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Vijay P. Singh
Shalini Yadav
Ram Narayan Yadava *Editors*

# Groundwater

## Select Proceedings of ICWEES-2016

Springer

# Water Science and Technology Library

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# Preface

Fundamental to sustainable economic development, functioning of healthy ecosystems, reliable agricultural productivity, dependable power generation, maintenance of desirable environmental quality, continuing industrial growth, enjoyment of quality lifestyle, and renewal of land and air resources is water. With growing population, demands for water for agriculture and industry are skyrocketing. On the other hand, freshwater resources per capita are decreasing. There is therefore a need for effective water resources management strategies. These strategies must also consider the nexus between water, energy, environment, food, and society. With these considerations in mind, the International Conference on Water, Environment, Energy and Society (WEES-2016) was organized at AISECT University in Bhopal, M.P., India, from 15 to 18 March 2016. The conference was fifth in the series and had several objectives.

The first objective was to provide a forum to not only engineers, scientists, and researchers, but also practitioners, planners, managers, administrators, and policy makers from around the world for discussion of problems pertaining to water, environment, and energy that are vital for the sustenance and development of society.

Second, the Government of India has embarked upon two large projects one on cleaning of River Ganga and the other on cleaning River Yamuna. Further, it is allocating large funds for irrigation projects with the aim to bring sufficient good quality water to all farmers. These are huge ambitious projects and require consideration of all aspects of water, environment, and energy as well as society, including economics, culture, religion, politics, administration, law.

Third, when water resources projects are developed, it is important to ensure that these projects achieve their intended objectives without causing deleterious environmental consequences, such as water logging, salinization, loss of wetlands, sedimentation of reservoirs, loss of biodiversity.

Fourth, the combination of rising demand for water and increasing concern for environmental quality compels that water resources projects are planned, designed, executed, and managed, keeping changing conditions in mind, especially climate change and social and economic changes.

Fifth, water resources projects are investment intensive and it is therefore important to take a stock of how the built projects have fared and the lessons that can be learnt so that future projects are even better. This requires an open and frank discussion amongst all sectors and stakeholders.

Sixth, we wanted to reinforce that water, environment, energy, and society constitute a continuum and water is central to this continuum. Water resources projects are therefore inherently interdisciplinary and must be so dealt with.

Seventh, a conference like this offers an opportunity to renew old friendships and make new ones, exchange ideas and experiences, develop collaborations, and enrich ourselves both socially and intellectually. We have much to learn from each other.

Now the question may be: Why India and why Bhopal? India has had a long tradition of excellence spanning several millennia in the construction of water resources projects. Because of her vast size, high climatic variability encompassing six seasons, extreme landscape variability from flat plains to the highest mountains in the world, and large river systems, India offers a rich natural laboratory for water resources investigations.

India is a vast country, full of contrasts. She is diverse yet harmonious, mysterious yet charming, old yet beautiful, ancient yet modern. Nowhere can we find as high mountains as snow-capped Himalayas in the north, the confluence of three seas and large temples in the south, long and fine sand beaches in the east as well as architectural gems in the west. The entire country is dotted with unsurpassable monuments, temples, mosques, palaces, and forts and fortresses that offer a glimpse of India's past and present.

Bhopal is located in almost the centre of India and is situated between Narmada River and Betwa River. It is a capital of Madhya Pradesh and has a rich, several century-long history. It is a fascinating amalgam of scenic beauty, old historic city, and modern urban planning. All things considered, the venue of the conference could not have been better.

We received an overwhelming response to our call for papers. The number of abstracts received exceeded 450. Each abstract was reviewed and about two-thirds of them, deemed appropriate to the theme of the conference, were selected. This led to the submission of about 300 full-length papers. The subject matter of the papers was divided into more than 40 topics, encompassing virtually all major aspects of water and environment as well energy. Each topic comprised a number of contributed papers and in some cases state-of-the-art papers. These papers provided a natural blend to reflect a coherent body of knowledge on that topic.

The papers contained in this volume, "Groundwater", represent one part of the conference proceedings. The other parts are embodied in six companion volumes entitled, "Hydrologic Modelling", "Energy and Environment", "Environmental Pollution", "Water Quality Management", "Climate Change Impacts", and "Water Resources Management". Arrangement of contributions in these seven books was a natural consequence of the diversity of papers presented at the conference and the topics covered. These books can be treated almost independently, although significant interconnectedness exists amongst them.

This volume contains three parts. Part I deals with some aspects of groundwater focusing on delineation of groundwater zones, spatio-temporal variability of groundwater, and aquifer vulnerability. Part II is on some aspects of groundwater recharge, dealing with recharge sources, management of recharge, and recharge technology. The concluding Part III covers groundwater quality, encompassing cause and sources of pollution, leachate migration, river bank filtration, variability of quality, and management of quality.

The book will be of interest to researchers and practitioners in the field of water resources, hydrology, environmental resources, agricultural engineering, watershed management, earth sciences, as well as those engaged in natural resources planning and management. Graduate students and those wishing to conduct further research in water and environment and their development and management may find the book to be of value.

WEES-16 attracted a large number of nationally and internationally well-known people who have long been at the forefront of environmental and water resources education, research, teaching, planning, development, management, and practice. It is hoped that long and productive personal associations and friendships will be developed as a result of this conference.

College Station, USA — Vijay P. Singh
Bhopal, India — Shalini Yadav
Hazaribag, Bhopal, India — Ram Narayan Yadava

# Acknowledgements

We express our sincere gratitude to Shri Santosh Choubey, Chancellor, and Dr. V.K. Verma, Vice Chancellor, Board of Governing Body, and Board of Management of the AISECT University, Bhopal, India, for providing their continuous guidance and full organizational support in successfully organizing this international conference on Water, Environment, Energy and Society on the AISECT University campus in Bhopal, India.

We are also grateful to the Department of Biological and Agricultural Engineering, and Zachry Department of Civil Engineering, Texas A&M University, College Station, Texas, USA, and International Centre of Excellence in Water Management (ICE WaRM), Australia, for their institutional cooperation and support in organizing the ICWEES-2016.

We wish to take this opportunity to express our sincere appreciation to all the members of the Local Organization Committee for helping with transportation, lodging, food, and a whole host of other logistics. We must express our appreciation to the Members of Advisory Committee, Members of the National and International Technical Committees for sharing their pearls of wisdom with us during the course of the Conference.

Numerous other people contributed to the conference in one way or another, and lack of space does not allow us to list all of them here. We are also immensely grateful to all the invited Keynote Speakers, and Directors/Heads of Institutions for supporting and permitting research scholars, scientists, and faculty members from their organizations for delivering keynote lectures and participating in the conference, submitting and presenting technical papers. The success of the conference is the direct result of their collective efforts. The session chairmen and co-chairmen administered the sessions in a positive, constructive, and professional manner. We owe our deep gratitude to all of these individuals and their organizations.

We are thankful to Shri Amitabh Saxena, Pro-Vice Chancellor, Dr. Vijay Singh, Registrar, and Dr. Basant Singh, School of Engineering and Technology, AISECT University, who provided expertise that greatly helped with the conference organization. We are also thankful to all the Heads of other Schools, Faculty Members and Staff of the AISECT University for the highly appreciable assistance in different organizing committees of the conference. We also express our sincere thanks to all the reviewers at national and international levels who reviewed and moderated the papers submitted to the conference. Their constructive evaluation and suggestions improved the manuscripts significantly.

# Sponsors and Co-Sponsors

The International Conference on Water, Environment, Energy and Society was Jointly organized by the AISECT University, Bhopal (M.P.), India, and Texas A&M University, Texas, USA, in association with ICE WaRM, Adelaide, Australia. It was partially supported by the International Atomic Energy Agency (IAEA), Vienna, Austria; AISECT University, Bhopal; M.P. Council of Science and Technology (MPCOST); Environmental Planning and Coordination Organization (EPCO), Government of Madhya Pradesh; National Bank for Agriculture and Rural Development (NABARD), Mumbai; Maulana Azad National Institute of Technology (MANIT), Bhopal; and National Thermal Power Corporation (NTPC), Noida, India. We are grateful to all these sponsors for their cooperation and providing partial financial support that led to the grand success to the ICWEES-2016.

# Contents

# About the Editors

**Prof. Vijay P. Singh** is a University Distinguished Professor, a Regents Professor, and the inaugural holder of the Caroline and William N. Lehrer Distinguished Chair in Water Engineering in the Department of Biological and Agricultural Engineering and Zachry Department of Civil Engineering at Texas A&M University. He received his B.S., M.S., Ph.D., and D.Sc. degrees in engineering. He is a registered professional engineer, a registered professional hydrologist, and an Honorary Diplomate of American Academy of Water Resources Engineers.

Professor Singh has extensively published the results of an extraordinary range of his scientific pursuits. He has published more than 900 journal articles; 25 textbooks; 60 edited reference books, including the massive *Encyclopedia of Snow, Ice and Glaciers and Handbook of Applied Hydrology*; 104 book chapters; 314 conference papers; and 72 technical reports in the areas of hydrology, ground water, hydraulics, irrigation engineering, environmental engineering, and water resources.

For his scientific contributions to the development and management of water resources and promoting the cause of their conservation and sustainable use, he has received more than 90 national and international awards and numerous honours, including the Arid Lands Hydraulic Engineering Award, Ven Te Chow Award, Richard R. Torrens Award, Norman Medal, and EWRI Lifetime Achievement Award, all given by American Society of Civil Engineers; Ray K. Linsley Award and Founder's Award, given by American Institute of Hydrology; Crystal Drop Award, given by International Water Resources Association; and Outstanding Distinguished Scientist Award given by Sigma Xi, amongst others. He has received three honorary doctorates. He is a Distinguished Member of ASCE, and a fellow of EWRI, AWRA, IWRS, ISAE, IASWC, and IE and holds membership in 16 additional professional associations. He is a fellow/member of 10 international science/engineering academies. He has served as President and Senior Vice President of the American Institute of Hydrology (AIH). Currently, he is editor-in-chief of two book series and three journals and serves on editorial boards of 20 other journals.

Professor Singh has visited and delivered invited lectures in all most all parts of the world but just a sample: Switzerland, the Czech Republic, Hungary, Austria, India, Italy, France, England, China, Singapore, Brazil, and Australia.

**Prof. Shalini Yadav** is a Professor and Head of the Department of Civil Engineering, AISECT University, Bhopal, India. Her research interests include Solid and Hazardous Waste Management, Construction Management, Environmental Quality, and Water Resources. She has executed a variety of research projects/consultancy in Environmental and Water Science and Technology and has got rich experience in planning, formulating, organizing, executing, and management of R&D Programs, Seminars, and Conferences at national and international level. She has got to her credit guiding an appreciable number of M.Tech and Ph.D. students. She has published more than 10 journal articles and 30 technical reports. Dr. Shalini has also visited and delivered invited lectures at different institutes/universities in India and abroad, such as Australia, South Korea, Kenya.

Professor Shalini Yadav graduated with a B.Sc. in Science from the Bhopal University. She earned her M.Sc. in Applied Chemistry with specialization in Environmental Science from Bhopal University and M.Tech in Civil Engineering with specialization in Environmental Engineering from Malaviya National Institute of Technology, Jaipur, India, in 2000. Then, she pursued the degree of Ph.D. in Civil Engineering from Rajiv Gandhi Technical University, Bhopal, India, in 2011. Also, she is a recipient of national fellowships and awards. She is a reviewer in many International journals. She has been recognized for one and half decades of leadership in research, teaching, and service to the Environmental Engineering Profession.

**Dr. Ram Narayan Yadava** holds position of Vice Chancellor of the AISECT University, Hazaribag, Jharkhand. His research interests include Solid Mechanics, Environmental Quality and Water Resources, Hydrologic Modelling, Environmental Sciences, and R&D Planning and Management. Yadava has executed a variety of research/consultancy projects in the area of Water Resources Planning and Management, Environment, Remote Sensing, Mathematical Modelling, Technology Forecasting, etc.

He has got adequate experience in establishing institutes/organizations, planning, formulating, organizing, executing and management of R&D Programs, Seminars, Symposia, Conferences at national and international level. He has got to his credit guiding a number of M.Tech. and Ph.D. students in the area of Mathematical Sciences and Earth Sciences. Dr. Yadava has visited and delivered invited lectures at different institutes/universities in India and abroad, such as the USA, Canada, UK, Thailand, Germany, South Korea, Malaysia, Singapore, South Africa, Costa Rica, and Australia.

He earned an M.Sc. in Mathematics with specialization in Special Functions and Relativity from Banaras Hindu University, India, in 1970 and a Ph.D. in Mathematics with specialization in Fracture Mechanics from Indian Institute of Technology, Bombay, India, in 1975. Also, he is recipient of Raman Research Fellowship and other awards. Dr. Yadava has been recognized for three and half decades of leadership in research and service to the hydrologic and water resources profession. Dr. Yadava's contribution to the state of the art has been significant in many different specialty areas, including water resources management, environmental sciences, irrigation science, soil and water conservation engineering, and mathematical modelling. He has published more than 90 journal articles; four textbooks; and seven edited reference books.

# Part I
# Groundwater

# Delineation of Groundwater Potential Zones in Jaisamand Basin of Udaipur District

**P. K. Singh, Praveen Dahiphale, K. K. Yadav and Manjeet Singh**

**Abstract** The groundwater potential zones in the Jaisamand Basin with a catchment area of 1813 $km^2$ have been delineated using various thematic layers including geomorphology, drainage, soil, land use, slope, topographic elevation, and net recharge. As the topography is highly undulating with rolling uplands and in-filled valleys, the velocity of runoff is high whenever the rainfall occurs during the monsoon months. Suitable relative weights have been assigned to the thematic layers on a scale of 1–5 based on their influence on the occurrence of groundwater potential, and thereafter integrated using ILWIS GIS software. The analysis indicated a net recharge of 2–5 cm per year takes place in about 62% of the study area. The study area has been divided into four groundwater potential zones, viz. 'good,' 'moderate,' 'poor,' and 'very poor,' which covers 12.82, 49.65, 33.21, and 4.32% of the study area. Since 37.53% of the study area has poor-to-very poor groundwater potential, immediate measures are required for ensuring sustainable groundwater management in the basin through supply–demand management as well as artificial groundwater recharge of potential aquifers. About 15% percent of the study area is suitable for artificial recharge in the southern part of the basin.

## Introduction

Water is a prime natural resource and a precious national asset. It is a major constituent of all living beings. Water is available in two basic forms, i.e., surface water and groundwater. Water is used for various purposes ranging from domestic, agricultural, industrial, and allied purposes. Water is probably the only natural resource to touch all aspects of human civilization from agricultural and industrial development to cultural and religious values embedded in society. Earth is also

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called as 'blue planet' because 70% area of it has been covered by water. The total amount of water on the earth is about 1.35 billion cubic kilometers. About 97.1% has been locked into oceans as saltwater and ice sheets, whereas glaciers contain 2.1%. Only the 0.2% freshwater present on the earth can be used by human beings for variety of purposes, whereas the remaining 0.6% occurs underground aquifers (Anonymous 2007).

The first groundwater potential estimates in Rajasthan were made during 1983–84. Despite an increase in the area of groundwater potential due to more exploratory studies, there has been a total decline of 39.89% in the groundwater potential from 1984 to 2001. As a result, 'safe' water zones (i.e., those safe for exploitation) declined from 86% in 1984 to 10.6% in 2004. Also in the year 2001, 70.3% of total groundwater potential zones were classified as 'dark' and 'gray' (Rathore 2005). Therefore, there is an urgent need to manage the available groundwater resources of Rajasthan to meet the future demands.

For delineating the groundwater potential/prospective zones, GIS has been found to be an effective tool. Several conventional methods such as geological, hydrogeological, geophysical, and photogeological techniques were employed to delineate groundwater potential zones. The Jaisamand lake catchment is located in the Udaipur district which falls under semiarid region of Rajasthan. Drought is normal phenomena of Rajasthan. In the southern region context, its intensity is once in three years, though this is valid only when long-term rainfall data are considered. There is urgent need for augmentation of water table through identification of potential recharge zones and managing aquifer recharge system. Looking to the magnitude of the problem of declining trend of water table and water scarcity in the Jaisamand catchment, an effort have made to conduct groundwater resources study of the basin which will provide a guide line to mitigate the drought and also to enhance the crop yield of the area through sustainable interventions of groundwater management.

## Materials and Methods

### *Description of Study Area*

The Jaisamand lake catchment is located in the Udaipur district which falls in semiarid region of Rajasthan bounded by 73° 45′–74° 25′E longitude and 24° 10′–24° 35′N latitude. The lake is also a prime source supply drinking water for the city of Udaipur located at a distance of about 52 km from the lake. The Jaisamand lake, with a gross capacity of 414.6 $mm^3$ and live storage of 296.14 $mm^3$, is Asia's second largest artificial water storage reservoir built across the Gomati River. In Jaisamand catchment, Gomati, Thavaria, Siroli, Kheradi, Jhamri, Sukhali, Godi, Makradi, and Bhangar are the major rivers. The location of the study area shown in Fig. 1.

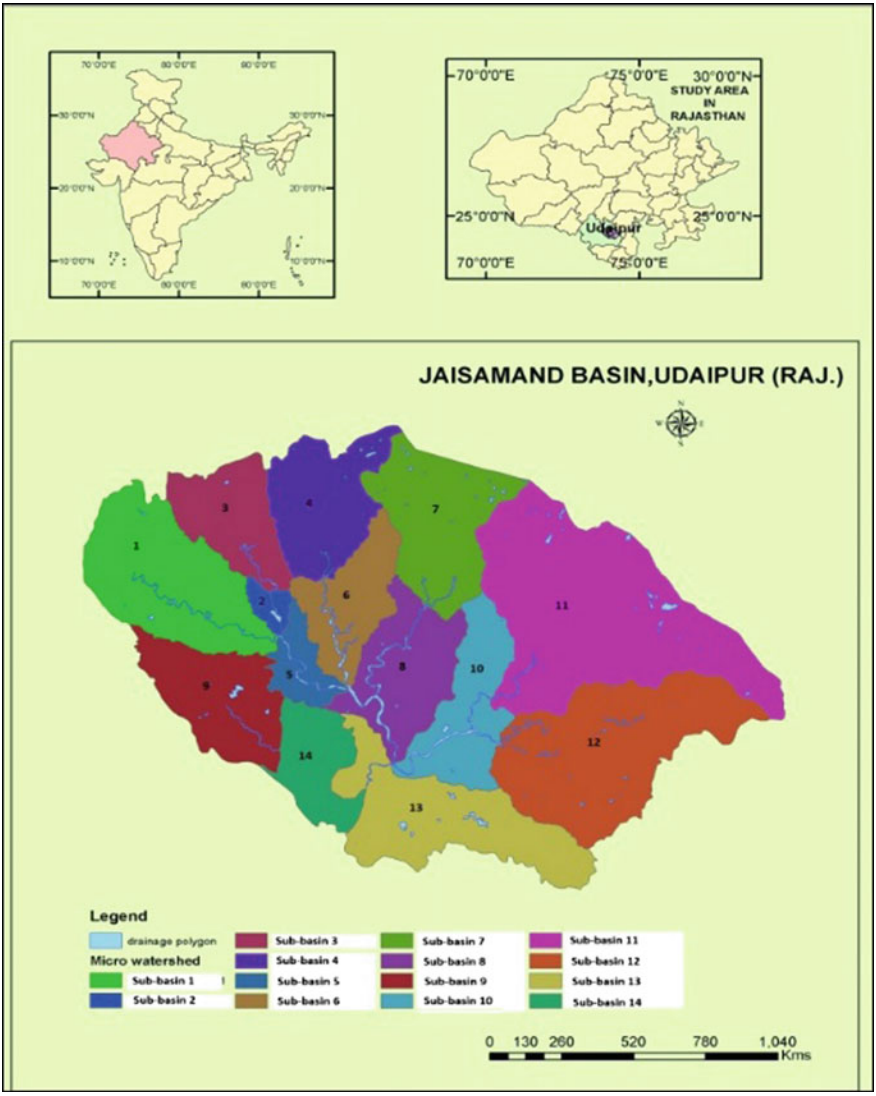


**Fig. 1** Location map of study area

## *Data acquisition*

(a) Extent of Jaisamand catchment and geomorphologic features was extracted from Geodetic Toposheets at 1:50,000 scale, which were procured from Survey of India (SOI), Dehradun.

(b) Soil information and soil map of the study area at 1:250,000 scales were gathered from the Regional Centre of National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), Udaipur, Rajasthan.
(c) Digital elevation model (DEM) for the study area was downloaded from the ASTER database.
(d) Pre- and post-monsoon groundwater depths in meter below ground surface (m bgs) in year 2013 were monitored in 109 selected open dug wells of the Jaisamand catchment.
(e) Aquifer characteristics (i.e., transmissivity and specific yield) were determined by conducting 12 pumping tests in selected wells of Jaisamand catchment.

## *Software Used*

Present study deals with use of GIS for preparation, handling, and processing of different thematic layers. All the GIS-related works were carried out by using ArcGIS 10 software. ArcGIS software is a PC-based GIS and remote sensing software, developed by the ESRI. ArcGIS desktop software products allow users to analyze, map, manage, share, and publish geographic information. At all levels of licensing, ArcMap, ArcCatalog, and ArcToolbox are the names of the applications comprising the desktop package. ArcGIS Explorer, ArcReader, and ArcExplorer are basic freeware applications for viewing GIS data.

## *Determination of Aquifer Parameters by Pumping Test*

Evaluation of aquifer characteristics is the prime task for harnessing an aquifer for optimum results yielding information about how much groundwater is available for development and what will be the consequences of withdrawing a certain quantity of groundwater.

Aquifer parameters, i.e., transmissivity ($T$) and specific yield ($S_y$), are often determined by means of pumping test. Scientifically planned pumping tests provide information for solution of many regional, as well as local, groundwater flow problems. It also provide information about the yield and drawdown of the well, which in turn is essential for selecting the type of pump, estimating cost of pumping, well efficiency, etc. Minimum spacing requirement between two wells to avoid mutual interference can also be determined with these parameters.

In a pumping test or an aquifer test, a well is pumped at constant/variable rate for a certain period. The effect of pumping on the water level is measured in the pumped well and in one or more observation wells, penetrating the aquifer in the vicinity of the pumped well with the help of stage gauge recorder or a measuring tape. Type of an aquifer is identified by plotting time-drawdown curve on double-logarithmic scale and comparing with standard drawdown curve on double-logarithmic scale. Aquifer parameters ($T$ and $S_y$) are then found with the help of the measured drawdown, discharge and the well function by use of a graphical technique called 'curve matching.'

In present study, a total 12 pumping tests were performed in different geological formations of selected wells (Fig. 2) in the Jaisamand catchment. Wells selected for pumping tests were large diameter shallow open dug wells, which while pumped extract groundwater from the unconfined aquifer. The pumping test of selected well and measurement of water level using acoustic water level indicator is shown in Fig. 3.

## *Analyzing Pumping Test Data by Curve-matching Technique*

Plentiful techniques are available for analyzing pumping test data depending upon the type of aquifer (e.g., confined, semi-confined, unconfined), type of pumping well (e.g., infinitesimal or large diameter), well penetration (full or partial), and

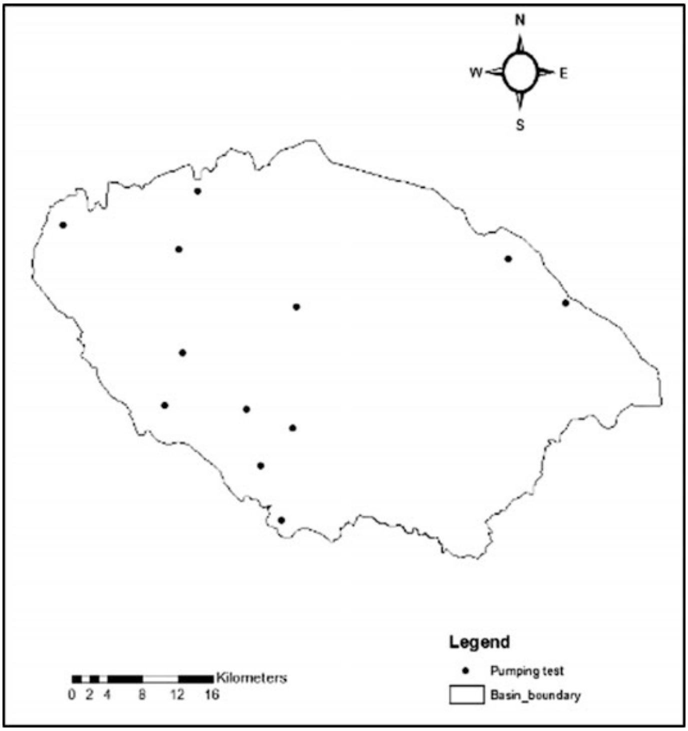


**Fig. 2** Location map of pumping test sites

**Fig. 3** Measurement of water level by using acoustic water level indicator

discharge rate (constant or variable). In this study, pumping tests were performed in large diameter open dug wells in shallow unconfined aquifer situated in hard-rock area of Jaisamand catchment. Moench method is available for analyzing the pumping test data of large diameter wells in unconfined aquifer. However, solution of Moench method is very complex for practical application. Some of the past studies conducted in Udaipur by Jat (1990) and Verma (2005) reported that Papadopulos and Cooper (1967) method can successfully be used for analyzing pumping test data of large diameter wells in unconfined aquifers after converting unconfined aquifer drawdown into equivalent confined aquifer's drawdown. Therefore, Papadopulos and Cooper (1967) curve-matching technique was adopted for determining aquifer properties in this study. The Papadopulos and Cooper solution accounts for well bore storage effects in a large diameter (finite diameter) pumping well. Papadopulos and Cooper method is described below.

## *Groundwater Potential Assessment by Using Remote Sensing and GIS*

The remote sensing (RS) technique provides synoptic coverage and accurate spatial information, which enable economical utilization over conventional methods of hydrogeological surveys. Rapid advances in the development of geographic information system (GIS), which provides spatial data integration and tools for natural resources management, have enabled integrating the data in an environment which has been proved to be an efficient and successful tool for groundwater studies.

This study utilized RS and GIS techniques for generating thematic layers of different factors influencing groundwater occurrence. The multi-criteria decision-making technique coupled with GIS has been used to identify groundwater potential zones in the study area. The procedures adopted to identify and delineate groundwater potential zones using RS, GIS, and MCDM techniques are illustrated in Fig. 4.

## *Selection of Thematic Layers*

In past groundwater studies concerning combined use of RS and GIS techniques, various thematic maps for delineating groundwater favorability zones were selected believing that all the thematic parameters have some influence on the occurrence of groundwater. The number of thematic layers used depends on the availability of data in an area.

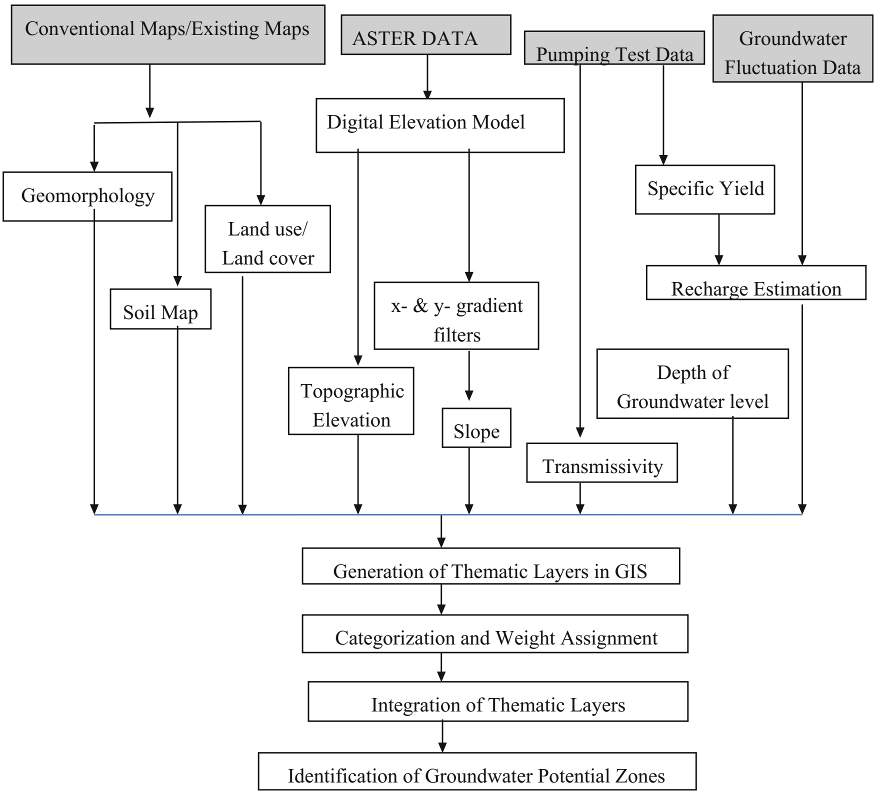


**Fig. 4** Flowchart for groundwater potential zoning using GIS

## Generation of Thematic Layers

In order to assess groundwater potential in the study area, eight thematic maps were generated using remote sensing and conventional data. Out of these thematic maps, topographic elevation and slope maps were generated from ASTER data, whereas the remaining maps were generated using conventional data. These thematic maps were developed using ArcGIS software.

## Groundwater Recharge Map

Recharge is broadly defined as water that reaches an aquifer from any direction. It can be classified as direct, localized, and indirect. The term direct recharge refers to the recharge derived from precipitation or irrigation that occurs fairly uniformly over large areas, whereas the term localized recharge refers to the concentrated recharge from depressions in surface topography such as streams and lakes. Point estimates of the net recharge at 109 sites for the study area were estimated using Water Table Fluctuation method. Using this point recharge values, a recharge map of the study area was prepared.

## Transmissivity Map

Aquifer transmissivity is very important factor as it governs groundwater movement and recharge process. The higher value of transmissivity increases the suitability of an area for artificial recharge. In this study, transmissivity values obtained in pumping test were used to prepare a thematic layer on transmissivity using ArcGIS software. Different transmissivity classes in the study area were identified and then assigned weights according to their transmissivity values using the Saaty's analytical hierarchy approach.

## Delineation of Groundwater Potential Zones

The thematic layers on geomorphology, soil, slope, topographic elevation, land use/land cover, post-monsoon groundwater depth, recharge, and transmissivity were used for the delineation of groundwater potential zones in the study area. To demarcate the potential zones, all these thematic layers were assigned weights and then were integrated using ArcGIS software. The weights of thematic map and their individual features were decided based on the experts' opinions and local field experience (Machiwal et al. 2011).

The weights of the different themes were assigned on a scale of 1–5 based on their influence on the groundwater potential. Different features of each theme were assigned weights on a scale of 1–9 according to their relative influence on groundwater potential. Based on this scale, the qualitative evaluation of different features of a given theme was performed as poor, moderate, good, very good, and excellent. The relative influence of the individual themes and features on groundwater potential was decided based on the experts' opinion, information, and local knowledge. Thereafter, a pair-wise comparison matrix was constructed using the Saaty's analytical hierarchy process to calculate normalized weights for individual themes and their features. To demarcate groundwater potential zones, all the eight thematic layers after assigning weights were added (overlaid) using ArcGIS software. The total weights of different polygons in the integrated layer were derived from the following equation to obtain groundwater potential index:

$$\begin{aligned}\mathrm{GWPI} = (&\mathrm{GM}_w\mathrm{GM}_{wi} + \mathrm{SO}_w\mathrm{SO}_{wi} + \mathrm{SL}_w\mathrm{SL}_{wi} + \mathrm{TE}_w\mathrm{TE}_{wi} \\ &+ \mathrm{LU}_w\mathrm{LU}_{wi} + \mathrm{WD}_w\mathrm{WD}_{wi} + \mathrm{RE}_w\mathrm{RE}_{wi} + \mathrm{TR}_w\mathrm{TR}_{wi})\end{aligned}$$

where

GWPI = groundwater potential index, GM = geomorphology, SO = soil type, SL = slope, TE = topographic elevation, LU = land use/land cover, WD = post-monsoon groundwater depth, RE = groundwater recharge, TR = transmissivity, $w$ = normalized weight of a theme, and $wi$ = normalized weight of the individual features of a theme.

GWPI is a dimensionless quantity that helps in indexing probable groundwater potential zones in the area. The range of GWPI values was divided into four equal classes (called zones), and the GWPI of different polygons falling under different range was grouped into one class. Thus, the entire study area was qualitatively divided into four groundwater potential zones, and a map showing these zones was prepared using ArcGIS software. The entire process of groundwater potential zoning is shown in Fig. 4.

## *Suitable Strategies for Sustainable Groundwater Resources Management*

For the management of groundwater resources, artificial recharge is a very important factor. Artificial recharge is the process of augmenting the natural