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Original Articles

Assessing the accuracy of GIS-based Multi-Criteria Decision Analysis approaches for mapping groundwater potential

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ABSTRACT

Groundwater is the most important natural resource for reliable and sustainable water supplies throughout the world. However, the over-exploitation of groundwater has led to groundwater depletion over the world. Sustainable development and management of this vital resource under changing environmental conditions is the one of the major challenges of the 21st century. To this end, this study focuses on the evaluation of groundwater prospect following an integrated multi-criteria analysis and geospatial approach. GIS-based Multi-Criteria Decision Analysis (MCDA) techniques viz., Analytic Hierarchy Process (AHP) and Catastrophe theory were used for delineating groundwater potential zones in a Canal Command of Eastern India. Thematic layers (maps depicting features of the factors influencing groundwater) such as 'runoff coefficient', 'drainage density', 'geology', 'slope' and 'proximity to surface water bodies' were considered in this study. Weights were assigned to the themes and their features according to AHP and Catastrophe theories. Thereafter, the themes were integrated in GIS to yield groundwater potential maps based on AHP and Catastrophe techniques. The AHP-based groundwater potential map revealed four zones with varying areal coverage: (a) 'very good' (19% of the study area), (b) 'good' (49%), (c) 'moderate' (28%), and (d) 'poor' (4%). On the other hand, the Catastrophe-based map indicated spatial variation of groundwater potential as: (a) 'very good' (14% of the area), (b) 'good' (63%), (c) 'moderate' (19%), and (d) 'poor' (5%). Thus, both the techniques indicated good groundwater potential in the study area. The validation of the results of these GIS-based MCDA techniques indicated that although both the techniques are suitable for mapping groundwater potential with a reasonably high accuracy (82% for the AHP technique and 74% for the Catastrophe technique), the performance of the AHP technique is somewhat superior to the Catastrophe technique. The findings of this study are very useful to the water managers for cost-effective and efficient planning and development of scarce groundwater resources so as to ensure sustainable water supply in the future.

1. Introduction

Groundwater is one of the most important natural resources that plays a vital role in ensuring reliable water supplies throughout the globe under changing environmental conditions. Due to the accelerated pace of development and intensive agriculture across the globe to meet increasing global food and energy demands, the over-exploitation of groundwater has led to declining groundwater levels and consequent ever-increasing stress on available groundwater resources in several parts of the world (e.g., Doell et al., 2014; Tiwari et al., 2009; Kerr, 2009). Nearly 60% of the irrigated areas in India are dependent on groundwater; the number of power-operated wells and tubewells grew from less than a million to 19 million during the 1960–2000 period (Shah et al., 2003). The water supply of the country will face severe problems in the future due to climate change (Mallick et al., 2015). The irrigation water demand predicted in the year 2010 was 557 km^3 and further projected to increase by 611 km^3 and 807 km^3 in the year 2025 and 2050, respectively. Projected domestic water demand in the year 2010 was 43 km^3 and was further projected to be increased to 111 km^3 in 2050. Further, industrial and environmental demands were projected to increase from 37 km^3 and 5 km^3 to 81 km^3 and 20 km^3, respectively during the period 2010–2050 (MOWR, 1999). Thus, the ever widening gap between water demand and water supply needs to be managed by exploring the additional conventional and non-conventional available water resources.

Surface water resources in West Bengal are estimated to be about 132.9 BCM (billion cubic meters), of which only about 40% can be utilized. The utilizable groundwater in West Bengal is about 17.6 BCM

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(CGWB, 2001). The unbalanced groundwater withdrawal and over exploitation has led to decrease in the groundwater table and also deterioration in the groundwater quality. Damodar Canal Command (DCC) is experiencing acute water scarcity problem during dormant season for both domestic and agricultural purposes. Hence, it is necessary to identify potential groundwater resources using appropriate and reliable scientific methods in West Bengal for augmentation of existing water resources. Conjunctive use can maximize the efficient use of surface water and groundwater resources and makes possible for storage of water resources due to the interrelationship between surface and ground water for use during the dormant season. Groundwater management can ensure efficient management of surplus and deficit water situations, where surplus water can be used for groundwater recharge and water deficit can be managed by extraction of groundwater. Thus, uncertainty in water demand and supply could be minimized through proper management of groundwater and therefore, it is necessary to identify the groundwater potential zones to explore the additional groundwater resources to address water demand and supply gaps in the Damodar Canal Command of West Bengal, India.

Delineation of groundwater potential zones for groundwater extraction has become an important issue in recent years due to excessive pumping of groundwater for meeting water demands in different sectors. Traditional methods for the identification of groundwater potential zones are not only time-consuming and costly but also need skilled manpower (e.g., Israil et al., 2006; Jha et al., 2010). GIS is a robust tool to handle a large amount of spatial data, and it can be successfully used for natural resources management (Bandyopadhyay et al., 2007; Jha and Chowdary, 2007; Chowdhury et al., 2009). Geospatial techniques have been proved to be an effective tool in the identification of groundwater potential zones (e.g., Murthy, 2000; Jaiswal et al., 2003; Rao and Jugran, 2003; Saraf et al., 2004; Chowdhury et al., 2009; Rose and Krishnan, 2009; Elewa and Qaddah, 2011; Jha et al., 2010; Machiwal et al., 2011; Rekha et al., 2011; Singh, et al., 2011; Gumma and Pavelic, 2013; Elmahdy and Mohamed, 2015; Sahoo et al., 2015). Most of these researchers used approaches that involved the assignment of weights to the selected themes and respective features of individual themes that influence groundwater potential in an area.

The review of literature revealed that an integrated remote sensing and GIS-based Multi-Criteria Decision Analysis (MCDA) approach using Analytic Hierarchy Process (AHP) technique were used for assessing groundwater potential in West Medinipur district of West Bengal, India (Chowdhury et al., 2009; Jha et al., 2010). Murthy and Mamo (2009) identified groundwater potential zones in Moyale-Teltele sub-basin, South Ethiopia using MCDA method. Agarwal and Garg (2016) delineated groundwater potential and recharge zones in Loni and Morahi watersheds, Unnao and Rae Bareli districts, Uttar Pradesh, India using remote sensing and GIS-based multi-criteria decision making techniques. Geospatial and AHP techniques were adopted for the evaluation of groundwater potential zones in the coal mining affected hard-rock terrain of Ramgarh and parts of Hazaribagh district, Jharkhand state, India (Kumar and Krishna, 2016). Further, Mandal et al. (2016) evaluated groundwater potential zones of coastal groundwater basin in the Balasore district of Odisha, India using remote sensing and multi-criteria decision making techniques. GIS, remote sensing and AHP techniques were applied for the delineation of groundwater potential zones in the Comoro watershed, Timor Leste using eight thematic layers namely drainage density, land use, lineament, lithology, rainfall, slope, soil and topography elevation (Pinto et al., 2017). On the other hand, some researchers applied geospatial and MCDA techniques for mapping recharge zones in different parts of the world (Chenini et al., 2010; Chowdhury et al., 2010; Rahman et al., 2012; Rahimi et al., 2014; Agarwal and Garg, 2016).

In the present study, well recognized GIS-based Multi-Criteria Decision Analysis (MCDA) technique such as Saaty's (1980) Analytic Hierarchy Process (AHP) and an emerging technique Catastrophe theory-based MCDA were used for mapping groundwater potential zones. Catastrophe theory was developed by French scientist Rene Thom in 1960s (Al-Abadi and Shahid, 2015). It is a special branch of dynamical systems theory (Kozak and Benham, 1974; Ghorbani et al., 2010). It is useful for the classification of various phenomena characterized by sudden shifts in behaviour arising from small changes in circumstances (Kam, 1992) and the phenomena of discontinuity (Benham and Kozak, 1976; Wang et al., 2011). The Catastrophe theory has environmental applications also. Yun-feng et al. (2007) adopted Catastrophe model for the prediction of water bloom in the Lake Chaohu, China. Zhang et al. (2009) applied Catastrophe progression method to predicting coal and gas outburst, while Wang et al. (2011) assessed pollution of near-shore coastal water using Catastrophe theory. In the recent past, the Catastrophe theory has been used to evaluate water security and adaptation strategy in the context of environmental change (Yang et al., 2012; Xiao-jun et al., 2014). Recently, Jenifer and Jha (2017) compared three methods viz., Analytic Hierarchy Process (AHP), Catastrophe and Entropy for evaluating groundwater prospect of hard-rock aquifer systems in Tiruchirappalli district, Tamil Nadu, India. On the other hand, limited studies on groundwater potential mapping using Catastrophe theory have been reported to date (Ahmed et al., 2015; Al-Abadi and Shahid, 2015; Sadeghfam et al., 2016) and the knowledge about the efficacy of the Catastrophe theory for mapping groundwater prospect compared to the conventional GIS-based MCDA technique in diverse hydrogeologic settings is fairly limited.

Although the study area "Damodar Canal Command of West Bengal" in Eastern India receives adequate rainfall, both domestic and irrigation sectors suffer from water scarcity problem during non-monsoon seasons due to short monsoon season (rainy season), large spatio-temporal variability of rainfall, and capricious nature of the monsoon. In view of growing water scarcity and environmental problems under changing climatic conditions at global, national and regional levels in general and in developing countries in particular, the present study was conducted with the objectives of: (a) delineation of groundwater potential zones in the study area using GIS-based Multi-Criteria Decision Analysis (MCDA) approaches such as AHP and Catastrophe techniques, and (b) to assess the efficacy of these two GIS-based MCDA approaches. Also, a novel method has been employed in this study for the validation of groundwater-potential results obtained by these MCDA approaches. The results of this study are very helpful to the water managers for formulating cost-effective and efficient plans and management strategies for sustainable groundwater withdrawal, which in turn can ensure dependable water supply for agriculture and domestic sectors as well as improved livelihoods and environmental security in the region.

2. The study area

The Damodar Canal Command (DCC) located in the upper Damodar River basin, south-central part of West Bengal, India (Fig. 1). The study area is situated between 22°31′25″ N and 23°42′48″ N latitude, 87°15′14″ E and 88°26′22″ E longitude. The total geographical area of the study command is ~7470 km^2 with an elevation ranges from 1 to 98 m (MSL). The DCC comprises of forty administrative units called 'blocks' falling under four districts namely Burdwan district (20 blocks), Hooghly district (12 blocks), Howrah district (4 blocks) and Bankura district (4 blocks). The study area has the sub-humid climate with four distinct seasons: (a) summer season (March–May), (b) monsoon season (June–September), (c) post-monsoon/autumn season (October–November), and (d) winter season (December-February). The average annual rainfall of the study area is 1913 mm and the rainfall period usually spans from mid-June to the end of October. The study area is classified into two agro-climatic zones, viz., Gangetic alluvial zone (Amta–I, Amta–II, Arambag, Balagarh, Chinsurah–Magra, Chnditala–I, Dhaniakhali, Haripal, Jagatballavpur, Jangipara, Pandua, Polba-Dadpur, Pursura, Singur, Tarakeswar and Udayanarayanpur), and Red and Laterite zone (Ausgram–I, Ausgram–II, Barjora, Bhatar, Burdwan–I, Burdwan–II, Galsi–I, Galsi–II, Indus, Jamalpur, Kalna–I, Kalna–II,