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Mapping and identification of potential groundwater development zones of an alluvial aquifer in parts of Ghaggar and Upper Yamuna basins in India

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Abstract Using an integrated analytical hierarchy process, remote sensing and geographic information system techniques, the current study aims to map and identify the potential groundwater zones of Kurukshetra District of Haryana, which is located in the Ghaggar and Upper Yamuna Basins in India. This is done in the context of a significant change in the use of groundwater pattern, with respect to its continuously increasing demand due to the growing population, expansion of area under irrigation and related economic factors. The amount and quality of groundwater are anticipated to be impacted by anthropogenic activities as well as natural factors such as geomorphology, soil type, lithology and rainfall variance owing to a changing climatic scenario. The potential index of groundwater for this study was calculated by using nine important factors, including geomorphology, rainfall, soil type, depth to groundwater level, lithology, land use land cover, normalized difference vegetation index, cumulative sand thickness and elevation. The integration of multiple thematic layers was accomplished using the overlay weighted method to generate a potential groundwater zonation map and the accuracy of the resulting map was validated against a groundwater resource potential map. Statistical measures demonstrate an 82% agreement between the two maps, indicating a high level of concurrence. Accordingly, three groundwater zones of good, average and bad potential have been identified in the study area. In the current study, a process that combines weighted ranking with spatial data transformation and harmonization has been developed to obtain information for accurate decision-making. The results accruing from this research have significant ramifications for creating regional sustainable groundwater management plans.

Keywords Potential groundwater development zones (PGDZs) · Analytical hierarchy process (AHP) · Geographic information system (GIS) · Overlay weighted method

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Introduction

Water is the most versatile natural resource which is essential to sustaining ecological systems, advancing economic and social progress and sustaining human life (Ifediegwu, 2022; Makonyo & Msabi, 2021). Climate change and human activities are the main causes of the current stress on the world's water resources. Population growth, rapid urbanization, industrialization and agricultural activities have all contributed to an increase in the demand for water (Chatterjee & Dutta, 2022; Ghosh et al., 2022). Groundwater is an invisible resource which has a visible impact everywhere. It plays a pivotal role in global food security and economic growth and is the basis of survival of the living beings. Groundwater is essential for preserving ecological harmony, ensuring human welfare and fostering economic growth (IPCC, 2001) and is utmost significance in our daily lives since it serves as a primary source of freshwater worldwide (Das & Pal, 2020). It has always been an important natural resource that has benefited people's needs, including food security and their socio-economic development (Avand et al., 2020; Chakrabortty et al., 2018). Lately, several nations around the world have faced significant socio-environmental challenges due to the groundwater level decline and the resulting water shortage. The steadily rising demands of human needs are also contributing to the gradually declining quality of groundwater (Das et al., 2019). The easy access to groundwater has rendered its use under tremendous pressure due to its continuously rising demand by population growth, an increase in the area under irrigated agriculture and economic progress that places less emphasis on environmental protection (Mondal & Dalai, 2017). On the global scale, household, agriculture and industries are responsible for 36%, 42% and 27% of all groundwater withdrawals, respectively (Taylor et al., 2013). Ninety percent of India's rural population and 30% of its urban population rely on groundwater for their basic necessities (Agarwal & Garg, 2016). Woefully, in India, there is a fairly common scenario of limited groundwater resources being used extensively without any scientific planning (Rodell et al., 2009). Anthropogenic developmental activities not only pose stress on the quantity of groundwater but also exaggerate its quality issues which further aggravate public health concerns as well as economic stress (Kupwade & Langade, 2013; Milovanovic, 2007; Pandey & Tiwari, 2009).

In order to manage groundwater resources sustainably, the arid and semi-arid regions that struggle with the scarcity of freshwater need immediate attention. Therefore, the prediction and evaluation of groundwater source in such areas are very crucial for the sustainability of this important resource. Continued withdrawal of groundwater is accelerating throughout the world and its excessive use may lead to a significant decline in groundwater level (Machiwal & Jha, 2014; Mende et al., 2007; Phien-wej et al., 2006). The groundwater depletion is an environmental condition caused by the consistent decline in the groundwater level, which practically threatens sustainability of aquifers (Akther et al., 2009). Further contraction of aquifer materials may be responsible for land subsidence (Konikow & Kendy, 2005) and recharge from wastewater sources lead to groundwater pollution (Hoque et al., 2007).

Haryana state of India is an agriculture dominant region which relies more on groundwater resources for its assured irrigation. Kurukshetra district of Haryana along with Karnal and Kaithal districts are known as constitutes a part of the 'Rice Bowl of India', which is facing serious problem of groundwater depletion (Kumari et al., 2009). The present study pertains to Kurukshetra district which falls in Ghaggar and Upper Yamuna River basins. Both surface and groundwater are used for irrigation in the district but almost 81% of farmers solely rely on groundwater resources (Statistical Abstract of Haryana, 2013). There are around 37,516 minor irrigation tube-wells in the area for irrigation (CGWB, 2013). This has resulted in aquifer overdraft in many locations during the last few decades, altering the system's natural equilibrium.

It is impossible to directly observe groundwater because it is a scarce and hidden natural resource. Groundwater resources are investigated using a variety of techniques, but mapping these resources is a difficult task. The most often employed procedures for establishing the location of boreholes and the thickness of aquifer materials to examine groundwater resources are drilling tests and stratigraphic investigations (Jha et al., 2010), although it takes a lot of time and money to use these methods to assess a region's groundwater resource availability. Several researchers have used techniques like evidential belief function (Nampak et al., 2014), the logistic regression model (Pourtaghi & Pourghasemi, 2014), the decision-tree

model (Lee & Lee, 2015), the frequency ratio (Al-Abadi et al., 2016; Guru et al., 2017) and the weights-of-evidence (Ghorbani Nejad et al., 2017), artificial neural networks (Lee et al., 2018) and the analytical hierarchy process (Roy et al. 2022a, b) to assess the groundwater resources in different areas. A majority of these methods rely on statistical techniques that are bivariate and multivariate, but they have restrictions on the sensitivity of their results and the ability to make assumptions before an investigation (Thapa et al., 2017). Given that groundwater is dynamic, it will be more appropriate to demarcate the potential groundwater development zones (PGDZs) in the area like Kurukshetra, where the groundwater can be extracted in an environmentally safe and economically viable manner in near future. Integrating remote sensing (RS) data in the geographic information system (GIS) gives useful insight for delineating these PGDZs (Agarwal & Garg, 2016). The RS technique uses a combination of different electromagnetic spectrum ranges radiated from various earthly features to repeatedly cover a region in an organized, synoptic and quick manner. Groundwater occurrence and movement are influenced by a variety of factors that can be quickly and effectively determined by satellite data (Aluko & Igwe, 2017). Additionally, GIS provides a superior working environment that helps people deal with large and complex spatiotemporal data effectively (Wieland & Pittore, 2017). The combination of remote sensing, GIS and the analytic hierarchy process (AHP) represents a widely adopted, dependable and cost-effective approach for evaluating groundwater identification, recharge and storage (Moodely et al., 2022). Groundwater potential mapping has been carried out by different workers using index-based approach and RS & GIS techniques (Chenini et al., 2010; Gumma & Pavelic, 2013; Jasrotia et al., 2016; Krishnamurthy et al., 1996; Madrucci et al., 2008; Moges et al., 2019; Sikdar et al., 2004). Based on its efficacy, the analytical hierarchy process (AHP) can be used to describe PGDZs and has become a popular and useful Multi Criteria Decision Analysis (MCDA) tool (Arulbalaji et al., 2019). The AHP has demonstrated its robustness in numerous studies involving multi-criteria decision-making, such as site suitability (Halder et al., 2020), risk assessment (Lyu et al., 2020) and groundwater potential zoning (Uc Castillo et al., 2022). This method provides decision-makers with valuable insights that can be applied in practical field

experience. GIS and AHP integration work as a process for transforming and harmonizing weighted ranking and geographic data to generate information for informed decision-making (Malczewski, 2006) which can delineate the PGDZs. In light of the above, the current study uses a combined strategy of RS along with the GIS to create thematic layers for the mapping and identification of PGDZs in District Kurukshetra of Haryana, India, using MCDA-AHP. The main objective of the current study is to demark the groundwater potential areas and evaluate their percentage distribution based on various selected parameters.

The study area has heterogeneous lithological units along with erratic rainfall distribution pattern, varied geomorphology, different soil types, changing land use land cover and groundwater extraction practices, which grossly influenced the groundwater recharge and discharge processes. Its pertinent to mention that though the area under investigation forms a part of Indo-Gangetic plains yet maximum recharge occurs in Shiwalik foot hills (Kumar et al., 2004). The well-developed canal network in the state of Haryana only caters to the areas falling in its domain and the farmers there have to queue for their turn to grab their share for irrigating their fields. This semi-arid agrarian district of Haryana (Kurukshetra) follows the monoculture of wheat-paddy water intensive crops which cannot rely solely on monsoonal/non-monsoonal rainfall and thus focuses on assured groundwater resources for fulfilling their water requirement. This reckless extraction of groundwater beyond recharge over the year have laid to the decline in the groundwater levels. This is a serious concern and might also impact the future food security. Therefore, conducting a district level study is crucial to identify potential areas of groundwater concern in agriculture dominant regions due to localized groundwater extraction patterns. The present study aims to delineate groundwater potential development zones in the Kurukshetra district from where locals can extract water to sustain their livelihoods and food production. Although a number of studies focusing groundwater potential using AHP method have already been conducted in different parts of India, it is the need of hour to identify and demarcate the PGDZs in Kurukshetra as this area has witnessed large decline in groundwater level since 2001 and has high drought frequency (Kaur et al., 2022). Therefore, this district level study will provide a comprehensive

evaluation of groundwater resources by incorporative different variables that controls occurrence of groundwater. It integrates various indicators/variables that are directly associated with groundwater occurrence in GIS. By employing the analytic hierarchy process (AHP) method, the aim is to identify potential groundwater zones for effective management and sustainable development of water resources in the area. Findings of the present study will offer crucial insights to decision-makers regarding the potential zones for groundwater resource. The utilization of the robust analytic hierarchy process (AHP) as a multi-criteria decision-making tool enhances the spatial reliability and accuracy of the study. Additionally, this research addresses the existing data integrity gaps. By employing a comprehensive approach to categorizing potential groundwater development zones (PGDZs), the study aims to ensure sustainable aquifer development and the formulation of economically viable, technically sound and reliable plans for efficient water management in arid and semi-arid regions, including the study area.

Material and methods

Study area

Haryana is one of Northwest India's most agriculturally productive regions. With Punjab, Himachal Pradesh and Rajasthan neighbour its northern, western and southern borders respectively, the Yamuna River defines its eastern boundary with Uttar Pradesh (Fig. 1). With a share of only 1.3% in the total land surface area of the country, it produces more than 6% food grains. Kurukshetra district is located in the Northeast part of Haryana lying between Latitude 29°53′00″N–30°15′02″N and Longitude 76°26′27″E–77°07′57″E and is surrounded by the district of Kaithal, Yamunanagar, Karnal and Ambala as depicted in Fig. 1.

Most of the district comes under the Ghaggar River Basin except the eastern fringe of Ladwa block, which forms a part of Upper Yamuna Basin. It occupies nearly 1680 km² of geographical area and has a total population of 964,231 (Census of India, 2011). The climate of the district is semi-arid type and the annual rainfall is 691 mm (CGWB, 2021). The groundwater recharge mainly takes place through the natural precipitation in the form of rainfall and the seepage from the surface water while the source of discharge includes agricultural extraction for irrigation, domestic uses and industrial purposes, through public and private-owned tube-wells, handpump and borewells. Kurukshetra is also called the granary and rice bowl of the State where the net irrigated area is 151,000 ha, out of which 123,000 ha (i.e. 81%) are irrigated with groundwater.

Geologically, the whole study area is occupied by Quaternary geological formations of the Ghaggar and Upper Yamuna River Basins, which include recent alluvial deposits from the Indus alluvial plains. Sands ranging from fine to coarse grains, with sporadic gravel and pebbles, make up the granular zone. The groundwater exploration work determined the parameters of the aquifer. During this process, CGWB measured the discharge of 5 exploratory wells that were constructed and found that the discharge varied from 1374 to 4140 lpm when there was a draw down of 3 to 6 m. The range of the transmissivity is 830 to 2424 m²/day. The values of the storage coefficient ranged from 1.38×10^3 to 6.6×10^4. The easternmost region of the district, which is located in the Upper Yamuna Basin, has the average transmissivity of 2200 m²/day, 700 m²/day and 500 m²/day for unconfined, semi-confined and confined aquifer group with storativity 0.12, 1×10^3 and 4.5×10^4 respectively (CGWB, 2013).

Data collection and methodology

Literature review used by different researchers for identifying potential groundwater development zones (PGDZs) is given in Table 1. From this table, it is observed that the choice of variable is random. Based on the inputs gathered from experts during consultation process and local area conditions, weights are assigned to different thematic layers and their classes. Numerous factors like geomorphology of the area, the soil type, rainfall, type of land use and land cover, normalized difference vegetation index, sand thickness, elevation and slope all have an impact on the presence and nature of groundwater in a given area. These variables differ in each study because the selection of variables is predominantly dependent upon: (a) the objective of the research work and (b) data availability. For accurately assessing the PGDZs in a specific location, the relevant selection
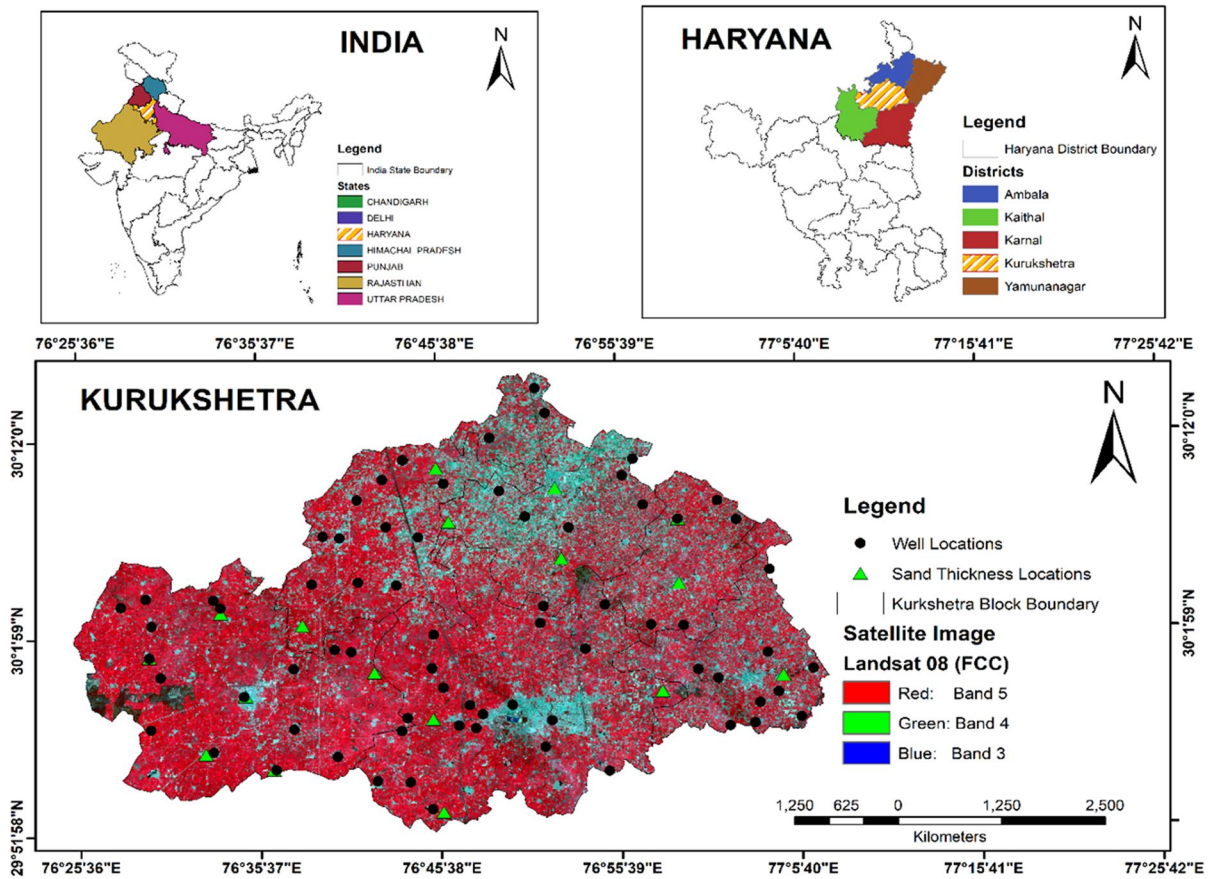
Fig. 1 Map of the study area showing the groundwater monitoring stations and litho-log locations in Kurukshetra, Haryana, India

of the variables is crucial. The groundwater recharge in an area of hard rock terrain is greatly influenced by the geology, geomorphology, elevation, slope, land use land cover type, rainfall and drainage density, while greater drainage density, higher relief and steeper slopes result in higher runoff generation. Consequently, in order to delineate the PGDZs, it is pertinent to identify and quantify these indicators (Kaur et al., 2020).

For the mapping and identification of PDGZs in the area under investigation, nine variables were carefully chosen, namely geomorphology, rainfall, soil type, depth to groundwater level (GWL), lithology, land use land cover (LULC) type, normalized difference vegetation index (NDVI), cumulative sand thickness (CST) and elevation to create the database for the present study. The derived variables used for this study namely geomorphology, lithology, rainfall, elevation, soil, LULC type,

NDVI, GWL and CST have been incorporated in previous studies for the delineation of PGDZs (Saha et al., 2010, Machiwal et al., 2011, Agarwal & Garg, 2016, Patra et al., 2018, Singh et al., 2018 and Kaur et al., 2020).

The sources of datasets are enlisted in Table 2. These datasets were geo-processed to generate thematic layers in GIS environment. In the study, all nine thematic layers that represent factors affecting groundwater recharge were prepared using the Arc-Map 10.4.1 software and are explained in sequel.

Geomorphology

Geomorphology is a branch of Earth Science that focuses on the analysis of landforms and the underlying processes that shape them, including groundwater potential zones and structural features (Swain, 2015). The integration of geomorphological, hydrogeological

Table 1 Literature review used to identification of potential groundwater development zones

Literature review	LULC	SOIL	GM	G	RR	DD	E	SL	LD	LI	NDVI	GWL	RF	TWI	SPI	CST
Saha et al. (2010)												✓				✓
Agarwal et al. (2013)	✓	✓	✓	✓		✓	✓	✓	✓			✓				
Bagyaraj et al. (2013)			✓	✓		✓		✓	✓							
Mahmoud and Alazba (2014)	✓	✓				✓	✓	✓								
Zaidi et al. (2015)	✓	✓	✓	✓		✓	✓	✓								
Senanayake et al. (2016)	✓	✓	✓	✓		✓	✓	✓	✓			✓				
Agarwal and Garg (2016)	✓	✓	✓	✓		✓	✓	✓								
Jasrotia et al. (2016)	✓	✓	✓			✓		✓				✓				
Patra et al. (2018)	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓			
Gnanachandrasamy et al. (2018)		✓	✓	✓	✓	✓		✓	✓	✓		✓				
Kaur et al. (2020)	✓	✓		✓				✓	✓			✓	✓			✓
Murmu et al. (2019)	✓	✓				✓	✓	✓	✓	✓		✓				
Saranya and Saravanan (2020)	✓	✓	✓	✓		✓	✓	✓	✓			✓				
Farootan and Seyedi (2021)	✓	✓		✓		✓	✓	✓				✓		✓		
Uc Castillo et al. (2022)	✓			✓	✓	✓	✓	✓	✓				✓	✓		
Radulović et al. (2022)	✓	✓	✓	✓		✓		✓								

LULC Land Use Land Cover, *GM* Geomorphology, *G* Geology, *RR* Recharge Rate, *E* Elevation, *Sl* Slope, *LD* Lineament Density, *LI* Lithology, *NDVI* Normalized Difference Vegetation Index, *GWL* Depth to Groundwater Level, *RF* Rainfall, *TWI* Topographic Wetness Index, *SPI* Standard Precipitation Index, *CST* Cumulative Sand Thickness

and structural analysis has been shown to be a highly effective method for identifying areas with high potential for groundwater resources (Bahuguna et al., 2003; Jagadeeswara Rao et al., 2004). Assessment of groundwater potential and probability of success in an area is significantly influenced by its geomorphological characteristics, which largely determine the subsurface movement of groundwater (Mukherjee e al., 2012). The geomorphology map was prepared using the geomorphology data available on the GSI-Bhukosh. The study area was almost plain and was only differentiated by the presence of water bodies, channels and dried-up palaeo-channels of the River Saraswati.

Rainfall

Precipitation in the form of rainfall in the region is a predominant factor, serving as a primary source of groundwater recharge (Shekhar & Pandey, 2015). The distribution of rainfall, combined with the steepness of the land, has a direct impact on how quickly water is absorbed into the ground and the potential for areas with high groundwater levels to form (Kumar et al., 2014). The infiltration rate is mainly governed by the type of material along with the intensity and duration of rainfall. The precinct receives rainfall from both northeast and southwest

Table 2 Data sources and type of data required

Variables	Resolution/scale	Data output type	Data source
Geomorphology	1:50,000	Raster	GSI-Bhukosh
Rainfall	0.25 × 0.25 degree	Raster	https://www.imdpune.gov.in/
Soil	1:500,0000	Raster	NBSS-LUP
GWL	Random	Vector	CGWB
Lithology	1:50,000	Raster	GSI-Bhukosh
NDVI	30 m	Raster	https://earthexplorer.usgs.gov/ (USGS)
LULC	30 m	Raster	Extracted from satellite image (Landsat 8)
Elevation	12.5 m	Raster	ALOS-PALSAR DEM
CST	Well location	Vector	CGWB

GSI Geological Survey of India, *NBSS-LUP* National Bureau of Soil Survey and Land Use Planning, *CGWB* Central Groundwater Board

monsoon but is unpredictable and unevenly distributed. The southwest monsoons contribute to mainly 81% of the rainfall from end of June to end of September every year and the annual rainfall in the study area is 691 mm (CGWB, 2021). Average rainfall data from 1986 to 2020 was interpolated using IDW (Inverse Distance Weighting) interpolation. IDW assigns weights to neighbouring observed values based on their distance to the interpolation location, and calculates the weighted average to obtain the interpolated value. This is commonly used in precipitation mapping methods (Frei & Schär, 1998; Rudolf & Rubel, 2005). While statistical interpolation methods such as Kriging are optimal in a statistical sense, they may not be robust in data sparse regions. Therefore, IDW is a deterministic interpolation method that is more suitable for such regions (Mukherjee et al., 2012). Indian Meteorology Department (IMD) is the nodal agency to collect and distribute the rainfall related data for entire India, and for the sake of research and non-commercial uses, IMD provides freely available rainfall data in the form of grid. New high spatial resolution gridded rainfall data (0.25×0.25 degree) from 1986 to 2020 for the entire India was taken from the Indian Meteorological Department (IMD) (Pai et al., 2014). The data were available in netcdf. file format and were converted to raster layer in GIS before proceeding with the preparation of the rainfall map of the study area. Bandyopadhyay et al. (2018) assessed the accuracy of this dataset with the in situ precipitation observations over India, and found its performance satisfactory (coefficient of determination (R^2) values between 0.6 and 0.8 and Nash–Sutcliffe efficiency (NSE) value greater than 0.5 in Haryana).

Soil

Infiltration of surface water, percolation and permeability rates are always regulated by the soil properties like porosity, texture, coefficient of permeability, consistency and adhesion. These qualities also have an impact on the soil's ability to retain water (Sedhuraman et al., 2014) and the volume of the unconsolidated material lying beneath the soil determines how much water reaches the water table (Arivalagan et al., 2014). The map depicting the soil-type association based on soil unit or polygon number was obtained from the National Bureau of Soil Survey & Land Use Planning in 2015

(NBSS & LUP, 2015) on a scale of 1:500,000. This map was created through the digitization of polygons and subsequent conversion to a raster format.

Groundwater level (GWL)

The groundwater in the study area occurs under unconfined to semi-confined condition at shallow depth and under confined condition in the deeper aquifer (CGWB, 2016; Roy et al. 2022a, b). Pre-monsoon water level data from 2015 to 2020 at 71 monitoring stations (Fig. 1) have been used for this study to show the spatial distribution of the groundwater level as groundwater is time dependent and dynamic in nature. GWL (groundwater level) data was procured from the CGWB (Central Ground Water Board) Regional Data Centre in Chandigarh. The data pertains to the average pre-monsoon period between the years 2015 to 2020. A total of 71 sampling locations were included in the dataset (as depicted in Fig. 1). In order to estimate GWL at locations where data was not available, IDW interpolation was performed in GIS.

Lithology

The lithological characteristics of the geological formations on the area's surface have a key influence on the presence of groundwater (Hachem et al., 2015). The groundwater movement and porosity are governed by lithological properties (Ayazi et al., 2010; Chowdhury et al., 2010; and Jhariya et al., 2016). In order to evaluate the potential for groundwater recharge, lithology or rock types, describes hydrogeological characteristics in terms of porosity and permeability of aquifer material. The groundwater potential zone delineation greatly depends on the geology of a region, as different geological formations possess varying abilities to hold water and exhibit diverse subsurface flow attributes (Sajil Kumar et al., 2022). The geologic data is freely available on the Geological Survey of India (GSI) portal-Bhukosh. Three lithological units were delineated, namely oxidized silt–clay with kankar and micaceous sand; grey sand, silt and clay; and grey micaceous sand, silt and clay. The study area was dominated by the Middle-Late Pleistocene age sediments forming the oxidized silt–clay with kankar and micaceous sand.

Land use/land cover (LULC)

Land use and land cover determine the amount of groundwater demanded and its consumption (Jhariya et al., 2016). Additionally, it provides data on groundwater recharge (Singh et al., 2013). The LULC pattern of a region significantly influences the rate of infiltration and surface runoff. Groundwater recharge and storage are significantly impacted by long-term and seasonal changes in LULC, precipitation and evapotranspiration (Scanlon et al., 2006; Siddik et al., 2022; Singh, 2014). The estimation of water recharge is more complicated in places with significant crop cover due to high irrigation frequency, which extract water from the source of recharging along with groundwater and generates diffuse recharge. LULC pattern detection is a prominent remote sensing application that plays an important role in groundwater resource development (Waikar & Nilawar, 2014). Therefore, the quantitative dependency on groundwater is defined by the land use in a given location. Satellite imagery from the Landsat-8 Operational Land Imager (OLI) of the year 2020 was acquired from the United States Geological Survey (USGS, 2020) Earth Explorer and was used to generate the LULC map.

Cumulative sand thickness (CST)

Sand/granular zones in the alluvial aquifers has the greatest capacity to retain water; therefore, CST is a crucial parameter in the assessment of groundwater potential zone. The occurrence of group-I potential aquifers or productive granular zones up to a depth of 110 m has been demarcated on the basis of aquifer wise sub surface mapping for the present study. The total saturated thickness of the granular zones or CST was derived from exploratory borehole data of 17 borewells (Fig. 1). Hydrological data from piezometric constructed by the Central Ground Water Board (CGWB) in the state of Haryana was utilized to generate a CST map. The map included 17 locations where the granular zone was identified (as shown in Fig. 1). Group-I CST data was interpolated using the inverse distance weighting (IDW) method to generate a continuous map in GIS.

Normalized Difference Vegetation Index (NDVI)

The normalized difference vegetation index is connected to the percentage of light absorbed by photosynthesis. When the NDVI of a surface is zero, then there is no green vegetation present, and when it is close to one (0.8–0.9), then there are as many green leaves as is physically possible (Mandal et al., 2016; Patra et al., 2018). The amount of absorbed photosynthetically active energy is the biophysical interpretation of NDVI. This characteristic of the NDVI is used as a proximate indicator of the presence of groundwater beneath the surface of earth. To generate NDVI map of the study area, cloud free Landsat 8 OLI (Operational Land Imager) image acquired on 04 March 2020 was used. The NDVI values were calculated using Eq. (1).

$$NDVI = (NIR - Red)/(NIR + Red) \qquad (1)$$

where NIR and RED represent the near-infrared and red band reflectance values, respectively, obtained from the Landsat 8 OLI imagery. The resulting NDVI map was classified into five classes using natural breaks, providing information on vegetation cover and health for the study area.

For easy data management in the GIS, all thematic layers were geo-rectified and projected to Universal Transverse Mercator (UTM) Projection, WGS 84 Datum Zone 43 North. For the Raster-weighted overlay analysis, all the weighted layers were rasterized and re-sampled to 12.5-m cell size. The weights assigned to each tier was established using the analytical hierarchy process once the databases for all nine layers were constructed.

Elevation

The elevation of the terrain is a critical factor influencing the replenishment of groundwater (Priya et al., 2022). Groundwater potential is greatly influenced by the terrain slope, which is inversely correlated with infiltration (Mogaji et al., 2015 & Morbidelli et al., 2015). The potentiality of groundwater in a drainage basin is determined by the stream gradient, which runs from the highest to the lowest altitude per unit area and the elevation is crucial in controlling the stream gradient (Ghosh et al., 2022). Orthorectified ALOS-PALSAR 12.5-m resolution DEM was used to prepare the elevation map of the study area. The elevation of the study area ranged from 174 m amsl in the western parts to 286 m amsl in the eastern.

Rank and weight assignment using AHP

The analytical hierarchy process is a structured decision-making procedure that involves creating an eigen value pairwise comparison matrix and using expert's opinion to assign the ranks based on multiple criteria approach first given by Saaty (1980). This method is excellent for making judgments in situations where several variables influence the result. Step 1 of this procedure entails the assignment of the weights to each parameter by taking into account the comparative significance of all the parameters as per Saaty's scale of relative importance given in Table 3 (Saaty, 2008).

In the second step, the factors influencing the outcome were organized into a structured hierarchy, and a pairwise comparison matrix was created. As mentioned above, total of nine parameters having the maximum impact of groundwater quantum and flow were selected for the present study. The pairwise matrix Eq. (2) with column and row evolved from Saaty's scale of relative importance are shown in Table 4. For further assessing the groundwater potentiality, each thematic layer was sub-divided into sub-classes based on Saaty's relative importance scale and is depicted in Table 5.

Using Eq. (3), the primary vector technique provided by Saaty was applied to normalize the weights (Agarwal & Garg, 2016; Ghosh et al. 2020a). Furthermore, for assessing the uniformity of the pairwise matrix consistency ratio (CR) and consistency index (CI) were calculated using Eqs. (4) and (5) respectively. The resulting matrix was verified for consistency, and when the consistency ratio was less than 0.1, the criteria weights

were employed for analysis. This strategy offers the decision-maker a variety of options. By assessing the consistency ratio, this method can also be used to check for subjectivity in the determined weights (Shekhar & Pandey, 2015). If the criterion is not met, i.e. the consistency ratio was greater than 0.1, then the matrix can be reconstructed using alternative options (Chandio et al., 2013).

(a) Pairwise matrix

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{1n} & p_{2n} & \cdots & p_{nn} \end{bmatrix} \tag{2}$$

where p_n denotes the nth indicator element with p_{nn} represents the judgement element of the matrix

(b) For calculating normalized weight

$$W_n = (GM_n / \sum\nolimits_{n=1}^{N_f} GM_n) \tag{3}$$

where the ith row of the geometric mean of the judgement matrices is calculated as

$$GM_n = \sqrt[N_f]{p_{1n}p_{2n}\cdots p_{nNf}}$$

(c) Calculation of consistency index (CI) and consistency ratio (CR) to test the consistency of the judgement

$$CR = \frac{CI}{RCI} \tag{4}$$

$$CI = \frac{\lambda\max - N_f}{N_f - 1} \tag{5}$$

Table 3 Satty's scale of relative importance

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judgments	When compromise is needed

Table 4 AHP matrix for potential groundwater development zone delineation

	Geomorphology	GWL	Rainfall	Soil	LULC	CST	Lithology	NDVI	Elevation	Normalized Weight
Geomorphology	8.5/8.5	8.5/8.5	8.5/8	8.5/7.5	8.5/7	8.5/9	8.5/7.5	8.5/5	8.5/4	0.13
GWL	8.5/8.5	8.5/8.5	8.5/8	8.5/7.5	8.5/7	8.5/9	8.5/7.5	8.5/5	8.5/4	0.13
Rainfall	8/8.5	8/8.5	8/8	8/7.5	8/7	8/9	8/7.5	8/5	8/4	0.12
Soil	7.5/8.5	7.5/8.5	7.5/8	7.5/7.5	7.5/7	7.5/9	7.5/7.5	7.5/5	7.5/4	0.11
LULC	7/8.5	7/8.5	7/8	7/7.5	7/7	7/9	7/7.5	7/5	7/4	0.11
CST	9/8.5	9/8.5	9/8	9/7.5	9/7	9/9	9/7.5	9/5	9/4	0.14
Lithology	7.5/8.5	7.5/8.5	7.5/8	7.5/7.5	7.5/7	7.5/9	7.5/7.5	7.5/5	7.5/4	0.11
NDVI	5/8.5	5/8.5	5/8	5/7.5	5/7	5/9	5/7.5	5/5	5/4	0.09
Elevation	4/8.5	4/8.5	4/8	4/7.5	4/7	4/9	4/7.5	4/5	4/4	0.06
Eigen value (λ) = 9.09										
Consistency ratio (C.R) = 0.008										

λ_{max} represents the eigenvalue of the matrix and can be derived as

$$\lambda_{max} = \sum_{n=1}^{N_f} \frac{(PW)_n}{N_f W_n} \qquad (6)$$

where W = column (weight vector), RCI = random consistency index and it can be acquired from the standard tables (Alonso & Lamata, 2006). To be acceptable, the value of CR should always be near or less than 0.10. AHP is a well-developed multi-criteria decision analysis tool and more details can be found in Saaty (1980), Patra et al. (2018) and Kaur et al. (2020).

Calculation of groundwater potential index (GPI)

Accordingly, GPI, a dimensionless value, used to model groundwater tract in the area under investigation was calculated using Eq. (7) as mentioned below:

$$\begin{aligned} GWPI = & G_r G_w + R_r R_w + S_r S_w + GW_r GW_w \\ & + Li_r Li_w + Lu_r Lu_w + N_r N_w \\ & + CST_r CST_w + E_r E_w \end{aligned} \qquad (7)$$

where GWPI-ground water potential index, G-geomorphology, R-rainfall, S-soil, GW-depth to groundwater level, Li-lithology, Lu-land use land cover, N-NDVI, CST-cumulative sand thickness and E-elevation. Suffix r represent the rank and w depicted the weight of each layer.

Firstly, the required thematic layers were converted from vector to raster format and then were re-sampled to generate similar cell size (12.5 m) and were finally reclassified. Furthermore, the MCDA-AHP process leading to normalized matrix with CI < 0.1 was carried out which was then subjected to GIS environment for weighted overlay analysis of all the nine thematic layers to finally generate the PGDZs in the Kurukshetra district forming a part of Ghaggar and Upper Yamuna River basins. The integrative framework is given in the flow chart (Fig. 2).

Validation model

To validate the PGDZ's map of the study area produced by integrating RS, GIS and multi-criteria decision-making process (i.e. AHP), a well-established method given by Central Ground Water Board (CGWB, 2016) on the basis of Ground Water Estimation Committee (1997) methodology was followed.

The groundwater resource potential (GWRP) map (validation map) takes into consideration both dynamics as well as in-storage groundwater resources Eq. (8).

$$GWRP = DGWR + IGWR \qquad (8)$$

Dynamic storage relates to the fluctuation of GWL which in turn depend upon infiltration of rainfall, evapotranspiration and related variables involved in

Table 5 List of parameters and AHP ratings and weights

S. No	Parameters	Weight	Sub-classes	Area %	Area (km^2)	Weight assigned	Normalized weight
1	**Geomorphology**	8.5	Older alluvium	90.38	1517.23	5	0.18
			Younger alluvium	9.23	154.84	7	0.38
			Water bodies	0.39	6.54	8	0.44
2	**GWL**	8.5	18.94–27.33	0.86	14.5	8	0.27
			27.34–33.98	11.15	187.3	7	0.23
			33.99–38.17	38.69	649.85	6	0.2
			38.18–42.43	35.09	589.29	5	0.17
			42.44–51.85	14.2	238.51	4	0.13
3	**Rainfall**	7.5	602.20–657.92	43.06	723.31	4	0.26
			657.93–704.61	37.97	637.78	5	0.23
			704.62–775.40	11.86	199.2	6	0.2
			775.41–868.77	4.86	81.64	7	0.17
			868.78–986.25	2.25	37.73	8	0.14
4	**Soil**	8	Loamy	65.57	1101.08	6	0.31
			Coarse loamy	24.64	412.99	7	0.4
			Fine loamy	9.79	163.85	5	0.29
5	**LULC**	7	Water bodies	0.34	5.7	8	0.42
			Agriculture	82.47	1385.25	4	0.21
			Forest	5.94	99.69	6	0.32
			Built-up	11.25	189.04	1	0.05
6	**CST**	9	42.00–53.01	9.23	152	5	0.14
			53.02–62.39	32.2	148.45	6	0.17
			62.40–71.77	44.85	977.74	7	0.2
			71.78–81.76	12.88	229.93	8	0.23
			81.77–93.99	0.84	171.46	9	0.26
7	**Lithology**	7.5	Oxidized silt-clay with kankar and micaceous sand	96.55	1620.85	5	0.28
			Grey sand, silt and clay	0.76	12.74	7	0.39
			Grey micaceous sand, silt and clay	2.69	45.09	6	0.33
8	**NDVI**	5	−0.05–0.17	10.42	175.09	1	0.05
			0.18–0.26	12.02	201.88	3	0.14
			0.27–0.35	12.09	203.11	5	0.23
			0.36–0.42	23.02	386.6	6	0.27
			0.43–0.54	42.45	712.95	7	0.32
9	**Elevation**	4	174–224	0.04	0.63	7	0.28
			224.01–242	18.96	318.46	6	0.24
			242.01–250	22.52	378.24	5	0.2
			250.01–258	30.05	504.8	4	0.16
			258.01–286	28.43	477.55	3	0.12

Fig. 2 Flowchart of methodology for the study
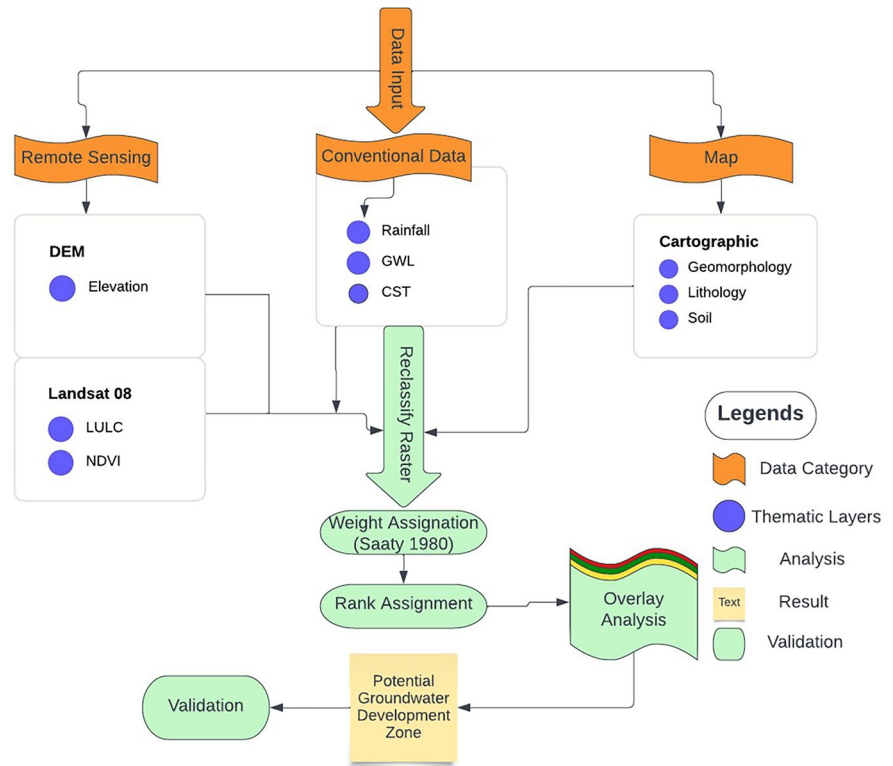
quantifying gain or loss to the groundwater regime. For the present study, the dynamic groundwater resource (DGWR) were calculated taking into account the depth to GWL data of 71 borewells (Fig. 1) in pre- and post-monsoon season according to Eq. (9).

$$
\begin{aligned}
DGWR = & \text{specific yeild of aquifer} \\
& \times (GWLpre - GWLpost) \\
& \times \text{Areal extent of the aquifer}
\end{aligned} \tag{9}
$$

The occurrence of potential aquifers or productive granular zones up to a depth of 110 m has been demarcated on the basis of aquifer wise sub surface mapping. The total saturated thickness of the granular zones or CST was derived from exploratory borehole data of 17 borewells (Fig. 1) for the present study. The granular zones occurring below the zones of water fluctuation up to the first confining layer has been considered static zone. The GWRP for this in-storage or static zone has been calculated using Eq. (10). The groundwater resource of this zone has been calculated considering 12% specific yield of the formation.

$$
\begin{aligned}
IGWR = & W \times \text{Specific yeild of aquifer} \\
& \times \text{Areal extent of aquifer}
\end{aligned} \tag{10}
$$

where GWRP-groundwater resource potential, DGWR-dynamic groundwater resource, IGWR-in-storage groundwater resource, W-aquifer thickness, GWLpre-groundwater level pre-monsoon, GWLpost-groundwater level post-monsoon.

Results

Geomorphology

In a flat land like the study area, lying in plains of River Ghaggar and Upper Yamuna, the occurrence of groundwater is greatly influenced by its geomorphology. Geomorphology not only helps in identifying and characterizing the landforms and structural features but also relates to the movement of water and freezing and thawing action (Arulbalaji et al., 2019). The geomorphic features here are carved out by the fluvial processes, and hence, the Kurukshetra district
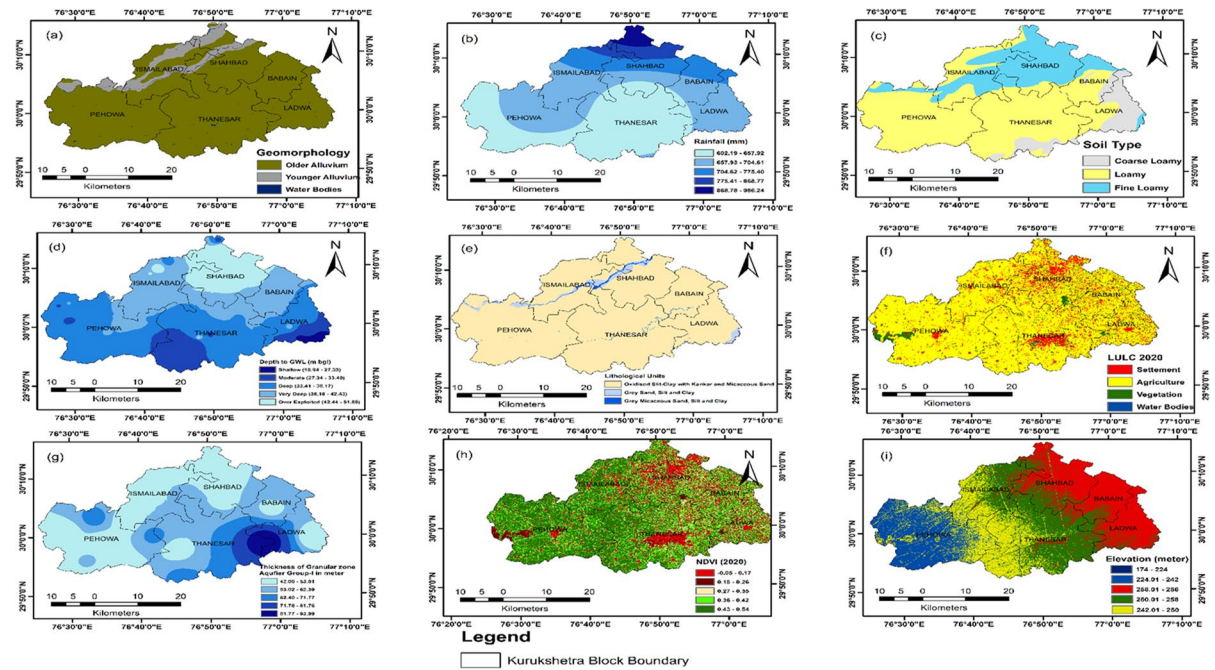
Fig. 3 Thematic layers of Kurukshetra, Haryana, India, **a** Geomorphology (GSI-Bhukosh), **b** rainfall, **c** soil type, **d** depth to GWL, **e** lithology (GSI-Bhukosh), **f** LULC, **g** CST, **h** NDVI, **i** elevation

was classified to three geomorphic units (Fig. 3a) namely (i) older alluvium, which occupies the major part of the study area covers approximately 90.38%;

(ii) younger alluvium can be seen in the northern to north western part of the district along the River Markanda and its small tributary and covers an area

Fig. 4 Potential groundwater development zone map of the study area
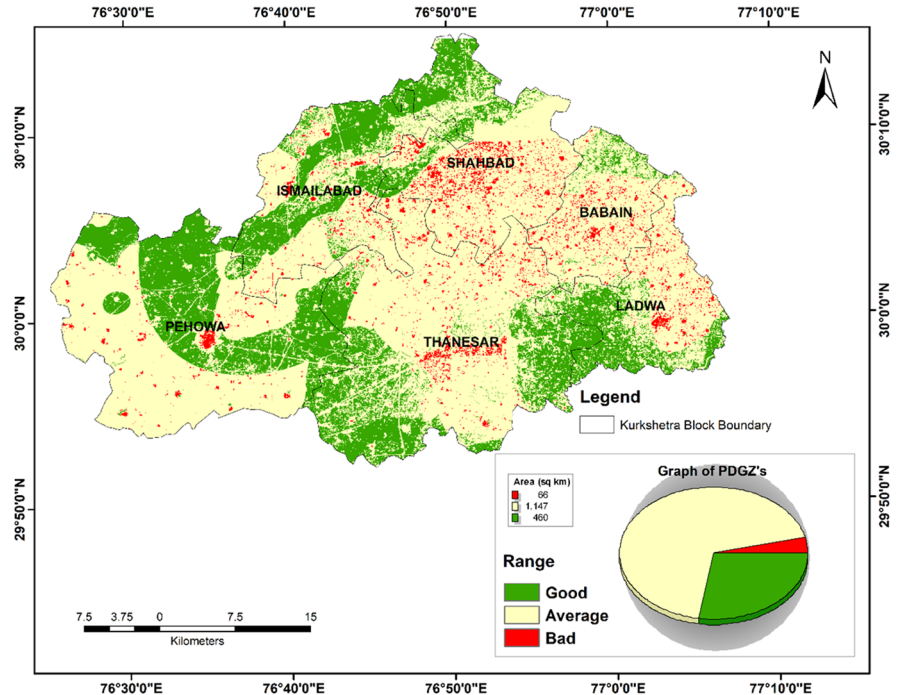
of 9.23%, whereas (iii) water bodies which cover a meagre area of 0.39% are seen scattered mainly in the area occupied by older alluvium (Table 5). Older alluvium in the study area is primarily composed of sediments, a majority of which are clay mixed with silt and kankar (Shekhar & Prasad, 2009), whereas younger alluvium is designated as unconfined aquifer (CGWB, 1996; Shekhar, 2006 and Rao & Manju, 2007). Since maximum recharge to groundwater is from water bodies followed by younger alluvium and older alluvium, the ranks and weights were also assigned accordingly. The overall weight for this layer was 0.13 (Table 4).

Rainfall

The rate of water infiltration and surface runoff, which depend on factors like rainfall volume, duration and intensity, is influenced by rainfall, making it a crucial factor in replenishing groundwater. The yearly average rainfall directly impacts groundwater recharge, with higher amounts indicating greater potential for replenishment, while lower amounts suggest a reduced potential for groundwater recharge. Therefore, in any study area, the timely and sufficient occurrence of rainfall plays a crucial role in increasing the groundwater potential (Muthu & Sudalaimuthu, 2021; Senapati & Das, 2022). The predicted rainfall map (Fig. 3b) exhibited a mean error (ME) of 0.002 and root mean square error (RMSE) of 0.07. A perusal of Fig. 3b and Table 5 confirms the categorization of rainfall zones into five classes with maximum weightage given to highest intensity range of rainfall as there will be more water available for infiltration. Accordingly, the areas with higher rainfall intensity are thought to be prospective PGDZs (Kaur et al., 2020; Rejith et al., 2019).

Soil type

As per Fig. 3c, the soil in the Kurukshetra district can be categorized into (i) coarse loamy or the soil of the flood plains which cover an area of approximately 24.61% and has been given the highest weight as these are the area along the present river or their tributaries and have coarse sand for best infiltration of flood or rain water. These soils cover the area along River Markanda and its tributary in the northern region along with the small strip in the eastern side, where River Yamuna flows and will make good PGDZs. (ii) Loamy

soil area is referred to soils of fluvo-aeolian plains and covers an area of 65.62% in almost all the blocks of the study area. (iii) Fine loamy soils are found in the north eastern region of the study area in parts of Ladwa and Babain blocks along with southern edge of Thanesar block, where the soils are from the piedmont plains and have moderate potential for groundwater and cover an area of 9.77%. The overall weight assigned to the soil type in this study is 0.11 (Table 4). The soil's ability to absorb water is influenced by its type, which is determined by the degree of saturation or desaturation of its pores (Ghosh et al., 2020b). The porosity of different soil types determines how water is transported into the soil; the soils with a coarse-grained matrix have a higher potential for groundwater, whereas those with a fine-grained matrix have a lower potential for groundwater (Ifediegwu et al., 2019). The weights assigned to the soil layer is primarily determined by the infiltration rate, leading to clayey soils being allocated the lowest weights, whereas sandy soils are assigned the highest weights (Sajil Kumar et al., 2022).

Depth to groundwater level (GWL)

As per the depth to GWL map pre-monsoon (May) (Fig. 3d), the study area has been categorized into five classes (i) shallow having depth to GWL between 18.94 and 27.33 m bgl covering a very small patch of 0.86% area on the eastern edge of Ladwa block, probably being recharged by the River Yamuna; (ii) moderate (27.34–33.98 m bgl) covering an area 11.15% mainly in the Thanesar block; (iii) deep (33.99–38.17 m bgl) covering an area of 38.69%; (iv) very deep (38.18–42.43 m bgl) covering an area of 35.09% and (v) overexploited (42.44–51.85 m bgl) covering an area of 14.20% falling totally in the Shahbad block which is located in the northern side of the Kurukshetra district. Deeper groundwater levels are caused by the vast occupancy of impregnable surfaces, the predominant reliance of agricultural activities, urban populations and industrial on groundwater (Kaur & Rishi, 2018). Hence, high weightage was assigned to shallower GWL and vice versa (Machiwal et al., 2011). A perusal of Fig. 3d indicates that only 12% of the area has shallow depth to groundwater, up to 34 m bgl and fall in the southern and eastern edge of the study area. The maximum exploitation concomitant with deeper GWL is more pronounced in the northern and central part of the area. Depth to

groundwater plays a crucial role in identifying the PGDZs and hence has an overall weight of 0.13 for the present research (Table 4).

Lithology

The predominant geological composition in the study area is oxidized silt–clay with kankar and micaceous sand, covering an area of 1620.85 km^2, which accounts for 96.55% of the total area. Grey micaceous sand, silt and clay, and grey sand, silt and clay cover smaller areas of 45.10 km^2 (2.69%) and 12.74 km^2 (0.76%), respectively. The highest importance weightage was assigned to grey sand, silt and clay, followed by grey micaceous sand, silt and clay, and oxidized silt–clay with kankar and micaceous sand. Alluvium or loose unconsolidated sediments typically have high porosity and permeability, making them ideal for higher groundwater recharge (Chatterjee et al., 2020). According to the aquifer material and their capacity to recharge, the lithological sub-classes were assigned respective weights (Table 5).

Land use land cover (LULC) type

LULC map (Fig. 3f) of the area under investigation has been classified into four categories out of which the most dominant is agriculture sector (82.47%), followed by settlements (11.28%), natural vegetation (5.94%) and water bodies (0.34%). The dependence of water intensive crops like paddy and wheat on groundwater has made agriculture as the main land use category. Also, the area under settlement increases the impervious areas and simultaneously decreases the recharge to groundwater and increase the surface runoff making it a less probable PGDZs. The maximum weightage was assigned to water bodies followed by natural vegetation, agriculture and built-up areas/settlements respectively. A closer look at LULC map (Fig. 3f) reveals that in the northern, eastern and a partially southern part of the study area is having more built-up area as compared to the western part. The overall weight of 0.11 has been assigned to this layer for the present research (Table 4). The impregnable nature of surfaces such as settlements, roads, rooftops, parking lots and surface underlain by hard rock does not permit rainwater infiltration into the soil and causes more surface runoff and disruption in the hydrological cycle. In contrast, the area

under vegetation cover reduces runoff velocity and increases water infiltration subject to the presence of a water source (Kaur & Rishi, 2018).

Cumulative sand thickness (CST)

The CST of the area under investigation was divided into five categories using natural break, i.e. 6.00–17.75 m (78.82%), 17.76–26.76 m (14.08%), 26.77–44.01 m (3.57%), 44.02–71.05 m (2.14%) and 71.06–105.92 m (1.38%) as depicted in Fig. 3g. The ME and RMSE of predicted groundwater level surface using IDW was −2.30 and 0.014 respectively. Higher weightage was assigned to the area in aquifer group-I with greater sand thickness and vice versa (Table 5). The southern eastern part of the study area has more cumulative sand thickness falling in Thanesar-Pewoha block boundary, ranging from 71.06 to 105.92 m and hence is a better potential groundwater development zone. As we move towards the northern side of the study area, the CST gradually decreases indicating declining capacity to hold water and categorizing it into bad PGDZs. Greater aquifer thickness has a beneficial impact on the potential for groundwater development, this is because a thicker aquifer holds large amount of available resources and a longer well screen length, which can improve the overall accessibility of groundwater (Saha et al., 2010).

Normalized difference vegetation index (NDVI)

A perusal of the Fig. 3i indicates that there are better prospects of groundwater in the western part of the study area as compared to the eastern part as NDVI values are higher there. Compared to other wavelengths, healthy vegetation (containing chlorophyll) reflects a greater amount of near-infrared (NIR) and green light, while absorbing more red and blue light. This is why our eyes perceive vegetation as green. Regions with a higher density of vegetation are more suitable for planting crops and are therefore more likely to have greater groundwater potential (Pradeep & Krishan, 2022). In the presented NDVI map, higher NDVI values were given higher weight to indicate areas with a higher density of vegetation. Furthermore, the impervious areas/settlements are also much curtailed in the western half of the study area making it prospective PGDZ as per LULC map (Fig. 3f). The

areas with lush green dense vegetation are frequently found to have shallow groundwater levels (Patra et al., 2018) and hence may be the probable PGDZs. Based on the NDVI map of the year 2020 Fig. 3h, the study area was classified into five categories: −0.05–0.17 (10.42%), 0.18–0.26 (12.02%), 0.27–0.35 (12.09%), 0.36–0.42 (23.02%) and 0.43–0.54 (42.45%).

Elevation

In general, the water flows from higher elevation towards lower elevation of the area; hence, there is more runoff at higher elevation which results in less percolation. Thus, the higher elevation was assigned lower weightage and vice versa (Table 5). The elevation of the study area ranging from 174 to 286 m amsl was further sub-categorized in five classes based on natural breaks value of the raster (Fig. 3i). A perusal of Fig. 3i indicates that the elevation decreases from Eastern to Western side of the study area indicating of having probable potential groundwater development zones on the western and southern side of the area under investigation. Regions with low elevation tend to hold water for a longer period, allowing for more infiltration of recharge water and resulting in less runoff during rainfall (Patra et al., 2018; Thapa et al., 2018). Conversely, areas with higher elevation tend to retain rainwater for shorter periods, leading to higher runoff. As a result, priority was given to areas with lower elevation in assigning weightage, as they are more conducive to groundwater recharge.

Potential groundwater development zonation

The study area, district Kurukshetra of Haryana State, falls in the Ghaggar and Upper Yamuna River Basins and is geomorphologically divided in older alluvium and younger alluvium and have litho-units and soils favourable for the groundwater infiltration and percolation. These factors coupled with moderate to good rainfall, gentle slope and availability of groundwater make it conducive for agricultural practices. As the society advances, modernization and urbanization add on to concretization and increase the settlement either in the form of housing cluster or industries which is clearly visible from the LULC map (Fig. 3f) of the study area.

The potential groundwater development zone map using the AHP method was obtained by the weighted overlay method of the selected nine thematic layers and is presented in Fig. 4. The PGDZ's map so obtained was classified into 3 zones on the basis of natural break (jenk) available in ArcMAP 10.4.1, i.e. good, average and bad having geographical area of 460.59 km² (27.52%), 1146.57 km² (68.52%) and 66.21 km² (3.97%) respectively (Fig. 4). The study found that approximately 27.52% of the research area is a promising zone for groundwater development, primarily located in the southwestern region. The area is characterized by good sand thickness, which allows for the storage of significant amounts of water. The groundwater potential in the southwestern part of the study area is also influenced by its young flood plain characteristics. The north-eastern parts of the study area, which encompass the Markanda river, are also classified as having good groundwater potential due to their young flood plain area.

The remaining 68.52% of the study area falls into the average potential groundwater development zone category. The distribution of this category is variable, with sporadic areas in the eastern part and primarily concentrated in the central and western regions. The groundwater potential in these areas is influenced by the soil type, depth to groundwater and land use characteristics.

However, the study also identified a bad potential groundwater development zone, which comprises only 3.96% of the study area. This zone is mainly prevalent in the northern block of Shahbad. The classification is due to a lower cumulative sand thickness to store water, despite receiving a higher amount of precipitation. Additionally, wherever there is more built-up area, surface runoff is favored over infiltration, resulting in deeper depth to groundwater. This ultimately reduces the potential for groundwater development.

Overall, the study area's potential for groundwater development and recharge varies spatially, with some areas being more favorable than others. This information can help stakeholders and decision-makers to decipher policies related to land use and groundwater management practices in concomitant with the potential groundwater development zones.

Validation

A map of groundwater resource potential (Fig. 5) as per well-established methodology of Ground Water

Estimation Committee (1997) was created for validation purposes by integrating dynamic and in-storage groundwater resources. Based on the groundwater prospects, the validation map (GWRP) was classified into three categories on the basis of natural break (jenks) available in ArcMAP 10.4.1 viz. good, average and bad having a geographical area of 31.30%, 41.16% and 27.54% respectively with significant mean error of 4.43 and root square mean error of 0.013 respectively. The 'good' groundwater prospects were discernible in the southern region comprising of mainly Ladwa block and small patches were also shown at the border of Pehowa-Thanesar block and north-eastern part of the study area where good alluvial flood plains of River Markanda prevail. Most of the area under the 'bad' category of groundwater resource potential were discernible in the northern part of the study area falling in Shahbad block, having minimal CST and maximum built-up area, and the remaining part of the region (41.16%) was classified under 'average' GWRP.

The PGDZ's map derived through AHP (Fig. 4) and the GWRP/validation map (Fig. 5) support each other. The zones of poor groundwater prospect are occupied mainly the northern region of the study area, i.e. Shahbad block in both the maps and the

main reason for the same is less CST, deeper GWL, more built-up area, steeper slope which over shadow the amount of precipitation received in this part of the study area. Table 6 shows the statistical measures of the validation results, which indicate that there is an 82% agreement between the two maps. This suggests that the PGDZ's map provides a reliable representation of the potential for groundwater development in the study area, as it aligns well with the GWRP map. These findings have important implications for decision-making related to groundwater management and development in the study area. Both the maps (Figs. 4 and 5) confirm the better groundwater development prospects in the south western part of the study area rather than the central and northern part, where all the factors are favourable.

Discussion

The study focused on mapping and identifying potential groundwater development zones in parts of the Ghaggar and Upper Yamuna basins in India, specifically in the district of Kurukshetra in Haryana State. The need to evaluate the groundwater resources has arisen due to the complex and ever-changing

Fig. 5 Groundwater resource potential (validation) map
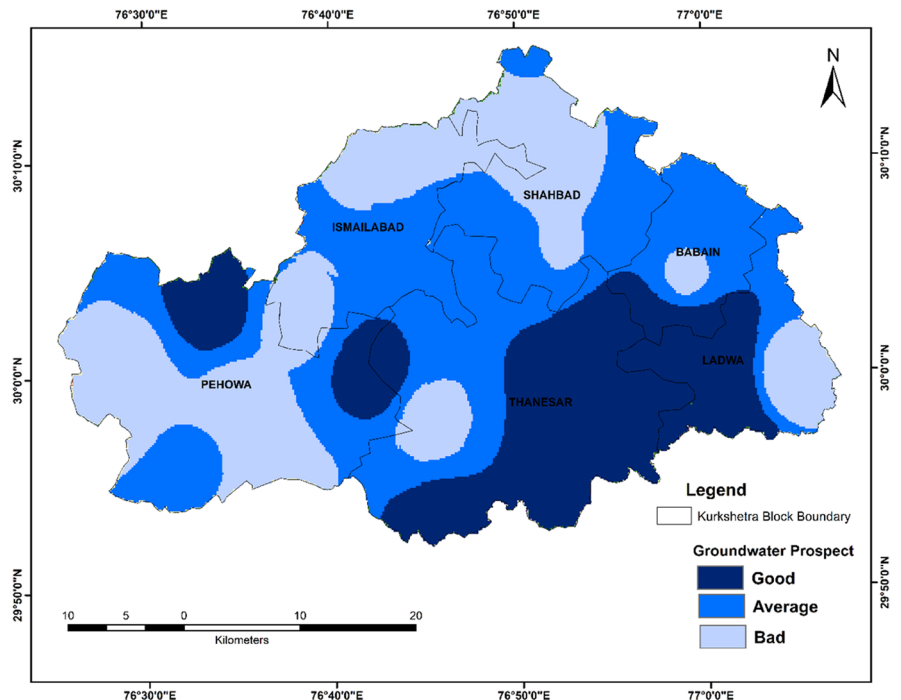
Table 6 Accuracy assessment of potential groundwater development zone map with groundwater resource potential

S.No	Location	Northing	Easting	Sand Thickness (m bgl)	Depth to GWL (m bgl)	As per PGDZ map	As per GWRP/ validation map	Agreement
1	Mathana	689,757.2	3,318,597	105.93	32.7	Good	Good	Agree
2	Ismailabad	663,996.4	3,320,249	33	27.62	Good	Good	Agree
3	Sharifagharh	680,679	3,331,041	15	-	Poor	Poor	Agree
4	Ajrana Kalan	670,584.7	3,334,422	21	48.77	Average	Average	Agree
5	Babain	691,189.8	3,328,755	12	-	Poor	Poor	Agree
6	Basantpur	669,462.6	3,339,486	9	-	Average	Poor	Disagree
7	Bhoresaidan	669,262.3	3,315,924	9	38.05	Average	Poor	Disagree
8	Malikpur	657,538.3	3,324,675	9	34.62	Poor	Poor	Agree
9	Ishag	643,851.6	3,321,600	12.5	39.65	Good	Poor	Disagree
10	Pehowa	652,475.8	3,318,021	9	51.85	Poor	Poor	Agree
11	Shahbad	680,088.6	3,337,659	10	-	Poor	Poor	Agree
12	Ladwa	700,561.4	3,320,143	6	36.12	Poor	Poor	Agree
13	Bateri	655,027.8	3,311,116	9	39.12	Poor	Poor	Agree
14	Thana	648,930.6	3,312,553	19	39.4	Average	Average	Agree
15	Hatira	670,200.7	3,307,193	30.5	37.62	Good	Good	Agree
16	Bodhni	650,225.2	3,325,811	35	37.33	Good	Good	Agree
17	Berthala (S)	691,085.5	333,4759	21	39.84	Average	Average	Agree

groundwater flow conditions influenced by human-induced land cover alterations, shifts in water usage patterns and uncertain climatic variations, particularly in semi-arid regions (Moodley et al., 2022). According to the study, around 27.52% of the study area has been identified as a favourable zone for the groundwater potential, with the majority of the promising locations being situated in the southwestern part of the region. Here, there were alluvial aquifers identified by substantial sand layer and soils coupled with moderate to good rainfall and a gentle slope that make it ideal for agricultural practices. The north-eastern parts of the study area, encompassing the Markanda river, were also classified as having good groundwater potential due to their young floodplain area. The hydrological behaviour of a basin is significantly impacted by its geomorphological features, which pertain to the landform of an area and constitute one of the critical factors in determining its groundwater potential (Senapati & Das, 2022). The older alluvium, younger alluvium and water bodies are the sites for groundwater recharge as the material associated with them are capable of retaining water and making them locations for good groundwater potential (Moges et al., 2019; Pande et al., 2018). The results of the present study

indicate that the distribution of built-up area and cumulative sand thickness plays a crucial role in identifying potential groundwater development zones (PGDZ) in the study area. LULC information plays a crucial role in providing significant insights into soil moisture, water infiltration, surface water and other water resources, as well as indicating groundwater demands. In assigning weights to LULC classes, water bodies, being primary recharge zones, were assigned the highest weight, followed by vegetation and cropland. Conversely, built-up land, which comprises impervious surfaces that lead to an increase in stormwater runoff and a reduction in infiltration capacity, is assigned a lower weight (Kom et al., 2022; Rather et al., 2022). The LULC map revealed that the north-eastern, and partially southern parts of the study area had a higher built-up area as compared to the western part. This indicates that the western part may have more suitable land for crop cultivation and hence may have greater groundwater potential. The potential for groundwater development is positively influenced by the thickness of the aquifer, as it will yield a larger volume of water with a longer length of well screen, thereby enhancing the accessibility of groundwater resources (Saha et al., 2010). Furthermore, analysis of the cumulative sand thickness

revealed that the south-eastern part of the study area had more thickness falling in Thanesar-Pehowa block boundary, ranging from 71.06 to 105.92 m, indicating a better potential groundwater development zone. However, as we move towards the northern side of the study area, the CST gradually decreases, indicating declining capacity to hold water and categorizing it into poor PGDZs. The outcomes of the study are consistent with the similar work conducted in Panipat district of Haryana by Kaur et al. (2020) In addition, the NDVI values were also analyzed to identify potential PGDZs in the study area. The results indicated that the western part of the study area had better prospects of groundwater as compared to the eastern part due to higher NDVI values. This can be attributed to the higher density of vegetation in the western part, which is more suitable for planting crops and hence is likely to have greater groundwater potential. The amount of absorbed photosynthetically active energy is the biophysical interpretation of NDVI. This characteristic of the NDVI is used as a proximate indicator of the presence of groundwater beneath the surface of earth. The areas with high quality vegetation are frequently found to have shallow groundwater levels (Patra et al., 2018). The study area falls into the average potential groundwater development zone category, with sporadic areas in the eastern part and primarily concentrated in the central and western regions. The groundwater potential in these areas is influenced by soil type, depth to groundwater and land use characteristics. However, the study also identified a poor potential groundwater development zone, comprising only 3.96% of the study area, mainly prevalent in the northern block of Shahbad. This zone has lower cumulative sand thickness to store water and surface runoff is favoured over infiltration, resulting in deeper depth to groundwater and reduced potential for groundwater development. Overall, the present study highlights the importance of considering multiple factors such as geomorphology, rainfall, depth to GWL, LULC, cumulative sand thickness and NDVI values to identify potential PGDZs in a given area. The results can be useful for policymakers and water resource managers to make informed decisions regarding groundwater management and sustainable agriculture practices. Artificial recharge techniques and participatory approaches can be used to raise the groundwater table in such areas. This study can serve as a guide to developing an effective plan for conserving watersheds and sustainable groundwater exploitation, as well as

serving as guidance for governmental organizations. We can thus conclude that the identification and mapping of potential groundwater development zone in the semi-arid, agrarian and groundwater dependent district of Kurukshetra will help the farmers in exploring the alternate locations for sustainably extracting groundwater and enabling to control the declining groundwater trend. The selection of sites for artificial recharge of groundwater can further check this trend and will stabilize and in due course of time revert the declining trend to rising trend.

Conclusion and recommendation

India being an agrarian economy is more dependent on groundwater resources as the case in the study area. Since water intensive crops like paddy are grown in the area under investigation, therefore it goes unsaid that the groundwater resources are extensively exploited for agriculture purposes. To ensure long-term agricultural sustainability as well as societal growth of a location, sustainability of groundwater use is essential component. Therefore, in the current study an effort has been made to delineate, identify and map the PGDZ's of district Kurukshetra falling Ghaggar and Upper Yamuna River Basins, by integrating AHP and GIS techniques. For this study, a total of nine parameters were considered namely geomorphology, rainfall, soil, depth to GWL, lithology, LULC, NDVI, CST and elevation to model and map the final PGDZ's of Kurukshetra district of Haryana. Since the area is covered by younger alluvium and older alluvium, it has good groundwater potentiality. Approximately 30% of the area has good groundwater development prospects due to favourable factors like geomorphology, falling in area of alluvial plains, good rainfall, good soil type and flat terrain, having good prospect of infiltration and good recharge. However, in the remaining 70% of the area falls under poor to moderate groundwater potentiality, there is need to develop groundwater sub management plan on urgent basis. In such area, where poor potentiality, artificial recharge techniques and participatory approaches can be used to raise the groundwater table. This study is based upon the application of GIS along with the AHP technique to provide reliable and satisfactory result which can be replicated

as such or with certain modifications in similar hydrographical regions. Additionally, this study may be helpful to environmentalists and policymakers in developing an effective plan for conserving watersheds and sustainable groundwater exploitation, as well as serving as guidance for governmental organizations.

Data availability   Data will be provided on request.

Declarations

Ethics approval   This research does not involve human participants and/or animals and no ethical approval is required.

Conflict of interest   The author declares no competing interests.

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