0.23
3.	Slope	7	0.19
4.	LULC	6	0.16
5.	Soil texture	4	0.13
6.	Drainage density	3	0.03

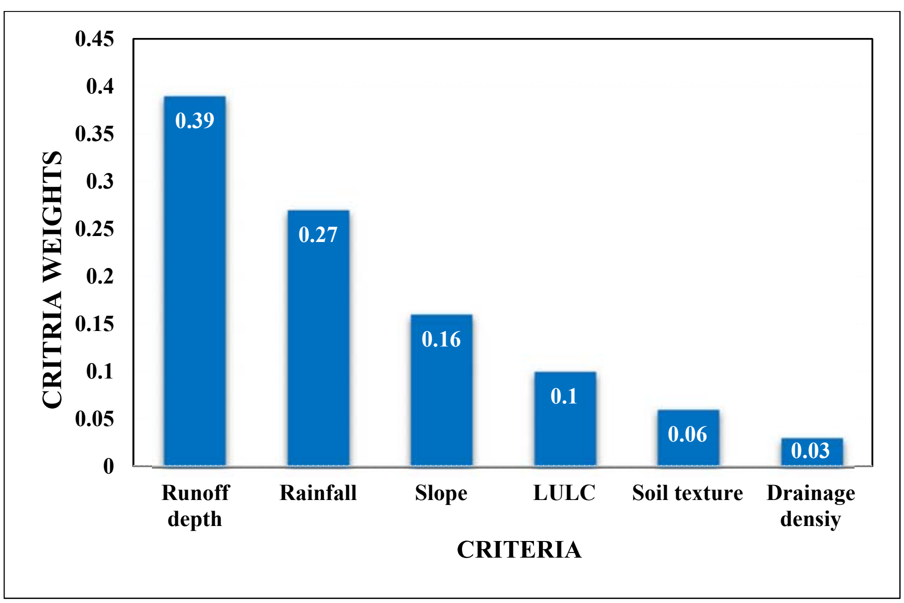

Fig. 4.23 Criteria weights for main criteria class.

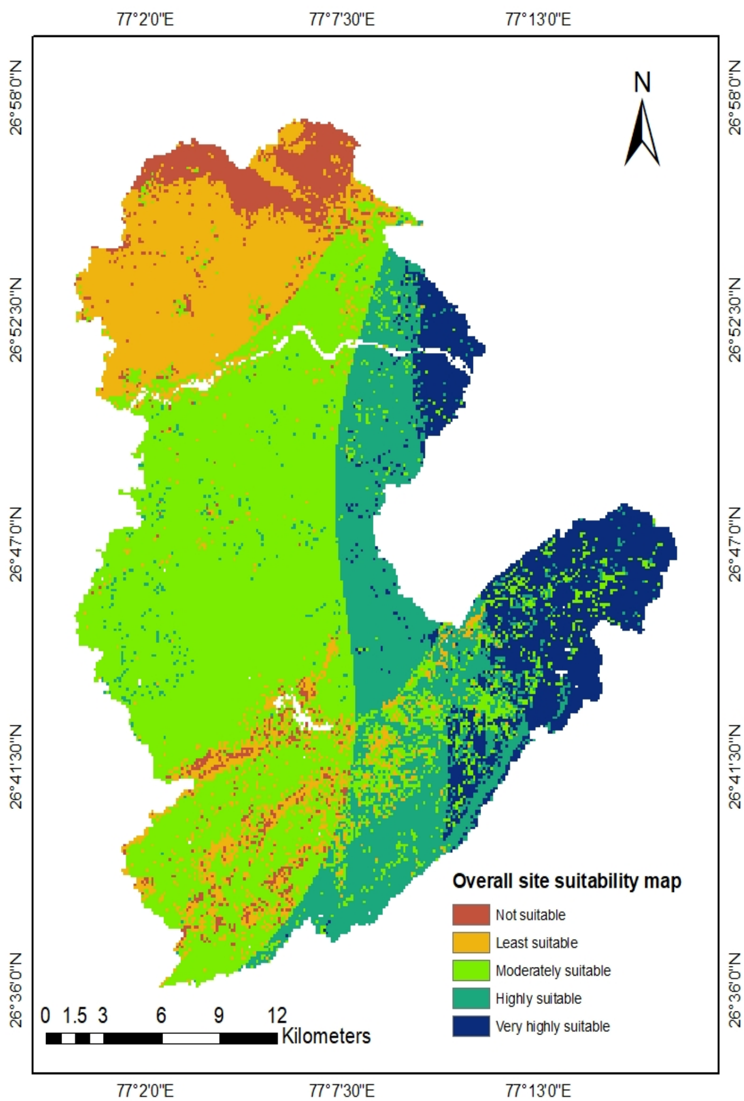

Fig. 4.24 Overall site suitability map of the *Gambhir* River watershed.

4.2.4 Site suitability analysis for RWHS

Boolean logic was used to prepare site suitability maps for a particular type of RWHS. The criteria for selecting a particular type of RWHS was adopted as mentioned in Table 3.2. Various thematic maps were prepared using Boolean logic which gives value of 1 to those sub-criteria that are suitable for a particular type of structure leaving other sub-criteria as zero. These maps were then overlaid using raster calculator which results in a map that gives suitable zones for a particular type of RWHS.

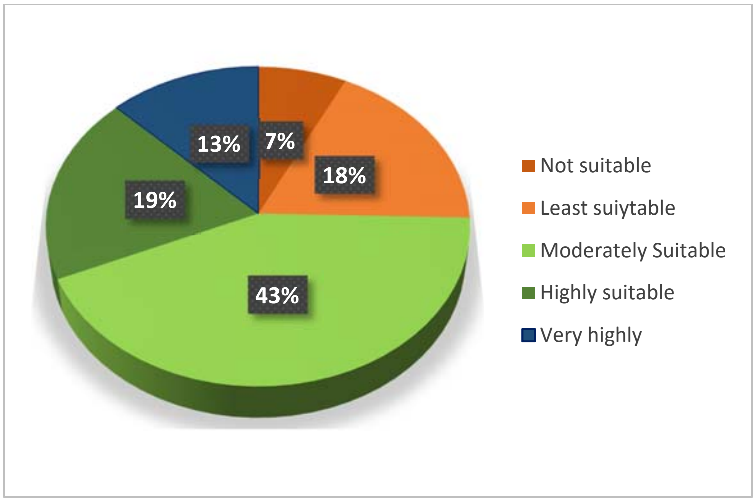

Fig. 4.25 Areal distribution of suitability classes**.**

4.2.4.1 Site suitability for farm ponds

Thematic layers of Slope, HSG, Runoff and LULC were prepared using Boolean logic based on the criteria shown in Table 3.7. These layers were added using raster calculator. The resulting map was classified into two classes as Highly Suitable Zones and Not Suitable Zones (Fig. 4.26). About 55 % area in the *Gambhir* River watershed was found to be highly suitable for construction of farm ponds while rest 45 % area was not suitable for farm pond construction (Fig. 4.27).

It is found that about 333.35 km^2 area is highly suitable whereas, 268.91 km^2 area is unsuitable for construction of farm ponds. It is found that most of the suitable area lies in the central part of the *Gambhir* River watershed. The farm ponds if constructed, would be able collect vast amount of runoff and thus result into the storage structures for irrigating the crops. If it is possible to give at least one life saving irrigation to the mustard crop at the time of vegetative critical crop growth stage, then the performance of brassica sp. will drastically improve upon and so the economic status of the farming and land less category of farmers.

The criteria for farm ponds was being satisfied mainly in the agricultural lands which require water for irrigation. If there will be stored water in the ponds and irrigation could be assured, farmers will be able to grow more remunerative crops by providing irrigation else more area can be commanded under less or low water requiring crops. Due to the water storage in the area many additional advantages will emerge over the period of time as have already been demonstrated in Lawa ka Baas, Alwar (Rajasthan), Gujarat, Madhya Pradesh, Chhattisgarh and Jharkhand by different workers. The locations based on stream order criteria were presented in (Annexure-II).

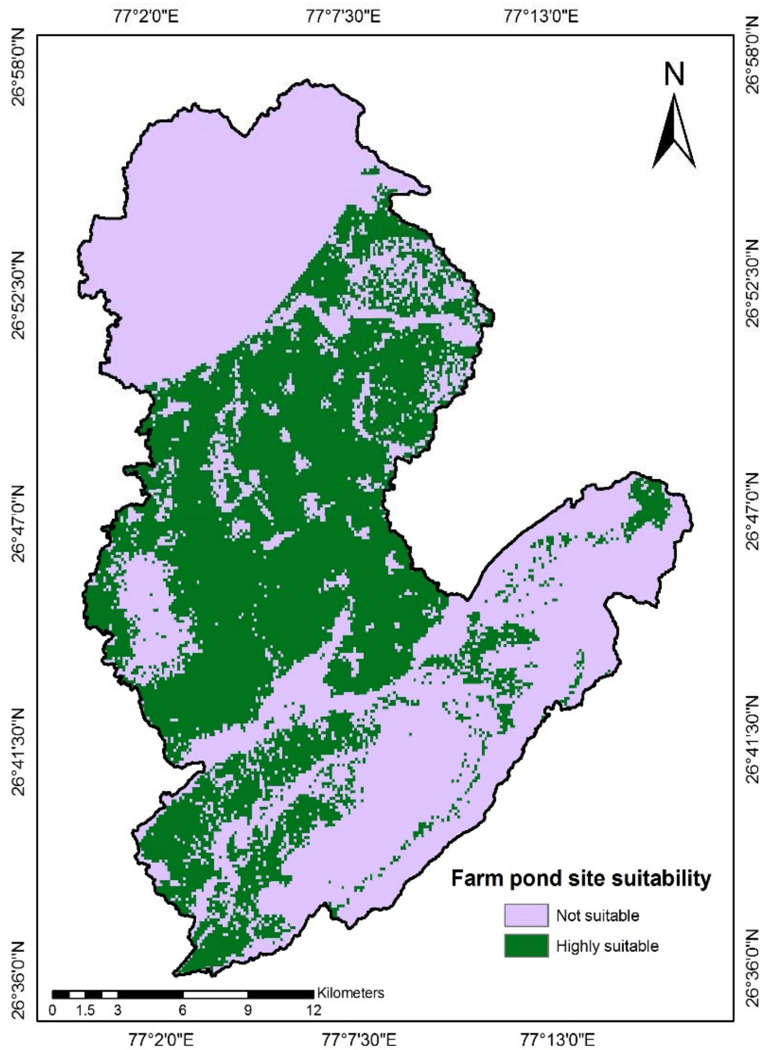

Fig. 4.26 Site suitability map for farm ponds.

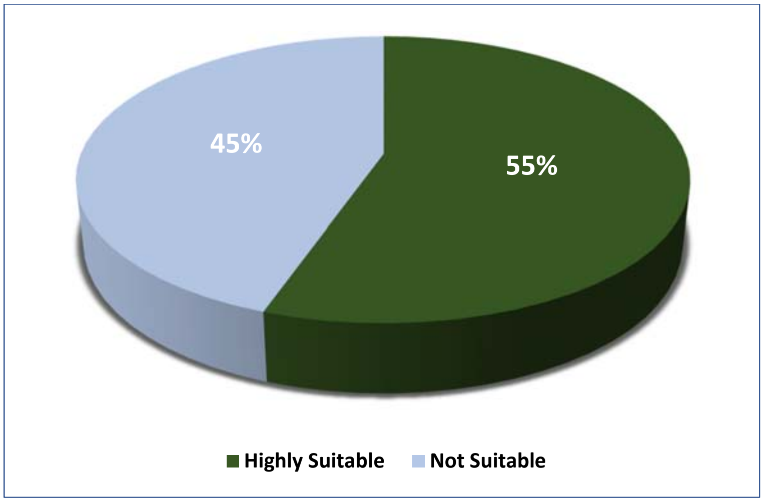

Fig. 4.27 Suitable areas for farm ponds.

4.2.4.2 Site suitability for percolation ponds

Thematic layers of the criteria shown in Table 3.7 were prepared using Boolean logic. These layers were added to get the site suitability map for percolation ponds as shown in Fig. 4.28. The resulting map is classified into three classes viz.; i) Highly suitable ii) Moderately suitble and iii) Not suitable. About 308.53 km^2 area (51%) was found to be in highly suitable category whereas 85.34 km^2 area (14%) was found to be unsuitable for construction of percolation ponds. Moderately suitable class covers 208.40 km^2 area (35%) (Fig. 4. 29). The locations based on stream order criteria were presented in (Annexure-III).

4.2.4.3 Site suitability for check dams

Same criteria as mentioned in Table 3.7 was used to prepare site suitability map. The required thematic layers prepared using Boolen logic were added to get the final suitability map. Check dams are constructed on stream orders of 3-4 preferably near agricultural lands. A total number of 15 check dams were proposed for construction as shown in Fig. 4.30.

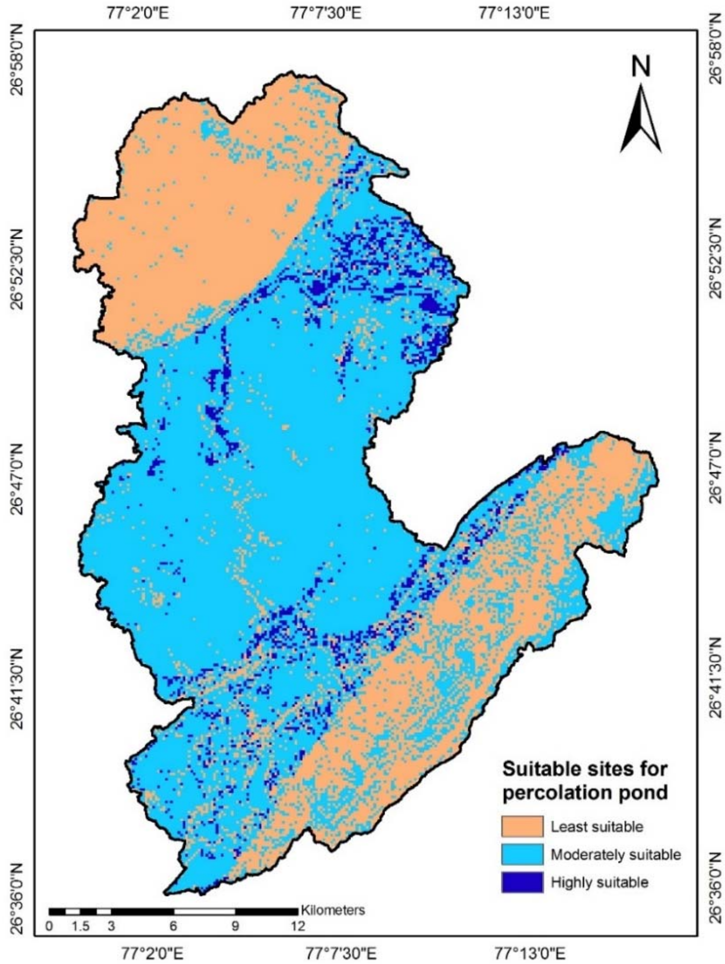

Fig. 4.28 Site suitability map for percolation ponds.

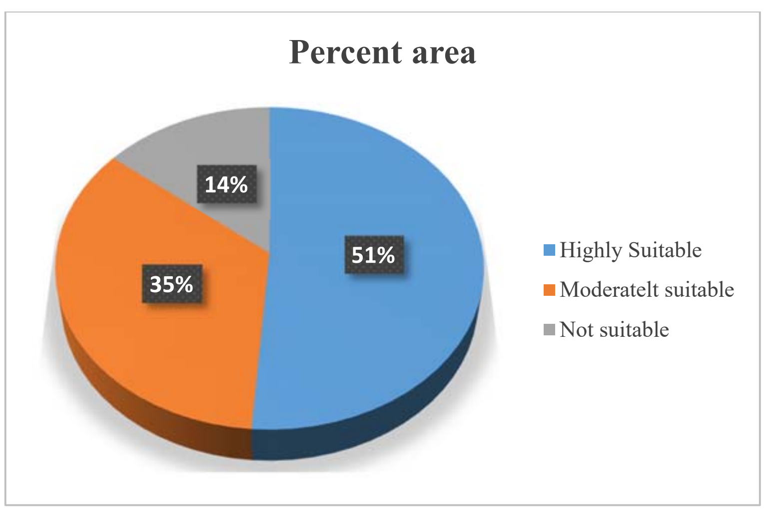

Fig. 4.29 Suitable areas for percolation ponds.

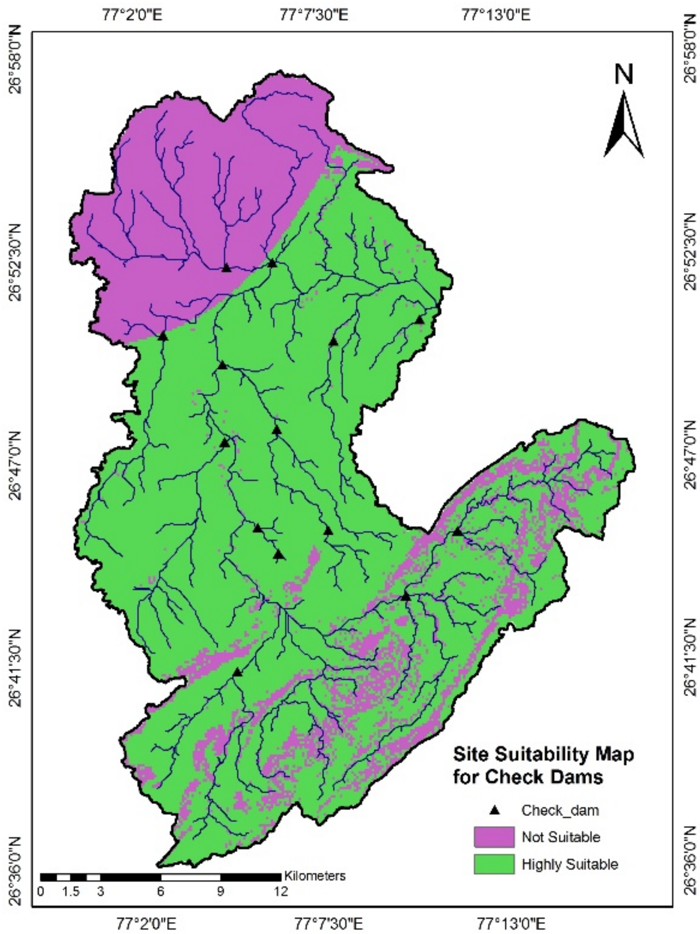

Fig. 4.30 Site suitability map for check dams.

4.2.4.4 Identification of locations of Farm ponds and Percolation ponds in *Gambhir* River watershed

Based on the site suitability map obtained from the AHP analysis using the detailed methodology as explained in section 3.6.1 and application of Boolean logic the most probable sites for Farm ponds and Percolation ponds in *Gambhir* River watershed were identified. The locations of the selected structures were assigned based on the stream order criteria as per Table 3.7. This gave the most appropriate sites for few selected structures which were then marked on the map of *Gambhir* River watershed. The point locations of different types of RWHS can be given based on the stream order criteria but the selected locations should be verified through ground truthing and with the consent of the owners of land and watershed beneficiaries. However, due to the limitations of time, all such structures could not be marked in the entire catchment because it required detailed ground truthing which was not feasible as the area of the *Gambhir* River watershed was 602.26 km^2. Hence, these maps are presented in the Appendix – 3 and 4 as technically feasible one but not as the final sites. A micro-watershed (MW-36) was therefore, then selected for detailed planning.

4.3 Detailed analysis for selected micro-watershed MW-36

The probable locations of farm ponds and percolation ponds were determined based on site suitability map and pre-decided stream order criteria. Because of the time limitations, we have selected a micro-watershed number-36 (MW-36) (Fig. 4.31) and suitable locations of different types of RWHS for this micro-watershed were suggested. The sites for proposed structures as identified by the AHP analysis were verified during field visit. The ground truthing was further augmented by zooming in the features on the ground. Hence, the most appropriate locations of selected micro-watershed are shown in Fig.4.32. However, the final decision would be made by taking into consideration the socio-economic, political aspect of the proposed location. The location of the proposed structures is presented in Fig. 4.31.

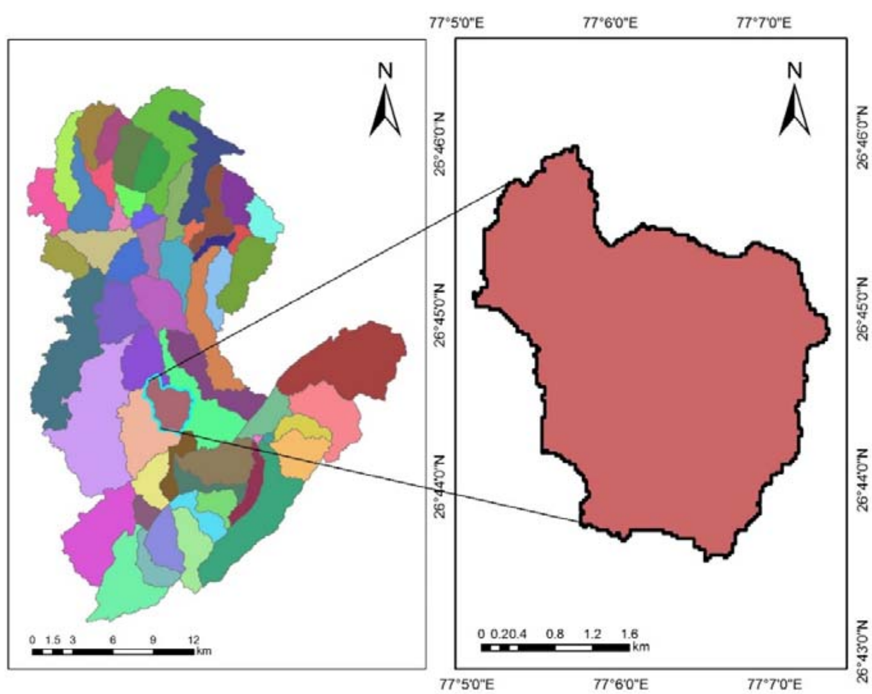

Fig. 4.31 Location of the selected micro-watershed MW-36.

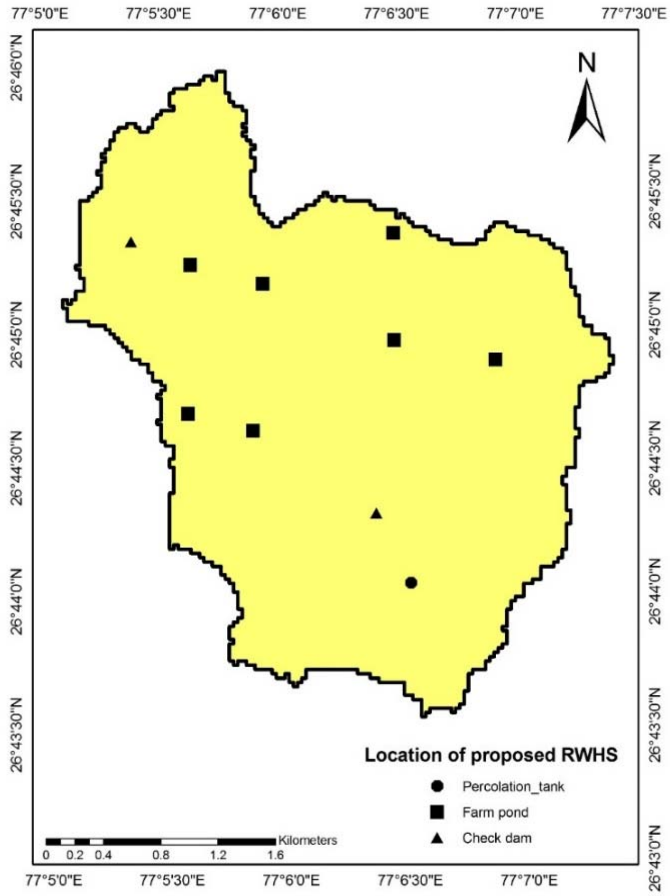

Fig. 4.32 Locations of proposed RWHS in the MW-36.

4.4 Design of Rainwater Harvesting Structures (RWHS)

For the selected micro-watershed MW-36, seven farm ponds, one percolation pond and two check dams were proposed for construction. Three locations for three different types of RWHS were randomly selected for the detailed design. The detailed hydrologic and hydraulic design of these RWHS were carried out and presented in the following sections.

4.4.1 Farm pond

The design dimensions of the dug-out type pond are computed are computed by using Prismoidal formula as given in equation (3.18). A rainfall 75 % probability compute using Weibull's distribution fitting is considered as a design rainfall. The rainfall at various probabilities is presented in Table 4.21. The catchment area of farm pond is determined using ArcGIS. The location of the selected farm pond is shown in

Fig. The design runoff is obtained by multiplying design rainfall with runoff coefficient. The design dimensions of the farm pond are shown in Table 4.22. The sample calculation is presented in Appendix-IV.

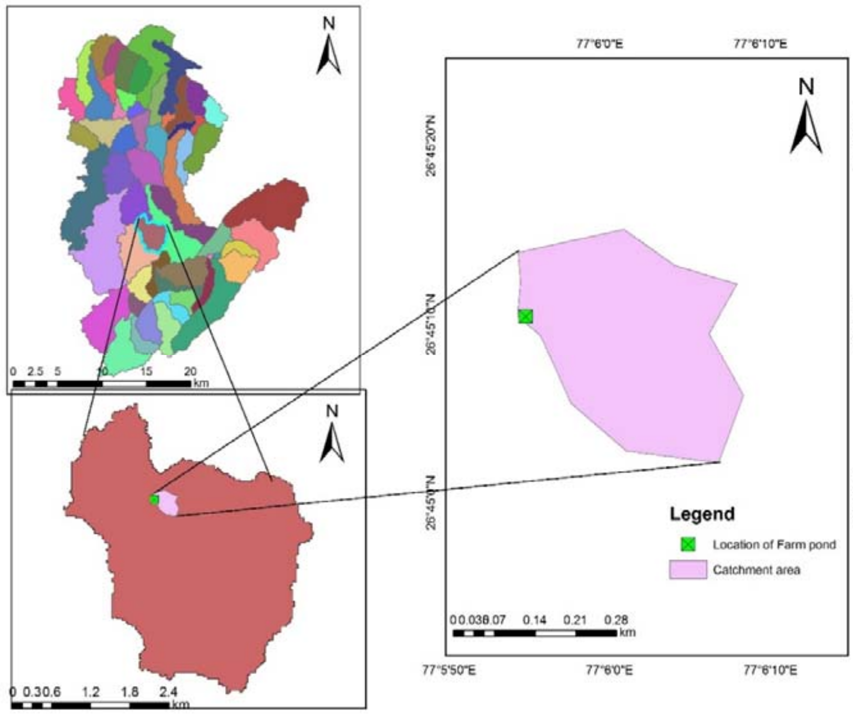

Fig. 4.33 Location and catchment area of the selected farm pond for design.

Table 4.21 Rainfall at various Probability levels using Weibull's distribution.

Year	Rainfall	Rank	Probability (%)
2016	842	1	0.08
2012	833	2	0.17
2013	825	3	0.25
2014	824	4	0.33
2008	811	5	0.42
2011	737	6	0.50
2007	523	7	0.58
2017	463	8	0.67
2009	419	9	0.75
2010	420	10	0.83
2015	359	11	0.92

Table 4.22 Design dimensions of the selected farm pond.

S. no.	Design Parameters	Value
1.	Rainfall at 75% probability	419 mm
2.	Runoff depth	134 mm
3.	Catchment area	10.66 ha
4.	Catchment yield	14284.4 m^3
5.	Assumed depth of pond	4
6.	Side slope	1.5:1
7.	Bottom width	50 m
8.	Bottom length	60 m
9.	Bottom area	3000 m^2
10.	Mid width	56 m
11.	Mid length	66 m
12.	Mid area	3696 m^2
13.	Top width	62 m
14.	Top length	72 m
15.	Top area	4464 m^2
16.	Volume of farm pond	14832 m^3

4.4.2 Check dam

The location of selected check dam is shown in Fig.4.34. **A**ccordingly, the hydrologic and hydraulic design of the check dam was attempted. Check dam was designed to for storing the volume of runoff water generated from the watershed. As the rainfall intensity data were limiting the peak rate of runoff was computed using Dickens formula instead of the rational formula. A rainfall at 75 % probability was considered as a design rainfall. The other dimensions were computed based on standard formula (Sharda et al., 2016). The computed dimensions are presented in Table 4.24. Designed sketch of the same is presented in Fig. 4.34. The sample calculation is presented in Appendix-V.

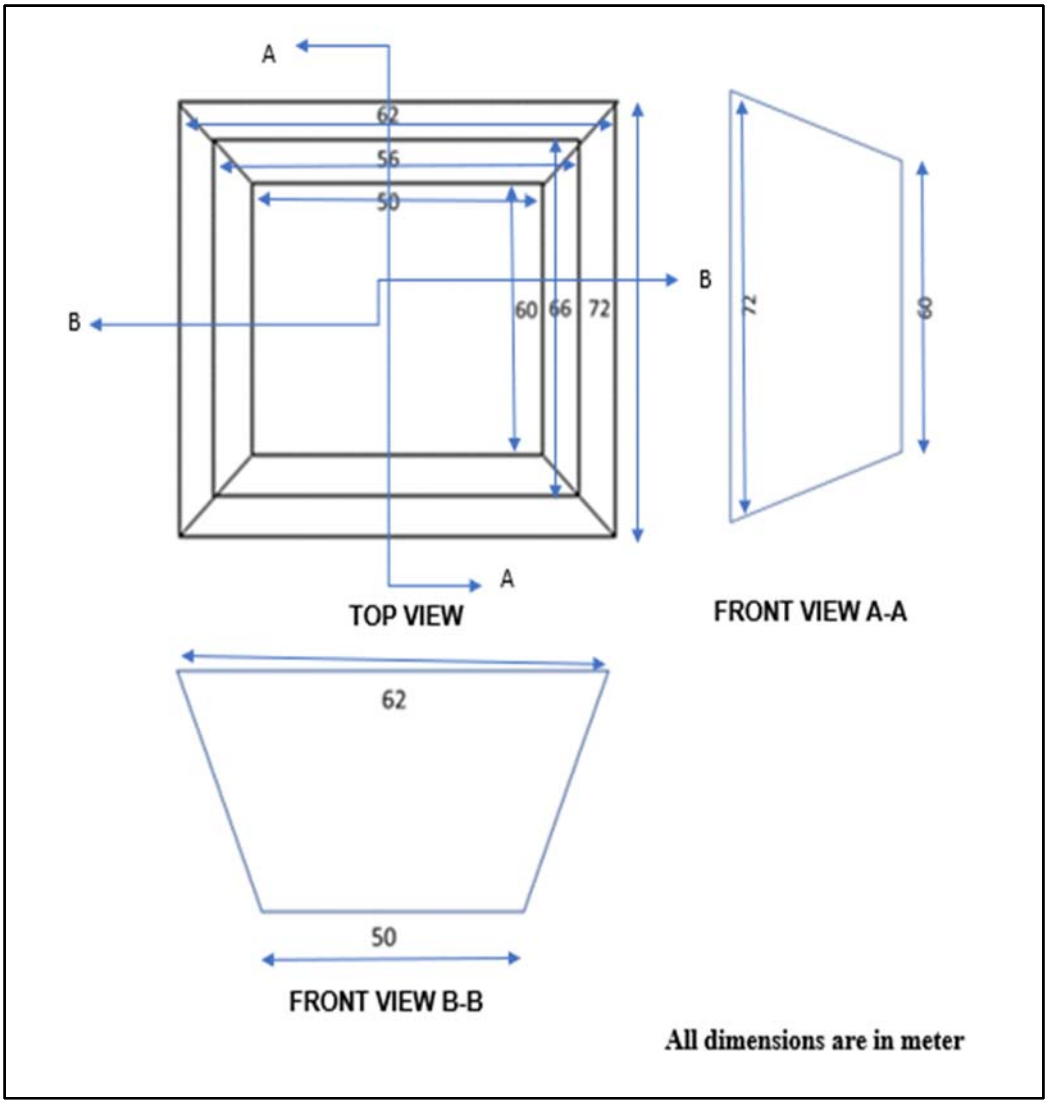

Fig. 4.34 Design dimensions of the model farm pond for storage capacity of 14,832 m^3.

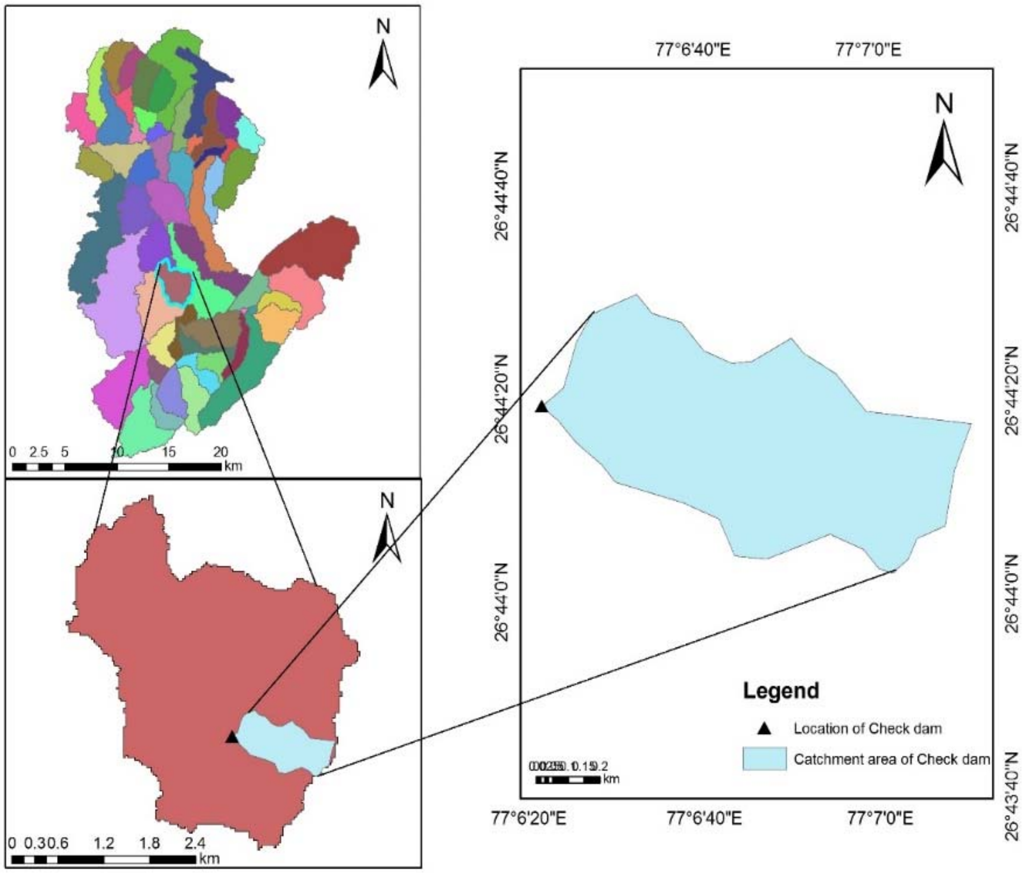

Fig. 4.35 Location of the check dam

Table 4.23 Assumed thickness and base width of design dimensions

Dimension	thickness	Base width
Head walll	0.45 m	4 m
Side wall	0.30 m	0.82 m
Wing wall	0.30 m	0.62 m

Table 4.24 Design dimensions of check dam.

S. No.	Design Dimension	Specification
1.	Peak runoff	3.147 m^3/s
2.	Net drop form top of transverse sill to crest (F)	1.5 m
4.	Total depth of weir including free board (h)	0.5 m
5.	Length of weir (L)	13.44 m
6.	Minimum length of headwall extension	2.85 m
7.	Length of apron	2.49 m
8.	Height of wing wall and side wall at junction (J)	1.5 m
9.	Height of tansverse sill	0.25 m
10.	Height of longitudinal sill (s).	0.1875 m
11.	M	1.98 m
12.	K	0.61 m
13.	Apron Thickness	25 cm
14.	Thickness of headwall extension	0.45 m

4.3.3 Percolation pond

Percolation pond was designed in the same way as a farm pond. Its sole purpose was to recharge groundwater as no lining was provided. The design dimensions of percolation pond are presented in Table 4.25. The sample calculation is presented in Appendix-VI.

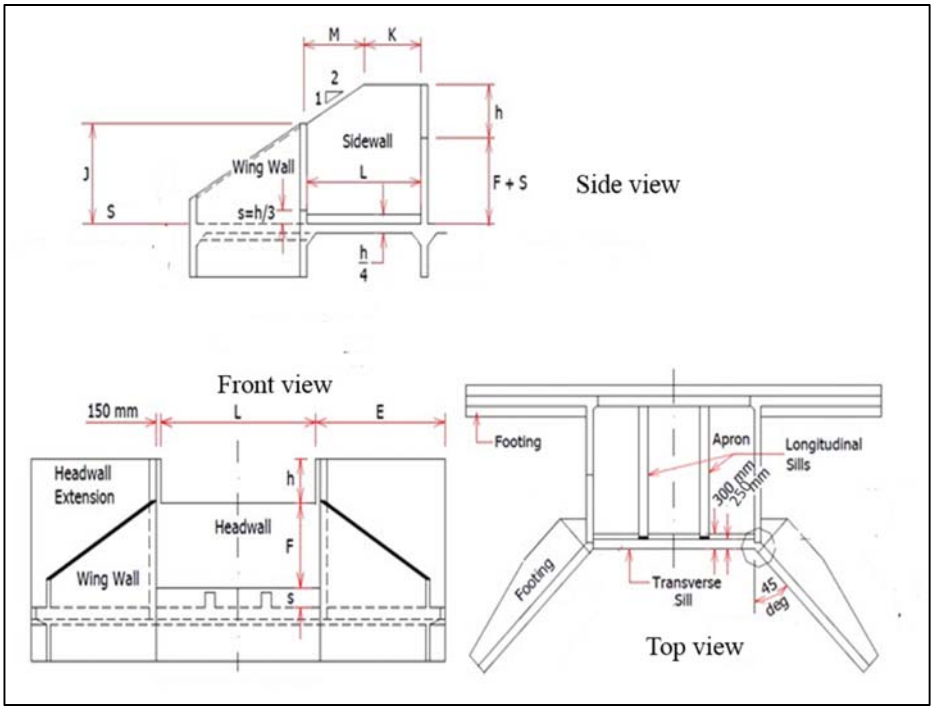

Fig. 4.36 Design sketch of Check dam.

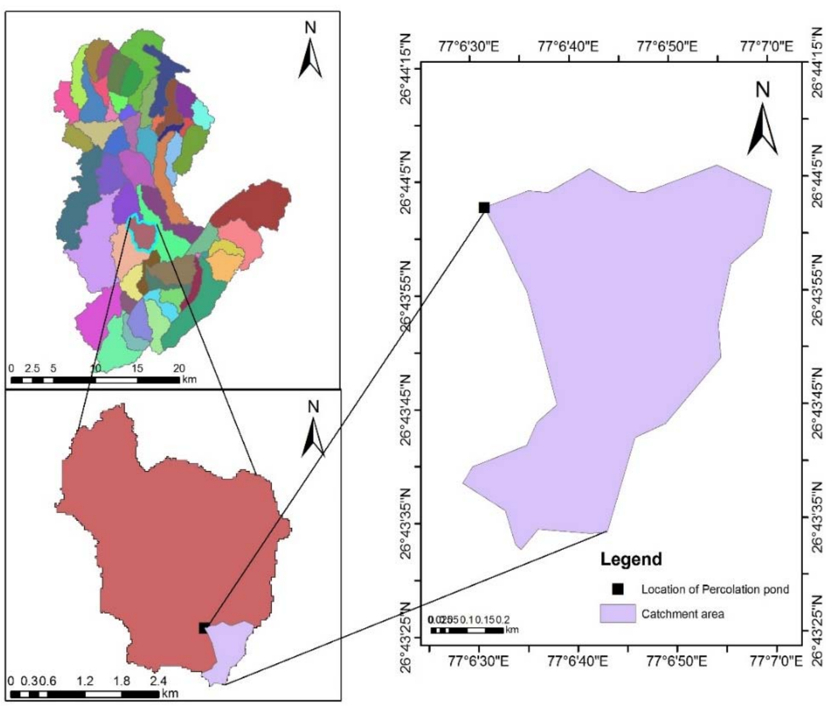

Fig. 4.37 Location of the selected percolation pond and its catchment for design.

Table 4.25 Design dimensions of Percolation pond.

Sr no.	Design Parameters	Value
1.	Rainfall at 75% probability	419 mm
2.	Runoff depth	134 mm
3.	Catchment area	26.866 ha
4.	Catchment yield	36000.44 m^3
5.	Assumed depth of pond	4 m
6.	Side slope	1.5:1
7.	Bottom width	80 m
8.	Bottom length	105 m
9.	Bottom area	8400 m^2
10.	Mid width	86 m
11.	Mid length	111 m
12.	Mid area	9546 m^2
13.	Top width	92 m
14.	Top length	117 m
15.	Top area	10764 m^2
16.	Volume of farm pond	38232 m^3

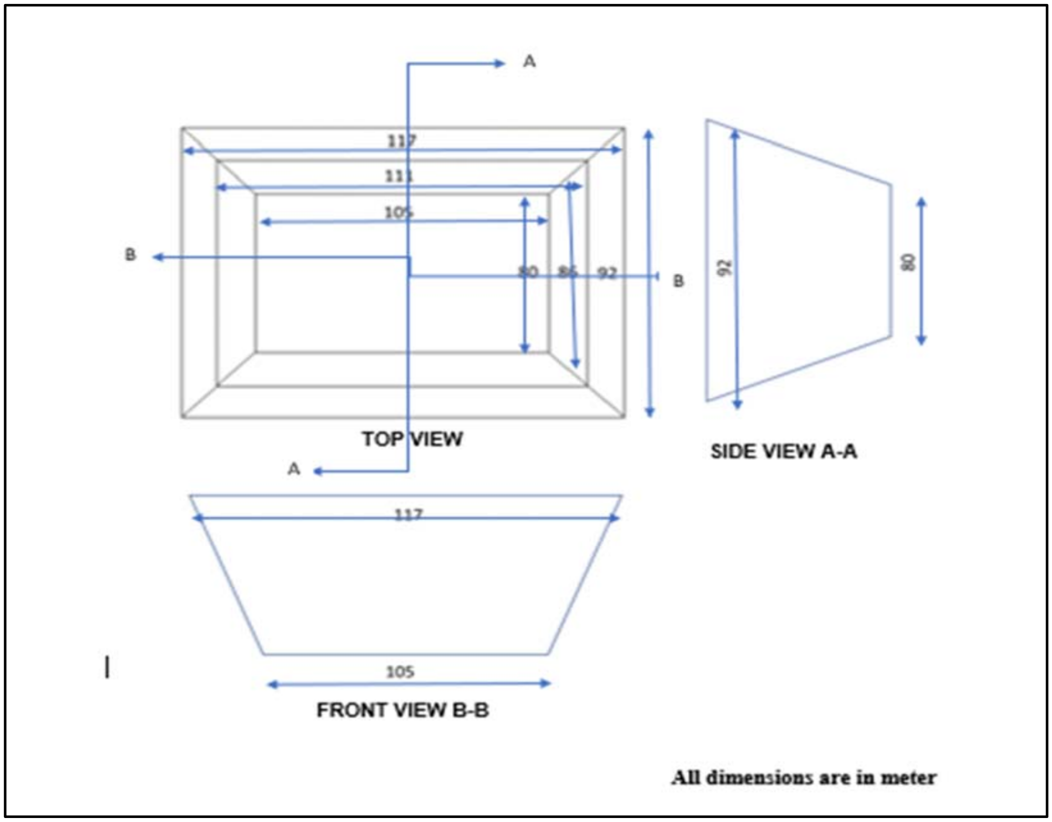

Fig. 4.38 Design dimensions of the model percolation pond for storage capacity of 38,232 m^3.

The AHP procedure adopted for micro-watershed planning could be upscaled to different other micro-watersheds of the *Gambhir* River catchment following the necessary ground truthing. Further, the novel methodology may also be applied to other areas as except a few locations specific criterion, all other databases are essentially required for this type of analysis and planning. Therefore, the present methodology can be considered as the most comprehensive and innovative to a larger extent for application in the area of watershed management. In all such type of works however, the final decision rests on the communities and watershed beneficiaries as well as the ultimate owner of the lands i.e. the government for allotment of land and final decision.

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Chapter 5

DISCUSSIONS

Water is life and around water many civilizations have flourished. Water brings prosperity so as the water storage structures. Water availability is a perennial problem in the *Gambhir* River watershed; which does receive a reasonably good amount of rainfall (av. Annual rainfall 640 mm) as compared to other parts of Rajasthan that could be harvested in the RWHS provided that the flow channels are clear and maintained. Spatio-temporal variations in the rainfall make the availability of surface as well as ground waters even worse as the surface water bodies; so vital for recharging the ground water, are facing a serious neglect of upkeep and maintenance. After analyzing the rainfall at *Hindaun* station located inside the *Gambhir* River watershed, it was found that the annual rainfall showed decreasing trend. A similar trend in Rajasthan was observed by Pingale et al., 2014 and Roy, 2015). Rainy days also followed a decreasing trend. Over the last six decades the heavy draft on ground water without proper attention to recharge has resulted into sharp declination in quantity and quality of the water (CWC, 2019). This makes a perfect case for creation of newer RWHS vis- a- vis rejuvenation of the older ones. This will not only help in quick recharging of the ground water but also in arresting the land resources degradation due to water erosion. Identification of suitable sites for (RWHS) is an important step for maximizing water availability and land productivity in the semi-arid areas.

In the past era, the most common method for determining potential site for RWHS for small area was the ingenuity and traditional knowledge of the people; about their resources and landscapes. Due to feudal nature of the land ownership, it was easy for the rulers to get large Rain Water Harvesting Structures created at appropriate locations without any problem and that was acclaimed as *Dharma*. The modern era is witnessing many new problems including the availability of land for creation of structures despite the benefits. More so, the lack of complete and correct methodologies, unwillingness of the watershed beneficiaries to part with their land and faulty construction; many RWHS constructed these days are either unused or abandoned after few years of operations. Methodology for designing RWHS has become much advanced from the most primitive nature; based on the advent of new tools and techniques of data collection and analysis.

These days GPS assisted field surveys using Total Stations, Remote Sensing, Drones, and Remotely Sensed data are increasingly being used for site selection against the old model field surveys (Srivastava et al., 2010; Shanwad et al., 2011; Suresh et al., 2013) that offer great challenge for selecting suitable sites in larger areas. Also, field surveys demand a lot of resources for collection of point data of temporal and spatial nature for planning (Glendenning et al., 2012). Such method consumes more time and it involves intensive labour which is costly task. Nevertheless, it results into collection of high-resolution information which are vital for Water Resources Planning (Mkiramwinyi et al., 2009; Mugo and Odera, 2018). However, in India, the availability of data of various kind is not very good as well as acquiring the available information is also a challenging task. As in case of *Gambhir* river watershed, due to the non-availability of rainfall intensity data, the rational method could not be employed for estimation of peak rate of runoff for designing the check dams. In an early attempt to use the modern tools, Gupta et al., (1997) estimated the rainwater harvesting potential for a semi-arid area of Rajasthan state, India using geographic information system (GIS) and remote sensing. However, the accuracy of results depended on the resolution of the data. Although the SCS runoff curve number model was used to compute the annual runoff potential for each basin due to change in the amount of the annual runoff volume the number of proposed structures were reduced. This was due to not being able to use the event-based rainfall due to lack of data.

Ramakrishnan et al., (2009) proposed a methodology for site selection of different RWH structures like check dam, percolation pond, farm pond, well and subsurface dyke in semi-arid Kali watershed of Gujarat based on spatially varying parameters like runoff potential, slope, fracture pattern and micro-watershed area using RS and GIS. The sites for water harvesting structures were located with the help of overlay and decision tree concepts in GIS supported with ground truthing. In designing the RWHS we have used the rainfall information of four meteorological stations. This has improved the accuracy of the basic parameter i.e rainfall for predicting the designed runoff. The spatial variability map was prepared and used based on the greater number of stations had reduced the uncertainty in rainfall. Many other workers have also recommended such data analysis for more accuracy in predicting the rainfall (Kadam et al., 2012; Prasad et al., 2014).

Remote sensing (RS) and geographical information systems (GIS) have been used by many investigators to locate suitable sites for different RWH systems in other parts of the country (Ramakrishnan et al., 2008; Chowdary et al., 2009) The RS and GISs are especially suited to meet the data requirements for selecting suitable locations for RWH in Arid and Semi-Arid regions as most of the areas are ungauged. RS and GIS increase the accuracy and precision of run-off prediction which finally helps in identifying potential locations for RWHS in cost-effective manner for better management of water resources of the region.

Many more workers have used RS, GIS and other ancillary data for identification of suitable sites of RWHS using the capabilities of GIS for superimposing various thematic layers and arriving at most suitable sites. A few workers have assigned weights to criteria and based on the composite index identified their site suitability (Kadam et al., 2012; Tumbo et al., 2013; Naseef and Thomas, 2016 and Rejani et al., 2017). The RS data used in all past works was of coarse resolution due to non- availability of fine resolution data. However, advanced technique for multi criteria decision analysis were also not used. In the present study, the Sentinal-2A data for LULC classification was used because of its high resolution and availability on free domain. The Sentinal- 2A data gave more accurate results and due to this the accuracy of prediction of runoff has improved. Similarly, for Digital Elevation Model (DEM) for generation of various thematic maps including the drainage map the ALOS data has been used which has very high resolution amongst the available sources of information.

Normally data analysis (GIS and Soft Computing Tools like Genetic Algorithm, Multi Criteria Decision Making Tools (MCDs)) including Analytical Hierarchical Programming, Artificial Neural Network and other Hybrid Models involving ANN and Wavelets/ Baysian Algorithms/ Ant Algorithm and others; are not very easy yet provide better solutions to planners. However, these techniques being highly advanced and complex in nature, are data intensive which is the major bottleneck in their application particularly in Indian watersheds which are not so well equipped as for as the data collection is concerned. In the present study, the AHP Multi Criteria Decision Analysis technique was used in tandem with probable rainfall and its spatial mapping, NRCS-CN generated designed runoff potential, soil and LULC, slope and drainage density following the methodology as innumerate in section 3.6. In this study Boolean logic was used for demarcating the suitable areas for specific type of RWHS. For siting the locations of RWHS stream order criteria was considered. Although Prasad et al., (2014) conducted a study to locate suitable sites for RWH structures using GIS and Multi Criteria Evaluation (MSE) technique; equal weightage was allocated to different thematic layers while integrating which seems unjustified.

Previously AHP was used to give percentage importance to different layers in a study to locate suitable site for RWH structures using GIS, RS and Multi Criteria Decision Making technique. Ahmad and Verma (2017); carried out site suitability investigation for locating different types of soil and water conservation structures using weighted overlay analysis. Mugo and Odera (2018) presented weighted overlay analysis approach to select potential sites for RWH structures using geospatial techniques. In our study however, a greater number of criteria supported with Boolean logic and stream order criteria were considered which was better than the previous works on this topic.

AHP and Fuzzy modelling were employed for developing RWH site suitability model to locate potential zones of RWH in Arsi Zone of Central Ethiopia (Haile and Suryabhagavan, 2019). Use of Fuzzy Extent Analysis to identify more influential criteria appears to be a better option provided data pertaining to many parameters; that could not be inferred well using common logic systems. In our research work however, we did not face any such difficulty. The most influential criteria observed in my study were runoff depth (39 %), rainfall (27 %), and slope (16 %). The drainage density did not influence the decision making for site selection (3 %). In the present study the efforts were made to overcome this problem by use of Boolean Logic technique which proved better than the previously established procedures. Therefore, the present methodology can be called as most innovative, comprehensive and logical hence, could be strongly recommended for such analysis for siting of RWHS in similar watersheds as well as other areas as propounded before.

The study by Haile and Suryabhagavan (2019) recommended that ground validation and socio-economic factors should be considered before implementation to increase the effectiveness of RWH which corroborates my conclusion and hence, for more detailed investigations and analysis a micro-watershed MW-36 was selected before finally locating various structures on ground duly supported with the ground truthing and its further rectification using Google map. Further in the present study, it was rightly and most appropriately concluded that using such advanced methodology, tools and techniques only the most feasible technical solutions can be proposed. Using the other important socio-economic and geo-political criteria viz.; land ownership and estimated benefits from the construction of RWHS; the real solutions may be generated. Finally, the ultimate decision for construction of RWHS should rest on the mutual consent of watershed beneficiaries and stakeholders.

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Chapter 6

SUMMARY AND CONCLUSIONS

The declining per capita land and fresh water availability, soil erosion and land degradation are posing serious threat to food, economic and ecological security of India in general and arid and semi-arid regions of Rajasthan in particular (Anonymous, 2019). Effective conservation through various conservation practices/structures (i.e. in-situ and ex-situ), efficient and prudent utilization and best management of these basic natural resources are some of the major issues for ensuring higher productivity, growth and development vis-à-vis natural resources sustainability in the country (Sharada et al., 2016). The demand of water in our country has increased drastically due to the exponential rise in human population over the last few decades (CWC, 2019). In present scenario of climate change; the need of water is growing twice as fast as growth of population. Out of 2.5% of global fresh water, only 1% is available for human consumption (Oki et al., 2006; Hoekstra, 2009). According to the World Bank, India will be in water stress zone by the year 2025 and water scare zone by 2050 (Anonymous, 2002).

In arid regions of Rajasthan, traditional rainwater harvesting structures are; Kui and *Tankas.* In some other parts of Rajasthan where rainfall is moderate; large water bodies such as *Baodis* and *Lakes* also have been created for harvesting the scanty rainfall for future utilization like drinking and other domestic purposes. Large RWHS are still found in almost all parts of the state such as; *Alwar, Udaipur, Jaipur and Puskar;Ajmmer.* Similarly, farmers have also tried to conserve the rain water in different types of ponds with limited success due to edaphic and climatic constraints. The harvested water gets evaporated fast and due to high rate of seepage; percolates underground. While the deep percolation of water augments the ground water; the evaporation losses need to be minimized. In order to collect and harvest the surplus rainwater originating as runoff, it is therefore, evident that concerted efforts should be made to conserve the water with the help of modern scientific knowledge and tools/techniques like Remote sensing and GIS.

It was hypothesized that RWH and its efficient utilization, a time-tested technology, can be successfully employed to increase the availability of water for crop and livestock production and to mitigate the adverse effects of incessant droughts. Therefore, the present study was undertaken in a selected experimental watershed in *Bharatpur* and Karauli districts located between 26° 36′ 0.8″ N to 26° 57′ 35″ North latitudes and 77° 0′ 2″ E to 77° 16′ 54″ E longitudes, that receives an average annual rainfall of 640 mm. Despite receiving relatively more rainfall as compared to other parts of the state, the productivity of different crops as well as the cropping intensity has been low. About 91 % of the total rainfall occurs in four months between June to September while remaining 8 months receive only 9% of the total rainfall. Due to this reason, there is an acute shortage of water in the non-monsoon months (October-May) even for drinking; as most of the villages get the drinking water through tankers. Due to water scarcity, low water holding capacity and high hydraulic conductivity (K) of the soils of the study area, only the Mustard crop, which requires very less water and tolerant to salinity is widely grown in the area during the *Rabi* cropping season. Area under vegetables and other R*abi* crops is also very limited due to water scarcity. Most of the area relies on rainfall and ground water pumping from tube wells for irrigation. However, as there are many other limitations on the groundwater resources due to which the status of groundwater development is also low. Farmers, having facility of lifting water in their fields; cultivate cash crops while the farmers of rainfed area practice single cropping system. The *Kharif* cropping season in the experimental watershed is predominantly rainfed with occasional rainfall excesses that may be conserved in the specially designed and constructed Rain Water Harvesting Structures with the provision of checking the seepage using different techniques like HDPE lining etc.

The main research gap as identified in the field surveys was non-scientific siting and sizing of RWHS which needed attention and therefore, the present study was initiated with the major objective of quantification of harvestable runoff as well as use of Analytical Hierarchal Process for optimization of possible location for construction of RWHS. Consequently, the present study was undertaken to fulfil the above objectives in an experimental watershed namely the *Gambhir* River Watershed which receives relatively moderately higher rainfall and has substantial area under agriculture requiring assured irrigation.

The selected study area was ungauged therefore, the surface runoff potential of the study area was estimated using the NRCS-CN method. The land use/land cover map, hydrologic soil group map and curve number maps were prepared in ArcGIS environment which were used to prepare runoff map of the study area. Various thematic maps i.e., land use/land cover map, runoff map, slope map, rainfall map, soil map, and drainage density map were considered for preparation of RWH potential zone map. Relative weights were assigned to all these criteria including sub-criteria of each these based on expert opinion by constructing pairwise comparison matrix using AHP. Each thematic layer was reclassified based to the weights assigned to sub-criteria of each main criteria. These thematic layers were integrated in ArcGIS environment based on weights of each main criteria using Weighted Linear Combination (WLC) method which gives a Water Harvesting Potential Index (RWHPI). The weight of each criterion obtained by AHP analysis was multiplied by the reclassified map to yield Rainwater Harvesting Potential Zone map.

Depending upon the predicted rainfall, estimated runoff, soil type, land use /land cover conditions, slope and soil hydraulic properties; three types of RWHS were identified as most suitable viz.; farm pond, check dam and percolation pond that were suggested for the given study area. Boolean logic was used to prepare site suitability maps for particular type of RWHS. The criteria for selecting a particular type of RWHS was adopted as mentioned in Table 3.2. Various thematic maps were prepared using Boolean logic which gave value of 1 to those sub-criteria that are suitable for a particular type of structure leaving other sub-criteria as zero. These maps were then overlaid using raster calculator which results in a map that gave suitable zones for a particular type of RWHS. The decision for precisely locating the RWHS however, should be made very carefully based on the ground truthing, socio-economic preferences (beneficiaries' choice and consideration) along with the scientific tools and techniques. Detailed methodology for selection of appropriate RWHS using AHP is given in Section 3.2.

For detailed analysis, one micro-watershed was selected and the locations of seven farm ponds, two check dams and one percolation pond were identified and mapped. Out of identified ten locations; three locations of these three different types of structures were randomly selected and the detailed hydrologic and hydraulic design procedures were followed to compute the design dimensions. The catchment area of these structures was demarcated and mapped. The design sketch of each of these structures were drawn. Following the comprehensive AHP analysis; the detailed methodology as described in detail in Chapter 3; the obtained results were presented in Chapter 4 and discussed. Following major conclusions could be drawn from the present research work:

1. The surface runoff from the experimental watershed estimated using NRCS-CN method was found to be 149.07 Million m^3 and the composite runoff coefficient of the area was 0.32 over a period of 11 years.
2. The runoff depth over the entire watershed varied from a minimum of 136 to a maximum of 321 mm based on spatial variability analysis.
3. About 75.54 km^2 (13%) area was very highly suitable whereas 114.56 (19%) area was highly suitable for construction of RWHS. About 43.77 km^2 area was not suitable at all for constructing any type of RWHS.
4. The study concluded that approximately 55% area in the experimental watershed was highly suitable for construction of farm ponds. The highly suitable areas for construction of farm ponds were identified and mapped.
5. About 308.53 km^2 (53%) area in the watershed was highly suitable for constructing percolation ponds. The most suitable areas for locations of percolation pond have been identified and mapped.
6. The study concluded that a total number of 15 check dams can be constructed in the experimental watershed to harvest the channel flows for future use at the identified sites based on AHP technique as these techniques work effectively in identifying potential sites for RWHS.
7. The standard designs of different types of RWHS (farm ponds, percolation ponds and check dams) for the corresponding designed runoff/ peak rate of runoff in the identified micro-watershed (MWS 36) located inside the main experimental watershed, were finalised.
8. AHP, one the most comprehensive decision-making technique for site selection of different types of RWHS, could be successfully employed to locate the RWHS as one of the identified check dams fell straight on the dam site of an existing RWHS namely; Jagar Dam, *Hindaun City*, district *Karauli*.
9. The study has demonstrated that AHP in combination with other techniques like Boolean logic, RS and GIS can further improve the accuracy of procedure that in turn can be successfully employed for sizing and siting of different other types of RWHS.

10. The study can be successfully employed in watersheds of same agro-climatic, edaphic and morphometric (terrain) conditions of Rajasthan state in particular and in other arid and semi-arid regions in general. This technique can also be employed for selecting the types and locations of the RWHS in other agro-climatic regions as well.

Major scientific contributions originating from the present research and addition to the existing know how of RWHS design using most modern tools of data collection and analytical techniques are as follows:

1. Because the accuracy of site selection depends on the quality of data used for the analysis; the present research work is of high accuracy as in the present study, a high-resolution LULC satellite data of 10 m spatial resolution (Sentinal-2A satellite) was. It is reported to be more accurate in LULC classification than commonly used Landsat-8 data. Also, ALOS data for DEM; whose effective resolution is much better than ASTER and SRTM satellite DEM data and gives more accurate river drainage network was used in the present study making the quality of the database quite good.

2. The RS and GIS in combination with most comprehensive Multi-Criteria Decision-Making Technique i.e., AHP (that was used for optimizing the site selection procedure in the present research) proved to be the most accurate methodology.

3. Apart from AHP, Boolean logic that was used in the present research, to demarcate the potential areas for various types of RWHS based on the pre-decided criteria, is its unique application in hydrology.

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ABSTRACT

The present study was undertaken in *Gambhir* River watershed in *Bharatpur* and *Karauli* districts of Rajasthan (India). The watershed was located between 26 36′ 0.8″ N to 26 57′ 35″ North latitudes and 77 0′ 2″ E to 77 16′ 54″ E longitudes. Most of the surveyed Rainwater Harvesting Structures (RWHS) in the study area (Check Dams, Anicuts, *Khadins* and Ponds etc.) were in dilapidated conditions; silted or dried up. The ground water recharge reduced while pumping (draft) steadily increased resulting in to sharp decline of water table requiring creation of new RWHS vis-à-vis repair and maintenance of the existing ones. Objectives of the present study were: (i) estimating surface runoff potential of the watershed using NRCS-CN method and Geospatial techniques; (ii) selection of most appropriate sites for different types of RWHS using Analytic Hierarchy Process (AHP); and (iii) design of different types of Rainwater Harvesting Structures (RWHS).

The average depth of surface runoff; estimated based on spatial variability analysis over a period of 11 years (2007-2017), i.e. the runoff potential of the watershed varied from 136 to 321 mm. While the runoff volume was estimated as 149.07 Million m^3 with a runoff coefficient of 0.32. Site suitability analysis for construction of different types of RWHS was attempted using RS, GIS, AHP and Boolean logic. Nearly 75.54 km^2 (13%) area was found to be very highly suitable whereas, 114.56 km^2 (19%) area was highly suitable for construction of RWHS. About 43.77 km^2 area was not suitable at all for construction of any type of RWHS. Three types of RWHS including farm pond, check dam and percolation pond were suggested for the given study area based on the criteria. Further, it was found that approximately 55% area in the experimental watershed was highly suitable for construction of farm ponds. About 308.53 km^2 (53%) area was highly suitable for constructing percolation ponds. A total number of 15 check dams were proposed for construction at appropriate locations as identified in this study. In the selected micro-watershed for detailed planning (MW 36) out of 59 micro-watersheds in the main watershed; about 7 farm ponds, 2 check dams and 1 percolation pond; were identified and mapped. The locations of 3 different types of structures were randomly selected in MW 36 for detailed hydrologic and hydraulic design following the scientific design procedures. The designed dimensions were computed and their drawings finalized corresponding to the designed runoff. The present research work demonstrated that the AHP was one of the most comprehensive decision-making techniques for site selection of different types of RWHS incorporating a large number of suitability criteria. The study has aptly demonstrated that AHP in combination with other techniques like Boolean logic, RS and GIS can be successfully employed for sizing and siting of different types of RWHS.

Keywords: Analytic Hierarchy Process (AHP), Rainwater Harvesting Structures (RWHS), Remote Sensing (RS), Geographical Information System (GIS) and Fuzzy Logic.

सार

वर्तमान अध्ययन राजस्थान (भारत) के भरतपुर और करौली जिलों में गंभीर नदी के जलग्रहण क्षेत्र में किया गया था । जलग्रहण क्षेत्र $26^0\ 36'\ 0.8''$ N से $26^0\ 57'\ 35''$ उत्तर अक्षांशों और $77^0\ 0'\ 2''$ पूर्व से $77^0\ 16'\ 54''$ पूर्व देशांतरों के बीच स्थित था । अध्ययन क्षेत्र में सर्वेक्षण की गयीं अधिकांशतर जल संग्रहण संरचनाएँ जैसे: चेक डैम, एनीकट्स, खडिन्स और तालाब आदि, जीर्ण-शीर्ण स्थितियों में थीं; मिट्टी और गाद से भरे हुयी अथवा या सूख गयी थीं । पंपिंग (ड्राफ्ट) के दौरान भूजल पुनर्भरण में लगातार कमी आई, जिसके परिणामस्वरूप जल तालिका में भारी गिरावट आई, जिससे वर्तमान जल संग्रहण संरचनाओं के पुनर्नवीनीकरण, मरम्मत और रखरखाव के साथ साथ नवीन जल संग्रहण संरचनाओं के निर्माण की आवश्यकता प्रतीत हुई । वर्तमान अध्ययन के उद्देश्य निम्न थे: (i) NRCS-CN विधि और भू-स्थानिक तकनीकों का उपयोग करके जलग्रहण क्षेत्र की सतह अपवाह क्षमता का आंकलन करना; (ii) विश्लेषणात्मक पदानुक्रम प्रक्रिया (AHP) का उपयोग करके विभिन्न प्रकार की जल संग्रहण संरचनाओं के लिए सबसे उपयुक्त स्थानों का चयन; और (iii) विभिन्न प्रकार की जल संग्रहण संरचनाओं का प्रारूपण।

विगत 11 वर्ष (2007-2017) की अवधि में, सतह अपवाह की औसत गहराई; स्थानिक परिवर्तनशीलता विश्लेषण के आधार पर अनुमानित, अर्थात् जलग्रहण क्षेत्र की अपवाह क्षमता, 136 से 321 मिमी तक पाई गयी । जबकि अपवाह मात्रा 149.07 मिलियन मीटर^3 (0.32 के अपवाह गुणांक के साथ) अनुमानित की गई । विभिन्न प्रकार की जल संग्रहण संरचनाओं के निर्माण के लिए स्थल उपयुक्तता विश्लेषण हेतु, सुदूर संवेदन, भौगोलिक सूचना प्रणाली (जीआईएस), विश्लेषणात्मक पदानुक्रम प्रक्रिया (एएचपी) और बुलियन लॉजिक का उपयोग करने का प्रयास किया गया । जल संग्रहण संरचनाओं के निर्माण के लिए लगभग 75.54 किमी ^{2} (13%) क्षेत्र बहुत अधिक उपयुक्त पाया गया, जबकि 114.56 किमी ^{2} (19%) क्षेत्र जल संग्रहण संरचनाओं के निर्माण के लिए अधिक उपयुक्त था । लगभग 43.77 किमी ^{2} क्षेत्र किसी भी प्रकार की जल संग्रहण संरचनाओं के निर्माण के लिए बिल्कुल भी उपयुक्त नहीं पाया गया । मापदंड के आधार पर दिए गए अध्ययन क्षेत्र के लिए खेत तालाब, चेक डैम और अवशोषण (परकोलेशन) तालाब सहित तीन प्रकार की जल संग्रहण संरचनाओं के निर्माण का सुझाव दिया गया । इसके अतिरिक्त, यह भी पाया गया कि प्रयोगात्मक जल ग्रहण क्षेत्र में लगभग 55% क्षेत्र खेत तालाबों के निर्माण के लिए अत्यधिक उपयुक्त था । लगभग 308.53 किमी^{2} (53%) क्षेत्र अवशोषण (परकोलेशन) तालाबों के निर्माण के लिए अत्यधिक उपयुक्त था । इस अध्ययन में पहचान के अनुसार उपयुक्त स्थानों

पर निर्माण के लिए कुल 15 चेक डैम प्रस्तावित किए गए। मुख्य जलग्रहण क्षेत्र में 59 सूक्ष्म जल ग्रहण क्षेत्र (माइक्रो-वाटरशेड) में से विस्तृत नियोजन के लिए चयनित सूक्ष्म जल ग्रहण क्षेत्र (माइक्रो-वाटरशेड) (MW 36); में लगभग 7 खेत तालाब, 2 चेक डैम और 1 परकोलेशन तालाबों के उपयुक्त स्थलों की पहिचान की गयी और मानचित्रण किया गया। विस्तृत वैज्ञानिक प्रारूपण (डिजाइन) प्रक्रियाओं के आधार पर जल विज्ञान और जलीय (हाइड्रोलिक) डिजाइन के लिए सूक्ष्म जल ग्रहण क्षेत्र (माइक्रो-वाटरशेड)) MW 36 में 3 विभिन्न प्रकार की संरचनाओं के स्थानों को सुनियोजित ढंग से चुना गया। प्रारूपित जल संग्रहण संरचनाओं के आयामों और परिमाण की गणना की गई और उनके मानचित्र भी बनाए गए। इस अध्ययन में यह भी पाया गया कि प्रारूपित की गयी जल संग्रहण संरचनाएँ अपवाह के अनुरूप थी। वर्तमान शोध कार्य ने यह प्रदर्शित किया कि विभिन्न प्रकार की जल संग्रहण संरचनाओं के स्थान निर्धारण के लिए विश्लेषणात्मक पदानुक्रम प्रक्रिया, सबसे व्यापक निर्णय लेने वाली तकनीकों में से एक थी, जिसमें बड़ी संख्या में उपयुक्तता मानदंड शामिल थे। इस अध्ययन ने उपयुक्त रूप से प्रदर्शित किया है कि बुलियन लॉजिक, सुदूर संवेदन और भौगोलिक सूचना प्रणाली अन्य तकनीकों के संयोजन में विश्लेषणात्मक पदानुक्रम प्रक्रिया (एएचपी) को विभिन्न प्रकार की जल संग्रहण संरचनाओं के आकार और आयाम के प्रारूपण हेतु सफलतापूर्वक प्रयुक्त किया जा सकता है।

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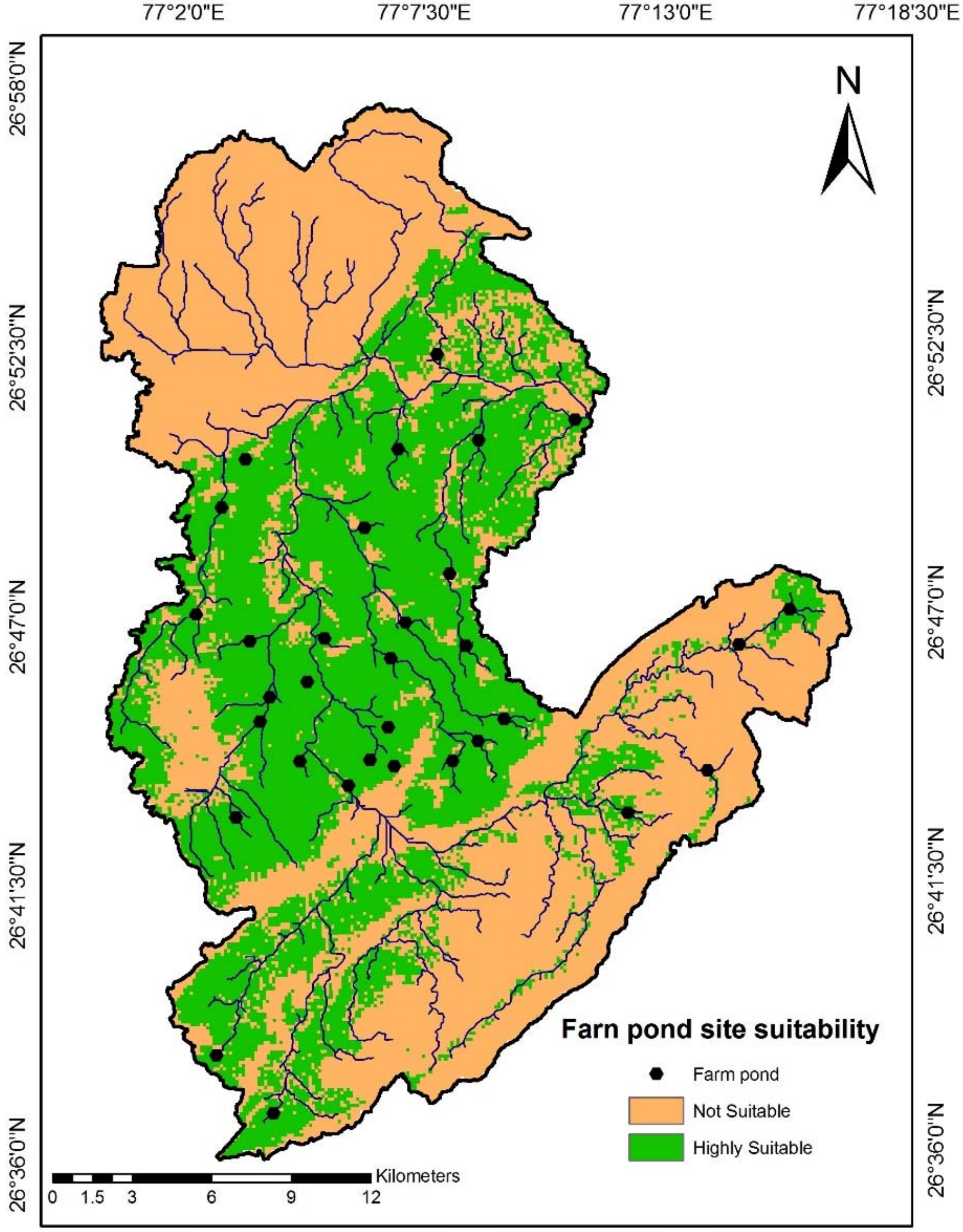
APPENDIX-I

Textural analysis of soil samples collected from five stations in the *Gambhir* River watershed

Soil samples	Latitude	Longitude	Sand	Silt	Clay	Soil texture
Sample 1	26.7776°	77.0800°	42.28	35	22.72	Loam
Sample 2	26.8055°	77.1416°	52.28	29	18.72	Sandy Loam
Sample 3	26.7570°	77.0936°	54.28	25	16.72	Sandy Loam
Sample 4	26.7183°	77.0321°	47.28	31	21.72	Loam
Sample 5	26.7088°	77.1500°	38.28	34	27.72	Clay loam

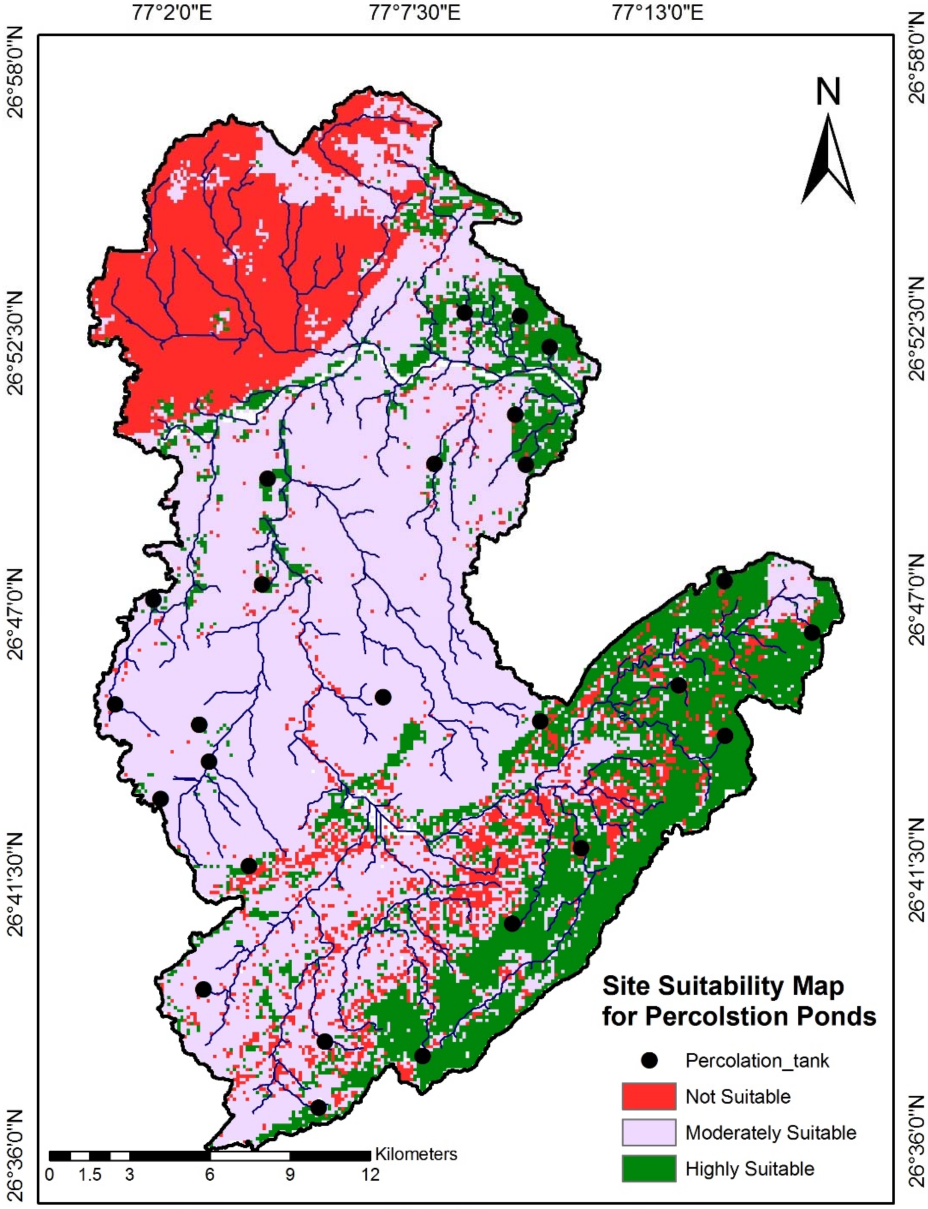
APPENDIX-II

Suitable locations for construction of farm ponds



APPENDIX-III

Suitable locations for construction of Percolation ponds



APPENDIX-IV

Design of Farm pond (dugout type)

Rainfall at 75% probability = 419 mm

Runoff depth = 0.32 × 419 = 134 mm

Catchment area = 10.66 ha

Catchment yield = 10.66 × 134 ha-mm

= 14284.4 m^3

Assuming depth of pond = 4m

Side slope = 1.5: 1

Bottom width = 50m

Bottom length = 60 m

Bottom area (C) = 50 × 60 m^2

Mid width = 50 + (2 × 1.5) × 2 = 56m

Mid length = 60 + (2 × 1.5) × 2 = 66m

Mid area (B) = 56 × 66 m^2

Top width = 50 + (4 × 1.5) × 2 = 62m

Top length = 60 + (4 × 1.5) × 2 = 72m

Top area (A) = 62 × 72 m^2

$$\mathrm{V} = \left(\frac{A + \ 4B + C}{6}\right) \times \mathrm{D} = \left[\frac{(62 \times 72) + (4 \times 56 \times 66) + (50 \times 60)}{6}\right] \times 4$$

= 14832 m^3

APPENDIX-V

Design of Check dam

Peak runoff (Dicken's formula)

$Q = CA^{3/4}$

$= 6 \times (0.472)^{3/4}$

$= 3.417\ m^3/s$

F= 1.5 h= 0.5 L=3.44

1. Minimum length of headwall extension

   E = 3h + 0.6 or 1.5 F

   E = 2.85 or 2.25

   E= 2.85m

2. Length of apron

$$L_h = F\left(2.28\frac{h}{F} + 0.52\right)$$

$$L_h = F\left(2.28 \times \frac{0.75}{1.5} + 0.52\right)$$

$$= 2.49m$$

3. Height of wing wall and side wall at junction (J). it is determined by using the following equations:

$$J = 2h \text{ or} \left[F + h + s - \frac{(L_h + 0.10)}{2}\right]$$

s = height of longitudinal sill

$$s = \frac{h}{4} = \frac{0.25}{4} = 0.875m$$

$$J = 20.75 \text{ or} \left[1.5 + 0.75 + 0.1875 - \frac{(2.49 + 0.10)}{2}\right]$$

$$= 1.5 \text{ or} 1.1424$$

$$J = 1.5m$$

4. Height of transverse sill. It is given by

$$h_i = \frac{h}{3} = \frac{0.75}{3} = 0.25m$$

5. Height of longitudinal sill (s). The following formula is used;

$$S = \frac{h}{4}$$

The parameter M and K are calculated by the following equations;

$$M = 2(F + 1.33\,h - J)$$
$$= 2(1.5 + 1.33 \times 0.75 - 1.5)$$
$$= 1.98m$$

$$K = (L_h + 0.1) - M$$
$$= (2.49 + 0.10) - 1.98$$
$$= 0.61m$$

6. Apron thickness

For F= 1.5, t = 25cm, for concrete structure

7. Wall thickness

The minimum wall thickness of head wall, side wall, wing wall and head wall extension are taken as

Thickness	**Base width**
Head wall= 0.45m	4.00
Side wall= 0.30m	0.82
Wing wall= 0.30m	0.62
Head wall extension= 0.45m	

APPENDIX-VI

Design of percolation pond for groundwater recharge

Rainfall at 75% probability = 419 mm

Runoff = $0.32 \times 419 = 134$ mm

Catchment area = 26866 ha

Catchment yield = 25.856×134 ha-mm

= $36000.44\ m^3$

Assuming depth of pond = 4m

Side slope = 1.5: 1

Bottom width = 80m

Bottom length = 105 m

Bottom area (C) = $80 \times 105\ m^2$

Mid width = $80 + (2 \times 1.5) \times 2 = 86$m

Mid length = $105 + (2 \times 1.5) \times 2 = 111$m

Mid area (B) = $86 \times 111\ m^2$

Top width = $80 + (4 \times 1.5) \times 2 = 92$m

Top length = $105 + (4 \times 1.5) \times 2 = 117$m

Top area (A) = $92 \times 117\ m^2$

$$V = \left[\frac{(92 \times 117) + (4 \times 86 \times 111) + (80 \times 105)}{6}\right] \times 4$$

= $38232\ m^3$

APPENDIX-VII

APPENDIX-II

Sample calculation of estimation of daily runoff in Microsoft excel sheet

Date	Daily Rainfall (mm)	5-day Cumulative Rainfall (mm)	AMC Condition	CN	S	0.2 S	Runoff (mm)
01-01-2016	0	0	AMC I	77.12	75.36	15.07	0
02-01-2016	0	0	AMC I	77.12	75.36	15.07	0
03-01-2016	0	0	AMC I	77.12	75.36	15.07	0
04-01-2016	0	0	AMC I	77.12	75.36	15.07	0
05-01-2016	0	0	AMC I	77.12	75.36	15.07	0
06-01-2016	0	0	AMC I	77.12	75.36	15.07	0
07-01-2016	0	0	AMC I	77.12	75.36	15.07	0
08-01-2016	0	0	AMC I	77.12	75.36	15.07	0
09-01-2016	0	0	AMC I	77.12	75.36	15.07	0
10-01-2016	0	0	AMC I	77.12	75.36	15.07	0
11-01-2016	0	0	AMC I	77.12	75.36	15.07	0
12-01-2016	0	0	AMC I	77.12	75.36	15.07	0
13-01-2016	0	0	AMC I	77.12	75.36	15.07	0
14-01-2016	0	0	AMC I	77.12	75.36	15.07	0
15-01-2016	0	0	AMC I	77.12	75.36	15.07	0
16-01-2016	0	0	AMC I	77.12	75.36	15.07	0
17-01-2016	0	0	AMC I	77.12	75.36	15.07	0
18-01-2016	0	0	AMC I	77.12	75.36	15.07	0
19-01-2016	0	0	AMC I	77.12	75.36	15.07	0
20-01-2016	0	0	AMC I	77.12	75.36	15.07	0
21-01-2016	0	0	AMC I	77.12	75.36	15.07	0
22-01-2016	0	0	AMC I	77.12	75.36	15.07	0
23-01-2016	0	0	AMC I	77.12	75.36	15.07	0
24-01-2016	0	0	AMC I	77.12	75.36	15.07	0
25-01-2016	0	0	AMC I	77.12	75.36	15.07	0
26-01-2016	0	0	AMC I	77.12	75.36	15.07	0
27-01-2016	0	0	AMC I	77.12	75.36	15.07	0
28-01-2016	0	0	AMC I	77.12	75.36	15.07	0
29-01-2016	0	0	AMC I	77.12	75.36	15.07	0
30-01-2016	0	0	AMC I	77.12	75.36	15.07	0
31-01-2016	0	0	AMC I	77.12	75.36	15.07	0
01-02-2016	0	0	AMC I	77.12	75.36	15.07	0
02-02-2016	0	0	AMC I	77.12	75.36	15.07	0
03-02-2016	0	0	AMC I	77.12	75.36	15.07	0
04-02-2016	0	0	AMC I	77.12	75.36	15.07	0

05-02-2016	0	0	AMC I	77.12	75.36	15.07	0
06-02-2016	0	0	AMC I	77.12	75.36	15.07	0
07-02-2016	0	0	AMC I	77.12	75.36	15.07	0
08-02-2016	0	0	AMC I	77.12	75.36	15.07	0
09-02-2016	0	0	AMC I	77.12	75.36	15.07	0
10-02-2016	0	0	AMC I	77.12	75.36	15.07	0
11-02-2016	0	0	AMC I	77.12	75.36	15.07	0
12-02-2016	0	0	AMC I	77.12	75.36	15.07	0
13-02-2016	0	0	AMC I	77.12	75.36	15.07	0
14-02-2016	0	0	AMC I	77.12	75.36	15.07	0
15-02-2016	0	0	AMC I	77.12	75.36	15.07	0
16-02-2016	0	0	AMC I	77.12	75.36	15.07	0
17-02-2016	0	0	AMC I	77.12	75.36	15.07	0
18-02-2016	0	0	AMC I	77.12	75.36	15.07	0
19-02-2016	0	0	AMC I	77.12	75.36	15.07	0
20-02-2016	0	0	AMC I	77.12	75.36	15.07	0
21-02-2016	0	0	AMC I	77.12	75.36	15.07	0
22-02-2016	0	0	AMC I	77.12	75.36	15.07	0
23-02-2016	0	0	AMC I	77.12	75.36	15.07	0
24-02-2016	0	0	AMC I	77.12	75.36	15.07	0
25-02-2016	0	0	AMC I	77.12	75.36	15.07	0
26-02-2016	0	0	AMC I	77.12	75.36	15.07	0
27-02-2016	0	0	AMC I	77.12	75.36	15.07	0
28-02-2016	0	0	AMC I	77.12	75.36	15.07	0
29-02-2016	0	0	AMC I	77.12	75.36	15.07	0
01-03-2016	0	0	AMC I	77.12	75.36	15.07	0
02-03-2016	0	0	AMC I	77.12	75.36	15.07	0
03-03-2016	0	0	AMC I	77.12	75.36	15.07	0
04-03-2016	0	0	AMC I	77.12	75.36	15.07	0
05-03-2016	2	2	AMC I	77.12	75.36	15.07	0
06-03-2016	17	19	AMC I	77.12	75.36	15.07	0.05
07-03-2016	0	19	AMC I	77.12	75.36	15.07	0
08-03-2016	0	19	AMC I	77.12	75.36	15.07	0
09-03-2016	0	19	AMC I	77.12	75.36	15.07	0
10-03-2016	0	17	AMC I	77.12	75.36	15.07	0
11-03-2016	0	0	AMC I	77.12	75.36	15.07	0
12-03-2016	0	0	AMC I	77.12	75.36	15.07	0
13-03-2016	10	10	AMC I	77.12	75.36	15.07	0
14-03-2016	0	10	AMC I	77.12	75.36	15.07	0
15-03-2016	0	10	AMC I	77.12	75.36	15.07	0
16-03-2016	0	10	AMC I	77.12	75.36	15.07	0
17-03-2016	0	10	AMC I	77.12	75.36	15.07	0
18-03-2016	0	0	AMC I	77.12	75.36	15.07	0
19-03-2016	0	0	AMC I	77.12	75.36	15.07	0
20-03-2016	0	0	AMC I	77.12	75.36	15.07	0
21-03-2016	0	0	AMC I	77.12	75.36	15.07	0

22-03-2016	0	0	AMC I	77.12	75.36	15.07	0
23-03-2016	0	0	AMC I	77.12	75.36	15.07	0
24-03-2016	0	0	AMC I	77.12	75.36	15.07	0
25-03-2016	0	0	AMC I	77.12	75.36	15.07	0
26-03-2016	0	0	AMC I	77.12	75.36	15.07	0
27-03-2016	0	0	AMC I	77.12	75.36	15.07	0
28-03-2016	0	0	AMC I	77.12	75.36	15.07	0
29-03-2016	0	0	AMC I	77.12	75.36	15.07	0
30-03-2016	0	0	AMC I	77.12	75.36	15.07	0
31-03-2016	0	0	AMC I	77.12	75.36	15.07	0
01-04-2016	0	0	AMC I	77.12	75.36	15.07	0
02-04-2016	0	0	AMC I	77.12	75.36	15.07	0
03-04-2016	0	0	AMC I	77.12	75.36	15.07	0
04-04-2016	0	0	AMC I	77.12	75.36	15.07	0
05-04-2016	0	0	AMC I	77.12	75.36	15.07	0
06-04-2016	0	0	AMC I	77.12	75.36	15.07	0
07-04-2016	0	0	AMC I	77.12	75.36	15.07	0
08-04-2016	0	0	AMC I	77.12	75.36	15.07	0
09-04-2016	0	0	AMC I	77.12	75.36	15.07	0
10-04-2016	0	0	AMC I	77.12	75.36	15.07	0
11-04-2016	0	0	AMC I	77.12	75.36	15.07	0
12-04-2016	0	0	AMC I	77.12	75.36	15.07	0
13-04-2016	0	0	AMC I	77.12	75.36	15.07	0
14-04-2016	0	0	AMC I	77.12	75.36	15.07	0
15-04-2016	0	0	AMC I	77.12	75.36	15.07	0
16-04-2016	0	0	AMC I	77.12	75.36	15.07	0
17-04-2016	0	0	AMC I	77.12	75.36	15.07	0
18-04-2016	0	0	AMC I	77.12	75.36	15.07	0
19-04-2016	0	0	AMC I	77.12	75.36	15.07	0
20-04-2016	0	0	AMC I	77.12	75.36	15.07	0
21-04-2016	0	0	AMC I	77.12	75.36	15.07	0
22-04-2016	0	0	AMC I	77.12	75.36	15.07	0
23-04-2016	0	0	AMC I	77.12	75.36	15.07	0
24-04-2016	0	0	AMC I	77.12	75.36	15.07	0
25-04-2016	0	0	AMC I	77.12	75.36	15.07	0
26-04-2016	0	0	AMC I	77.12	75.36	15.07	0
27-04-2016	0	0	AMC I	77.12	75.36	15.07	0
28-04-2016	0	0	AMC I	77.12	75.36	15.07	0
29-04-2016	0	0	AMC I	77.12	75.36	15.07	0
30-04-2016	0	0	AMC I	77.12	75.36	15.07	0
01-05-2016	0	0	AMC I	77.12	75.36	15.07	0
02-05-2016	0	0	AMC I	77.12	75.36	15.07	0
03-05-2016	0	0	AMC I	77.12	75.36	15.07	0
04-05-2016	0	0	AMC I	77.12	75.36	15.07	0
05-05-2016	0	0	AMC I	77.12	75.36	15.07	0
06-05-2016	0	0	AMC I	77.12	75.36	15.07	0

07-05-2016	0	0	AMC I	77.12	75.36	15.07	0
08-05-2016	0	0	AMC I	77.12	75.36	15.07	0
09-05-2016	0	0	AMC I	77.12	75.36	15.07	0
10-05-2016	0	0	AMC I	77.12	75.36	15.07	0
11-05-2016	0	0	AMC I	77.12	75.36	15.07	0
12-05-2016	0	0	AMC I	77.12	75.36	15.07	0
13-05-2016	0	0	AMC I	77.12	75.36	15.07	0
14-05-2016	0	0	AMC I	77.12	75.36	15.07	0
15-05-2016	0	0	AMC I	77.12	75.36	15.07	0
16-05-2016	0	0	AMC I	77.12	75.36	15.07	0
17-05-2016	0	0	AMC I	77.12	75.36	15.07	0
18-05-2016	0	0	AMC I	77.12	75.36	15.07	0
19-05-2016	0	0	AMC I	77.12	75.36	15.07	0
20-05-2016	0	0	AMC I	77.12	75.36	15.07	0
21-05-2016	0	0	AMC I	77.12	75.36	15.07	0
22-05-2016	2	2	AMC I	77.12	75.36	15.07	0
23-05-2016	0	2	AMC I	77.12	75.36	15.07	0
24-05-2016	2	4	AMC I	77.12	75.36	15.07	0
25-05-2016	1	5	AMC I	77.12	75.36	15.07	0
26-05-2016	0	5	AMC I	77.12	75.36	15.07	0
27-05-2016	0	3	AMC I	77.12	75.36	15.07	0
28-05-2016	1	4	AMC I	77.12	75.36	15.07	0
29-05-2016	0	2	AMC I	77.12	75.36	15.07	0
30-05-2016	1	2	AMC I	77.12	75.36	15.07	0
31-05-2016	0	2	AMC I	77.12	75.36	15.07	0
01-06-2016	0	2	AMC I	77.12	75.36	15.07	0
02-06-2016	0	1	AMC I	77.12	75.36	15.07	0
03-06-2016	0	1	AMC I	77.12	75.36	15.07	0
04-06-2016	0	0	AMC I	77.12	75.36	15.07	0
05-06-2016	0	0	AMC I	77.12	75.36	15.07	0
06-06-2016	0	0	AMC I	77.12	75.36	15.07	0
07-06-2016	0	0	AMC I	77.12	75.36	15.07	0
08-06-2016	0	0	AMC I	77.12	75.36	15.07	0
09-06-2016	0	0	AMC I	77.12	75.36	15.07	0
10-06-2016	0	0	AMC I	77.12	75.36	15.07	0
11-06-2016	0	0	AMC I	77.12	75.36	15.07	0
12-06-2016	12	12	AMC I	77.12	75.36	15.07	0
13-06-2016	0	12	AMC I	77.12	75.36	15.07	0
14-06-2016	0	12	AMC I	77.12	75.36	15.07	0
15-06-2016	0	12	AMC I	77.12	75.36	15.07	0
16-06-2016	0	12	AMC I	77.12	75.36	15.07	0
17-06-2016	0	0	AMC I	77.12	75.36	15.07	0
18-06-2016	0	0	AMC I	77.12	75.36	15.07	0
19-06-2016	0	0	AMC I	77.12	75.36	15.07	0
20-06-2016	3	3	AMC I	77.12	75.36	15.07	0
21-06-2016	0	3	AMC I	77.12	75.36	15.07	0

22-06-2016	27	30	AMC I	77.12	75.36	15.07	1.63
23-06-2016	0	30	AMC I	77.12	75.36	15.07	0
24-06-2016	0	30	AMC I	77.12	75.36	15.07	0
25-06-2016	0	27	AMC I	77.12	75.36	15.07	0
26-06-2016	0	27	AMC I	77.12	75.36	15.07	0
27-06-2016	0	0	AMC I	77.12	75.36	15.07	0
28-06-2016	0	0	AMC I	77.12	75.36	15.07	0
29-06-2016	10	10	AMC I	77.12	75.36	15.07	0
30-06-2016	0	10	AMC I	77.12	75.36	15.07	0
01-07-2016	0	10	AMC I	77.12	75.36	15.07	0
02-07-2016	15	25	AMC I	77.12	75.36	15.07	0
03-07-2016	0	25	AMC I	77.12	75.36	15.07	0
04-07-2016	0	15	AMC I	77.12	75.36	15.07	0
05-07-2016	0	15	AMC I	77.12	75.36	15.07	0
06-07-2016	13	28	AMC I	77.12	75.36	15.07	0
07-07-2016	2	15	AMC I	77.12	75.36	15.07	0
08-07-2016	3	18	AMC I	77.12	75.36	15.07	0
09-07-2016	0	18	AMC I	77.12	75.36	15.07	0
10-07-2016	13	31	AMC I	77.12	75.36	15.07	0
11-07-2016	0	18	AMC I	77.12	75.36	15.07	0
12-07-2016	7	23	AMC I	77.12	75.36	15.07	0
13-07-2016	8	28	AMC I	77.12	75.36	15.07	0
14-07-2016	0	28	AMC I	77.12	75.36	15.07	0
15-07-2016	0	15	AMC I	77.12	75.36	15.07	0
16-07-2016	126	141	AMC III	93.88	16.56	3.31	108.1
17-07-2016	120	254	AMC III	93.88	16.56	3.31	102.19
18-07-2016	75	321	AMC III	93.88	16.56	3.31	58.24
19-07-2016	0	321	AMC III	93.88	16.56	3.31	0
20-07-2016	0	321	AMC III	93.88	16.56	3.31	0
21-07-2016	0	195	AMC III	93.88	16.56	3.31	0
22-07-2016	0	75	AMC III	93.88	16.56	3.31	0
23-07-2016	0	0	AMC I	77.12	75.36	15.07	0
24-07-2016	0	0	AMC I	77.12	75.36	15.07	0
25-07-2016	0	0	AMC I	77.12	75.36	15.07	0
26-07-2016	0	0	AMC I	77.12	75.36	15.07	0
27-07-2016	5	5	AMC I	77.12	75.36	15.07	0
28-07-2016	0	5	AMC I	77.12	75.36	15.07	0
29-07-2016	4	9	AMC I	77.12	75.36	15.07	0
30-07-2016	6	15	AMC I	77.12	75.36	15.07	0
31-07-2016	0	15	AMC I	77.12	75.36	15.07	0
01-08-2016	2	12	AMC I	77.12	75.36	15.07	0
02-08-2016	0	12	AMC I	77.12	75.36	15.07	0
03-08-2016	16	24	AMC I	77.12	75.36	15.07	0.01
04-08-2016	14	32	AMC I	77.12	75.36	15.07	0
05-08-2016	5	37	AMC II	86.76	38.76	7.75	0
06-08-2016	0	35	AMC I	77.12	75.36	15.07	0

07-08-2016	0	35	AMC I	77.12	75.36	15.07	0
08-08-2016	18	37	AMC II	86.76	38.76	7.75	2.14
09-08-2016	12	35	AMC I	77.12	75.36	15.07	0
10-08-2016	0	30	AMC I	77.12	75.36	15.07	0
11-08-2016	9	39	AMC II	86.76	38.76	7.75	0.04
12-08-2016	15	54	AMC III	93.88	16.56	3.31	4.84
13-08-2016	27	63	AMC III	93.88	16.56	3.31	13.94
14-08-2016	17	68	AMC III	93.88	16.56	3.31	6.19
15-08-2016	0	68	AMC III	93.88	16.56	3.31	0
16-08-2016	0	59	AMC III	93.88	16.56	3.31	0
17-08-2016	0	44	AMC II	86.76	38.76	7.75	0
18-08-2016	36	53	AMC II	86.76	38.76	7.75	11.91
19-08-2016	2	38	AMC II	86.76	38.76	7.75	0
20-08-2016	9	47	AMC II	86.76	38.76	7.75	0.04
21-08-2016	0	47	AMC II	86.76	38.76	7.75	0
22-08-2016	0	47	AMC II	86.76	38.76	7.75	0
23-08-2016	0	11	AMC I	77.12	75.36	15.07	0
24-08-2016	87	96	AMC III	93.88	16.56	3.31	69.87
25-08-2016	2	89	AMC III	93.88	16.56	3.31	0
26-08-2016	0	89	AMC III	93.88	16.56	3.31	0
27-08-2016	5	94	AMC III	93.88	16.56	3.31	0.16
28-08-2016	5	99	AMC III	93.88	16.56	3.31	0.16
29-08-2016	0	12	AMC I	77.12	75.36	15.07	0
30-08-2016	0	10	AMC I	77.12	75.36	15.07	0
31-08-2016	0	10	AMC I	77.12	75.36	15.07	0
01-09-2016	0	5	AMC I	77.12	75.36	15.07	0
02-09-2016	0	0	AMC I	77.12	75.36	15.07	0
03-09-2016	0	0	AMC I	77.12	75.36	15.07	0
04-09-2016	0	0	AMC I	77.12	75.36	15.07	0
05-09-2016	0	0	AMC I	77.12	75.36	15.07	0
06-09-2016	0	0	AMC I	77.12	75.36	15.07	0
07-09-2016	0	0	AMC I	77.12	75.36	15.07	0
08-09-2016	0	0	AMC I	77.12	75.36	15.07	0
09-09-2016	0	0	AMC I	77.12	75.36	15.07	0
10-09-2016	0	0	AMC I	77.12	75.36	15.07	0
11-09-2016	0	0	AMC I	77.12	75.36	15.07	0
12-09-2016	0	0	AMC I	77.12	75.36	15.07	0
13-09-2016	0	0	AMC I	77.12	75.36	15.07	0
14-09-2016	0	0	AMC I	77.12	75.36	15.07	0
15-09-2016	0	0	AMC I	77.12	75.36	15.07	0
16-09-2016	0	0	AMC I	77.12	75.36	15.07	0
17-09-2016	0	0	AMC I	77.12	75.36	15.07	0
18-09-2016	0	0	AMC I	77.12	75.36	15.07	0
19-09-2016	0	0	AMC I	77.12	75.36	15.07	0
20-09-2016	0	0	AMC I	77.12	75.36	15.07	0
21-09-2016	0	0	AMC I	77.12	75.36	15.07	0

22-09-2016	54	54	AMC III	93.88	16.56	3.31	38.21
23-09-2016	0	54	AMC III	93.88	16.56	3.31	0
24-09-2016	0	54	AMC III	93.88	16.56	3.31	0
25-09-2016	0	54	AMC III	93.88	16.56	3.31	0
26-09-2016	0	54	AMC III	93.88	16.56	3.31	0
27-09-2016	0	0	AMC I	77.12	75.36	15.07	0
28-09-2016	0	0	AMC I	77.12	75.36	15.07	0
29-09-2016	0	0	AMC I	77.12	75.36	15.07	0
30-09-2016	0	0	AMC I	77.12	75.36	15.07	0
01-10-2016	0	0	AMC I	77.12	75.36	15.07	0
02-10-2016	0	0	AMC I	77.12	75.36	15.07	0
03-10-2016	0	0	AMC I	77.12	75.36	15.07	0
04-10-2016	0	0	AMC I	77.12	75.36	15.07	0
05-10-2016	0	0	AMC I	77.12	75.36	15.07	0
06-10-2016	22	22	AMC I	77.12	75.36	15.07	0.58
07-10-2016	0	22	AMC I	77.12	75.36	15.07	0
08-10-2016	0	22	AMC I	77.12	75.36	15.07	0
09-10-2016	0	22	AMC I	77.12	75.36	15.07	0
10-10-2016	0	22	AMC I	77.12	75.36	15.07	0
11-10-2016	0	0	AMC I	77.12	75.36	15.07	0
12-10-2016	0	0	AMC I	77.12	75.36	15.07	0
13-10-2016	0	0	AMC I	77.12	75.36	15.07	0
14-10-2016	0	0	AMC I	77.12	75.36	15.07	0
15-10-2016	0	0	AMC I	77.12	75.36	15.07	0
16-10-2016	0	0	AMC I	77.12	75.36	15.07	0
17-10-2016	0	0	AMC I	77.12	75.36	15.07	0
18-10-2016	0	0	AMC I	77.12	75.36	15.07	0
19-10-2016	0	0	AMC I	77.12	75.36	15.07	0
20-10-2016	0	0	AMC I	77.12	75.36	15.07	0
21-10-2016	0	0	AMC I	77.12	75.36	15.07	0
22-10-2016	0	0	AMC I	77.12	75.36	15.07	0
23-10-2016	0	0	AMC I	77.12	75.36	15.07	0
24-10-2016	0	0	AMC I	77.12	75.36	15.07	0
25-10-2016	0	0	AMC I	77.12	75.36	15.07	0
26-10-2016	0	0	AMC I	77.12	75.36	15.07	0
27-10-2016	0	0	AMC I	77.12	75.36	15.07	0
28-10-2016	0	0	AMC I	77.12	75.36	15.07	0
29-10-2016	0	0	AMC I	77.12	75.36	15.07	0
30-10-2016	0	0	AMC I	77.12	75.36	15.07	0
31-10-2016	0	0	AMC I	77.12	75.36	15.07	0
01-11-2016	0	0	AMC I	77.12	75.36	15.07	0
02-11-2016	0	0	AMC I	77.12	75.36	15.07	0
03-11-2016	0	0	AMC I	77.12	75.36	15.07	0
04-11-2016	0	0	AMC I	77.12	75.36	15.07	0
05-11-2016	0	0	AMC I	77.12	75.36	15.07	0
06-11-2016	0	0	AMC I	77.12	75.36	15.07	0

07-11-2016	0	0	AMC I	77.12	75.36	15.07	0
08-11-2016	0	0	AMC I	77.12	75.36	15.07	0
09-11-2016	0	0	AMC I	77.12	75.36	15.07	0
10-11-2016	0	0	AMC I	77.12	75.36	15.07	0
11-11-2016	0	0	AMC I	77.12	75.36	15.07	0
12-11-2016	0	0	AMC I	77.12	75.36	15.07	0
13-11-2016	0	0	AMC I	77.12	75.36	15.07	0
14-11-2016	0	0	AMC I	77.12	75.36	15.07	0
15-11-2016	0	0	AMC I	77.12	75.36	15.07	0
16-11-2016	0	0	AMC I	77.12	75.36	15.07	0
17-11-2016	0	0	AMC I	77.12	75.36	15.07	0
18-11-2016	0	0	AMC I	77.12	75.36	15.07	0
19-11-2016	0	0	AMC I	77.12	75.36	15.07	0
20-11-2016	0	0	AMC I	77.12	75.36	15.07	0
21-11-2016	0	0	AMC I	77.12	75.36	15.07	0
22-11-2016	0	0	AMC I	77.12	75.36	15.07	0
23-11-2016	0	0	AMC I	77.12	75.36	15.07	0
24-11-2016	0	0	AMC I	77.12	75.36	15.07	0
25-11-2016	0	0	AMC I	77.12	75.36	15.07	0
26-11-2016	0	0	AMC I	77.12	75.36	15.07	0
27-11-2016	0	0	AMC I	77.12	75.36	15.07	0
28-11-2016	0	0	AMC I	77.12	75.36	15.07	0
29-11-2016	0	0	AMC I	77.12	75.36	15.07	0
30-11-2016	0	0	AMC I	77.12	75.36	15.07	0
01-12-2016	0	0	AMC I	77.12	75.36	15.07	0
02-12-2016	0	0	AMC I	77.12	75.36	15.07	0
03-12-2016	0	0	AMC I	77.12	75.36	15.07	0
04-12-2016	0	0	AMC I	77.12	75.36	15.07	0
05-12-2016	0	0	AMC I	77.12	75.36	15.07	0
06-12-2016	0	0	AMC I	77.12	75.36	15.07	0
07-12-2016	0	0	AMC I	77.12	75.36	15.07	0
08-12-2016	0	0	AMC I	77.12	75.36	15.07	0
09-12-2016	0	0	AMC I	77.12	75.36	15.07	0
10-12-2016	0	0	AMC I	77.12	75.36	15.07	0
11-12-2016	0	0	AMC I	77.12	75.36	15.07	0
12-12-2016	0	0	AMC I	77.12	75.36	15.07	0
13-12-2016	0	0	AMC I	77.12	75.36	15.07	0
14-12-2016	0	0	AMC I	77.12	75.36	15.07	0
15-12-2016	0	0	AMC I	77.12	75.36	15.07	0
16-12-2016	0	0	AMC I	77.12	75.36	15.07	0
17-12-2016	0	0	AMC I	77.12	75.36	15.07	0
18-12-2016	0	0	AMC I	77.12	75.36	15.07	0
19-12-2016	0	0	AMC I	77.12	75.36	15.07	0
20-12-2016	0	0	AMC I	77.12	75.36	15.07	0
21-12-2016	0	0	AMC I	77.12	75.36	15.07	0
22-12-2016	0	0	AMC I	77.12	75.36	15.07	0

23-12-2016	0	0	AMC I	77.12	75.36	15.07	0
24-12-2016	0	0	AMC I	77.12	75.36	15.07	0
25-12-2016	0	0	AMC I	77.12	75.36	15.07	0
26-12-2016	0	0	AMC I	77.12	75.36	15.07	0
27-12-2016	0	0	AMC I	77.12	75.36	15.07	0
28-12-2016	0	0	AMC I	77.12	75.36	15.07	0
29-12-2016	0	0	AMC I	77.12	75.36	15.07	0
30-12-2016	0	0	AMC I	77.12	75.36	15.07	0