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Recognition of district-wise groundwater stress zones using the GLDAS-2 catchment land surface model during lean season in the Indian state of West Bengal

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Abstract

Water is essential for irrigation, drinking and industrial purposes from global to the regional scale. The groundwater considered a significant water resource specifically in regions where the surface water is not sufficient. Therefore, the research problem is focused on district-wise sustainable groundwater management due to urbanization. The number of impervious surface areas like roofing on built-up areas, concrete and asphalt road surface were increased due to the level of urban development. Thus, these surface areas can inhibit infiltration and surface retention by the impact of urbanization because vegetation/forest areas are decreased. The present research examines the district-wise spatiotemporal groundwater storage (GWS) changes under terrestrial water storage using the global land data assimilation system-2 (GLDAS-2) catchment land surface model (CLSM) from 2000 to 2014 in West Bengal, India. The objective of the research is mainly focused on the delineation of groundwater stress zones (GWSZs) based on ten biophysical and hydrological factors according to the deficiency of groundwater storage using the analytic hierarchy process by the GIS platform. Additionally, the spatiotemporal soil moisture (surface soil moisture, root zone soil moisture, and profile soil moisture) changes for the identification of water stress areas using CLSM were studied. Finally, generated results were validated by the observed groundwater level and groundwater recharge data. The sensitivity analysis has been performed for GWSZs mapping due to the deficit of groundwater storage. Three correlation coefficient methods (Kendall, Pearson and Spearman) are applied for the interrelationship between the most significant parameters for the generation of GWSZ from sensitivity analysis. The results show that the northeastern (max: 1097.35 mm) and the southern (max: 993.22 mm) parts have high groundwater storage due to higher amount of soil moisture and forest cover compared to other parts of the state. The results also show that the maximum and minimum total annual groundwater recharge shown in Paschim Medinipore [(361,148.51 hectare-meter (ham)] and Howrah (31,510.46 ham) from 2012 to 2013. The generated outcome can create the best sustainable groundwater management practices based upon the human attitude toward risk.

Keywords Soil moisture · Terrestrial water storage · Groundwater storage · Catchment land surface model · Groundwater stress · GIS

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Introduction

Groundwater plays a vital role in agriculture, domestic and industrial sectors for the development of the arid and semi-arid zones because of the unavailability or insufficiently of surface water. Groundwater depletion is one of the major problems in India because of population pressure, rapid urbanization, irregularity in precipitation and intensive use of groundwater for agricultural activity (Chatterjee et al. 2020). Regional-level groundwater storage depletion mainly

depends on temporal responses from natural and artificial effects.

Groundwater represents a source of freshwater that can be withdrawn even during dry season compared to problematic use of surface waters which may have little or no water during lean seasons. Moreover, groundwater is usually less polluted than surface water. On the other hand, abstracting groundwater is technically more demanding and expensive as in case of surface water. However, in some regions, such as India, safe surface water may no longer be available (Kundewicz and Döll 2009).

It is evident that groundwater is subject to stress with respect to both quantity and quality. For instance, many aquifers are being overexploited, especially, in semi-arid and arid regions. Groundwater recharge thus represents a significant factor which influences the groundwater withdrawal (Döll and Fiedler 2009). Groundwater recharge is connected to atmospheric, surface and subsurface components of the water balance and is sensitive to both climatic and anthropogenic factors, such as, precipitation land use/cover change, and urbanization (Herrera-Pantoja and Hiscock 2008; Holman et al. 2009; Jyrkama and Sykes 2007; Mohan et al. 2018).

The increased water demand, especially in regions with limited surface supplies, and the continued deterioration of surface water quality are placing the groundwater resources under increasing stress. Water consumption can also significantly increase due to natural phenomena as well e.g. the novel coronavirus disease (COVID-19) which causes increasing washing hands more frequently. This subsequently raises sustainability concerns that are connected to sustainable groundwater planning and management (Vaux 2011; Jakeman et al. 2017). Meanwhile, recently several studies have been also conducted to improving the water consumption behavior (Salimi et al. 2019).

Geographic information systems (GIS) and remote sensing (RS) techniques are very useful for modeling groundwater depletion, recharge and stress zones (Anderson et al. 2015; Rodell et al. 2009; Famiglietti et al. 2011; Gleeson and Wada 2013; Voss et al. 2013; Castle et al. 2014; Da Costa et al. 2019; Das and Pal 2019a, b). In particular, satellite-based groundwater data provide a primary investigation of groundwater conditions. The National Aeronautics and Space Administration (NASA) Catchment Land Surface Model (CLSM) is one of the land components models which can be used for studying spatiotemporal changes in groundwater storage under terrestrial water storage from the global land data assimilation system (GLDAS) (Rodell et al. 2004). Different methods could be applied to study the groundwater stress; storage change as well as recharge e.g. WaterGAP global hydrology model (WGHM) (Döll et al. 2003).

Few studies dealt with the regional-scale groundwater storage change using gravity recovery and climate experiment (GRACE) data with correlated groundwater monitoring levels in India. Shamsudduha et al. (2012) tested groundwater storage change with GRACE data under basin-scale dynamics of hydrologic systems for dry and wet season from 2003 to 2007 for the Bengal Basin in Bangladesh. They estimated GWS by deducting the contribution of changes in remaining terrestrial water stores including soil moisture, surface water, and ice and snow and also explained substantial increases in groundwater abstraction for lean monsoon irrigation. Dasgupta et al. (2014) studied the relationship between groundwater storage and soil moisture signature based on the GRACE data in order to observe the groundwater depletion in the Gangetic plain. It is noted that monthly, seasonal and annual hydrologic signals were considered for this analysis. Singh et al. (2017) calculated the spatial and seasonal variation of the surface water budget using the GRACE data during 2003–2012 and geospatial technology in the north-western region of India. It is observed that groundwater storage change and GRACE stipulated storage change loss was in the value range of ± 86.43 km^3/y representing an average of 10 years of data.

Chinnasamy et al. (2018) developed the volume of groundwater recharge based on crop irrigation water use from water table depth of pre-monsoon and post-monsoon seasons for the hard rock area in the Udaipur district of Rajasthan. In addition, this study proved that the groundwater recharge can be estimated without needing a calibration of groundwater model. During the last decade, the information derived from RS technology provides tremendous potential for identification, monitoring, and assessment of water related applications, especially for regions with sparse in situ observations (Sharifi et al. 2019). Wakode et al. (2018) estimated natural recharge from the precipitation, actual evapotranspiration (ET), and surface runoff using RS and GIS techniques for the city of Hyderabad in India. The soil conservation service curve-number (SCS-CN) method was used for the calculation of urban water balance. It is an empirical approach-based rainfall-runoff model to calculate direct surface runoff from rainfall. This model indicates the relationship between rainfall and ground conditions (e.g., soil). The tropical rainfall measuring mission (TRMM) data were utilized for the estimation of accumulated rainfall during the research work. Han and Cao (2018) analyzed the phase differences between groundwater storage and groundwater level fluctuation for internal stress change in an aquifer-aquitard system in North China Plain aquifer. They also identified the episodic components of groundwater storage and groundwater level by the singular spectrum analysis (SSA). Mukherjee et al. (2018) studied the reduction in the groundwater base flow by groundwater storage depletion using remote sensing data in the adjoining Gangetic aquifer. It is observed that net Ganga river water reduce due to reduction because domestic water supply, irrigation water

requirement, river transport, ecology and dense population. It is directly affecting impacting food production vulnerability of 100 million populations. Sridhar et al. (2019) assessed the total water storage based on the GRACE satellites for seven major river basins: James, Patuxent, Potomac, Rappahannock, Susquehanna, Western Shore, Eastern Shore, and York. The parameter-elevation regressions on independent slopes model (PRISM) precipitation, variable infiltration capacity (VIC)-simulated ET and moderate resolution imaging spectroradiometer (MODIS)-derived ET were utilized for total water storage change (TWSC) prediction of the watershed.

Singh et al. (2019) studied the impact of land water storage variation on agriculture using the GRACE and GLDAS data in India. The results showed that the runoff was very high for the monsoon season and accumulated rainfall was 76.58 cm for the year 2015 over India. Singh and Kumar (2019) performed mean annual per capita water availability (PCWA) change analysis for demographic control under 1.5, 2.0 and 3.0 °C levels of global warming over India. Based on the results, the PCWA will decrease for all the warming scenarios across India. The results also showed that the population and mean annual rainfall were very sensitive factors for policies that aim to manage water scarcity. Bhanja et al. (2020) studied usable groundwater storage based on the GRACE satellite data with correlated in situ data for water security, drinking water supply, food production at the state level in India. They used 3907 groundwater monitoring wells for the analysis. Chatterjee et al. (2020) assessed the groundwater potential recharge based on groundwater storage change using the GRACE data for sustainable groundwater management of northeast India. This study indicated the terrain suitability for groundwater recharge based on hydrogeology and terrain parameters with integrated average monsoon recharge.

These recent advances in groundwater stress analysis methods have improved our understanding of groundwater availability to meet current water demands (Richey et al. 2015; Herbert and Döll 2019). Based on the available literature, it is noticeable that there is scope for the development of a framework for district-wise future groundwater planning under climate uncertainty. Therefore, this study aims to analyze the identification of district-wise groundwater stress zone (GWSZ) based on biophysical and hydrological parameters by AHP method. The study also aims to spatiotemporally assessment of the groundwater storage changes under terrestrial water storage from 2000 to 2014 corresponding with observed groundwater level and groundwater recharge in the Indian state of West Bengal. Additionally, the study focuses on an analysis of the spatiotemporal surface soil moisture, root zone soil moisture and profile soil moisture for identification of the water stress areas. Present research works considered only pre-monsoon season, which implies

major water problem in this period. Eventually, this study provides the real problem-solving framework for improved district-wise sustainable groundwater management.

Study area

West Bengal is the 13th largest state of India with total area 88,752 km². It extends from the Himalaya to the Bay of Bengal. It is a dense river network-based state. The Major River is Bhagirathi-Hooghly distributaries of the Ganga River and length is 260 km long. There are various tributaries like Mayurakshi, Ajoy, Damodar, Dwarakeswar, Shilabati, Rupnarayan, and Kangsabati in the middle to lower part of the state. There is no any hydraulic structure across the Ajoy and Dwarakeswar Rivers have for water control in the river system. The upper part has a Mahananda River originates from the Himalayas at an elevation of 2100 m above mean sea water level and enters Bangladesh near Tentulia Panchagarh district. It is a trans-boundary river that flows through West Bengal, Bihar, in India and Bangladesh. Although there is water scarcity problem in this state because of the sedimentation that considered the major problem in the river system, the sedimentation load has been increased and decreased by human activities. Thus, these kinds of problem affected in the terrestrial water storage system under changing climatic conditions.

It is divided into nine physiographic provinces. However, West Bengal is divided into nineteen districts (Fig. 1). Now it is included four extra districts like Kalimpong, Alipurduar, Paschim Bardhaman and Jhargram. It has a common border with Nepal, Bhutan and Sikkim (India) in the north, Assam (India) and Bangladesh in the east, Bihar (India) in the west and Orissa (India) in the southwest. It has three divisions, namely Bardhaman division, Presidency division, and Jalpaiguri Division. It has included the Darjeeling Himalayan hill region, the Ganges delta, the Rarh region and the coastal Sundarbans. The Sundarbans is a mangrove dominated area in the delta and one of the three largest single tracts of mangrove forest of the world (Islam and Gnauck 2009). Sundarbans has four protected areas under United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Sites (Sundarbans National Park, Sundarbans West, Sundarbans South and Sundarbans East Wildlife Sanctuaries). The Sagar Island one of the big island in West Bengal under part of Sundarbans. It is a place of Hindu Pilgrimage lying on the Continental Shelf of Bay of Bengal about 100 km south of Kolkata. However, elevation values vary from 0 to 4000 m. The highest day temperature values between 38 and 45 °C and the average temperature is 30 °C. It is observed that the rainy season showed between July to end of the September and the average rainfall is 175 cm. It is also observed that heavy rainfall (> 250 cm) showed in the
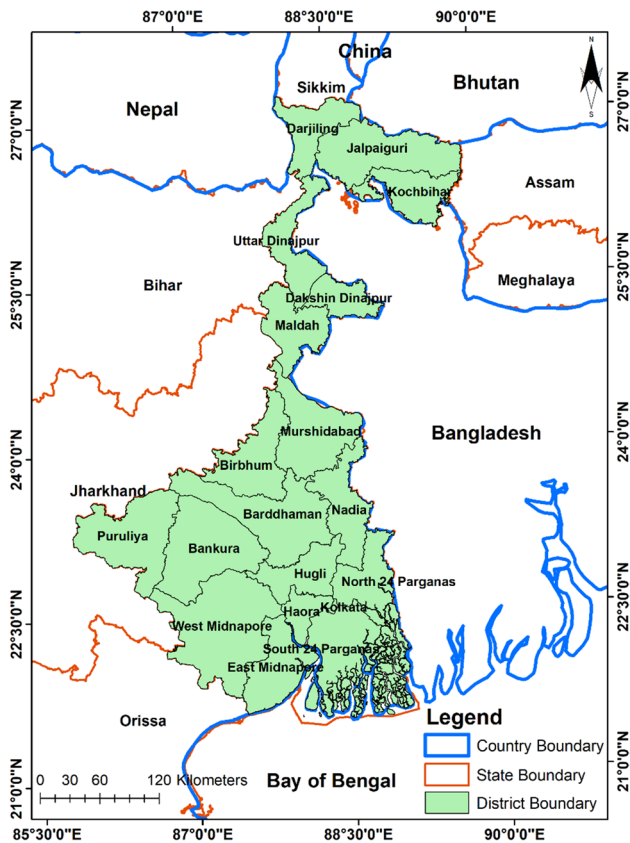
Fig. 1 Location map of the study area (West Bengal)

district of Darjeeling, Jalpaiguri and Cooch Behar. It also shows the common occurrences of drought conditions in the district of Bankura and Purulia. Besides, this state 88% covers by cultivable area and cropping intensity are 177%. It is the largest producer of rice and the second-largest producer of potatoes in India. However, this state is also the first rank in freshwater fish production. Thus, sustainable water resources planning (surface water and groundwater) are very important for future water management. The detailed physiographic information is available in Bandyopadhyay et al. (2014). The present research work considered only old nineteen districts.

Material and methodology

Surface soil moisture, root zone soil moisture, profile soil moisture, terrestrial water storage, groundwater storage data are collected for the period of 2000 to 2014, from the Global Land Data Assimilation System (GLDAS) Catchment Land Surface Model L4 daily 0.25 × 0.25 degree V2.0 (https://disc.gsfc.nasa.gov). The GLDAS is an ingest satellite, ground-based, and model outputs for water resources applications. These data were collected from NASA GLDAS-2

catchment land surface model (CLSM). The GLDAS-2 CLSM model-based data were directly utilized for district-wise spatiotemporal changes of soil moisture (SM), terrestrial water storage (TWS) and groundwater storage (GWS). Furthermore, one can mention that the modeled hydrological components contain some degree of uncertainties, and observational data from satellites might be an acceptable alternative in near future when a more robust data will be available, and therefore GWS data with less uncertainty can be obtained. However, inverse distance weighting (IDW) interpolation technique was used in order to generation the annual-basis spatiotemporal TWS and GWS maps. The maximum, minimum and mean values of the district-wise GWS were calculated from the generated maps for 2000 to 2014. Soil moisture represents the amount of water between the soil particles. It is a very significant variable because of evapotranspiration estimation; irrigation water can be calculated through water balance techniques (Li et al. 2019). It is a very important indicator for crop cultivation challenging to calculate from coarse spatial resolution satellite images. It is also an important variable for health or stress on the land surface ecosystem. Thus, land surface model data can be estimated as long-term spatiotemporal changes in soil moisture. In the present study, the GLDAS-2 CLSM model was used for spatiotemporal soil moisture changes to identify the water stress areas. High soil moisture values spreader over the central, north-eastern and southern India during the last few decades. Lower values have been observed over the Indo-Gangetic plains, whereas the lowest values have been noted over the western arid region. The nature of the heterogeneous distribution of soil moisture in changing spatial scales is noticed from the climatic mean. However, three kinds of soil moisture like surface soil moisture, root zone soil moisture, and profile soil moisture are considered for the analysis. Surface soil moisture indicates the dry or wet soil in the topmost layer. It can be used for the analysis of the root zone soil moisture. Root zone soil moisture is very important for the regulation of water and energy budget. Profile soil moisture represents the standard deviation and the coefficient of variation significantly differs surrounded by farmland, forest land and grassland (Li et al. 2019). It is noted that the variations of these three types of soil moisture indicate the predicting variation of precipitation, surface temperature, drought, and flood. Soil moisture data (surface soil moisture, root zone soil moisture, and profile soil moisture) was utilized to identify the water stress areas. Population data is collected for 1991–2011 from the Census of India and used for identifying the groundwater stress zones at the district level. Groundwater data (2012–2017) was collected from India-Water Resources Information System (India-WRIS), Central Ground Water Board, Irrigation and Waterways Directorate, Government of West Bengal.

NASA GLDAS is a satellite and groundwater observation data product using the advanced land surface model and data assimilation techniques to estimated optimal fields of land surface states and fluxes (Rodell et al. 2004). Four land surface models (Noah, Catchment, CLM, and VIC) are available for GLDAS drives. However, GLDAS-2 product is a couple by MODIS based land surface parameters and the model simulations are also forced by global meteorological forcing data. Thus, this dataset is very significant for district-wise water resources management considering climate uncertainty. This methodology focuses on district-wise spatiotemporal groundwater storage change under terrestrial water storage using GLDAS Catchment Land Surface Model because these kinds of data are available in this model. This study is included two objectives: (a) the spatiotemporal soil moisture change for identification of water stress areas, (b) identification of groundwater stress zones and spatiotemporal groundwater storage change for the district level.

However, the district-wise TWS and GWS are calculated for how much water is available for future water management. Finally, GWS data evaluated with the corresponded observed groundwater level and groundwater recharge data to support the accuracy of the obtained results. The overall methodological framework is shown in Fig. 2.

Groundwater stress zone (GWSZ)

The groundwater stress zones (GWSZ) are very important for future groundwater planning and management purposes. Ten biophysical and hydrological parameters [i.e., terrestrial water storage (TWS), groundwater storage (GWS), surface soil moisture (SSM), root zone soil moisture (RZSM), profile soil moisture (PSM), canopy water evaporation (CWE), direct evaporation from bare soil (DEBS), potential evaporation rate (PER), plant canopy surface water (PCSW), and soil temperature (ST)] are considered for the generation
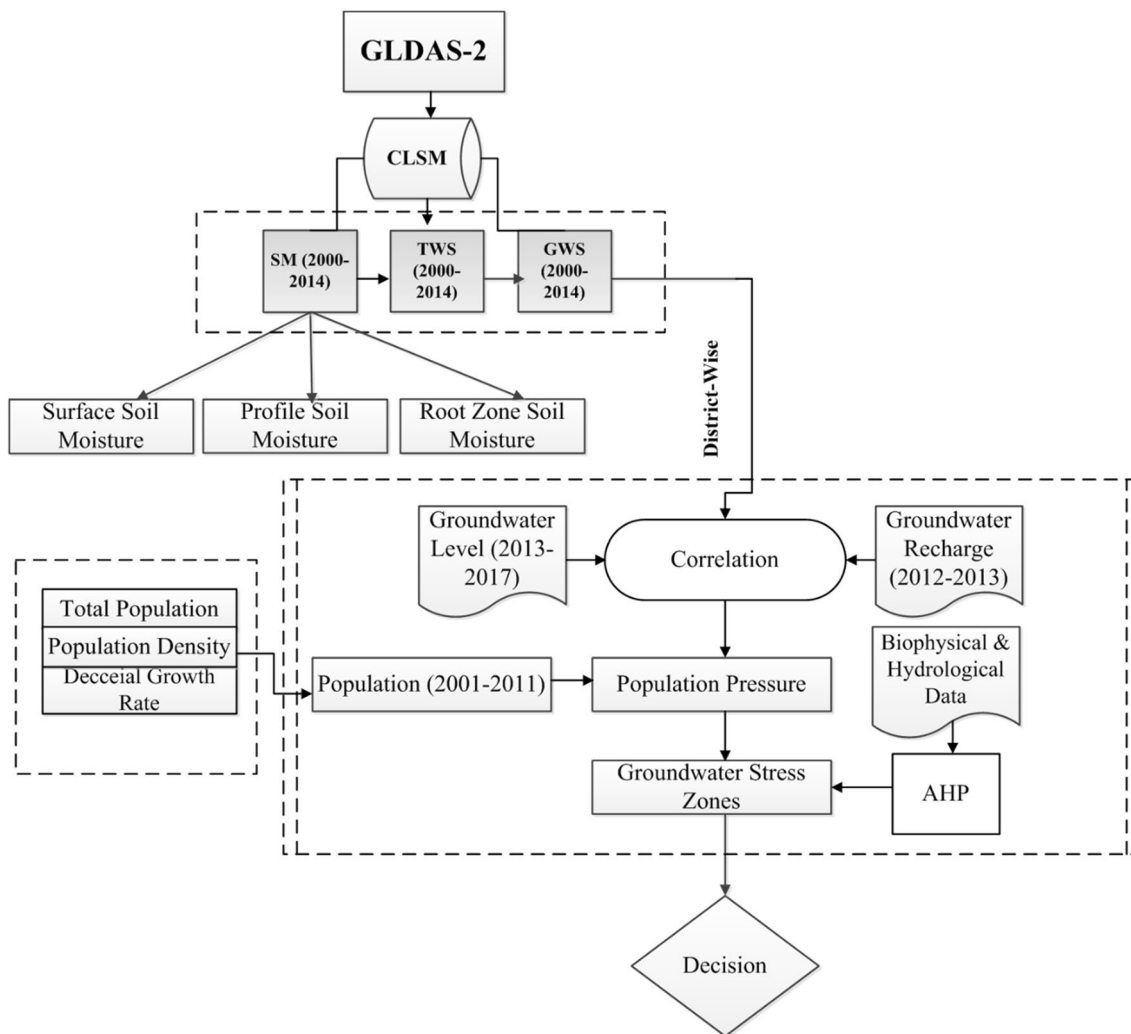

Fig. 2 Overall methodological framework

of GWSZ from GLDAS using analytic hierarchy process (AHP) by GIS techniques. The AHP method mainly developed based on the theory of prioritization from human judgments by Saaty (1980, 1990). The AHP is a structured technique for analyzing complex decisions and quantifying the weight of decision criteria. Individual expert opinion is very important to estimate the relative magnitudes factors by pairwise comparison matrixes. The pair-wise comparison matrix is evaluated into two criteria by 1–9 scale: (i) a criterion is precisely as significant of B criteria, then the index is 1, (ii) a is more dominant than B, the index is 9. All row values are filled into a cross matrix and diagonal matrix filled only value of 1. However, multiple decision criteria are involved when the selection of one alternative. It is a powerful multi-criteria decision making techniques (Torres-Rua et al. 2016) to delineate district-wise GWSZ. It should be mentioned that all parameters have direct and/or indirect impact on the groundwater system.

GWSZ can be calculated as (Dhar et al. 2015):

$$\text{GWSZ}_{i,j} = \sum_{k \in F} W_k \left(\sum_{l \in S_k} w_l^k \chi_{A_l^k} \left(C_{i,j}^v \big|_k \right) \right), \tag{1}$$

where index (i,j) denote row column location of a pixel; F denotes the set of all features (F), K denotes elements of features set; S_k denotes set of sub-features for kth feature; l denotes element of sub-feature set; W_k normalized weight of kth feature; w_l^k denotes normalized weight of lth sub-feature for kth feature; $\left| C_{i,j}^v \right|_k$ denotes the class value of the cell (i,j) for kth feature; A_l^k denotes the sub-feature interval, $X_{A_l^k}$ denotes the indicator function for l sub-feature of kth feature.

$$\chi_{A_l^k} \left(C_{i,j}^v \right) = \begin{cases} 1 \text{ if } C_{i,j}^v \big|_k \in A_l^k, \\ 0 \text{ if } C_{i,j}^v \big|_k \notin A_l^k \end{cases} \tag{2}$$

In AHP (Saaty 1980) 1–9 scale is adopted for constructing judgment matrices.

The following steps are adopted for calculation of weights and consistency ratio (C.R.): development of judgment matrices (A) by pair-wise comparison.

Calculation of relative weight W_i:

$$W_i = \frac{\text{GM}_i}{\sum\limits_{m=1}^{N_F} \text{GM}_m} \tag{3}$$

where the geometric mean of the ith row of judgment matrix is calculated as

$$\text{GM}_i = \sqrt[N_F]{a_{i1} a_{i2} \ldots a_{iN_F}}.$$

Strength assessment of judgment matrix-based consistency ratio (C.R.) which is a comparison between consistency index (C.I) and random consistency index (R.C.I or R.I) (Piantanakulchai and Saengkhao, 2003; Youssef 2015). It is randomly generated reciprocal matrixes by 1/9 scales. The consistency ratio (C.R.) is calculated as

$$\text{C.R.} = \text{C.I.}/\text{R.C.I.} \tag{4}$$

Consistency Index (C.I.) is evaluated as

$$\text{C.I.} = \frac{\lambda_{\max} - N_F}{N_F - 1} \tag{5}$$

where the latent root of judgment matrix is calculated as

$$\lambda_{\max} = \sum_{m=1}^{N_F} \frac{(\mathbf{AW})_m}{N_F W_m} \tag{6}$$

where W is the weight vector (column). C.R. value less than 0.1 is acceptable for a specific judgment matrix. However, revision in judgment matrix is needed for C.R. ≥ 0.1.

Same procedure should be followed for w_k^i calculation. Finally, GWSZ map can be generated by using Eq. (1).

Results

Spatiotemporal changes of soil moisture to identify the water stress areas

Surface soil moisture (SSM) estimation is considered 0–20 cm in CLSM from GLDAS2 (Fig. 3). The district-wise soil moisture (SSM, RZSM, and PSM) data is extracted through the GIS platform. The high level of SSM shows that Uttar Dinajpur, Birbhum, Burdwan, Bankura, North 24 Parganas, South 24 Parganas and Howrah for 2005 compare to another year. In 2014, SSM is 5.77, 5.68, 5.64, 5.94, 5.60, 5.45 and 6.62 kg/m² for above indicated seven districts of West Bengal, and it depends on precipitation and vegetation cover. Very high vegetation/forest covers conduct to more organic ground cover to help secure the SSM from evaporation. It is observed that a high level of RZSM for 2005 comes under these districts because it depends on SSM. PSM represents an integral understanding of soil moisture dynamics based on the depth of layers. The deeper layer significantly influences the SSM. Moreover, SSM is a key role for crop cultivation purpose compare to other soil moisture. Soil moisture can identify water stress because of the potential ability of plants to extract water. Soil moisture stress indicates the water in a plant's cell reduced to less than a normal level. However, low soil moisture indicates high water stress, and low water stress represents high soil moisture. The results show that few districts come under high water stress zones like Birbhum, Bankura, Purulia. The
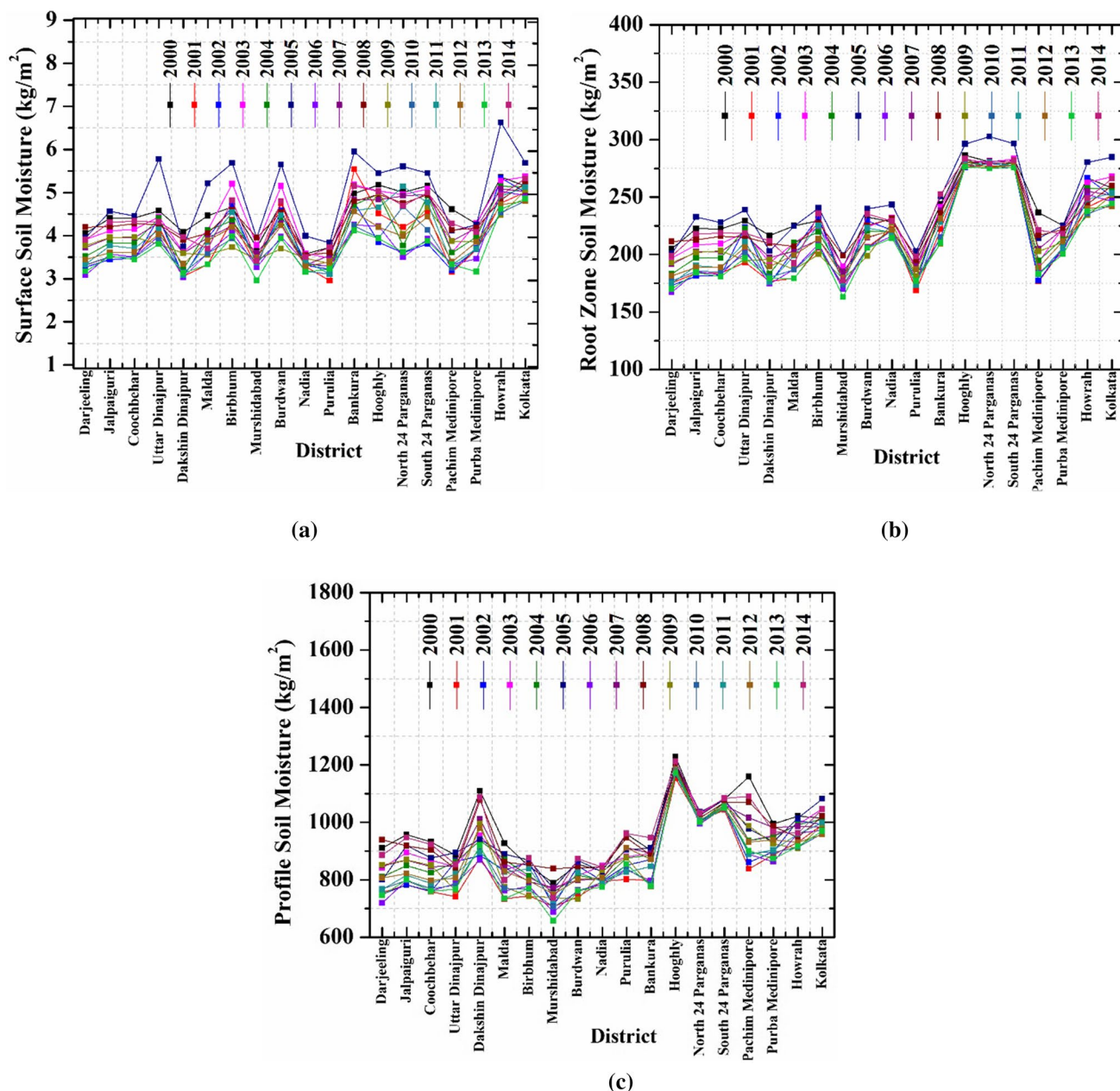
(a)

(b)

(c)

Fig. 3 District-wise spatiotemporal changes of **a** surface, **b** root zone and **c** profile soil moisture from 2000 to 2014

average SSM values in these three district are 4.47, 4.78 and 3.38 kg/m² from 2000 to 2014. The results also show that the Darjeeling, Jalpaiguri, Cooch Behar, Uttar Dinajpur, Dakshin Dinajpur, Malda, Nadia, Burdwan, and Hooghly come under moderate water stress zones.

Spatiotemporal changes in terrestrial water storage (TWS)

Terrestrial water storage (TWS) represents the summation of all water on the land surface and in the subsurface and stored in the vegetation, lake, and river water (Girotto and Rodell 2019). TWS indicates the surface water storages and SSM, RZSM, groundwater, ice, and snow water. It is significantly affected by the river water system in major river basins.

GLDAS2 CLSM data has been used to district-wise spatiotemporal variability changes for pre-monsoon in TWS (Fig. 4). The results show that the northern (600–800 mm), middle (800–900 mm) and western (1000–1100 mm) parts have has low water comparing to another parts, because these areas come under high water stress zones. It is observed that these districts like Bankura, Birbhum, Purulia

have low cultivation areas due to low precipitation and very high temperature. In Purulia, the government increased the number and storage capacity of tanks and ponds (10,533) in surface flow schemes for agricultural and domestic purposes according to Minor Irrigation Census (2013–2014). The results also show that North 24 Parganas (1056 mm), South 24 Parganas (1125 mm), Purba Medinipore (1100 mm), part of the Paschim Medinipore (1281 mm), Darjeeling (1196 mm), and Jalpaiguri (1077 mm) have high water storage that might be happen due to the close connection of those districts to Himalaya and Bay of Bengal. The pre-monsoon maximum and minimum TWS show in the year 2000 (1372 mm) and 2010 (597 mm) in the whole state. It is also observed that surface water is the major problem because rivers have low water for the pre-monsoon season. Thus, these districts mainly dependent on monsoon rainfall for agriculture cultivation, although groundwater was also used for pre-monsoon cultivation purposes. Moreover, surface water and groundwater are also utilized for crop cultivation and domestic purposes at the district level. TWS is highly impacted by climatic variability and anthropogenic activities (Frappart et al. 2019). Thus, proper surface water planning and management are required due to changing climatic conditions shortly.

Spatiotemporal changes in groundwater storage (GWS)

The groundwater crisis is in alarming proportions into the world, especially in India. Groundwater plays a key role in the terrestrial hydrological cycle and in sustaining ecosystems as the largest reservoir of freshwater on Earth. It is becoming a strategic importance for global water and food security under global change due to its major resource of

Fig. 4 Spatiotemporal changes of terrestrial water storage for pre-monsoon season from 2009 to 2014
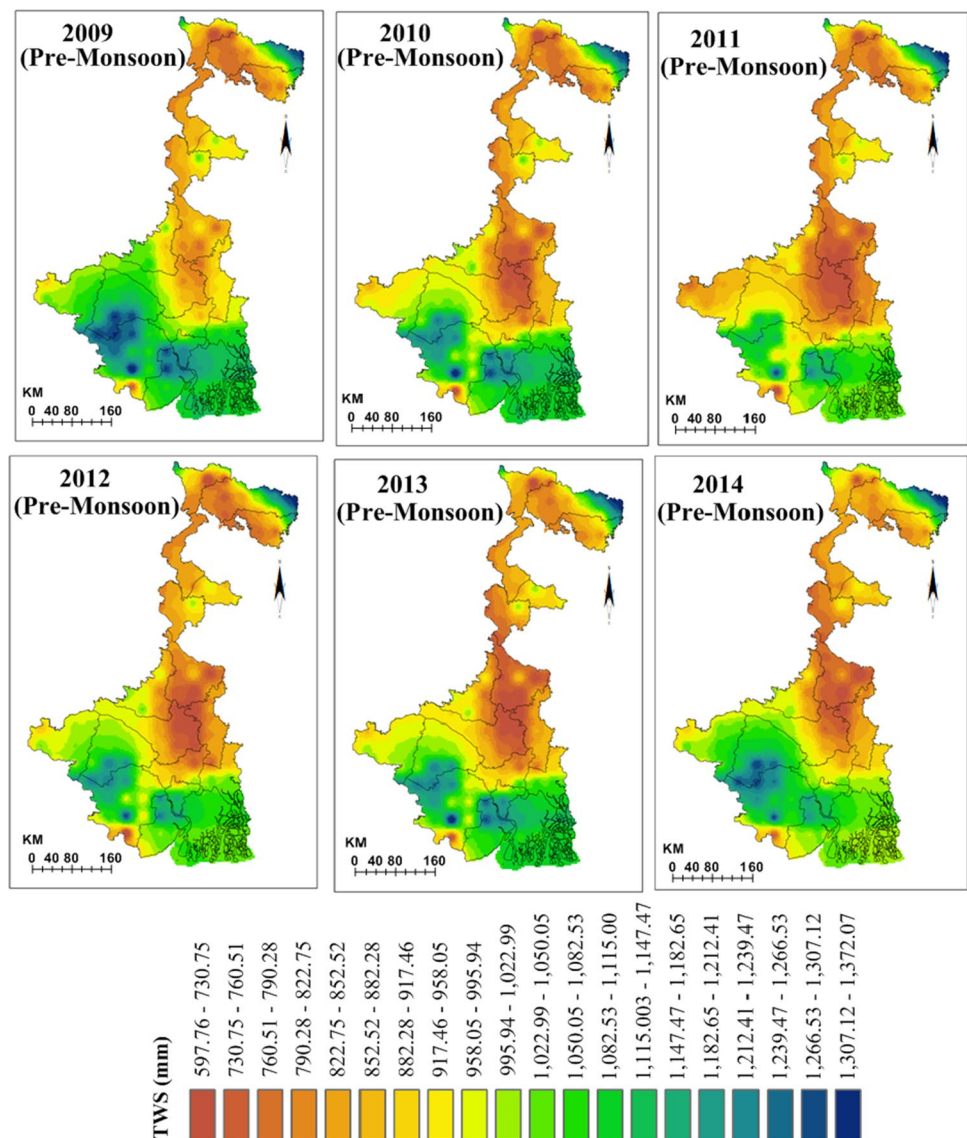
freshwater supply of the world population and the world food production. However, groundwater will be much more important resource when there is shortage in surface water. It is naturally replenished by surface water from rainfall, streams, and rivers. Major groundwater problems are water logging, sanitization, water table depletion, groundwater pollution and dying of aquifers. It can be seen that the groundwater dec1ining rate is 1–2 m/year in many parts of India (Singh and Singh 2002). However, arsenic content is increased in the shallow aquifers of West Bengal reported by groundwater users. It is noted that the past three decades' groundwater exploitation and depletion is the major environmental problem in India addressing by Rodell et al. (2004). The nature of the groundwater problem in India is different because of different hydrogeological settings and socioeconomic situations (Shankar et al. 2011). It is also noted that the highest use of groundwater for agriculture purposes in India disclose by Shah (2009). Thus,

water management is required for sustainable future water planning.

GLDAS2 CLSM (grid: $0.25° \times 0.25°$) is a land surface modeling based ingests and ground observational data. It can be directly utilized to calculate hydrological components (e.g. groundwater) for global to local scale. GLDAS2 CLSM data has been also used to district-wise spatiotemporal variability changes for pre-monsoon in GWS from 2000 to 2014 (Fig. 5). The results show that the northern to the middle portion of the state comes under low groundwater storage (438.59–858.56 mm). The results also show that high groundwater storage in the northeastern and south, southwestern parts of the state (883.24–1152.44 mm). The maximum part of the state covers by the high groundwater stress because of more use of groundwater for agricultural purposes. Thus, surface water is the major problem in West Bengal and that might be the reason of high usage of groundwater. It is observed that Jalpaiguri, small part of

Fig. 5 Spatiotemporal changes of groundwater storage for pre-monsoon season from 2009 to 2014
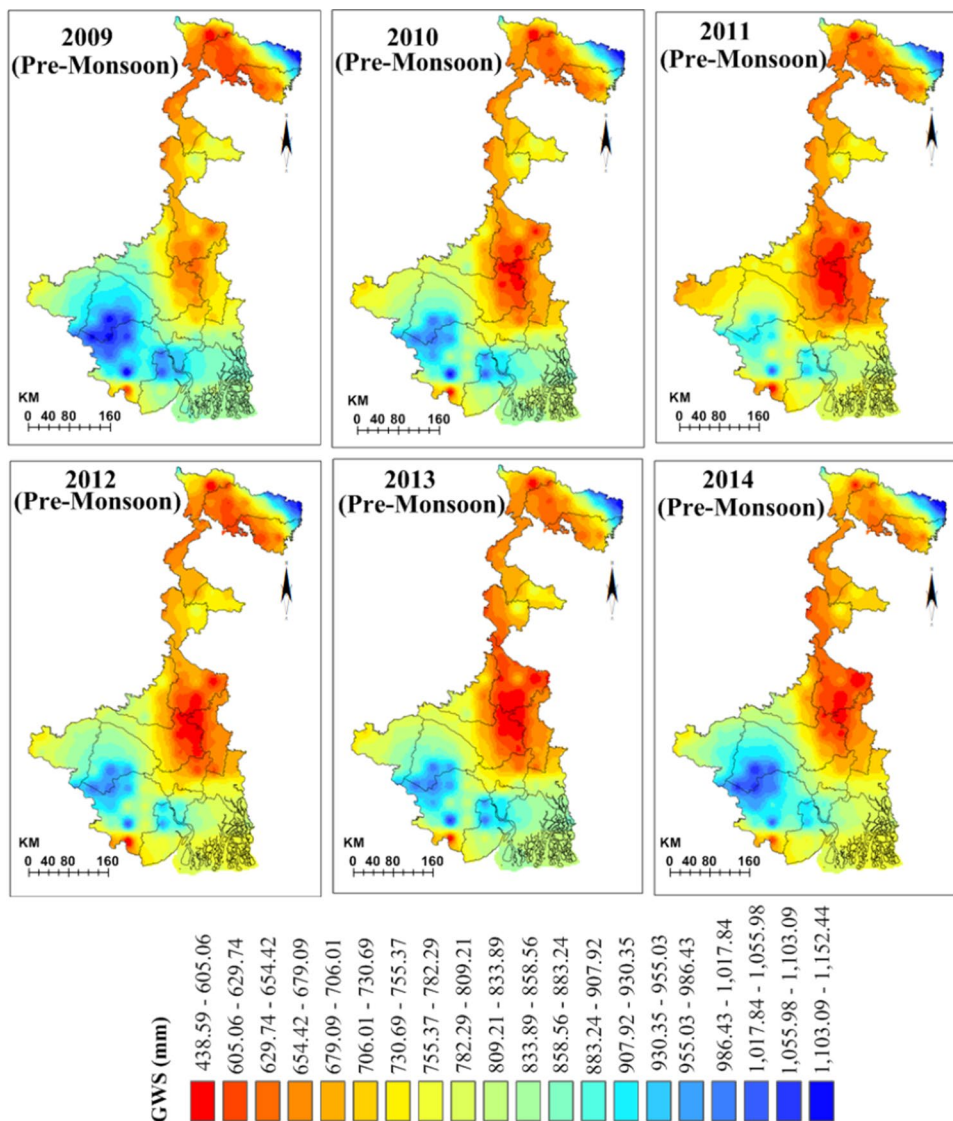
the Bankura, Paschim Medinipore and Purba Medinipore have high groundwater storage which is due to less agricultural productivities and having dense forest. The district-wise max, min and mean of groundwater storage values presented in Figs. 6 and 7 from 2000 to 2014. It is observed that maximum groundwater storage values are shown in the Darjeeling, Jalpaiguri, Cooch Behar, Purulia, Bankura, Paschim Medinipore. Kolkata Municipal Corporation (KMC)

is withdrawal heavy amount of groundwater. This district groundwater flow direction is toward the Bay of Bengal and the hydraulic gradient varies between 1–03 m/km. Baruipur-Sonarpur is one of the highest arsenic prone areas in the aquifer within 50 m bgl under South 24 Parganas. Purba Medinipore has coastal sand dune in the Digha-Ramnagar area formed by sea contain fresh groundwater and groundwater depth between 6–8 m bgl from a near-surface aquifer.
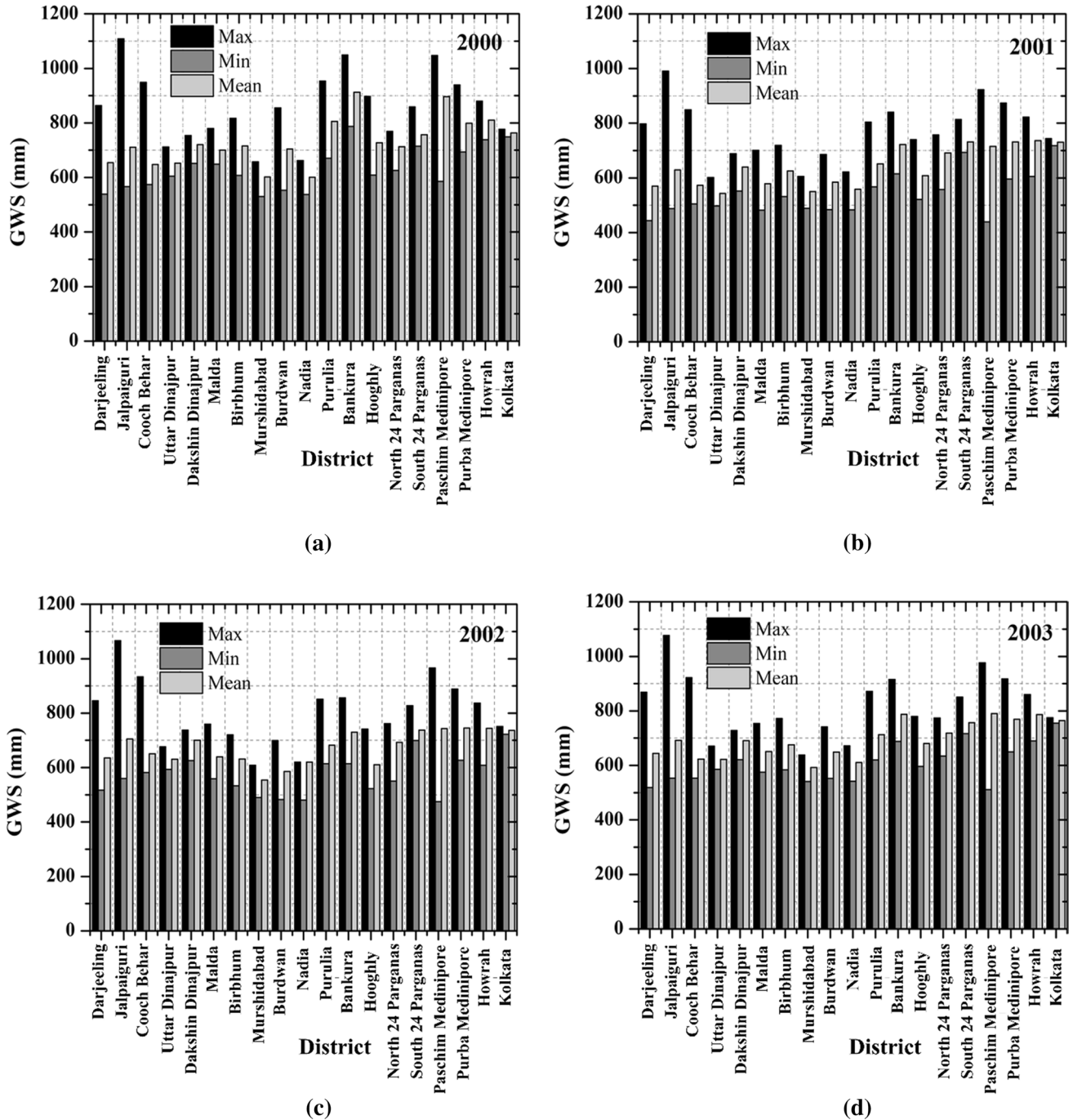

(a)

(b)

(c)

(d)

Fig. 6 District-wise max, min and mean values of groundwater storage for pre-monsoon season from 2000 to 2007 (a–h)
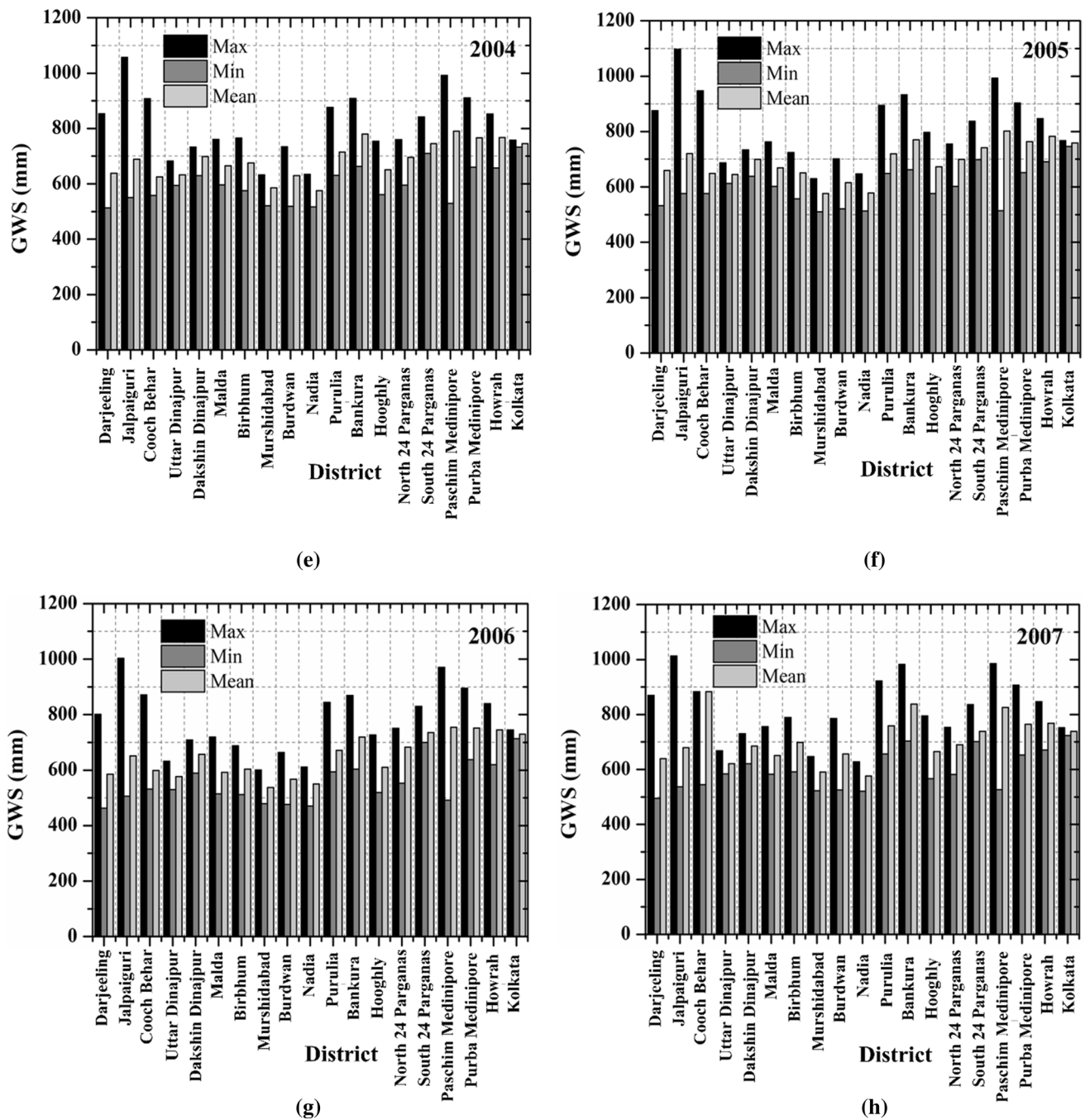
(e)

(f)

(g)

(h)

Fig. 6 (continued)

However, as above mentioned the population is very important for groundwater utilization. High population pressure is responsible for groundwater stress because per person required a minimum of 40-L water per day. It is observed that the highest population is shown in the district of North 24 Parganas from 2001 to 2011 because of the Kolkata metropolice. It is also observed that high population pressure is shown in the district of Howrah and Kolkata according to population density (Fig. 8). It is found that the highest decennial growth rate shows in districts of Uttar Dinajpur, Malda, Murshidabad and North 24 Parganas from 1991 to 2011. Thus, population control is very important for groundwater saves the near future. Finally, groundwater storage has been validated by the groundwater level and groundwater recharge (Fig. 9). It is perceived that groundwater level and recharges very well justified the district-wise groundwater storage (e.g. Paschim Medinipore).
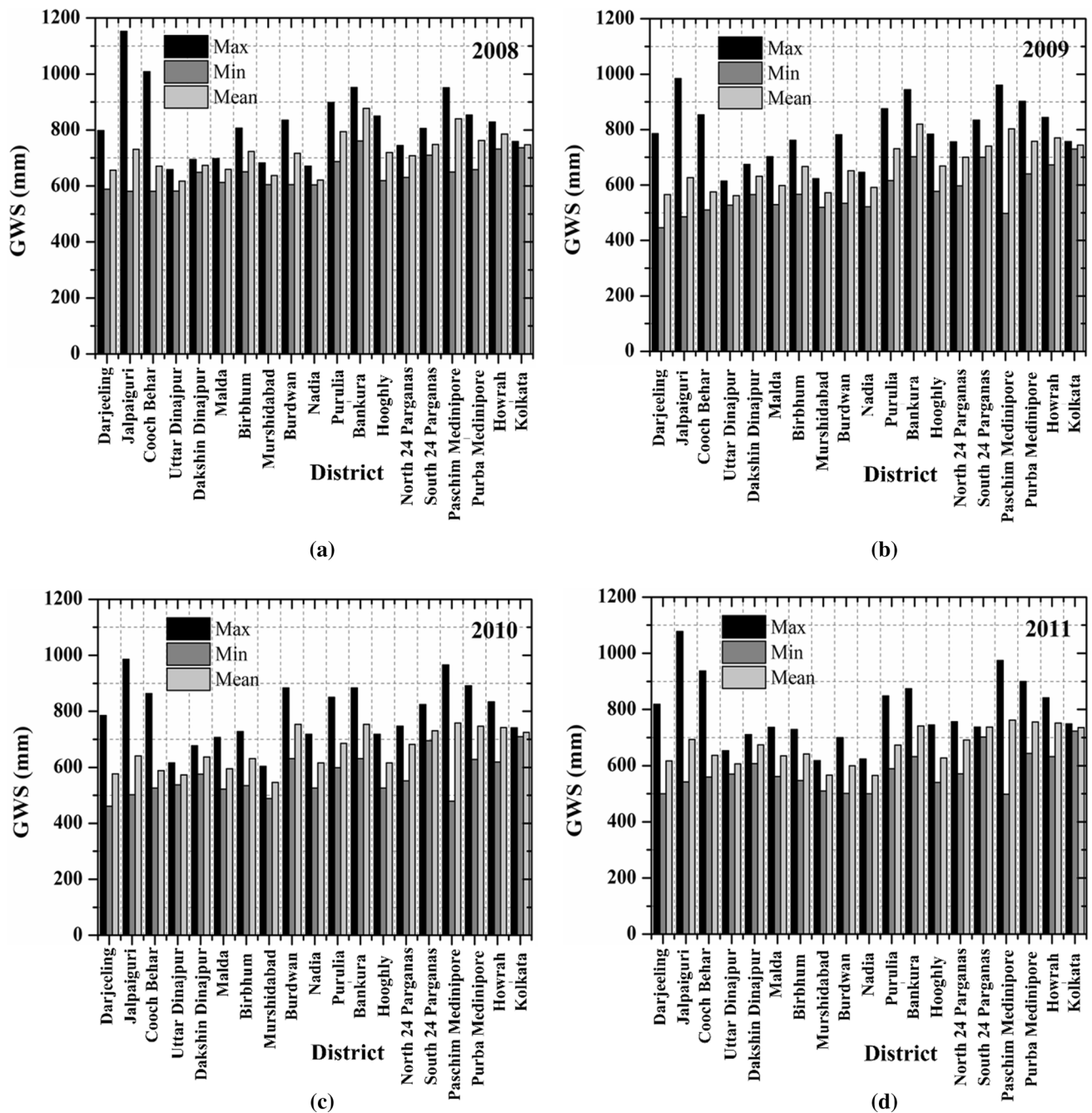
Fig. 7 District-wise max, min and mean values of groundwater storage for pre-monsoon season from 2008 to 2014 (**a–g**)

Delineation of groundwater stress zones (GWSZ)

The delineation of groundwater stress zones has been performed based on ten biophysical and hydrological parameters using the AHP method using the GIS technique tools. All biophysical and hydrological parameters like terrestrial water storage (TWS), groundwater storage (GWS), surface soil moisture (SSM), root zone soil moisture (RZSM), profile soil moisture (PSM), canopy water evaporation (CWE),

direct evaporation from bare soil (DEBS), potential evaporation rate (PER), plant canopy surface water (PCSW), and soil temperature (ST) are calculated for pre-monsoon season of 2014 from the GLDAS2 CLSM. Soil moisture is very important for water stress areas under crop water management. Hydrological applications depend on soil and vegetation components. CWE indicates the interception by the canopy of a tree and evaporates from the leaves. PCSW representing the storage of rainwater on plant canopies that
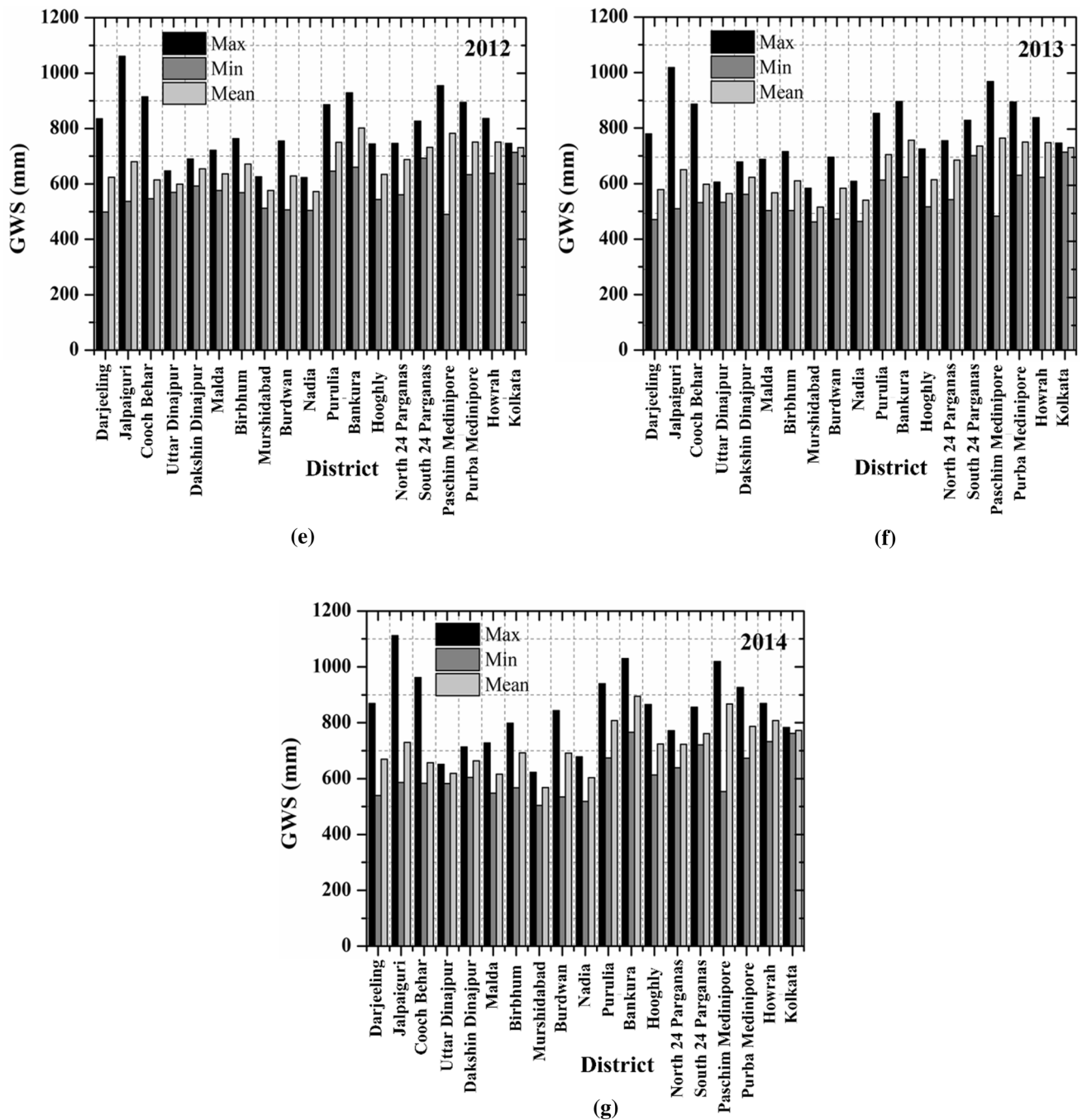
(e)

(f)

(g)

Fig. 7 (continued)

important implication for the energy and water balance of densely vegetated surface areas (Ghosh et al. 2016). DEBS represents a crucial pathway of water loss and does not contribute to crop production (Das et al. 2019). Moreover, all parameters are a direct and indirect impact on global to local groundwater system considering climate uncertainty (Figs. 10, 11). At first, all parameters are converted into raster format then the individual parameter is reclassified into sub-parameters based on normalized values through

the AHP method (Table 1). The AHP based normalized value is calculated from the individual expert opinion weight assign for different parameters (Table ST1–ST10). Finally, all parameters are integrated by an overlay method based on AHP based normalized values to the generation of district-wise groundwater stress zone (GWSZ) for pre-monsoon of 2014 (Table 2). The resulting map has been classified into five classes (Fig. 12) (i) extreme (21.58%), (ii) high (22.42%), (iii) moderate (30.03%), (iv) low (17.72%)

(a)

(b)

(c)
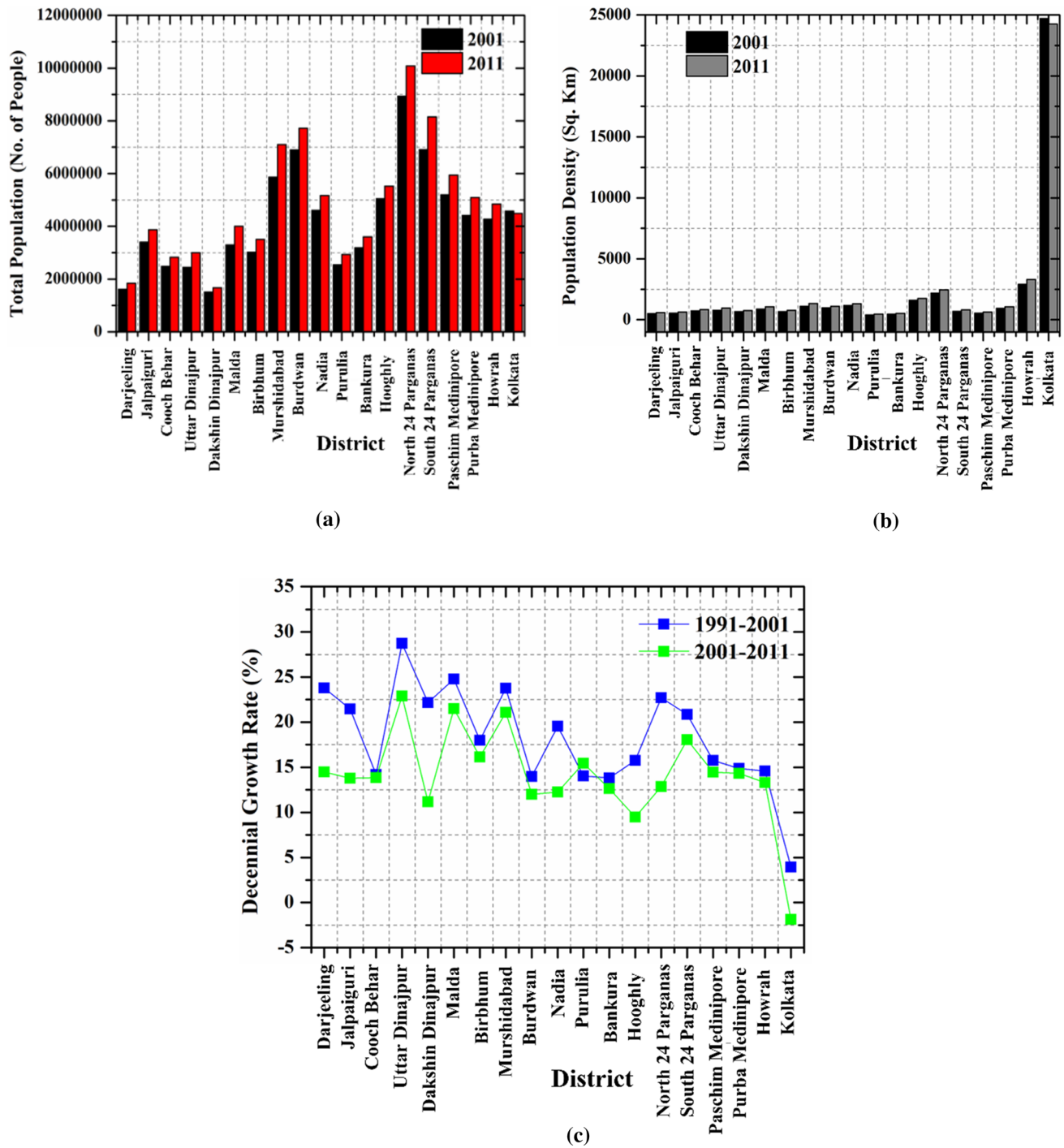
Fig. 8 District-wise graphical representation of the **a** total population, **b** population density and **c** decennial growth rate

and (v) very low (8.26%). It is observed that high GWSZ showed in Birbhum, Murshidabad, Malda and small parts of the Darjeeling, Jalpaiguri, Cooch Behar, and Uttar Dinajpur. It is also observed that low GWSZ has shown in small parts of the Bankura, Paschim Medinipore, Howrah and Purba Medinipore because of high groundwater storage (1000–1152 mm).

Finally, GWSZ map very well justified by annual groundwater level and recharge values. It is found that Purba Medinipore shows a maximum average pre-monsoon groundwater level (18.31 mbgl) for 2013. The results indicated that Birbhum (12.71 mbgl), Murshidabad (10.81 mbgl), Burdwan (12.28 mbgl), Hooghly (16.43 mbgl), Purba Medinipore (15.92 mbgl) and Howrah (12.86 mbgl) yielded

Fig. 9 District-wise spatiotemporal changes of pre-monsoon **a** groundwater level for 2013–2017, **b** groundwater recharge, discharge and availability based on observed data from 2012–2013
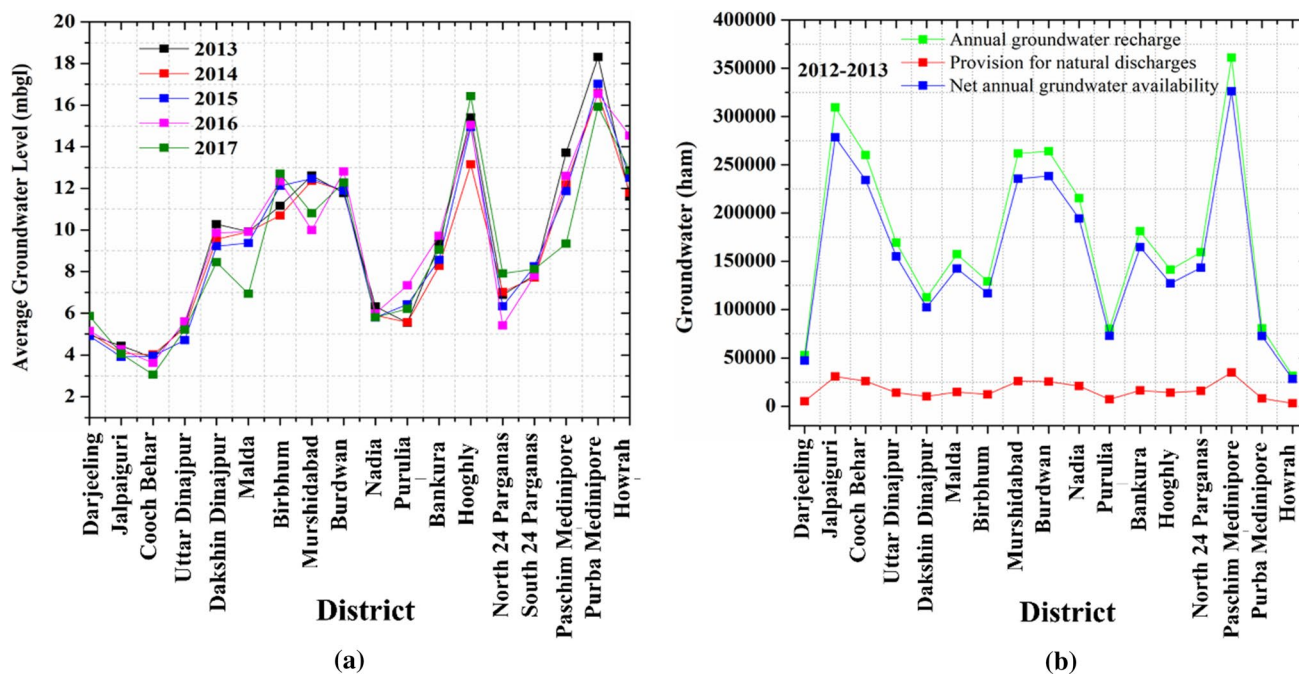
high average groundwater level compared to other districts for 2017. Moreover, the population data showed high correlation with the GWSZ map.

Sensitivity analysis of GWSZ

The sensitivity analysis indicates how various sources of the uncertainty contribute to output of a system performance. Ten biophysical and hydrological parameters are considered for this analysis by omitting individual parameters using AHP method (De Ridder 2001).

AHP-based normalized values are calculated from the previous literature and expert opinion and utilized for the generation of GWSZ by omitting individual features (Table ST11). The results show that the GWS has high impact on low and moderate GWSZs compared to another feature (Table 3). It is observed that terrestrial water storage (TWS), surface soil moisture (SSM), root zone soil moisture (RZSM), profile soil moisture (PSM), plant canopy surface water (PCSW), and soil temperature (ST) have higher impact on high and extreme GWSZs. It is also found that all parameters have a major impact on high and extreme GWSZ compared to other zones.
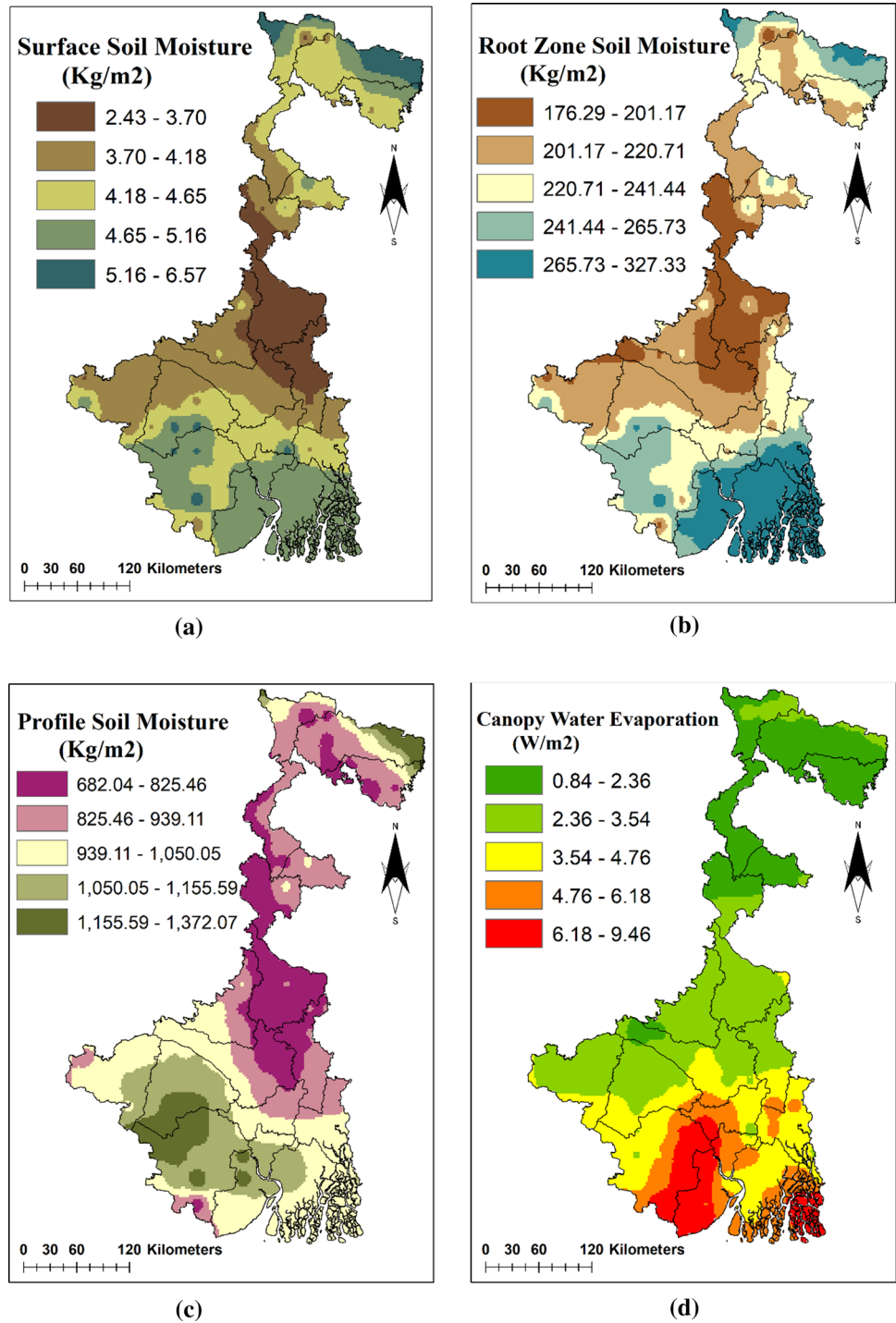
After that, most five sensitive parameters have been performed for inter-connectivity between dominant characteristic using Kendall, Pearson, and Spearman methods (Table 4). Kendall, Pearson, and Spearman are rank correlation coefficient methods that indicate an original association

between two variables (Dhar et al. 2014; Liu et al. 2018). It is a non-parametric hypothesis test for a relationship between two variables. It is an efficient and robust way of identifying a monotone relationship. The values of these correlation coefficient methods range from +1 to −1 where +1 and −1 indicate perfect positive and negative relationships and 0 indicates no relationship. The district-wise pixel-based five parameter values are utilized for correlation coefficient analysis which is extracted concerning the centroid point of each district. The results show a similar relationship between the three methods for most sensitive groundwater stress parameters. It is observed that TWS, GWS, RZSM, PSM have negative strong relation with DEBS. It is also observed that all parameters (four) show a positive relation excluding DEBS. Thus, TWS, GWS, RZSM, and PSM have a very strong positive impact on groundwater scenarios. DEBS is an unfavorable parameter for the delineation of groundwater stress zones according to the correlation analysis.

Discussion

The groundwater is one of the nation's most important natural resources. More than 90% of the groundwater used for drinking purposes for the rural population. A huge amount of groundwater withdrawals represents the increasing in population and the limitation of surface reservoir. The

district-wise sustainable groundwater planning and management are required.

Water storage of Indian has decreasing trend over the past few years. Several studies show that the nature and characteristics of depletion using various models and among them, the Gravity Recovery and Climate Experiment (GRACE) observation has significant importance (Bhanja et al. 2020). According to numerous literature

regarding GRACE and groundwater, it is obvious that there are very few studies have been conducted on Indian region (Panda and Wahr 2016; Chinnasamy et al. 2013; Long et al. 2016). Therefore, the specific yield wise database is still not available in Indian regions. Thus, fixed specific yield values have been used to estimate the groundwater levels for these regions (Rodell et al. 2009; Panda and Wahr 2016).

Fig. 11 **a** DEBS, **b** PCSW, **c** PER and **d** ST mapping from GLDAS data for pre-monsoon season of 2014

pre-monsoon season of 2014.

(a)

(b)

(c)

(d)
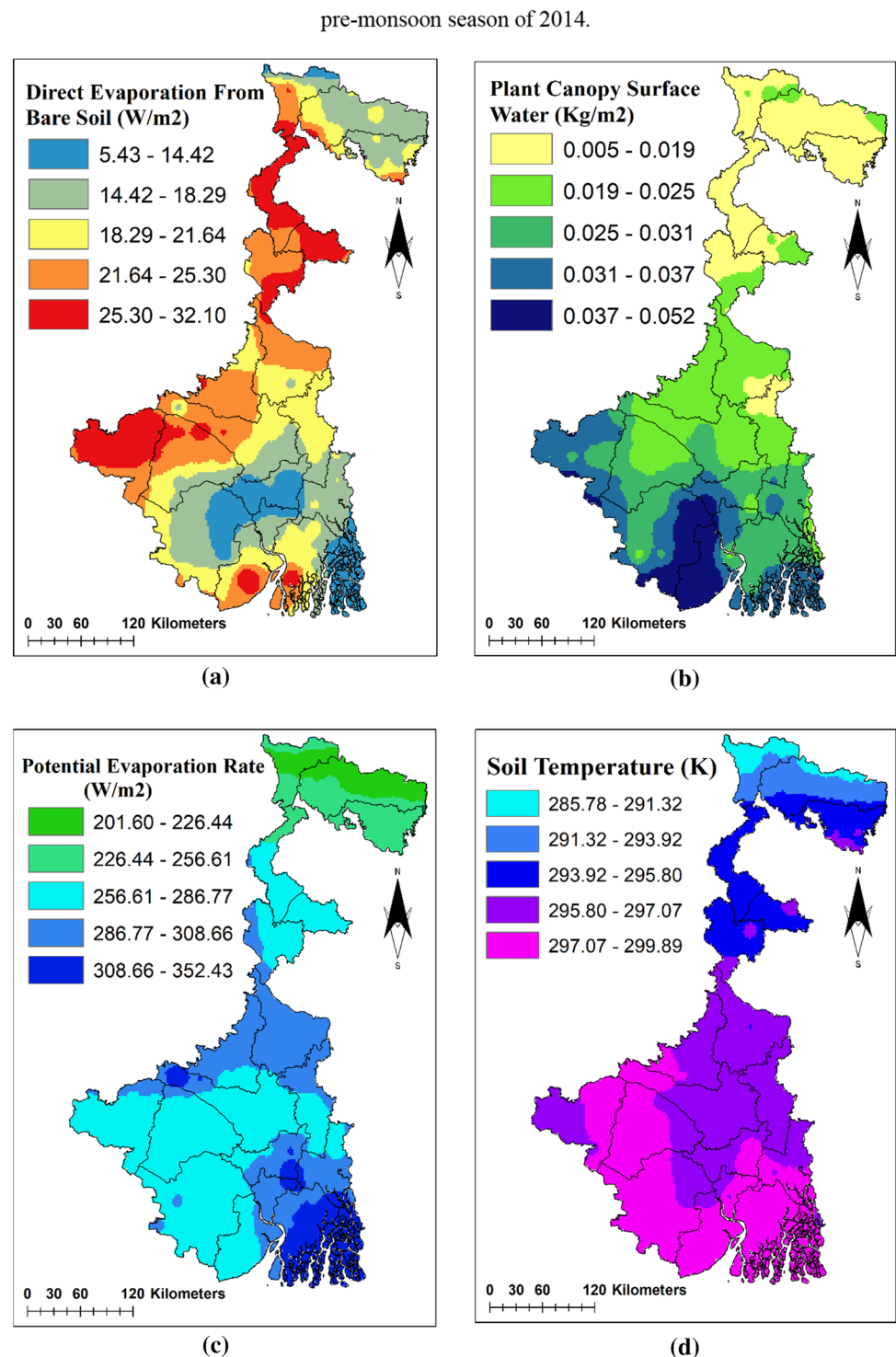
In India, high exploited groundwater zones are located in Punjab, Haryana, and Delhi regions due to agricultural and population increments which were reported in Central Groundwater Board report 2017–2018. In this connection, the gross extraction of groundwater was increased 62–63% over the Indian region. In the case of West Bengal, this depletion is caused by dying of wells due to continuous temperature rise and submersible pumping in the agricultural field which creates a vulnerable condition for Bankura, Puruliya, and West Midnapore districts (Halder et al. 2020). A significant transition of land use and land cover over the Bengal regions is also in a changing nature which has a significant impact on the groundwater levels and leads toward its imprints in groundwater scarcity. In this connection,

Table 1 Assigned and normalized weights of the individual features of the ten feature for groundwater stress zoning

SL No	Feature	Weight	Feature classes	Area in %	Weight assigned	Normalized weight
1	Terrestrial water storage (mm)	8	682.04–828.16	19.46	8	0.3333
			828.16–941.82	23.18	6	0.2500
			941.82–1052.76	33.40	5	0.2083
			1052.76–1155.59	16.15	3	0.1250
			1155.59–1372.07	7.81	2	0.0833
2	Groundwater storage (mm)	9	503.97–620.71	21.36	8	0.2759
			620.71–704.09	20.52	7	0.2414
			704.09–801.77	31.60	6	0.2069
			801.77–906.59	18.70	5	0.1724
			906.59–1111.48	7.83	3	0.1034
3	Surface soil moisture(Kg/m^2)	6	2.43–3.70	14.19	7	0.3889
			3.70–4.18	26.71	5	0.2778
			4.18–4.65	27.10	3	0.1667
			4.65–5.16	28.09	2	0.1111
			5.16–6.57	3.92	1	0.0556
4	Root zone soil moisture(Kg/m^2)	6	176.29–201.17	15.84	6	0.3529
			201.17–220.71	29.83	5	0.2941
			220.71–241.44	21.68	3	0.1765
			241.44–265.73	15.45	2	0.1176
			265.73–327.33	17.19	1	0.0588
5	Profile soil moisture(Kg/m^2)	5	682.04–825.46	19.51	6	0.3529
			825.46–939.11	24.21	5	0.2941
			939.11–1050.05	30.88	3	0.1765
			1050.05–1155.59	17.23	2	0.1176
			1155.59–1372.07	8.17	1	0.0588
6	Canopy water evaporation (W /m^2)	3	0.84–2.36	22.80	1	0.0476
			2.36–3.54	34.41	2	0.0952
			3.54–4.76	21.94	5	0.2381
			4.76–6.18	11.49	6	0.2857
			6.18–9.46	9.35	7	0.3333
7	Direct evaporation from bare soil (W /m^2)	3	5.43–14.42	10.83	2	0.0909
			14.42–18.29	26.21	3	0.1364
			18.29–21.64	23.45	4	0.1818
			21.64–25.30	24.02	6	0.2727
			25.30–32.10	15.49	7	0.3182
8	Potential evaporation rate (W /m^2)	2	201.60–226.44	6.09	1	0.0500
			226.44–256.61	9.99	3	0.1500
			256.61–286.77	48.65	4	0.2000
			286.77–308.66	26.08	5	0.2500
			308.66–352.43	9.19	7	0.3500
9	Plant canopy surface water (Kg /m^2)	4	0.005–0.019	23.78	7	0.2927
			0.019–0.025	28.58	6	0.2509
			0.025–0.031	22.10	5	0.2091
			0.031–0.037	17.11	4	0.1673
			0.037–0.052	8.43	2	0.0800

Table 1 (continued)

SL No	Feature	Weight	Feature classes	Area in %	Weight assigned	Normalized weight
10	Soil temperature (K)	2	285.78–291.32	3.14	2	0.0952
			291.32–293.92	6.26	3	0.1429
			293.92–295.80	14.75	4	0.1905
			295.80–297.07	36.93	5	0.2381
			297.07–299.89	38.92	7	0.3333

Table 2 Pair-wise comparison matrix (ten feature layers) developed for AHP based groundwater stress zoning

Feature	TWS	GWS	SSM	RZSM	PSM	CWE	DEBS	PER	PCSW	ST	Normalized weights
TWS	8/8	8/9	8/6	8/6	8/5	8/3	8/3	8/2	8/4	8/2	0.1667
GWS	9/8	9/9	9/6	9/6	9/5	9/3	9/3	9/2	9/4	9/2	0.1875
SSM	6/8	6/9	6/6	6/6	6/5	6/3	6/3	6/2	6/4	6/2	0.1250
RZSM	6/8	6/9	6/6	6/6	6/5	6/3	6/3	6/2	6/4	6/2	0.1250
PSM	5/8	5/9	5/6	5/6	5/5	5/3	5/3	5/2	5/4	5/2	0.1042
CWE	3/8	3/9	3/6	3/6	3/5	3/3	3/3	3/2	3/4	3/2	0.0625
DEBS	3/8	3/9	3/6	3/6	3/5	3/3	3/3	3/2	3/4	3/2	0.0625
PER	2/8	2/9	2/6	2/6	2/5	2/3	2/3	2/2	2/4	2/2	0.0417
PCSW	4/8	4/9	4/6	4/6	4/5	4/3	4/3	4/2	4/4	4/2	0.0833
ST	2/8	2/9	2/6	2/6	2/5	2/3	2/3	2/2	2/4	2/2	0.0417

TWS terrestrial water storage, *GWS* groundwater storage, *SSM* surface soil moisture, *RZSM* root zone soil moisture, *PSM* profile soil moisture, *CWE* canopy water evaporation, *DEBS* direct evaporation from bare soil, *PER* potential evaporation rate, *PCSW* plant canopy surface water, *ST* soil temperature
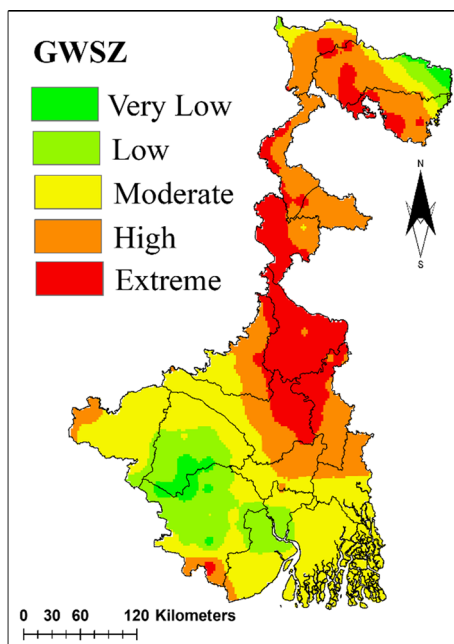
Fig. 12 Delineation of groundwater stress zone (GWSZ) mapping using AHP method for pre-monsoon season of 2014

the poor recharge trends in the south-west monsoon along with very slow recharge trends in post-monsoon have been notices due to poor precipitation consistency and infiltration rates. Simultaneously, the changes in the pattern of rainfall intensity in certain periods also create a negative impact on groundwater recharge. High precipitation in a shorter time duration, on one hand increase the potential for flooding, and also secure water supply (Salimi et al. 2019), on the other hand, with the erosion of topsoil creates a negative ambiance for natural groundwater recharge over the Bengal region over the last few decades which are one of the key factors of groundwater scarcity.

Few numbers of researchers worked on the identification of groundwater potential zones in West Bengal. Ghosh et al. (2016) studied groundwater potential zone in the hard rock terrain of Kumari watershed in the western part of West Bengal. It is observed that very low crop cultivation in this watershed covered by Purulia district because of this region under high water stress. Thus, excessive groundwater used for irrigation, domestic and various purposes (Mandal et al. 2016). Identification of groundwater recharge potential zone based on AHP method in the critical Goghat-II

Table 3 Area under different classes change with exclusion of each groundwater stress parameter

i	Feature	% Change				
		Very low	Low	Moderate	High	Extreme
1	TWS	+0.12	− 0.92	**+2.27**	**+3.49**	**− 4.96**
2	GWS	**− 2.77**	**− 10.42**	**+10.69**	− 0.03	**+2.54**
3	SSM	+0.09	+0.64	+0.26	**+2.42**	**− 3.41**
5	RZSM	+0.16	+0.25	+0.91	**+3.48**	**− 4.80**
5	PSM	+0.12	− 0.92	**+2.27**	**+3.49**	**− 4.96**
6	CWE	+0.16	+0.79	+0.20	+1.98	**− 3.13**
7	DEBS	+0.06	+0.54	+0.71	**+2.83**	**− 4.13**
8	PER	− 0.09	+0.50	− 0.57	− 1.15	+1.30
9	PCSW	+0.11	+0.66	+0.37	**+2.10**	**− 3.24**
10	ST	− 0.01	+0.34	+0.85	**+2.05**	**− 3.23**
S_F	All feature	8.26	17.72	30.03	22.42	21.58

Bold values indicate significant results

Table 4 Correlation between five most sensitive parameters for the generation of groundwater stress zone (GWSZ) using Kendall, Pearson and Spearman methods

	TWS_{t-1}	GWS_{t-1}	$RZSM_{t-1}$	PSM_{t-1}	$DEBS_{t-1}$
Kendall					
TWS_{t-1}	1	1	0.6000	0.8000	− 0.2000
GWS_{t-1}	1	1	0.6000	0.8000	− 0.2000
$RZSM_{t-1}$	0.6000	0.6000	1	0.4000	− 0.6000
PSM_{t-1}	0.8000	0.8000	0.4000	1	0
$DEBS_{t-1}$	− 0.2000	− 0.2000	− 0.6000	0	1
Pearson					
TWS_{t-1}	1	1	0.7000	0.9000	− 0.3000
GWS_{t-1}	1	1	0.7000	0.9000	− 0.3000
$RZSM_{t-1}$	0.7000	0.7000	1	0.6000	− 0.7000
PSM_{t-1}	0.9000	0.9000	0.6000	1	− 0.1000
$DEBS_{t-1}$	− 0.3000	− 0.3000	− 0.7000	− 0.1000	1
Spearman					
TWS_{t-1}	1	1	0.7000	0.9000	− 0.3000
GWS_{t-1}	1	1	0.7000	0.9000	− 0.3000
$RZSM_{t-1}$	0.7000	0.7000	1	0.6000	− 0.7000
PSM_{t-1}	0.9000	0.9000	0.6000	1	− 0.1000
$DEBS_{t-1}$	− 0.3000	− 0.3000	− 0.7000	− 0.1000	1

TWS_{t-1} terrestrial water storage at time, *GWS_{t-1}* groundwater storage at time, *$RZSM_{t-1}$* root zone soil moisture at time, *PSM_{t-1}* profile soil moisture at time, *$DEBS_{t-1}$* evaporation from bare soil at time

block, Hooghly is available in Das et al. (2019). The results show that moderate groundwater recharge (33.51%) is presented in this block because of the low lying flat plain of the northeastern portion. Patra et al. (2018) also studied AHP-based groundwater potential zone delineation in the whole district of Hooghly for sustainable development. The results show that Arambag, Chinsurah-Mogra, Goghat-I, Pandua, and Polba-Dadpur comes under the semi-critical groundwater development category. John et al. (2018)

studied the groundwater level is falling in many parts of the state because of the maximum areas cover by the agricultural land. It is observed that the groundwater declining trend shows in the arsenic prone areas. Sahoo et al. (2019) delineated future groundwater potential zone based on AHP method in the Dwarakeswar-Gandherswari river basin covered by Bankura and Purulia district. The future groundwater results show that the Bankura district comes under poor groundwater potential because of more use of groundwater for irrigation purposes. Marwah (2018) studied arsenic contamination is not serious problems to agriculture in West Bengal but threats to drinking water purposes. However, groundwater contamination is highly increased by arsenic and heavy metal in the twenty administrative districts of Assam (Nath et al. 2018). Thus, the analysis of groundwater contamination is very significant for potable groundwater reserves. Our results agreed with previous publications for district-wise spatiotemporal groundwater storage change from 2000 to 2014.

Significance of the research work for policy and practice

This study is a pioneering step in applying data science technologies to developing a sustainable water management framework. In this research, terrestrial water storage (TWS) and groundwater storage (GWS) scenarios will be used for solving the problem of water for agriculture and domestic purpose under climate uncertainty. This approach is effective as it considers future climate data of agricultural activities for the development of innovative technologies and management systems. Future climate data can strengthen their capacity for adaptation to climate based upon the farmer's attitude toward risk.

Recommendation for sustainable groundwater management

The groundwater is valuable natural resources for the present and future agriculture, cities, health, and environment. It provides a dependable and long-term water supply for current and future generations and also provides additional water for drought when there is not enough snow or rainfall (Menon 2007; California Water Foundation 2014). The following recommendations should be advanced in order to ensure groundwater sustainable for India, particularly for West Bengal:

- Adopting an actual definition of sustainable groundwater management.
- Established local groundwater management authorities.
- Established a system of prioritization for all sub-basins.
- Properly utilized of surface water for agriculture cultivation.
- Eco-efficient agriculture planning is required for sustainable agriculture management.
- Interconnection between groundwater and surface water.
- Improve groundwater data availability through an open-source web service portal.
- Increasing groundwater storage for highly variable water supplies due to climate uncertainty.
- Full control over the exploitation of the study area's natural resources is necessary to promote socioeconomic development.
- Providing financial support for groundwater management.

Conclusions

The groundwater is very relevant for the effect of future climate change on groundwater resources worldwide. In the present research, district-wise spatiotemporal GWS changes have been performed under TWS using GLDAS2 CLSM data for pre-monsoon season to correlated with observed groundwater level and recharge values. The research objective mainly focuses on the delineation of the groundwater stress zone based on ten biophysical and hydrological parameters [i.e. terrestrial water storage (TWS), groundwater storage (GWS), surface soil moisture (SSM), root zone soil moisture (RZSM), profile soil moisture (PSM), canopy water evaporation (CWE), direct evaporation from bare soil (DEBS), potential evaporation rate (PER), plant canopy surface water (PCSW), and soil temperature (ST)] using AHP method by the GIS environment. During current work, the district-wise spatiotemporal pre-monsoon soil moisture change were analyzed to identify the water stress areas. Pre-monsoon season is only considered because of the water stress problem shown in this season. Population data also considered for the identification of groundwater stress zones. The results indicated that moderate water stress zones are shown in the district of Birbhum, Bankura, Purulia (max: 3.82 kg/m$^{2)}$ according to surface soil moisture condition. The results showed that the districts Jalpaiguri (max: 1097.35 mm), Paschim Medinipore (max: 993.22 mm), Purba Medinipore (max: 903.43 mm) and a small part of the Bankura (max: 932.69 mm) had high groundwater storage. The TWS components like soil moisture, surface waters, snow, glaciers, and biomass did not significantly contribute to the decline of the total water level. It can be a cause of unstainable groundwater for irrigation and other anthropogenic activities. The results also indicated that the groundwater stress zone in the district of North 24 Parganas (max: 755.12 mm) due to the highest population pressure compared to the other districts. The sensitivity analysis has been performed to identify the most significant high impact parameters on groundwater stress zones (GWSZ). However, the total urban and rural population in West Bengal is 57,748,946 and 22,427,251 under 80,176,197 total populations from 2001 due to the degree of urbanization. These population values proved that the increased urban population for this state. The decennial growth rate is increased from 1991 to 2001 compared to 2001 to 2011. Thus, groundwater is more utilized for drinking and agriculture purposes. Proper scientific and systematic planning is required for district-wise sustainable groundwater management shortly. The major drawback of present study is the lack of groundwater data. Several groundwater data can be utilized for the more accuracy of the district-wise groundwater output. This research output can be utilized for regional future sustainable groundwater planning and management.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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