Chapter 13
Groundwater Management for Irrigated Agriculture Through Geospatial Techniques

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Contents

Abstract Groundwater irrigation plays an important role in sustainable agricultural development through protective shield during droughts and dry spells and intensifying and diversifying of the cropping system. The measuring, monitoring, and

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modeling of groundwater availability, condition, and distribution are the major step to formulate a sustainable groundwater management plan for agricultural use. The conventional methods to manage groundwater are tedious and costly. However, the modernization of geospatial techniques, namely, remote sensing (RS), geographic information system (GIS), Global Positioning System (GPS), etc., along with differential proximity sensing has enabled groundwater management both spatially and temporally. It can help in surveying, analyzing, detecting, differentiating, characterizing, mapping, monitoring, and modeling of the groundwater quantity, quality, distribution, extent, and association of groundwater resources. The major interventions of geospatial techniques in groundwater management are groundwater quality assessment, spatial zonation for irrigation, groundwater prospects mapping, dynamicity of groundwater storage, saltwater intrusion, etc. These applications have made a huge impact on groundwater management for crop and land resources on a sustainable basis. The multiparametric approach of geospatial techniques can minimize the time, labor, and money and thereby enable quick decision-making for efficient water resources management. However RS data has some inherent limitations of spatial, spectral, and temporal resolution, which sometimes makes it difficult to understand and asses the groundwater condition. Still, it is very important for the areas/regions especially developing nations where data scarcity in terms of quantity and quality is often an obstacle for solving real-world water problems. This chapter highlights the various approaches of groundwater management for irrigated agriculture using geospatial tools and techniques.

Keywords Geographic information system · Groundwater irrigation · Groundwater prospects · Groundwater sustainability · Remote sensing

Abbreviations

BIS	Bureau of Indian Standards
DC	Dharwar Craton
EC	Electrical Conductivity
EMAG	Earth Magnetic Anomaly Grid
EO	Earth Observation
ERT	Electrical Resistivity Tomography
EVI	Enhanced Vegetation Index
FAO	Food and Agricultural Organization
FCC	False Color Composite
GIS	Geographic Information System
GPR	Ground Penetrating Radar
GRACE	Gravity Recovery and Climate Experiment
GWP	Groundwater Potential
IDW	Inverse Distance Weighted
LISA	Local Indicators of Spatial Autocorrelations
LULC	Land Use and Land Cover

NDMI	Normalized Difference Moisture Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NGLM	National Geomorphological Layer Mapping
NRDWP	National Rural Drinking Water Program
OECD	Organization for Economic Co-operation and Development
RSC	Residual Sodium Carbonate
SAR	Sodium Absorption Ratio
SWIR	Shortwave Infrared
TDS	Total Dissolved Solids
TWS	Total Water Storage
VNIR	Visible and Near-Infrared

13.1 Introduction

Groundwater is the portion of water present below the Earth's surface in pore spaces of soil/unconsolidated rocks and in the fractures/fissures of crystalline rock formations, etc. Groundwater constitutes about 30% of the world's freshwater supply, which is about 0.76% of the entire world's available water (Gleick 1993). Groundwater distribution in the globe is heterogeneous and varied both spatially and temporally. Diverse geomorphic conditions along with uneven precipitation type may be the reason. The fracture/lineament distribution, variation in lithology and geomorphology, and hydrological characteristics produce heterogeneous and inconsistent yield as well as the depth of groundwater. Groundwater serves as a dependable source of water for various purposes including irrigated agriculture and domestic and industrial uses. It is the major contributor in areas with high populations, irrigated agriculture, and insufficient surface water resources (Shah et al. 2001). The use of groundwater for agricultural irrigation overthrows the rest of other uses (Burke 2002). The world has witnessed the rapid growth of groundwater irrigation for crops over the past five to six decades (Shah 2014). Asia has contributed about 70% of this groundwater for irrigation use leading to substantial improvement in agriculture and food security (Siebert et al. 2010). This has positively impacted the economic growth and improves millions of household financial condition from poverty. It balanced marginal to submarginal farming by mitigating drought effects, allowing farmers to intensifying, diversifying, and changing in cropping patterns. It has also allowed farmers to adopt cultivation of high-value crops, multiple cropping, etc.

The innovation in tubewells and pumping technologies has excelled in the growth of groundwater irrigation. As a part of a long-established practice, groundwater use was initially limited to arid regions and rechargeable shallow alluvial aquifers of Ganga and parts of the Indus river basin. However, with the progress of time, it has rapidly spread over other regions with diverse environmental and geological setup. It got spread to hard rock terrains of peninsular India to the hot and humid southeastern Asian countries and northeastern part of Sri Lanka, where aquifer storage is inconsistent with low yield (Shah 2010). It was observed that in Indian subcontinent, annual groundwater abstraction increased from 10–20 km^3 before 1950 to 240–260 km^3 in 2009 (Shah 2010). European countries like Spain had experienced a huge demand increase in groundwater draft for agricultural irrigation purposes from 2 km^3 during 1960 to 6 km^3 during 2000 (Martinez-Cortina and Hernandez-Mora 2003). South Asian countries' groundwater irrigation development has reached a plateau, whereas in countries in sub-Saharan Africa, Southeast Asia, and South America, groundwater use is just beginning to grow (Barker and Molle 2005; Giordano 2006; Shah 2010; Shah 2014). The Food and Agricultural Organization (FAO) reported that groundwater irrigates around one-third of the world's total irrigated area out of that more than 70% area belongs to Asia (Siebert et al. 2010). However the estimates provided by South Asian countries like India and China show a periodical upward revise trend of groundwater-irrigated area over surface water-irrigated area (Shah 2010). These data indicate that in Asia groundwater-irrigated area is significantly greater than FAO estimates.

Excel in groundwater irrigation is the result of a high demand from agricultural industries. This is due to the stability provided by groundwater during drought season and contribution over dry land which helps in crop intensification and diversification (Tsur 1990). These also all affect countries' agricultural and socio-economic development. Groundwater irrigation has created many dry season crops in several South Asian countries (Barker and Molle 2005). Vietnam became the largest producer of pepper and robusta coffee by adopting groundwater irrigation (Zhu et al. 2007). Groundwater irrigation has enabled and intensified pre-summer Boro rice cultivation in Bangladesh, which revolutionizes the country from food borrower to a rice exporter (Palmer-Jones 1999). It has positively impacted the economy by raising the land value in the USA and Spain (Lee and Bagley 1972; Garrido et al. 2006).

Groundwater monitoring and management is very crucial for sustainable agriculture and economic growth of a country. Hence, continuous monitoring of such is required both spatially and temporally at global or regional scale. As the conventional methods are laborious, costly, and time-consuming, geospatial techniques can play a meaningful role. Remote sensing (RS) and geographic information systems (GIS) are very useful to extract information on groundwater-irrigated areas and their historical evolution (Sharma et al. 2018). However, use of only RS data in case of precise estimation of groundwater irrigation is very difficult as fragmented land-holdings, intense cloud cover in tropical regions, issues with satellite data resolution and repeativity, and spectral and spatial heterogeneity of crops (Velpuri et al. 2009; Thenkabail et al. 2009a, b). Nowadays census-based data along with sensing-based approaches have been used to generate groundwater-irrigated land statistics at a regional or national scale. But there are variations in data used, method of approaches, and results (Thenkabail et al. 2005; Thenkabail et al. 2009a, b). Interpolation methods are commonly used to assess spatial variability of groundwater (Corwin and Lesch 2005; Gunarathna et al. 2016). But such approaches may not be enough to understand the spatial and temporal distribution of water to formulate groundwater management plans for agricultural purposes. Even though there is a huge advancement in the RS imaging capabilities, accurate identification and monitoring is still an enormous challenge for groundwater resources, i.e., managing at micro-watershed level (Robert et al. 2017). Besides, various other socioeconomic factors along with diversified farming practices increase the difficulty in assessing groundwater-irrigated areas. Thus integrated use of RS and GIS is needed with various optical indices, classification algorithms, data assimilation, as well as data modeling (Gunaalan et al. 2018). Satellite image-derived indices were mostly used by various researchers to differentiate between irrigated and nonirrigated cropland area. These are generally dependent on spatial, spectral, and temporal differences water and/or vegetation cover (Jin and Sader 2005; Dutrieux et al. 2016; Ambika et al. 2016). Normalized Differential Moisture Index (NDMI) (Jackson et al. 2004; Jin and Sader 2005; Dutrieux et al. 2016) and Normalized Differential Vegetation Index (NDVI) were generally used to identify the irrigated cropland and land use and land cover (LULC) classification at different scales using various spatiotemporal resolution satellite images (Thenkabail et al. 2010; Dhiman 2012; Ambika et al. 2016). However multiple indices (vegetation, surface moisture, and surface temperature)-based approach is mostly preferable for irrigated and nonirrigated cropland classification (Ozdogan and Gutman 2008; Shahriar Pervez et al. 2014). The temporal NDVI and Enhanced Vegetation Index (EVI) data are commonly used to represent seasonal rhythms and phenological variations for different land-use types which showcase the groundwater irrigation impact (Jin and Sader 2005).

Groundwater occurrence and distribution vary spatially and temporarily depending upon lithology-geomorphology, hydrogeology, lineament/fracture distribution, and stream/drainage network and which eventually control its yield and depth. This spatiotemporal variability along with other associated factors makes it very complicated and time-consuming to identify its occurrence by conventional field mapping. The integration of RS and GIS with filed data could provide various impact components of groundwater occurrence and its movement depending on geology, geomorphology, soils, LULC, drainage, and lineaments (Jha et al. 2007). Modernization and sophistication in RS and GIS can help to integrate the data collected from various sources and methods. Many researchers have used such data to delineate groundwater prospects zones in different geological terrains (Prasad et al. 2008; Chowdhury et al. 2009; Rashid et al. 2012; Magesh et al. 2012; Adiat et al. 2012; Satapathy and Syed 2015; Agarwal and Garg 2016; Das et al. 2017; Ahmed and Mansor 2018). This chapter highlights the aptness of the geospatial technologies for groundwater irrigation and its positive impact on the socioeconomic environment through agriculture and food security. It also gives an insight into the groundwater usage regime that fits well with a nation's hydrogeological and socio-ecological reality.

13.2 Groundwater Usages in Irrigated Agriculture: Global Scenario

It is essential to manage groundwater resources to stabilize and increase agricultural production. Groundwater has contributed significantly toward agricultural transformation in Asia, the Middle East, and North African countries over the last five to six decades. A total of 38% of the world's irrigated area is currently supported by groundwater irrigation (Siebert et al. 2013). Groundwater contributes 13% of world total food production and 44% of world total irrigated food production (CGIAR 2017). The dependence on groundwater irrigation for crops is highest in South Asia followed by East Asia, Organization for Economic Co-operation and Development (OECD) countries, and East African and North African countries, respectively (Fig. 13.1).

Nowadays most countries like the USA, China, India, Spain, Bangladesh, Vietnam, and many African countries are managing groundwater resources for sustainable agricultural production (Shah 2014). This social and economic well-being by agriculture was associated with a high increase of groundwater abstraction (Shah 2010). Thus the global usages of groundwater for irrigation purposes show a steep increase (Fig. 13.2). As per FAO estimates, earth's total irrigated area is 307 million ha (Mha) out of which around 90% area belongs to Asia and America (Siebert et al. 2013). Table 13.1 represents the total area equipped with irrigation as well as area with surface and groundwater irrigation. In America, Asia and Europe the usage of groundwater for irrigation purpose are around 47, 38 and 31%, respectively, but in other continents, it is less than 25% (Fig. 13.3). Africa has a large potential for groundwater irrigation across the continent. Recent studies show that the semiarid Sahel and the eastern regions, stretching from Ethiopia to Zimbabwe, may have significant potential for groundwater irrigation (CGIAR 2017). Large portions of the region in Southern and Northern Africa have overexploited the groundwater

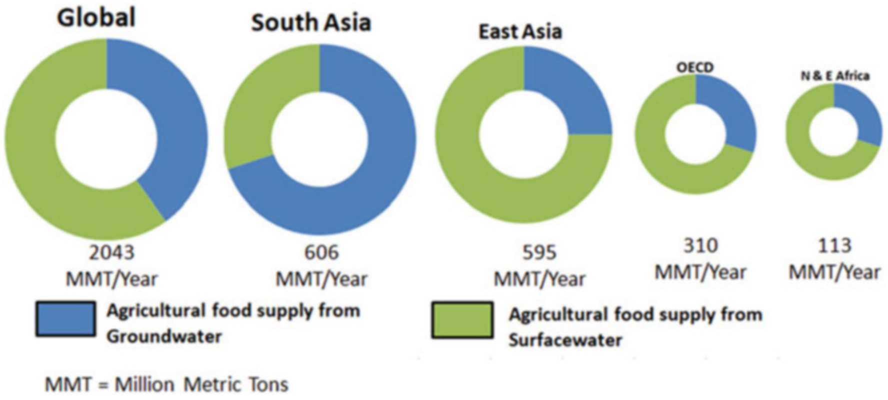

Fig. 13.1 Global scenario of dependence on groundwater irrigation for agriculture. (Modified, CGIAR 2017)

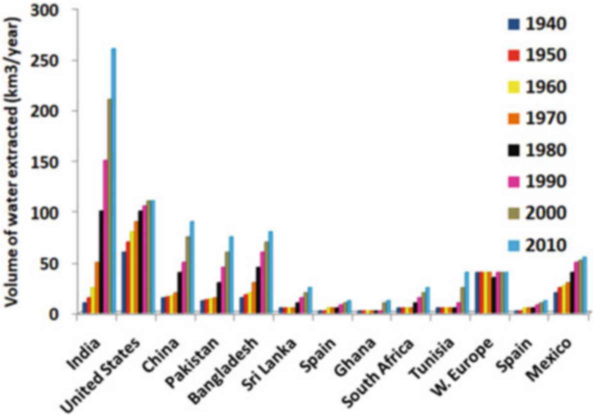

Fig. 13.2 Growth trends of global groundwater use

resources without considering the recharging capacities of aquifers and other geo-environmental factors (Shah et al. 2001; Hamed et al. 2014;Ahmed et al. 2014; Closas and Villholth 2016).

This has potentially ended the sustainable development of groundwater irrigation (Altchenko and Villholth 2015). Several studies have indicated that many Southern African countries are at greater risk of climate change and groundwater drought in the future (Villholth et al. 2013). Asia's groundwater-irrigated area contributes to almost 70% of the world's groundwater-irrigated area (Siebert et al. 2013). Asia demonstrates a blended representation of areas with potential and overexploited groundwater irrigation (Shah 2014). Countries like India, China, Pakistan, Bangladesh, and Sri Lanka where groundwater irrigation experienced rapid increases show a mixed picture of potential and overexploited areas (CGWB 2011; CGIAR 2017). In parts of South and Western India, extensive use exhausted the groundwater resources. However, there is plenty of opportunity for groundwater irrigation in Northeastern India. In India and Bangladesh, the uses of groundwater for irrigation are more than 60% (www.fao.org) of total irrigated areas. However, the statistics are on the lower side in countries like Afghanistan, Sri Lanka, and Indonesia (Fig. 13.4).

In Northern America, groundwater-irrigated area is around 59% of the total irrigated area, while it is on the lower side in Central and Southern America. However, Europe shows a very diverse picture of groundwater irrigation. In Eastern Europe, the groundwater-irrigated areas are around 10%, while in Central and Western Europe, it shows a higher value. Countries like Germany, the UK, and Spain show a prosperous picture on groundwater irrigation (Fig. 13.4). In Australia groundwater irrigation is around one-fourth of total irrigated land of the country.

Table 13.1 Total area equipped for irrigation and area with surface and groundwater irrigation (Adopted, Siebert et al. 2013)

Area equipped for irrigation (ha)				
Region	Total	Area equipped with groundwater	Irrigation with surface water	% area under groundwater irrigation
Northern Africa	6,400,826	2,113,437	4,273,626	33
Sub-Saharan Africa	7,148,268	399,210	6,747,858	6
Africa total	13,549,094	2,512,647	11,021,483	19
Central America and Caribbean	1,865,268	651,185	1,214,083	35
Northern America	36,411,337	21,355,866	15,055,471	59
Southern America	13,055,707	2,235,854	10,819,854	17
America total	51,332,312	24,242,905	27,089,407	47
Central Asia	13,657,552	1,085,033	12,572,518	8
Middle East	24,083,108	10,747,301	13,130,305	45
Southern and Eastern Asia	175,983,556	68,929,063	107,054,494	39
Asia total	213,724,215	80,761,397	132,757,317	38
Eastern Europe	5,198,729	494,759	4,703,970	10
Western and Central Europe	19,138,579	7,004,714	12,133,292	37
Europe total	24,337,308	7,499,473	16,837,262	31
Australia and New Zealand	4,688,259	1,135,787	3,478,479	24
Other Pacific Islands	4471	759	3712	17
Oceania total	4,692,730	1,136,546	3,482,191	24
World	307,635,659	116,152,968	191,187,660	38

13.3 Sources of Groundwater for Agricultural Use

The source of groundwater origin is from rainfall, lakes, rivers, streams snow, and ice, which is a part of the water cycle. Groundwater is the part of the water that is present beneath Earth's surface in soil pore spaces and in the fractures/fissures of rock formations, etc. below the zone of aeration (Todd 1980). This zone of aeration is nothing but the region between the earth's surface and the water table. Below the zone of aeration, the earth rock strata or sedimentary layer holds a considerable amount of water; this is called an aquifer. Aquifers are of porous which allows water

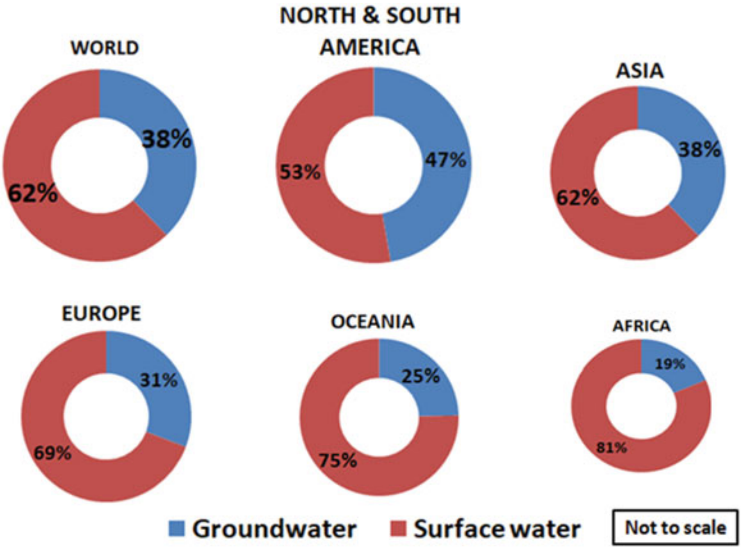

Fig. 13.3 Continent-wise groundwater vs surface water irrigation area. (Data source: www.fao.org)

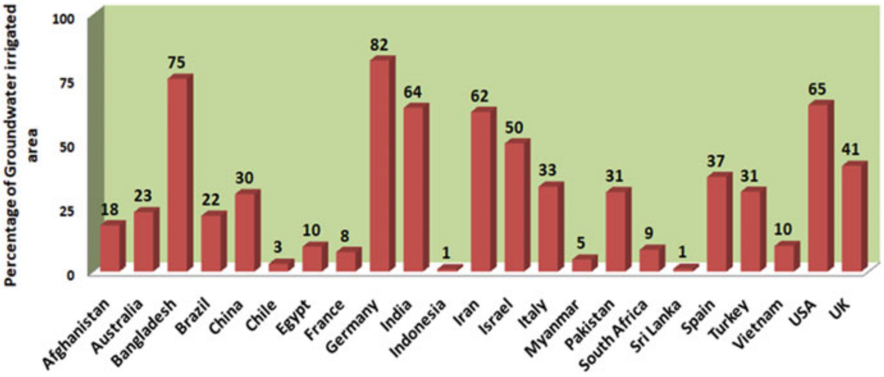

Fig. 13.4 Country-wise groundwater-irrigated area (%) with respect to total irrigated area. (Data source: www.fao.org)

to flow or percolate. Depending upon the nature of flow or recharge, aquifers are characterized. Surface water when directly flows to the aquifer-saturated zone is called unconfined aquifer or vadose zone (Fig. 13.5a). If the aquifer is sealed with impermeable layers at the bottom and top, it is called confined aquifers. These impermeable layers with very low porosity are called aquitard, and if it stops, the flow is called aquiclude.

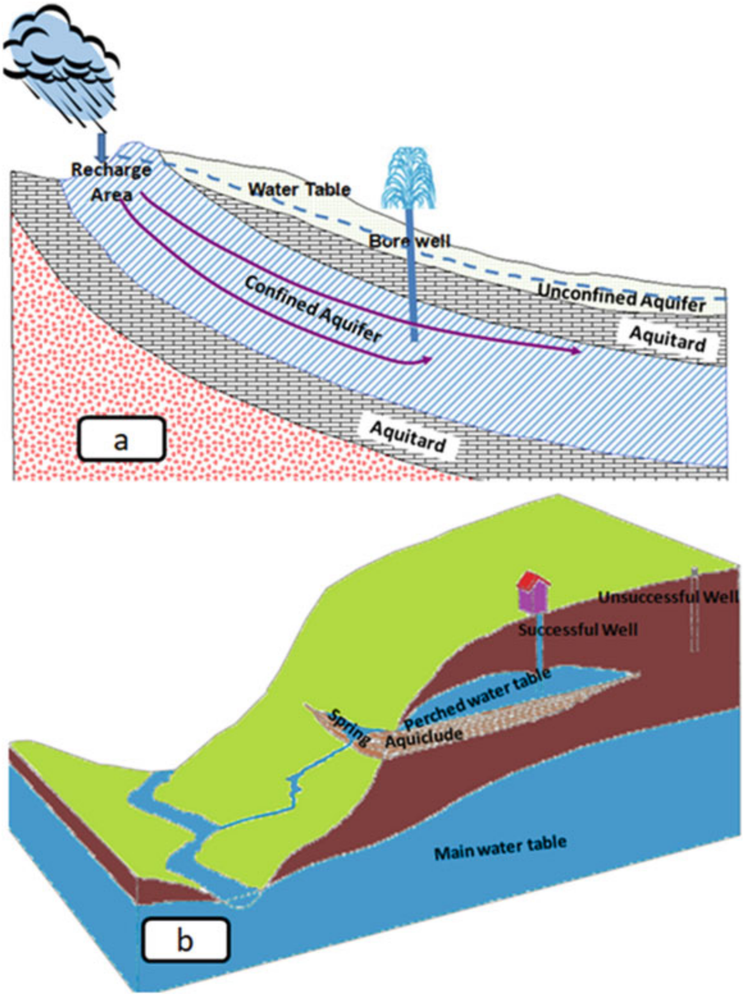

Fig. 13.5 (**a**) Schematic diagram of confined and unconfined aquifer with recharge zone; (**b**) schematic diagram of perched water table, springs, successful and unsuccessful wells

Groundwater constitutes about 30% of the world's freshwater supply, which is about 0.76% of the entire world's available water (Gleick 1993; USGS 2020). Groundwater resources in the world are heterogeneously distributed both spatially and temporally. Diverse geomorphic and lithological conditions along with uneven precipitation type give rise to the heterogeneous distribution of groundwater (Preeja et al. 2011; Saha et al. 2018). The fracture/lineament distribution system, variation in lithology and geomorphology, and hydrological characteristics produce heterogeneous and inconsistent yield as well as the depth of groundwater. Furthermore, groundwater occurrence and distribution in hard rock terrain is much more complicated than the soft rock terrain. The majority of groundwater use for agricultural irrigation are from various groundwater resources, like unconfined aquifer sources by dug well and hand pumps, confined aquifer sources through bore well, and perennial and seasonal spring's water in hilly terrains. Usually, in the soft rock terrains of alluvium zones, sandy aquifers of semiarid to arid regions water are of unconfined condition. The water from the confined aquifers mainly hard rock terrains of arid to the semiarid region is used by bore-well pumping technologies. These unconfined and confined waters of these aquifers are used for sustainable agricultural purposes where surface water is unavailable and during droughts as well as spells. In the hilly regions, perennial and seasonal spring water (Fig. 13.5b) is channelized to the agricultural fields for usage, when a surface water source is unavailable. There are many other sources of groundwater like well in the perched water table and artesian wells groundwater, and qanat well is used for agricultural usage. In this way groundwater plays a pivotal part in socioeconomic development in arid to semiarid region by backing agricultural activities; otherwise it couldn't sustain.

13.4 Groundwater Management Through Conventional Methods

There are various conventional groundwater management practices that have been used across the world since ancient times (Fig. 13.6). These practices are usually dependent on local socioeconomic environmental factors linked with surface and groundwater extraction and management. In many countries such as Spain, Morocco, Iran, and Syria and Central and Eastern Asia, a conventional water extraction and transporting technique called "qanat" is prevalent for a long period of time (Hartl 1989; Canvas 2014). This is a subsurface mildly sloping tunnel constructed to guide water from high elevated region to habitations situated below (Fig. 13.7a). Qanat is also called khettara in Morocco and kariz (kahrez) in Central and Eastern Asia including China. In Spain it is known as galerias (Taghavi-Jeloudar et al. 2013; Canvas 2014). This system has been operating for centuries to extend well-being of life in deserts (Hartl 1989; Canvas 2014). Traditional practices in Borana and Konso communities of Ethiopia include Ella (wells) and Harta (ponds) (Behailu et al. 2016).

The primary cause of conventional water management is water shortage and the need for survival. In arid regions where rainfall is low and the temperature is extremely high with a deeper groundwater table (~300 m), qanat is the only means of harvesting water for domestic and irrigational use (Taghavi-Jeloudar 2013; Canavas 2014). In the semiarid regions where rainfall is erratic, rainwater harvesting techniques such as the construction of ponds, check dams, nala bundh, nala pluge, etc. allowing runoff to percolate into shallow unconfined aquifers are practiced for centuries to secure the water needs of respective communities (Akpinar Ferrand and Cecunjanin 2014). The conventional groundwater management systems are related

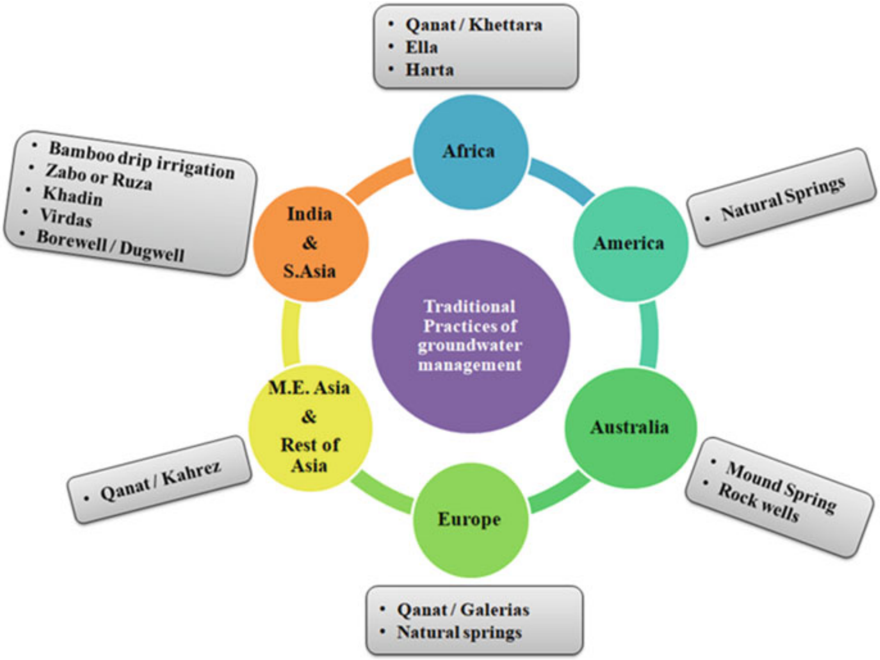

Fig. 13.6 Conventional groundwater management practices around the world

to water sources which include springs, shallow wells, and deep wells in Borana and qanat systems which are very much existent in the developing countries. Many European countries such as Sweden and Finland traditional beliefs governed their water management practices (Katko 2000; Knutsson 2014). The various sources to procure water were public wells and natural springs, and their management was governed by local customs.

In countries like India and China, groundwater harvesting techniques have been used for over 4000 years to meet the domestic and agricultural demand (Oweis et al. 2004). The major traditional practices used in India are as follows:

I. **Bamboo Drip Irrigation System**: This system of water conservation uses bamboo pipes to distribute spring water. Different diameter bamboo is used in perennial as well as seasonal springs for irrigation purposes in northeastern state of Meghalaya (Singh and Gupta 2002).
II. **Zabo:** It is also known as “Ruza,” a unique combination of water conservation with animal care, forests, and agriculture. Practiced in Nagaland (Singh and Gupta 2002).
III. **Khadin:** In this water conservation technique, surface runoff is stored for agricultural purposes. An embankment is usually constructed around the

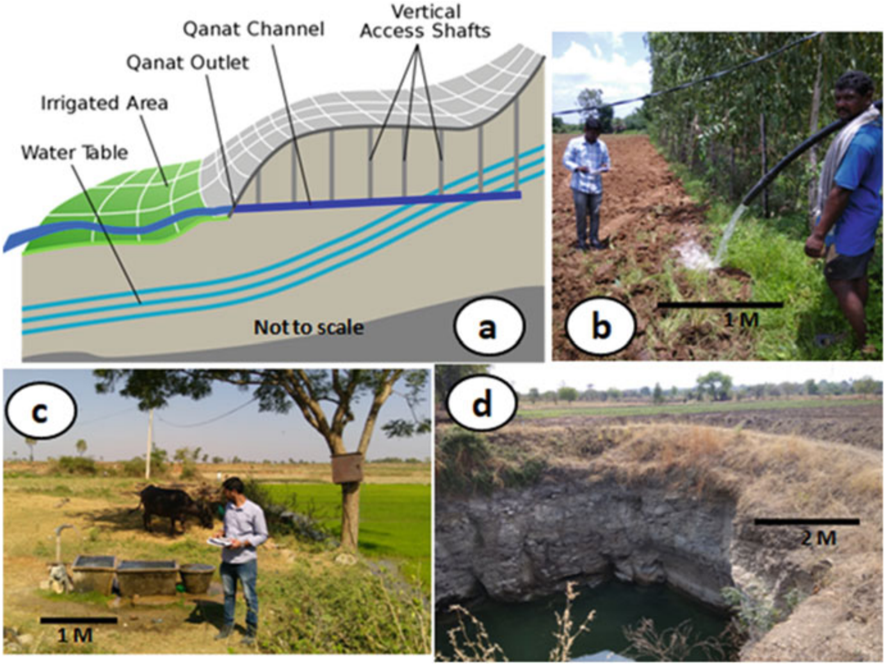

Fig. 13.7 (**a**) Schematic diagram of qanat well (Adopted, Wikipedia); (**b** and **c**) Representing bore-well-driven groundwater irrigation techniques in peninsular India; (**d**) Representing dug well irrigation system in Basaltic terrains of India

slope to collect and distribute groundwater to the agricultural fields. Generally a dug well is constructed nearby to get advantage from groundwater recharging. This practice is usually seen in arid regions of Rajasthan (Kolarkar et al. 1983).

IV. **Virdas:** Developed by Maldhari nomadic tribes of Rann of Kutch, these are shallow wells dug within a natural depression (jheel). It is an intelligent way to extract freshwater from saline groundwater (Machiwal et al. 2018).

V. **Bore Well and Dug Well:** Bore wells are constructed and used for flooding irrigation where there is plenty of groundwater (Fig. 13.7b–d).

The USA is predominantly surface water-dependent; hence, traditional methods of groundwater conservation are not used so much. One of the very popular conventional methods of groundwater irrigation in Australia is a mound spring. Carbonated water fed these springs which later rises to the surface through fissure/cracks in the overlying strata (Michael et al. 2018). Another traditional method of using groundwater is through rock wells, which are open entries to fractured rock aquifers.

13.5 Role of Geospatial Technologies in Groundwater Management for Irrigated Agriculture

Geospatial technologies have demonstrated huge potential in agricultural groundwater management. Lithology, geomorphology, structure along with physical processes such as climatic control, weathering pattern, and erosional agents acting upon a terrain for a substantial period control the terrain's groundwater regime. With the remarkable progress in RS technologies, satellite data of various electromagnetic wavelengths, types, and resolution gives valuable information about groundwater occurrence and distribution either directly or indirectly. Even though much of the earth surface is covered by soil or vegetation, RS has capabilities to provide subsurface aquifer information up to an assertive level (Rose and Krishnan 2009; Muralitharan and Palanivel 2015). This can provide indirect information on groundwater potential. RS along with GIS-integrated studies provide a double dimension, firstly, to visualize any earth feature in variable spectral, temporal, and spatial resolution and, secondly, to overcome the inaccessibility and duration of field investigation. Various decisive geospatial indicators may be of direct, indirect, or derived in nature and provide the probable location of groundwater occurrence as well as its variability (Fig. 13.8) for agricultural use.

Optical RS data can provide qualitative and quantitative information on tone, texture, pattern, shape, size, shadow, association, and resolution which are very essential in groundwater prospects study (Navalgund et al. 2007; Bennia et al. 2013).

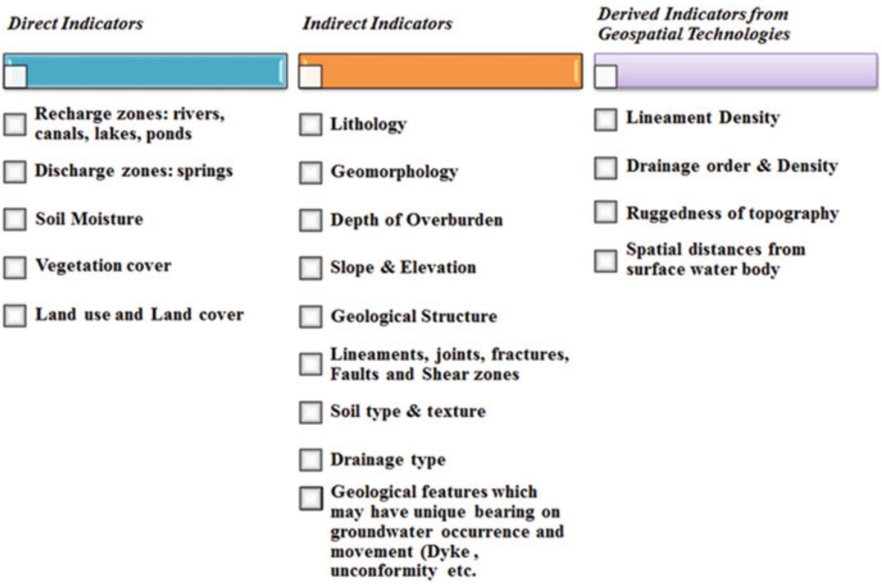

Fig. 13.8 List of decisive geospatial indicators for groundwater prospecting. (Ellyett and Pratt 1975; Singhal and Gupta 2010; Gupta 2003)

Lithological characteristic, moisture content, porosity, etc. of an aquifer can be characterized through tonal variations of satellite images, which give potential groundwater site information (Solomon and Quiel 2006; Adham et al. 2010; Abdalla 2012). Integrated use of RS elements such as texture, pattern, etc. and resolution can provide information on geomorphology, geological structures, the extent of major lineaments, change in moisture content, and hydrogeological characteristics. These eventually indicate the spatial and temporal variability of groundwater occurrence as well as distribution. Thermal RS data has shown enormous potential in determining lithotypes, major geological structures, buried lineament, soil moisture, canal, water body seepages, etc., which provides information of probable water-bearing horizons (Gupta 2003). Hyperspectral RS data provides information on an altered and lateritic zone within the earth's surface, thus providing indirect evidence of unconfined storage of water (Jensen 2016). Microwave RS data is very useful in delineating major litho units, mapping, and identification of major structural discontinuities like fold, fault, joint planes, and shear zones as well as the orientation of bedding plain, dipping strata, etc. (Lillesand et al. 2015). These determine the lithological, geomorphological, and structural variability of the earth's surface for identification as well as an understanding of aquifer heterogeneity and diversity. Eventually, this diversity and heterogeneity denote differential yield and depth of groundwater. Different geospatial sensors are capable to capture variable magnetic anomalies arising from geological features that enhance or reduce the local magnetic fields. The quantification and interpretation of these magnetic anomalies provide variable information on conduits and barriers (fracture, lineament, and dyke) of groundwater movement and characterization of aquifers (Subrahmanyam and Rao 2009). Gravity data from Gravity Recovery and Climate Experiment (GRACE) satellite is useful to calculate the change in total water storage (Tiwari et al. 2011; Dasgupta et al. 2014). The assimilation of additional datasets (evapotranspiration, runoff, precipitation, soil moisture) along with gravity data helps to find out a change in storage and temporal variability of groundwater. This is particularly useful in the modeling of groundwater impact assessment and depletion studies (Rodell et al. 2009; Feng et al. 2013) due to abstraction. Digital elevation model (DEM) also provides valuable information about physiography of any area, which helps in the delineation of geomorphic control on groundwater (Vittala et al. 2006; Singh et al. 2015). NDVI, NDMI, and other various satellite-derived parameters as well as indices are useful in differentiating irrigated cropland and LULC (Seeyan et al. 2014; Sharma et al. 2018).

13.6 Application of Geospatial Technologies for Groundwater Management

Geospatial technologies applications are very crucial in mapping, monitoring, and modeling of natural resources, especially for groundwater as it is very dynamic (Teeuw 1995). The systematic and integrated use of RS and GIS along with other ancillary information provide decisive information about groundwater studies (Naqa et al. 2009; Dar et al. 2010; Gupta and Srivastava 2010). Remotely sensed earth observation (EO) datasets are valuable sources for creating major geospatial indicators for groundwater occurrence and distribution (Ganapuram et al. 2009; Shaban 2010). The list of satellite data and sensors used for water management is presented in Table 13.2. The major applications of geospatial techniques in agricultural groundwater management are described as follows.

13.6.1 Groundwater Prospects Mapping for Site Suitability

The role of remotely sensed EO data and GIS in groundwater targeting and prospecting is enormous both locally and regionally (Prithviraj 1980; Parker 1988, Das et al. 1997; Thomas et al. 1999; Pratap et al. 2000; Sreedevi et al. 2005; Elbeih 2015; Naghibi et al. 2016; Gopinathan et al. 2019; Haque et al. 2020). Groundwater is very dynamic and multidisciplinary and acts as an integrated function of geology, geomorphology, structure, hydrology, slope, elevation, and LULC. RS data provides information about these decisive factors which directly or indirectly govern the movement and occurrence of groundwater within the aquifer (Gupta 2003; Jha et al. 2007; Machiwal et al. 2011). These factors can control the groundwater regime both quantitatively and qualitatively. Geospatial techniques can provide an efficient platform through GIS where all the satellite-derived thematic layers are integrated with large ancillary information and spatial and nonspatial data to delineate suitable groundwater prospects zone for irrigation (Stafford 1991, Machiwal et al. 2011; NRDWP 2012). The integration of RS data along with electrical resistivity tomography (ERT) is very efficient to assess the geo-structural settings and groundwater prospects with subsurface perspective, finer resolution, and larger coverage (Stan and Stan-Kleczek 2014). Thermal remote-sensed data can provide a regional and local flow of groundwater (Thakur et al. 2017). Integrated modeling (1D, 2D, and 3D) of thermal RS data along with groundwater prospects data and GPS-based field observations can provide groundwater zonation with more spatial and temporal accuracy (Gao 2002).

13.6.2 Dynamicity of Groundwater Storage

GRACE satellite data gives temporal gravity field and total water storage (TWS) dynamics of the entire Earth, with a coarse spatial resolution ~300 kilometers. Geospatial techniques make it possible to integrate GRACE data with various hydrological models for a better understanding of hydro-dynamicity, with higher accuracy at a regional scale (Swenson et al. 2003; Wahr et al. 2004). Modernization of geospatial technologies has provided quantitative dynamicity of groundwater storage and its impact using GRACE data (Rodell et al. 2009; Tiwari et al. 2011;

Table 13.2 The list of satellite data and sensor used for groundwater management

Sl No.	Satellite/ sensor/ geophysical sensor	Resolution	Band specification	Uses in groundwater management	Source
1	IRS 1C/D; Resourcesat-1 and Resourcesat-2 (LISS-III)	23.5 m	Consists of four spectral bands B2 (green; 0.52–0.59 μm), B3 (red; 0.62–0.68 μm), B4 (NIR; 0.77–0.86 μm), and B5 (SWIR; 1.55–1.70 μm) Repeativity 24 days	Thematic mapping of decisive spatial layers which controls the groundwater occurrence and movement. Indices like NDVI, NDWI, NDMI	bhuvan.nrsc.gov.in
2	Cartosat-1 DEM	10 m	Consists of a single panchromatic band with circular accuracy of 15 m and vertical accuracy of 10 m	Topographic controls in GWP mapping	bhuvan.nrsc.gov.in
3	Landsat-8/ OLI	15 m for Pan 30 m for visible, NIR, SWIR 100 m for thermal	Different bands 11 spectral bands (0.433–0.453; 0.450–0.515; 0.525–0.600; 0.630–0.680; 0.845–0.885; 1.560–1.660; 2.100–2.300; 1.360–1.390; 10.6–11.2; 11.5–12.5; 0.500–0.680 in μm)	Thematic mapping of decisive spatial layers which controls the groundwater occurrence and movement. Indices like NDVI, NDWI, NDMI, and EVI, regional and local flow of groundwater	www.usgs.gov
4	ASTER TM	15 m for Pan 30 m for visible, NIR, SWIR 90 m for thermal	Different bands 14 spectral bands (0.520–0.60; 0.630–0.690; 0.760–0.860; 1.600–1.700; 2.145–2.185; 2.185–2.225, 2.235–2.285; 2.295–2.365; 2.360–2.430; 8.125–8.475; 8.475–8.825; 8.925–9.27; 10.250–10.950; 10.950–11.650 in μm)	Thematic mapping of decisive spatial layers which controls the groundwater occurrence and movement. Indices like NDVI, NDWI, NDMI, and EVI, regional and local flow of groundwater	asterweb.jpl.nasa.gov

(continued)

Table 13.2 (continued)

Sl No.	Satellite/ sensor/ geophysical sensor	Resolution	Band specification	Uses in groundwater management	Source
5	GRACE	~330 km	Earth gravity anomaly	Dynamicity of ground water storage	gracefo.jpl.nasa.gov
6	EMAG2	~3.5 km	Magnetic anomaly grids compiled from satellite, ship, and airborne magnetic measurement	Magnetic anomalies provide variable information on conduits and barrier (fracture, lineament, and dyke)	www.ngdc.noaa.gov/geomag/emag2
7	GPR	Depth of penetration up to 40 m	Multifrequency (25, 80, 200, 400, 600, and 900 MHz)	Saltwater intrusion and coastal geomorphology study	Jol and Smith (1991), Neal and Roberts (2000a, b) and Bennett et al. (2009)

Longuevergne et al. 2010; Chinnasamy et al. 2013). Determination of groundwater storage both qualitatively and quantitatively at finer temporal and spatial scale is challenging because of the limitations of data. The coarse GRACE data can be integrated with other hydrological parameters having finer spatial resolution to determine a change in groundwater storage for a better understanding of groundwater management (Bates et al. 2007; Dasgupta et al. 2014). Magnetic anomaly data quantification and interpretation provide variable information on conduits and barriers (fracture, lineament, and dyke) of groundwater movement and characterization of aquifers (Subrahmanyam and Rao 2009).

13.6.3 Assessing Spatial Variability of Groundwater Quality Using GIS

Water quality depends upon various biological, physical, and chemical characteristics (Apha 2005). Irrigation water quality mainly depends upon physical and chemical parameters. The methods for suitability assessment of irrigated water include the following: (i) calculation of sodium, borate, and chloride ion and excessive presence of these affects sensitive crops (Wilcox 1955; Todd 1980); (ii) residual sodium carbonate (RSC) indicates alkalinity hazard (Richards 1954); (iii) trace elements and toxicity affect susceptible crops (Ayers and Westcot 1994); (iv) sodium absorption ratio (SAR) indicates sodium hazard affects infiltration rate of water into the soil (Richards 1954); and (v) electrical conductivity (EC) and total dissolved solids (TDS) indicate salinity hazard affects crop water availability (Wilcox 1955). GIS enabled the interpolation techniques by which spatial distribution maps of water quality elements (field-collected and lab-analyzed data) can be prepared. Such spatial maps are useful to formulate irrigation management plans for agricultural crops. The spatial distribution of water quality parameters by inverse distance weighted (IDW) method demonstrates accurate estimation (Corwin and Lesch 2005; Asadi et al. 2007; Mir et al. 2017). These interpolation results can be classified based on national or international irrigational quality standards (FAO 1985; BIS 2002) for suitability zonation as per groundwater quality (Richards 1954; Wilcox 1955; Donen 1964; Ayers and Westcot 1985). Gradient analysis methods provide spatial variability patterns more accurately of key elements, where the boundary conditions are heterogeneous. It generally creates multiple ring buffers around the point known point origin (Chen et al. 2016; Ranagalage et al. 2017). Local indicators of spatial autocorrelations (LISA) is a dimension of spatial relationships; it creates clusters of key elements under the assumption that a spatial pattern is a nonrandom distribution, which enables us to understand the spatial relationship (Anselin 1995; Anselin et al. 2010; Guo et al. 2015). These techniques help to know the spatial extent, inter-variability, relationship, and distributions of quality parameters of groundwater for irrigation purposes, which eventually allow us to map, monitor, and measure irrigation suitability spatially.

13.6.4 Assessment and Monitoring of Saltwater Intrusion

The coastal aquifers occupy some of the most potential aquifer systems in the world, but they are very vulnerable to seawater intrusion and salinity hazard from the host aquifer lithology (Frind 1982; Jalali 2007; Das et al. 2016). These external factors determine the quality of groundwater in coastal aquifers. The lowering of groundwater table by excessive abstraction, sea-level rise, and nonscientific processes of pumping groundwater by puncturing both fresh and saline aquifers are the main causes of seawater intrusion (Lee and Song 2007; Werner and Simmons 2009; Sebben et al. 2015). Apart from this geology, geomorphology, lineament, change in land-use pattern, and drainage also play a major role in seawater intrusion (Custodio and Bruggeman 1987; Dagan and Zeitoun 1998; Held et al. 2005; Kerrou and Renard 2010). Multifrequency ground-penetrating radar (GPR) is one of the major geophysical techniques used in groundwater studies by many researchers (Beres and Haeni 1991; de Menezes Travassos and Menezes (2004); Doolittle et al. 2006). It gives a good knowledge about coastal aquifer subsurface geology, which controls groundwater occurrence (Leatherman 1987). GPR measures and maps the water table indirectly by responding to the saturated conditions within or near the top of the capillary fringe (Doolittle et al. 2006). GPR has also been used to define recharge and discharge areas, identify groundwater flow patterns, and understand near-surface hydrological conditions (Steenhuis et al. 1990; Beres and Haeni 1991). GPR profiles of various frequencies provide a continuous image of the subsurface, from which groundwater depth to the water table and interface between saltwater and freshwater can be determined (Lee and Song 2007). GPR detects the electrical discontinuities both in liquid and solid medium in shallow subsurface conditions (Neal 2004). Differences in the dielectric constant usually cause strong reflections from lithological boundaries in the subsurface (Jol and Smith 1995). Besides, saline water attenuates and absorbs the GPR signal. This helps in the identification of saltwater intrusion, depth of fresh- and saltwater interface zone, and magnitude of the intrusion (Lee and Song, 2007). This helps in understanding the coastal aquifer characteristics for groundwater management.

13.7 Assessing Site Suitability for Groundwater Irrigation Using Geospatial Techniques: A Case Study

Identifying the groundwater in hard rock terrain is one of the major challenging tasks for hydrogeologists in the groundwater research domain. The objective of the present case study is to identify suitable sites for groundwater irrigation in a peninsular gneissic terrain, part of Dharwar Craton, India. The complexity of geology and structural origin of the study area is the major obstacle to delineate suitable groundwater prospects zone. Accordingly, a systematic procedure of geospatial techniques was adopted by integrating various thematic inventory and remotely sensed data in conjunction with limited field observations. The results highlight the importance of geospatial techniques to understand/identify suitable sites for groundwater for irrigated agriculture.

13.7.1 Study Area: Location and Hydrogeological Setup

The study area Palcherla watershed is a part of the granodiorite and hornblende-biotite gneissic province of Dharwar Craton (DC). It is situated in the Anantapur district of Andhra Pradesh, India, with latitude-longitude ranges between 14°20′00″ N to 14°36′30″ N and 77°21′30″ E to 77°34′30″ E (Fig. 13.9). The study area is a macro-watershed covering 214 sq. Km. The study area represents undulating topography, where the elevation ranges from 294 m to 593 m above mean sea level (MSL) (Fig. 13.10f). It demonstrates gently to the moderately dipping slope of 2–10°, but in some places, the slope is greater than 15° (Fig. 13.10b). The lithology of the site consists of granodiorite and hornblende-biotite gneisses of Archean age, which is crosscut by basic dolerite dikes of Paleocene to Cretaceous age. The field evidence also supported the fact that the host rocks gneiss was intruded by basic dolerite dykes at a later stage (Fig. 13.10a). The presence of metabasaltic rock of Archean age is also observed in the study area (Taylor et al. 1984; Rao et al. 1992). The lithology of this watershed is constituted by medium- to coarse-grained gneisses with very little porosity. The area shows predominantly pediplains of various depths weathering

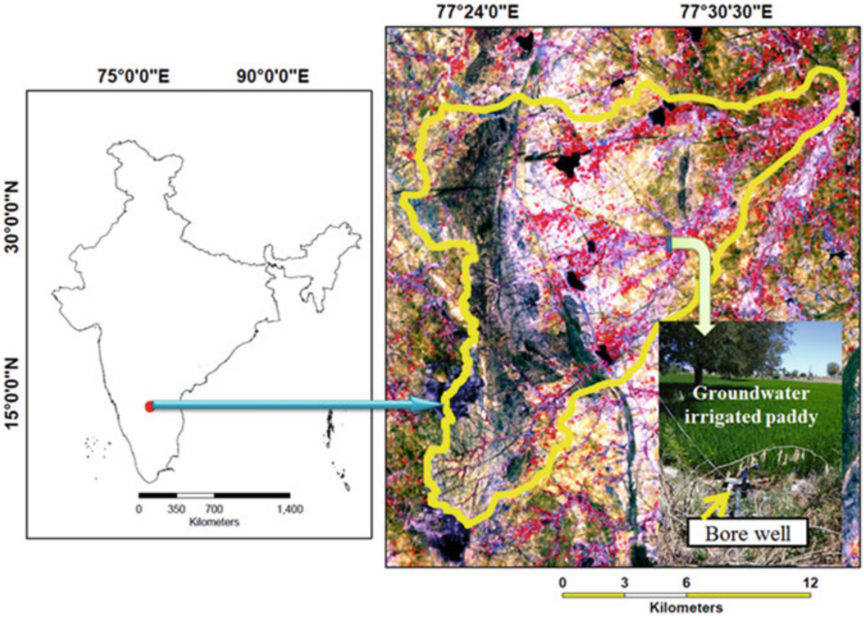

Fig. 13.9 Location of the study area. (It is shown in Resourcesat-2 LISS-III FCC composite with field photograph of bore-well irrigation)

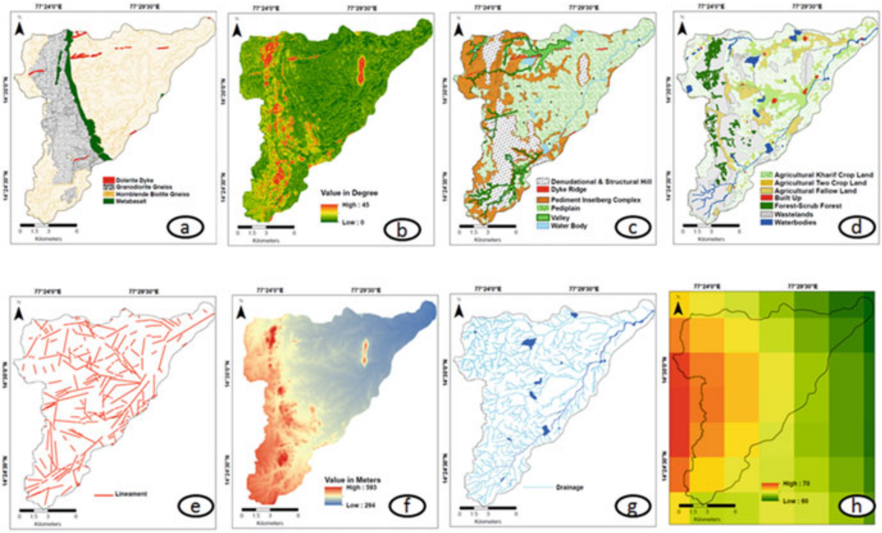

Fig. 13.10 (**a**) Lithology map showing the variation of different gneissic rocks and metabasalts; (**b**) slope map representing the slope variation in degrees; (**c**) geomorphology map showing different geomorphic features; (**d**) LULC map represents different patterns; (**e**) spatial distribution of lineaments; (**f**) variation of elevation in meters; (**g**) distribution of drainage and water body; and (**h**) EMAG2 data showing variation in earth magnetic anomaly datasets and method of approach

thickness, ranging between less than a meter and 30 m, and structural as well as residual hills. The weathered pediplains are mostly of shallow depths; only in some parts, it demonstrates moderate to a deeper thickness of overburden. The overburden material consists of particles of variable size and textures ranging from clay soil to gravelly soil to loamy soil. The hills are mainly of two types of residual hills which represent severe weathering pattern and hills with prominent structural control. The rest of the study area is covered by a pediment inselberg complex, valley fills (Fig. 13.10c) (NRDWP 2012; NGLM 2005). Regional lineament pattern reveals NE-SW and NNW-SEE trend (Fig. 13.10e). Dendritic to a sub-dendritic pattern of drainages is observed with streams trending in a NE-SW direction and very few tanks in this watershed region (Fig. 13.10g). LULC pattern of the study area shows a majority of the area comes under wasteland, followed by single-crop, double-crop, and fallow agricultural land; the rest is covered with forest and built-up area (Fig. 13.10d) (LULC 2015–2016).

13.7.2 Datasets and Method of Approach

13.7.2.1 Satellite Data

Resourcesat-2 LISS-III satellite data with a spatial resolution of 23.5 m was used in the current study (bhuvan.nrsc.gov.in). The false-color composite (FCC) data along with Cartosat DEM (10 m spatial resolution) (bhuvan.nrsc.gov.in) was used to generate various thematic layers related to geology, geomorphology, and hydrology. EMAG2 (Earth Magnetic Anomaly Grid) data (~3.5 km) was (www.ngdc.noaa.gov/geomag/emag2) integrated with the hydrogeomorphic unit to get the suitable site for groundwater irrigation purposes. These anomaly data grids provide insightful knowledge into subsurface structures which mostly act as conduits and barrier for groundwater movement.

13.7.2.2 Field and Ancillary Data

The field-based observations, i.e., GPS location, groundwater yield depth, geological formation, geomorphology, and LULC, were collected from the study site. These datasets were integrated with geospatial information to create site suitability map for groundwater irrigation. A set of field observations were also used to validate the site suitability map derived through geospatial techniques. To gain knowledge about the hydrogeological characteristics of the study area, hydrogeomorphology maps (NRDWP 2012), available well-drilled data, reports (CGWB 2013), and historical records were also collected from various sources. Such information gives an insight into aquifer characteristics in a holistic manner.

13.7.2.3 Method of Approach

The brief methodology of the study is presented in Fig. 13.11. The LISS-III image was processed and enhanced to bring the spectral and spatial variability between the features. The various thematic layers related to geology, geomorphology, structure, hydrology, slope, elevation, and LULC were prepared using LISS-III data and DEM. All the thematic layers were integrated into a GIS environment based on their relative importance in the spatiotemporal occurrence of groundwater (Fig. 13.11) to delineate the hydrogeomorphic unit. These different hydrogeomorphic units were later combined with the earth's magnetic anomaly data and field observation. The integration of satellite imagery-DEM-derived thematic layers, ancillary datasets, and field information has been made in a GIS platform to delineate suitable sites for groundwater irrigation.

13.7.3 *Salient Findings*

The site suitability zonation map of groundwater for the study site is presented in Fig. 13.12. The map consists of four suitability classes: (i) highly suitable, (ii) moderately suitable, (iii) slightly suitable, and (iv) unsuitable (Fig. 13.12). The spatial distribution shows that the slightly suitable and unsuitable zones are mainly concentrated in the western side of the watershed. Result shows that around half of the watershed is unsuitable or slightly suitable for groundwater irrigation for agriculture. These zones mainly consist of a structural or residual hill, where soil cover is

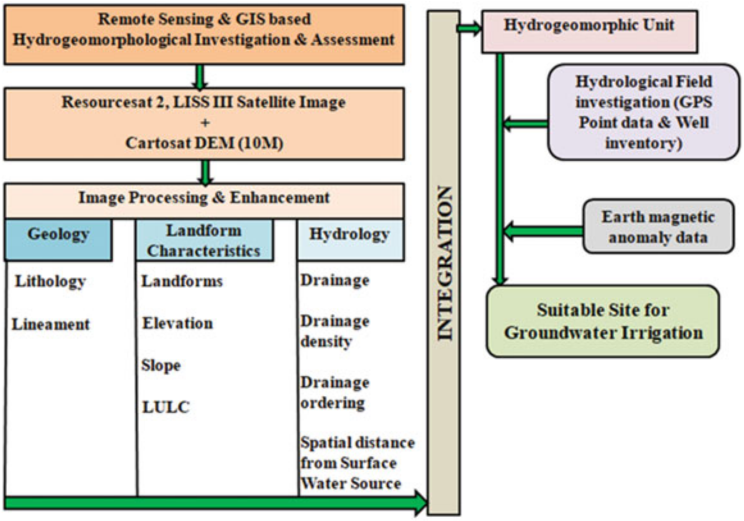

Fig. 13.11 Brief methodology of the study

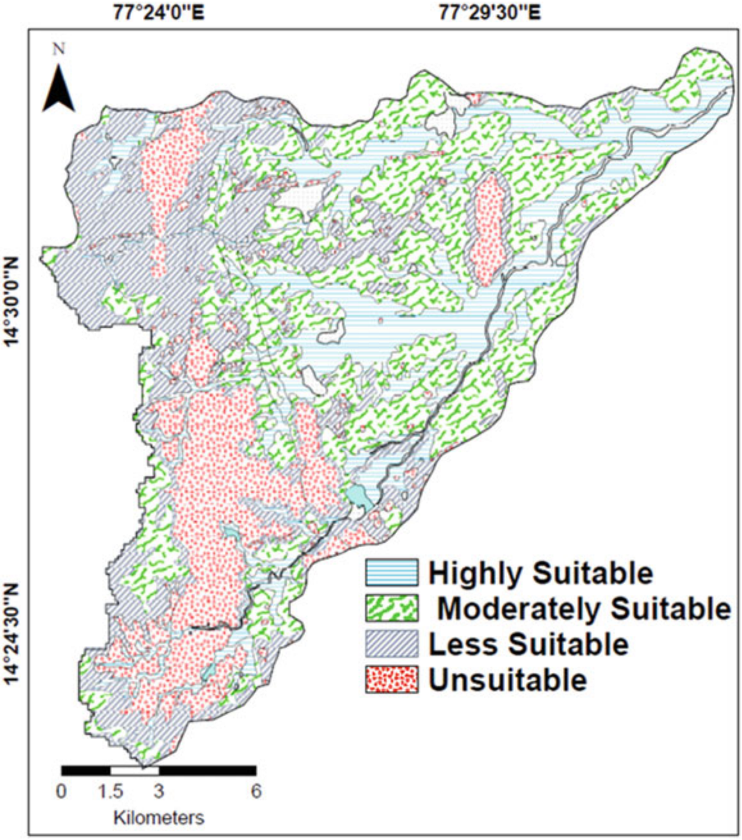

Fig. 13.12 Site suitability zonation map of groundwater for irrigation

almost nil for any agriculture vis-à-vis no groundwater source is available. The spatial distribution also shows the areas which are highly suitable to moderately suitable are the zones of weathered pediplains and valleys with the presence of a considerable amount of weathered overburdens/soils. These areas are usually characterized by a gentle slope, high lineament, and drainage density as well as high prospects for groundwater irrigation. The findings of the study area are in good agreement with the field observations and available data from different sources.

The study area Palcherla is a dry macro-watershed covering 214 sq. km which is part of the gneissic province of Dharwar Craton facing water shortage for irrigation purposes for the past few years. The overdependence on agriculture and unpredictable retreating monsoon has worsened the scenario. The result of the present case study can guide the groundwater irrigational practices in the study area as well as similar geological provinces. This study using geospatial techniques involving RS and GIS data interpretation with minimum groundwater field survey can drastically reduce the time, labor, and money and enables quick solution. Even though there are several limitations, the methods and results of the study show the potentialities of geospatial tools and techniques for solving real-world water problems.

13.8 Groundwater Management for Irrigated Agriculture Using Geospatial Approaches: Current Status and Challenges

The integrated use of geospatial tools and techniques are encouraging enough to be used in different groundwater management plans (Srivastava et al. 2011; Srivastava et al. 2012a, b). This involves the assimilation of near real-time information and their various utilizations (Yaduvanshi et al. 2015). The use of geospatial technologies are cheaper, more efficient, and time effective than conventional approaches (Okoye and Koeln 2003) and can be used for automated analysis using different approaches and modeling techniques. Advanced modeling is carried out to improve the knowledge about the quality/quantity of groundwater and related studies, such as prediction studies on how the vegetation changes with change in parameters of groundwater. Many advanced nations conduct drone surveys to generate real-time datasets which help in better monitoring of water resources (Lally et al. 2019). The mapping of groundwater resources in arid regions is well documented from Namibia (https://cals.arizona.edu/OALS/ALN/aln51/ednote51.html), America, and other countries. India is emerging as a global player in utilizing geospatial technologies to map groundwater potential zones as demonstrated by the National Rural Drinking Water Programme (NRDWP 2012). According to the survey carried out by Devex and CRS (2019), geospatial analysis and mapping will be the fourth major sector which will have a great impact in the development sector, in the coming 5 years with the Asia Pacific being the most accepted region (geospatialworld.net).

However, there are several limitations associated with the use of space-based sensors for groundwater monitoring. A huge volume of datasets needs to be monitored and is essential for real-time monitoring purposes. The remotely sensed data should be properly calibrated and validated with ground truth data (reference data). Another challenge in RS is the unavailability of spatiotemporal datasets with low revisit time. Besides, the RS datasets should be available in different formats so that it can be processed in different software with ease. The majority of the satellites have a short life span barring a few which makes it difficult to analyze changes over a while for impact assessment studies. Most of the commercially available satellites with high temporal resolution provide medium spatial resolution datasets which are sometimes inefficient in monitoring small irrigated landholdings. Besides, people are largely unaware of the benefits of geospatial technologies and are afraid to use them. Very high-resolution datasets with high temporal resolution are essential to carry out water management-related studies and policymaking decisions. Lack of skilled personnel is another challenge; hence hands-on training should be given to handle the datasets and process them which are essential at a grassroots level.

13.9 Conclusions and Future Perspectives

All over the world, groundwater irrigation provides a significant contribution to food security and socioeconomic development. Various scientific and conventional approaches have been adopted for groundwater irrigational practices. The use of geospatial technology in groundwater irrigation and management has grown very rapidly in the last two and half decades. The use of geospatial techniques by integrating EO data derived inputs as well as other ancillary information in a GIS platform to measure, monitor, and model the groundwater and provide another dimension to groundwater irrigation for agricultural purposes. The multiparametric approach of geospatial techniques can minimize the time, labor, and money and thereby enable quick decision-making for efficient water resources management. But RS data have some inherent limitations of spatial, spectral, and temporal resolution, which sometimes makes it difficult to understand and asses the groundwater condition as it is not directly visible and present below the Earth's surface in pore spaces of soil/unconsolidated rocks and in the fractures/fissures of crystalline rock formations, etc. In spite of limitations, the conjunctive use of RS data along with other ground-based and available ancillary information makes it a valuable practical tool. Thus it is very important for the areas/regions especially developing nations where data scarcity in terms of quantity and quality is often an obstacle for solving real-world water problems. But this advancement has a potential seed of a grave danger hiding. The ever-increasing dependence on groundwater and scientific as well as technological advancement of its abstraction has resulted in indiscriminate extraction without due regard to the recharging capacities of aquifers and other geo-environmental factors. This may result in further depletion of groundwater sources globally by impacting sustainability. Hence the groundwater extraction should be made with proper regards to recharge, and overexploitation should be curtailed to create a sustainable scenario.

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