

Full Length Research Paper

A rational approach to comprehensive groundwater resource mapping and management in india

Vallabhbhai Kalam^{1*} and Salam O. Dhoni²

¹Geomatics Solutions Development Group, Centre for Development of Advanced Computing (C-DAC), Pune, India.

²Hydrogeology Division, National Remote Sensing Centre (NRSC), ISRO, Hyderabad, India.

Accepted 22 May, 2016

Climate change may influence hydrogeological processes and groundwater resources directly and indirectly in various modes. Therefore, a systematic planning, management and adaption are challenging task. Considering the importance of climate change impact, the study was to identify the sustainable Groundwater (GW) / Drinking Water (DW) resources potential zones, suitable locations for GW harvesting structures, recommendation for GW quality management and GW extraction methods for Dhubri District of Assam, India and also with emphasis on Non-Covered (NC) and Partially-Covered (PC) habitations in the rural area of Dhubri District. The quality and quantity of GW/DW resources potential of the region is under extreme threat due to frequent flood, drought and population pressure. geographic information system (GIS) and Remote sensing (RS) technology along with on-field investigations were used to achieve the goal. GW availability is controlled by the local hydro-geomorphology, geology and geological structures of the area. Based on these controlling factors the GW resource Potential Zone Maps of the study area were prepared. Well inventorisation was also carried out including depth to water level, water level fluctuation, yield range and well-type, etc. It was found that more than half of the area falls under shallow GW table zone. The GW resource potential zones were successfully delineated based on Weightage Value (WV). The entire study area has been classified into various classes that is, excellent, very good, good, moderate and poor. To enhance and manage the GW resources in this area, GW recharge structures such as check-dams, percolation tanks and recharge-pits were suggested. Various types of GW extraction methods such as, Ring Well (RW), Tube Well(TW), Bore Well(BW) were recommended for this region.

Key words: Climate change, groundwater, water quality, water harvesting structures, groundwater management, geographic information system (GIS) and remote sensing.

INTRODUCTION

Climate change and the global water cycle are closely linked (Stoll et al., 2011). Changes in the spatio-temporal distribution of weather conditions will have a direct impact

on water resources. Climate change ensuing in dryer dry seasons and wetter rainy seasons, and consequently heightened risks of more intense and frequent floods and

*Corresponding author: E-mail:dr.haikalam08@gmail.com

Author(s) agreed that this article remain permanently open access under the terms of the Creative Commons Attribution License 4.0 International License

drought. The changing climate conditions are expected to increase flood damage in the future (Simonovic, 2010). It will also have significant impacts on the availability, quality, quantity and accessibility of water. Assam is more vulnerable to climate change than its neighbouring states. The climate induced water hazards are more vulnerable in this area, because of its location on the foothills all around.

Several districts in Assam suffered drought-like conditions for two years consecutively in 2005 and 2006, bearing the signature of climate change as vindicated by the IPCC report (IPCC, 2007). Such a situation lead to intense water crisis throughout the year. In this region, there is a need for a database on water availability, water quality as well as access to data sources for different uses and applications (AGT, 2011).

Assam is the most flood-affected region in India. Consequently, to a greater extend researches are focused on flood management towards climate change, but somewhat less has been studied about the impact of climate change on water resources in a regional scale / basin scale (Sivakumar, 2013; Ghosh et al., 2010; Gosain et al., 2011; Treidel et al., 2011). GW/DW resources potential of the region is under extreme threat due to frequent floods and drought. This is exacerbated by population migrations towards a single location with each change in the Brahmaputra River dynamics. This puts excessive pressure on DW resource of this region.

Groundwater is one of the most valuable natural resources due to its limited existence, which helps to support the enormous human health, economic development and ecological diversity. In India, more than 85% of the populations depend upon groundwater for drinking and daily domestic utilization (WHOINDIA, 2010). On account of its near universal availability, dependability and low capital cost, it is possibly the most preferred source of water to meet the requirements of various user sectors in India. As per statistics, the demand for water is much higher than the available surface and GW resources combined. It is also expected that by around 2020, India will be a 'water stressed' state with per capita availability declining to 1600 cu. A country is said to be water stressed when the per capita availability of water drops below 1700 cu (Gosain et al., 2011; Khurana et al., 2008). Stress on available land and water resources is already higher in India compared to many other countries. It is expected that the stress would increase further in the coming years with the increase in population (Rakesk et al., 2005; Mitra et al., 2009).

The increasing dependence on GW as a reliable source of quality water has resulted in its large-scale and often indiscriminate use in various parts of the country, without due regard to the recharging capacities of aquifers and other environmental factors (Jha et al., 2009). Getting quality water also poses as a major problem due to natural disaster such as flood, drought, etc.

According to Khurana's (2008) report, in India around 37.7 million people are affected by waterborne diseases annually. Due to diarrhea, every year around 1.5 million children are affected. Because of waterborne diseases, the economic burden is estimated at \$600 million a year (Khurana et al., 2008). The problems of chemical contamination are also prevalent in India with 195,813 habitations in the country affected by poor water quality. The major chemical parameters of concern are fluoride and arsenic. Iron is also emerging as a major problem with many habitations showing excess iron in the water samples (Mridul et al., 2010). The world is still on track for reaching the safe DW target, but the trend appears to be deteriorating lately. Based on the current trends, the world will miss the sanitation target by more than half a billion people and 84% of the population without access to an improved source of DW in rural areas (WHO, 2006).

A balanced water supply is necessary for the rural areas to maintain a healthy life style and in the process enhance their living standard, aid in economic growth and overall development, etc. Worldwide, many programs have been initiated to target the 'good' GW resources and managing them for unfulfilled areas using different techniques. In India, Ministry of Drinking Water and Sanitation (MDWS), Government of India has embarked upon a major programme, "Rajiv Gandhi National DW Mission," for preparing a scientific database using RS and GIS techniques to provide safe DW supply to all the habitations across the country (Radhakrishnan, 2008). The prime goal was to target the non-covered (NC) and partially-covered (PC) habitations in the rural areas of the country. The classification was carried out under Rural Water Supply Programme as (i) non covered (NC-habitation which means the safe DW source / point does not exist within 1.60 km of the habitation in the plains or 100 m elevation in the hilly areas), (ii) partially covered (PC-habitation means the habitation which has a safe DW source / point (either public or private) within 1.60 km in plains and 100 m in hilly areas but the capacity of the system ranges between 10 lpcd (Litres per Capita per Day) to 40 lpcd) and (iii) fully covered (FC-habitation means the entire population of the habitation is provided with safe DW (RWSP, 2003). Figure 1 shows the different type of habitations with locations.

The systematic planning of GW exploitation using modern technologies is essential for the proper utilization of this precious natural resource (Jaiswal et al., 2003). GIS and RS have emerged as some of the powerful tools in analyzing and quantifying multivariate aspects of GW occurrence. Using GIS, it is very helpful in delineation of GW prospect and deficit zones integrating multi-criteria evaluation (Carver, 1991). Many studies have also been carried out using satellite imagery for mapping the hydro-geomorphological units and GW potential zones (Anbazhagan et al., 2011; Sahai et al., 2005; Reddy et al., 1996; Mohanty et al., 2010; Subramanian et al., 2010).

Considering climate change impacts on GW resource, this study made an effort to identify the sustainable GW / DW resource potential zones, suitable locations for water harvesting structures, recommendation for GW quality management and GW extraction methods to Dhubri District of Assam, India and also with emphasize on non-covered (NC) and partially-covered (PC) habitations in the rural area of Dhubri District. RS and GIS technology along with field investigations were used for this study.

Study area

The Dhubri District is located between 89.59° to 90.28° east longitude and 25.28° to 26.01° north latitude (Figure 1). The average elevation is 35 m above mean sea level. The district is bounded by Kokrajhar District in the north, Bongaigaon and Goalpara District in the east, Meghalaya in the South and West Bengal and Bangladesh in the west. The Brahmaputra River divides the district into two parts. This district is one of the most densely populated districts of India with a density of 584 persons per km² and total population being 1637344 (as per 2001 census). According to the Central Rural Sanitation Programme, Government of India, Dhubri District encompasses 214 NC, 179 PC and 634 status unavailable habitations (DDWS, 2008).

Geology and climate

Geologically, the district is underlain by two distinct rock formations that is, Archaean to Quaternary (Figure 4). The Archaean and Precambrian group of rocks comprising gneisses, schists, phyllites and quartzites form the basement over which Quaternary formations were deposited. The sediments consist of indurated yellowish, brownish or reddish clay with sand, gravel, pebble, cobbles and small boulders. The thickness of the alluvium varies depending upon the configuration of basement rock. The geo-climatic condition of Dhubri District is unique compared to other districts of Assam. The climate of the district is very damp and humid due to heavy rains and high temperature. Yearly average rainfall is 2453 mm and temperature varies between 3 to 39°C. Generally, the period from May to October is considered as flood season in this district (SDMASSAM, 2010).

Hydro-geomorphology

Hydro-geomorphologically, the study area is divided into various units namely, flood plain, younger alluvial plain, older alluvial plain, pediplain, residual hills, denudational hills and fluvial features such as oxbow lake, meander scar, river paleo-channel, natural levee and channel island.

MATERIALS AND METHODS

GW/DW resource potential zone map was prepared based on geology, hydro-geomorphology, lineaments and hydrogeological /hydrological conditions (well yield, rainfall, and water level, etc.) of the study area. The overall approach for achieving the objective is shown in Figure 2 and is described as follows.

Thematic layers generation

Geomatica 10.0 and ESRI ARC GIS 9.3 softwares were used for generating the thematic layers. For the preparation of thematic layers, NRSA 2007 guidelines have been adopted (NRSA, 2007). Satellite data of IRS-P6 LISS-III geo-coded False Color Composite (FCC) dated 10 February, 2006 was used to prepare the detailed hydro-geomorphological and structural maps for the study area. It has a spatial resolution of 23.5 m in visible region of the electromagnetic spectrum. Enhancement technique of the satellite data was performed before further processes were carried out. Enhancement using linear enhancer, standard-deviation and some resetting of the brightness and contrast were applied to improve the visual contrast of the image to an appreciable degree. Visual analysis of the enhanced image (LISS III Band combinations 2, 3, 4; 3, 2, 1 and 4, 3, 1) clearly showed separability between/within geomorphic, geologic and other landform/land cover units. Median filter (filter window size of 3 * 3) was used to map the structural units. It computes the median value of the grey level value within the rectangle filter window surrounding each pixel, resulting in smooth image data and preserving sharp edges.

On-screen visual interpretation technique was used to prepare all the thematic layers. Geological map was prepared from Geological Survey of India (GSI) map and updated with satellite data. Survey of India (SOI) toposheets (1:50000) were used to map the drainage, road, habitation, river, railway line, waterbody, etc., and updated these maps with satellite images. Habitation map was classified into NC, PC and others habitation based on Rural Water Supply Programme (RWSP) classification scheme (RWSP, 2003).

Field survey

Field verification was carried out in the region in order to check the classification accuracy of various thematic maps. Thematic maps were evaluated with field data and collateral data sets. It was found that overall > 90% of accuracy was obtained. Few maps and class boundary were updated with field data. The well inventories were carried out including depth to water level, water level fluctuation, yields range, well type and other additional information for 121 wells through field survey. The depth to water level contour map was prepared based on field inventory data to understand the spatial variation of water level in this area (Figure 5). Yield chart was prepared using field information for understating GW movement with respect to hydro-geomorphic unit (Figure 6).

Overlay analysis

Thematic layers were analyzed and integrated in to ARC GIS 9.3 software platform. Linear probability-weightage (LPW) approach was applied for the thematic layers that is, geomorphology, geology and lineaments. LPW is a simple and straightforward method for determining the inter-class/inter-map dependency (Surabuddin et al., 2008). The efficacy of this method lies in that, where human decision can be incorporated in the analysis. A weight represents the relative importance of a parameter vis-à-vis the objective of the study (Abdel et al., 2008). Weightages were assigned for different

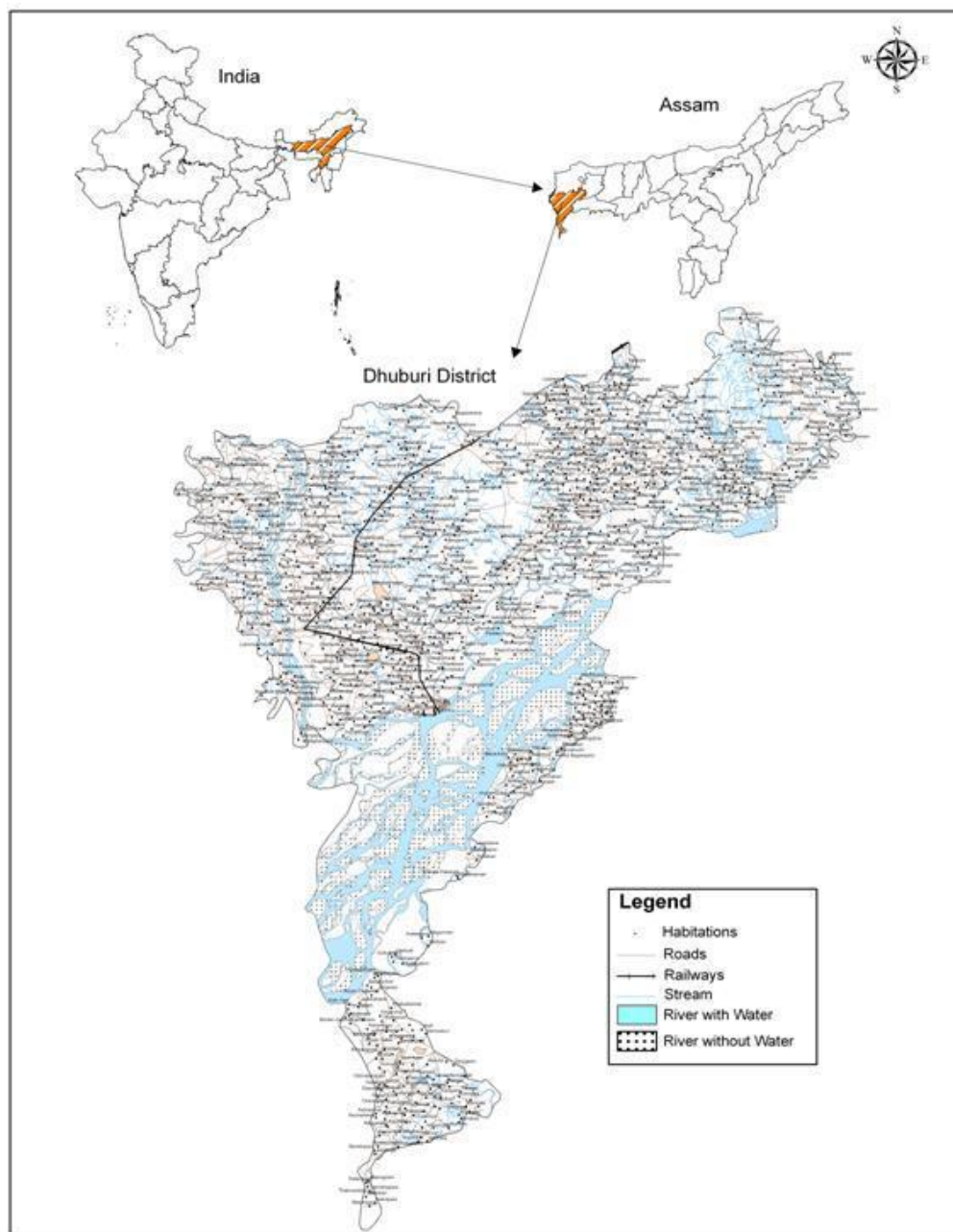


Figure 1. Study area.

themes on a scale of 1 to 5 based on their influence on the groundwater development (water holding capacity) (Tables 1 and 2). Thematic layers were transformed into user-friendly/common formats and integrated into GIS platform. GW resources were evaluated based on overlay analysis results and terrain parameters.

RESULT AND DISCUSSION

Hydro-geomorphologically, the area is divided into the following units: Alluvial Plain Older Deep (AOD), Alluvial Plain Younger Deep (AYD), Channel Islands (CI),

Channel Meandering (CM), Denudational Weathered Pediplain (DWP), Flood Plain Deep (FPD), Fracture Valley (FV), Natural Levees (NL), Inselberg (I), Valley Fill Shallow (VFS), Paleochannel (PC), Oxbow Lake (OL) and Residual Hill (RH). Figure 3 shows hydro-geomorphological map of the study area. These hydro-geomorphic units developed on various lithological units are presented in Table 3. Based on GW resource potentiality, the study area has been classified as excellent, very good, good, moderate and poor classes/zones.

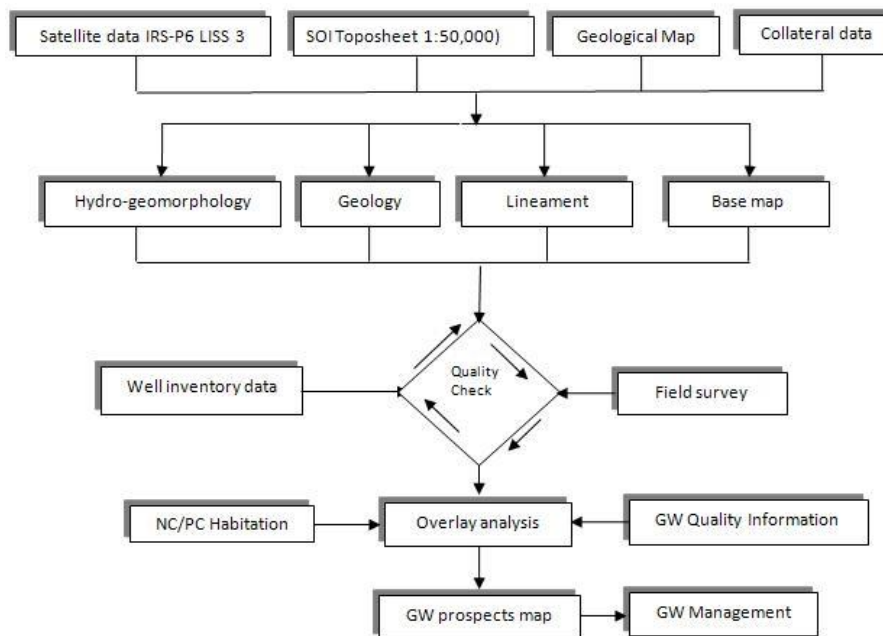


Figure 2. Methodology flow chart.

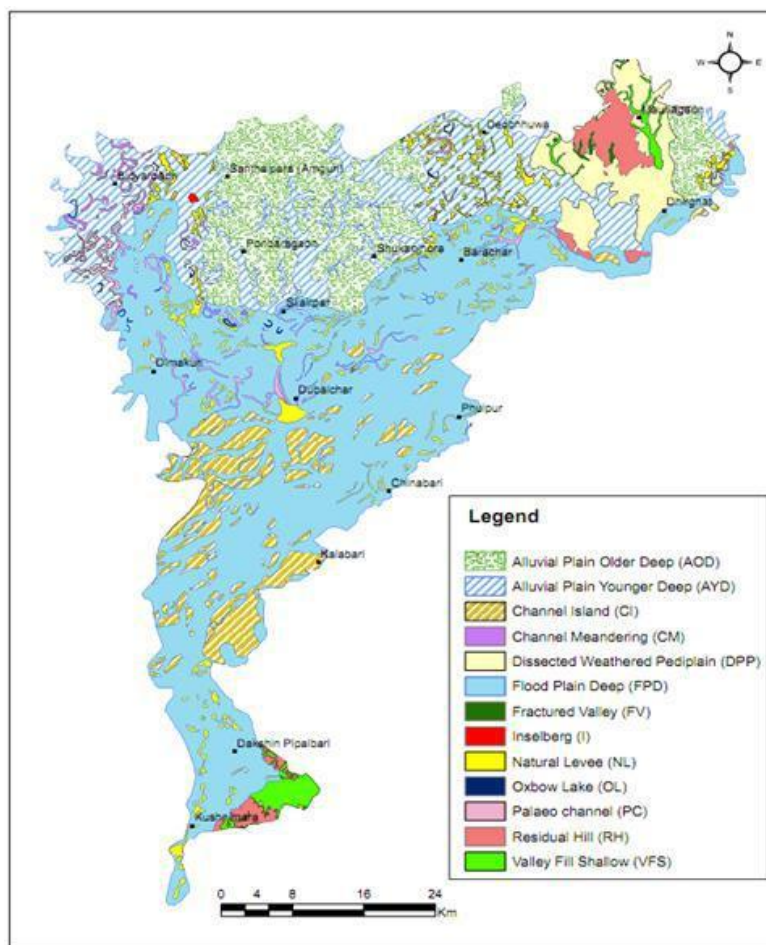


Figure 3. Hydro-geomorphology map.

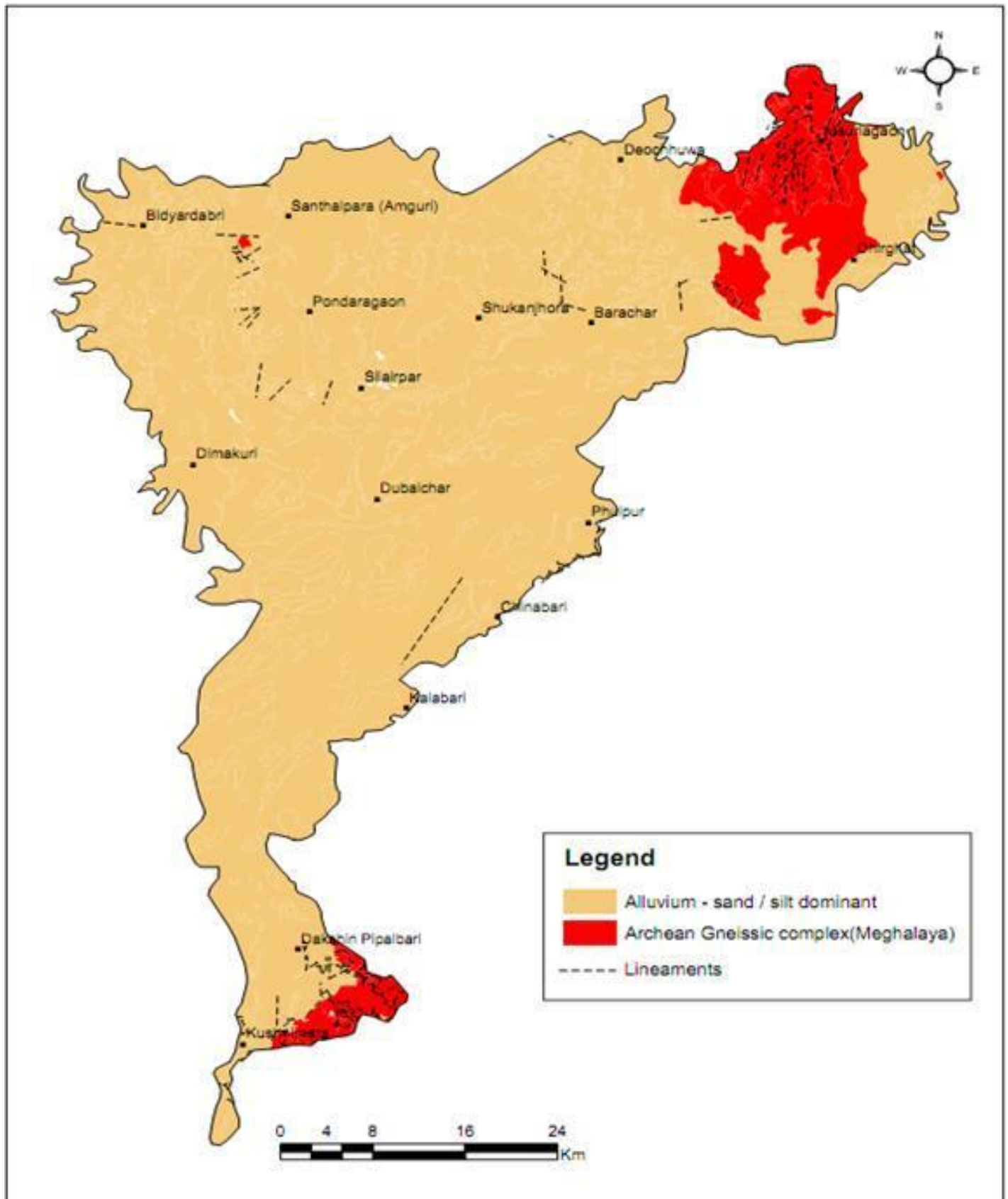


Figure 4. Geology and Lineaments Map.

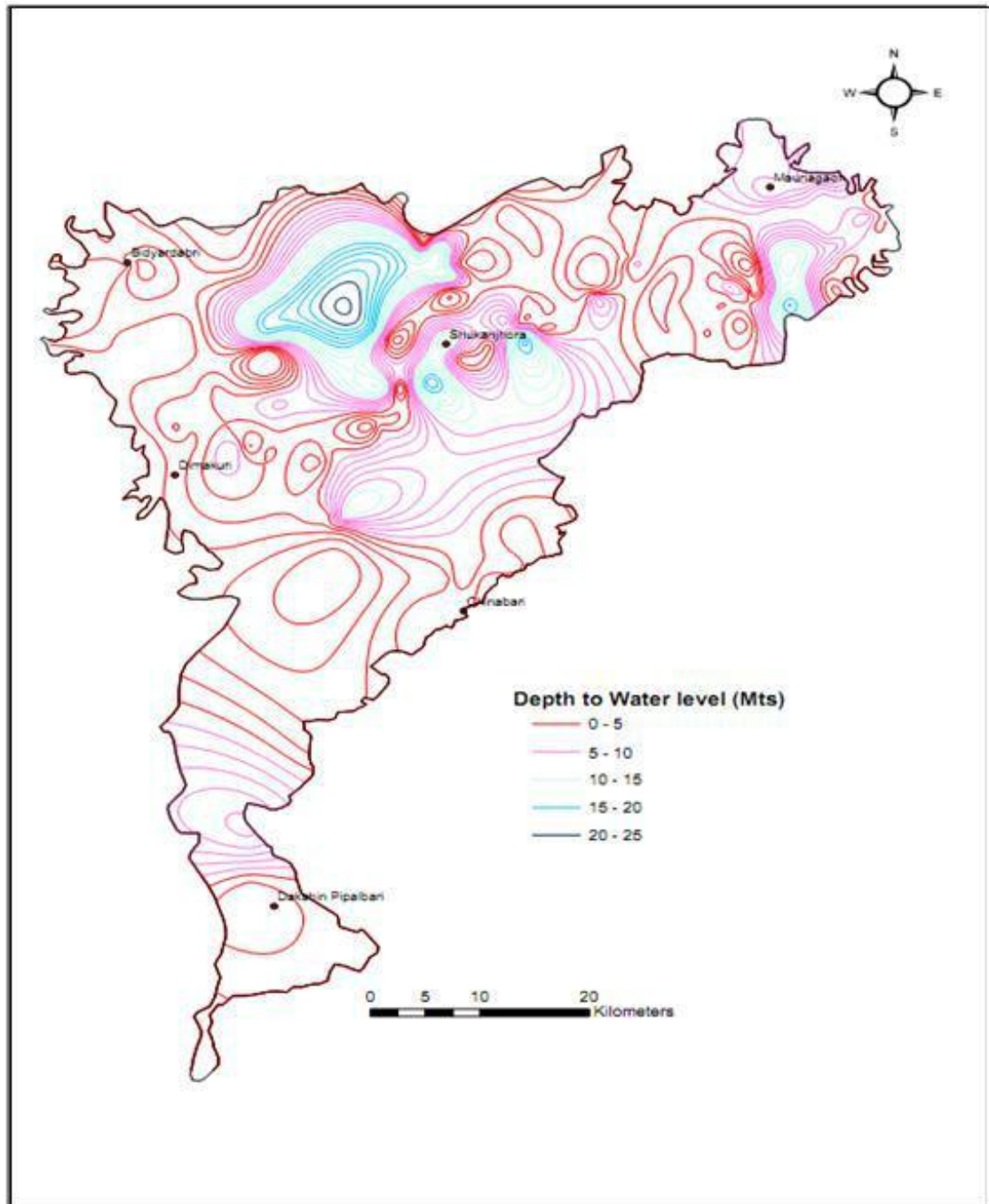


Figure 5. Depth to Water level contour map.

(Figure 8). The GW prospects and management for different hydrogeomorphic units were identified as follows.

Flood plain

Flood plain was extensively found on both sides of the

riverbank. It is a highly porous and permeable zone and thickness of the sediments is more than 20 m. In these units, the GW resources potential is categorized as excellent, and can be tapped through dug wells, ring wells and tube wells. The water table conditions are very shallow (~2 to 3 m) and yield of the well is very high (> 800 L/min - LPM). The appropriate quality of the GW/DW is found below ~6 m well depth. It is suggested

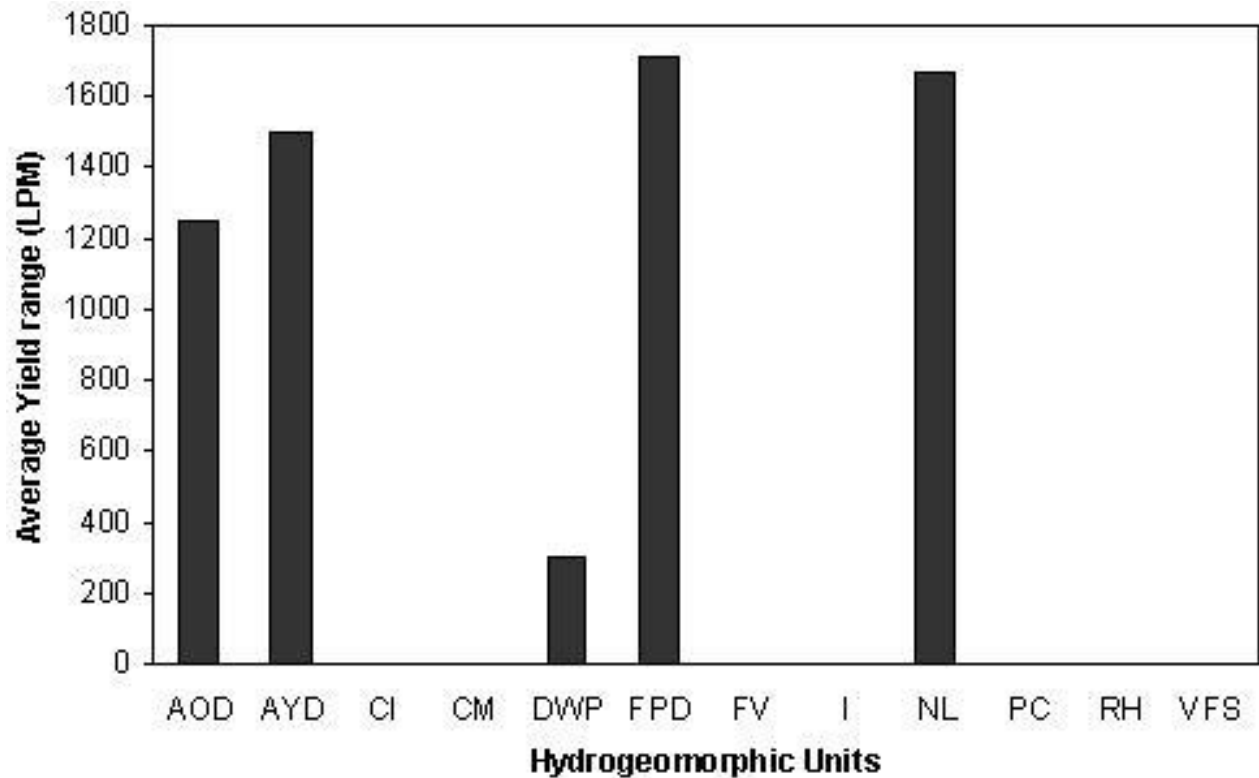


Figure 6. Hydro-geomorphic units vs Dug Well average Yield range (Well yield data are not available for CI, CM, FV, I, PC, RH & VFS).

Table 1. Weightage value given for GWP based on hydro-geomorphic units.

S. No.	Hydro-geomorphic units	Weightage given	GWP
1	AOD	4	Very Good
2	AYD	4	Very Good
3	CI	5	Excellent
4	CM	5	Excellent
5	DWP	2	Good
6	FPD	5	Excellent
7	FV	2	Good
8	I	1	Poor
9	NL	5	Excellent
11	PC	5	Excellent
12	RH	1	Poor
13	VFS	3	Good

Table 2. Weightage value given for lineaments.

S. No.	Lineaments	Weightage given	GWP
1	Presents	2	Good
2	Absents	1	Poor

that tube wells is suitable for extracting DW in this unit. Well-casing is required up to the loose sediments that is, ~3 m.

Alluvial plain younger deep

Younger Alluvial Plain Deep is identified in the northern part of the study area. It is packed with recent sediments that is, sand, silt, clay and gravel (Figure 9). The thickness of younger alluvium is more than 20 m at many places and varies with the configuration of the basement rock. Depth to water level varies from 3 to 6 m and yield range various from 600 to 800 LPM. GW resources potential is very good in this unit and GW can be tapped through shallow and deep wells. This study recommends that suitable depth of the dug wells is 7 to 10 m depth and tube wells as 10 to 20 m depth. Casing is required up to unconsolidated material that is 2 to 4 m from the ground surface.

Alluvial plain older deep

Alluvial Plain Older Deep is present in the topographically elevated region of the study area. It was observed that a deep reddish coloured soil is evolved over the older

Table 3. Hydro geomorphic units vis-à-vis lithostratigraphy of the study area.

Map unit	Hydro-geomorphic unit	Lithological unit	Description
FPD	Flood plain Deep	Sand, Silt and Clay	Alluvium deposited along the river / stream courses due to repeated flooding. Based on the thickness of alluvium, it is classified into 3 categories - 1) Shallow (0 to 10 m), 2) Moderate (10 to 20 m) and (3) Deep (>20 m).
AYD	Younger Alluvial plain Deep	Sand, Silt and Clay	Alluvium deposited along the river / stream courses due to repeated flooding. Based on the thickness of alluvium, it is classified into 3 categories - 1) Shallow (0 to 10 m), 2) Moderate (10 to 20 m) and (3) Deep (>20 m).
AOD	Older Alluvial plain Deep	Sand, Silt	Alluvium deposited along the river / stream courses due to repeated flooding. Based on the thickness of alluvium, it is classified into 3 categories - 1) Shallow (0 to 10 m), 2) Moderate (10 to 20 m) and (3) Deep (>20 m).
CI	Channel Island	Sand, Silt	Sand bar formed in the braided river course due to vertical accretion of the sediments.
DPP	Dissected Weathered Pediplain	Archaean, Gneissic, Complex (Meghalaya)	Gently undulating plain of large areal extent often dotted with inselbergs formed by the coalescence of several pediments. Based on the depth of weathering, weathered pediplains are classified into 3 categories - 1) Shallow (0 to 10 m), 2) Moderate (10 to 20 m), and 3) Deep (more than 20 m).
VF	Valley fill	Archaean, Gneissic, Complex (Meghalaya)	Valleys of different shapes and sizes occupied by valley fill material (partly detrital and partly weathered material). They are classified into 3 categories - 1) Shallow (0 to 10 m), 2) Moderate (10 to 20 m), and 3) Deep (more than 20 m).
FV	Fracture valley	Archaean, Gneissic, Complex (Meghalaya)	Narrow linear valleys formed along fracture / fault.
RH	Residual hill	Archaean, Gneissic, Complex (Meghalaya)	Relict hills which have undergone the process of denudation.
I	Inselberg	Archaean, Gneissic, Complex (Meghalaya)	Isolated hill, surrounded by plains on all sides.

geological formation (Figure 10). The thickness of the material is very high that is, more than 20 m and it comprises sand, gravel and silt with higher proportion of clay in this unit. This unit is mostly covered under thick vegetation cover. Depth to water table varies from 3 to 15 m and yield range varies from 400 to 600 LPM. GW prospects are very good in this unit and water can be extracted using deep dug and tube wells. It is recommended that to extract the GW, required depth of the dug wells is 8 to 15 m and tube well is 20 to 25 m. Well casing is required upto the loose sediments about 4 m in this unit.

Channel island

In this study area, many habitations are located on the Channel Islands. It is found in many locations that formed in the braided river course due to vertical accumulation of

the sand, silt, gravels and clay sediments. The GW table is very shallow in this unit and GW prospecting is excellent. Quality of the GW is considered good below 5 m depth. Tube well is suitable for this unit and well casing is required up-to the loose material.

Dissected weathered pediplain

This unit is characterized by the presence of a relatively thicker weathered material. It is classified as shallow dissected weathered pediplain. Depth of the weathered material was found to be 1 to 10 m in this unit. This unit was observed on the oldest rock type of Archaean-Gneissic complex with dominant forest cover. Weathering is not uniform throughout this unit; hence the GW prospects are moderate. Fracture/ fault zones present in the area provide moderate to good GW prospecting. Dug well 10 to 15 m depth and bore well >40 m depth are

feasible for this unit and casing is required up to loose weathered material (3 to 5 m). During well inventory survey, the well yield range was observed that 30 to 50 LPM and 60 to 100 LPM of dug and bore well respectively.

Valley fill

Valley fills are identified in between the hill ranges and are filled with pebbles, cobbles, gravel, sand and silt. It was found that the thickness of the sediments range about 4 m with surrounding/underlying weathered rocks. These units are found to have a good GW potential due to underlying weathered rocks. GW can be extracted in these units through ring well and dug-cum bore wells and well casing is required up to the loose weathered materials to avoid the well collapse.

Fracture valley

The unit is observed in the northeastern part of the area, which formed, on the Archaean Gneissic complex. They are identified along fractures and filled with colluvial deposits. The thickness of the valley fill material varies from 5 to 10 m. These units are highly favorable for GW occurrence and GW resource potential is categorized as a good GW zone. Bore wells are suitable for these units and depths of the wells vary between 30 to 40 m.

Residual hill

Residual hills of Archaean Gneissic complex are found in the southern and northeastern part of the area. They act as runoff zones and GW prospects are limited to narrow fractured controlled valley. GW resource potential is suitable for this unit.

Inselberg

These are isolated hills made up of Archaean Gneissic rocks with limited areal extension surrounded by low-level alluvial plain. They act as a runoff zone and GW potentiality is poor in this unit.

Lineaments

The lineaments' map is one of the important inputs to understand the GW resource availabilities in a hard rock terrain. The most obvious structural features that are important from the GW point of view are the lineaments. GW occurrence and movements are controlled by secondary porosity and permeability resulting from

folding, faulting, fracturing, etc (Dar et al., 2010).

The majority of the lineaments are present in the residual hills and dissected weathered pediplain, which are considered as moderate GW potential zones. The lineaments, which are mapped in fracture valley and valley fill sediments, are considered as good GW potential zones. The lineament map of the study area is shown in Figure 4.

Ground water quality management

The physical and chemical quality of GW is important in deciding its suitability for drinking purposes (CGWB, 2010). During well inventory, villagers have reported that the iron contamination in the water is high, which is also supported by many studies. Iron concentration has been documented to be above the permissible limits (1.00 Mg L^{-1}) in Dhubri region (CGWB, 2010; GBPIHED, 2010). Water containing iron does not show deleterious effect on human health, however, its presence in DW is objectionable for various reasons. Excessive iron content makes the hardness, water turbid, discolored and imparts an astringent taste to water (GBPIHED, 2010). As per the standards set by BIS, the permissible level of iron found in Dhubri region's DW is not considered to be suitable for drinking purposes (BIS, 2010). This study suggested that quality of GW can be explored and restrict the iron concentration in the unconsolidated formation using deep tube wells and deep ring wells with well casing (Bamboo, Cement, Iron coated pipe, etc.). Casings are essential upto the loose sediments (Table 4).

CONCLUSIONS AND RECOMMENDATIONS

Remote sensing and GIS technology are powerful tools and aided us to improve our understanding of GW system in this area. GW resource potential of the area has been categorized as poor, good, very good and excellent (Figure 8.). Table 4 shows depth to water level, yield, well type and GW extraction methods at various hydro-geomorphic units. The average depth to water level varies from ~3 to 15 m. However, in the dissected weather pediplain, residual hill and older alluvial plain are with deeper GW level. In the greater part of the flood plain and channel island areas, the water level rests around 3 m from land surface. Based on the available well inventory data, the highest yield ($> 800 \text{ LPM}$) was identified in the FPD, NL, AYD, AOD and poor yield ($< 200 \text{ LPM}$) was in the dissected weathered pediplain, near inselberg complex, etc. The majority of the NC/PC/Other habitations fall in the FPD, AYD and NL units (Figure 7). These units are categorized as excellent to very good GW resource potential zones. In this study area, GW can be explored through shallow and deep tube wells. The well casing is necessary upto the loose sediments due to

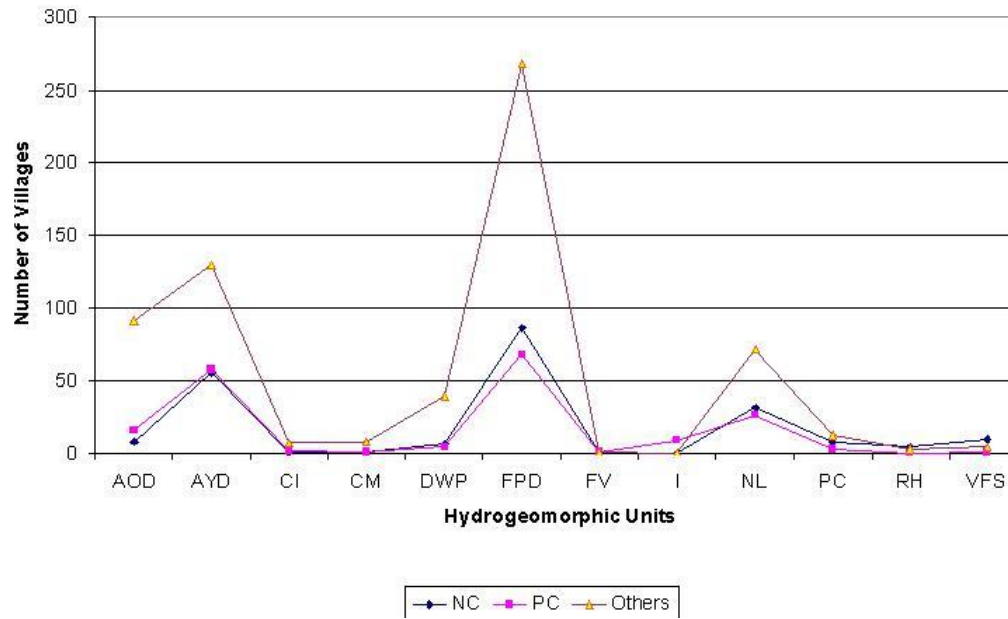


Figure 7. Hydro-geomorphic units vs NC/PC/Other habitations.

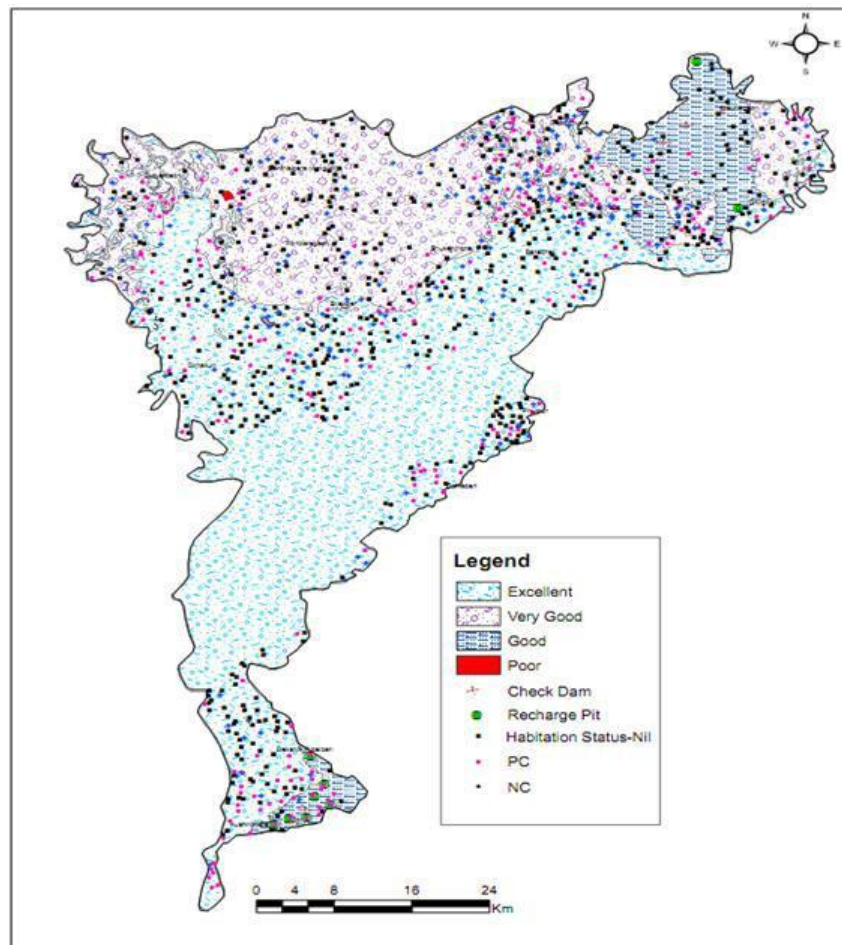


Figure. 8. Groundwater potential zone map.



Figure 9. Younger Alluvial Plain.



Figure 10. Older Alluvial Plain.

Table 4. GW extraction methods at various hydro-geomorphic units.

S. No.	Hydro-geomorphic unit	Depth to water level-surveyed (m)	Yield range surveyed (Lpm)	Well type (Suggestion)	Depth of well (for new constructing) (Suggestion) (m)	Well casing depth (Suggestion) (m)
1	Flood plain Deep	2-4	>800	TW	>6	~3
2	Younger Alluvial plain Deep	3-5	600-800	RW/TW	7-10 / 10-20	3-4
3	Older Alluvial plain Deep	3-15	400-600	RW/TW	8-15/20-25	2-4
4	Channel Island	2-3	>800	TW	>5	~4
5	Dissected Weathered Pediplain	5-10	60-100	RW/BW	10-15/>40	3-5
6	Valley fill	4-10	150-200	RW/BW	5-8/30-40	<5
8	Fracture valley	-		BW	30-40	>4
9	Residual hill	-		BW	>40	>3

loosely packed Quaternary sediments. It controls the GW contamination and avoids the well collapse due to the loose sediments. In the dissected weathered pediplain zone, GW can be harnessed by constructing large diameter dug well and bore well at structurally weak zones.

Water harvesting structures have been suggested for augmenting GW based on the characterization of channel confluence, lineament intersections, geology and hydro-geomorphic unit. Recharge structure types such as recharge-pits and check-dams have been suggested in the southeast of Brahmaputra river, particularly in Manjuri, Murchhi, Damalkona, Banshli, Gopalpur, Puthimari, Pankata, Kodaldhoo, Kalapara, Pushkarnipara, Dobajani, Tikasali, Kushnimara and Pokrapara villages and also in the northeastern side of Brahmaputra river that is, near Mauriagaon village (Figure 8). This research output may serve as a preliminary input as baseline information that may express future GW mapping, management and water quality assessment studies with respect to climate change scenario in the study area. Future work will focus on coupled groundwater-climate change modeling for quantitative GW resource zonations

(micro scale) and its impact assessment to expand the present work.

ACKNOWLEDGEMENTS

This work was supported by NRSC, ISRO, Dept. of Space, under the programme of RGNDWM. Authors of C-DAC are thankful to SK Srivastava, AD and HOD - GSGD, C-DAC for his encouragement and Biju, Asima and Bishwarup, GSDG, C-DAC for GIS data QC. The authors also express their gratitude to A. Bhattacharyya, Former DD-AA, NRSC for his suggestion at various stages in preparing thematic layers. The authors also express their gratitude to P Phukan, Gauhati University, Assam for his valuable suggestion and KK Sharma, Kuntala and Somerjeet Sing, NE-SAC, Shillong for their various levels of support. The help extended by Upasana, GSDG, C-DAC for thematic layers QC and her valuable comments to improve the manuscript is greatly acknowledge. Thanks are also due to members of GSDG, C-DAC, for their moral support. Last but not the least authors are grateful to the anonymous reviewers for their

constructive comments which helped to improve the manuscript.

REFERENCES

- Abdel A, Omran KA (2008). Integration of Remote Sensing, Geophysics and GIS to Evaluate Groundwater Potentiality – A Case Study In Sohag Region, Egypt. The 3rd International Conference on Water Resources and Arid Environments and the 1st Arab Water Forum. <http://faculty.ksu.edu.sa/72005/Papers%20of%20Interest%20Remote%20Sensing/Integration%20of%20Remote%20Sensing,%20Geophysics%20and%20Gis.pdf>. (Accessed July 2012).
- AGT (2011). Recommendations for State of Assam's Strategy and Action Plan on Climate Change. A report by Climate Cell, Environment Division Assam Science Technology & Environment Council, Bigyan Bhawan, GS Road, Guwahati-781005. <http://www.indiawaterportal.org> (Accessed August 2012).
- Anbazhagan S, Subramanian SK, YANG X (2011). Geoinformatics in Applied Geomorphology. CRC Publisher. ISBN-13:978-1439830482.
- BIS (2010). Drinking Water Quality Standards. Available online at: <http://www.bis.org.in/> (Accessed December 2010).
- Carver SJ (1991). Integrating multicriteria evaluation with geographical information systems. Int. J. Geogr. Inf. Syst. 5:321-339.

- CGWB (2010). Ground Water Quality in shallow aquifers. http://cgwb.gov.in/documents/Waterquality/GW_Quality_in_shallow_aquifers.pdf (Accessed December 2010).
- Dar MA, Sankar K, Dar IA (2010). GW prospects evaluation-based on hydrogeomorphological mapping: A case study in Kancheepuram district, Tamil Nadu. *Indian J. Rem. Sens.* 38(2):333-343.
- DDWS (2008). NCPH Habitation. http://ddws.nic.in/data_bank.html 2003 as on March 2008 (Accessed December 2010).
- GBPIHED (2010). Available online at: http://gbpihed.gov.in/envis/HTML/vol16_1/A.K.%20Singh.pdf (Accessed December 2010).
- Ghosh S, Raje D, Mujumdar PP (2010). Mahanadi streamflow: Climate change impact assessment and adaptive strategies. 98(8):1084-1091. http://www.currentscience.ac.in/Downloads/article_45295.pdf (Accessed August 2012).
- Gosain AK, Rao S, Arora A (2011). Climate change impact assessment of water resources of India. 101(3):356-371. <http://www.currentscience.ac.in/Volumes/101/03/0356.pdf> (Accessed August 2012).
- IPCC (2007). Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jaiswal RK, Mukherjee S, Krishnamurthy J, Saxena R (2003). Role of remote sensing and GIS techniques for generation of GW prospect zones towards rural development: An approach. *Int. J. Rem. Sens.* 24(5):993-1008.
- Jha BM, Sinha SK (2009). Asian Regional Conference of INCID, special session on Ground water, New Delhi. <http://cgwb.gov.in/documents/papers/incidpapers/Paper%201-B.M.Jha.pdf> (Accessed December 2010).
- Khurana I, Romit S (2008). DW quality in rural India- Issues and approaches. http://www.wateraid.org/documents/plugin_documents/drinking_water.pdf (Accessed June 2012).
- Mitra AK (2009). Water Resources of North East- Its Management and Conservation, ENVIS Newsletter, issue October – December pp. 1-7.
- Mridul C, Hari PS, Saumen B, Lokendra S, Jaydev D (2010). Use of surface water for drinking purpose in Golaghat district of Assam, India. *Int. J. Chem. Technol. Res.* 2(1):269-277.
- Mohanty C, Behera SC (2010). Integrated remote sensing and GIS study for hydrogeomorphological mapping and delineation of GW potential zones in Khallikote block, Ganjam district, Orissa. *Indian J. Rem. Sens.* 17(10):345-354.
- National Remote Sensing Agency (NRSA) (2007). Ground Water Prospects mapping using Remote Sensing and Geographic Information System, Rajiv Gandhi National DW Mission Project, Manual.
- Radhakrishnan K (2008). Major Thrust Areas of Remote Sensing and GIS Applications in Geosciences – An Overview. *J. Geol. Soc. India.* 71(2):153-170.
- Rakesh K, Singh RD, Sharma KD (2005). Water Resources of India. *Curr. Sci.* 89(5):794-811.
- Reddy PR, Vinod Kumar K, Seshadri K (1996). Use of IRS-1C data in GW studies. *Curr. Sci.* 70(7):600-605.
- Rural Water Supply Guidelines (RWSP) (2003). Rural Water Supply Guidelines, revised and updated second edition, Rural Water Supply, Archives. http://ddws.gov.in/popups/Guidelines_RWS_2003.pdf (Accessed September 2010).
- Sahai B, Battacharya A, Hegde (2005). IRS-1A Application for Groundwater Targeting, *Curr. Sci.* 61(3&4):172-179.
- SDMASSAM (2010). Available online at: http://sdmassam.nic.in/download/districtplan_dhubri.pdf (Accessed December 2010).
- Simonovic SP (2010). A new methodology for the assessment of climate change impact on a watershed scale. *Curr. Sci.* 98(8):1047-1055. http://www.currentscience.ac.in/Downloads/article_45290.pdf (Accessed August 2012).
- Sivakumar V (2013). Climate Change Impact: The Need of Eco-Earth Stewardship in India. *Int. J. Curr. Res. Rev.* 5(2):27-27. www.scopemed.org/?mno=33779. (Accessed March 2013).
- Stoll S, Hendricks FHJ, Butts M, Kinzelbach W (2011). Analysis of the impact of climate change on groundwater related hydrological fluxes: A multi-model approach including different downscaling methods. *Hydrol. Earth Syst. Sci.* 15:21-38. <http://www.hydrol-earth-syst-sci.net/15/21/2011/hess-15-21-2011.pdf>. (Accessed August 2012).
- Subramanian SK, Seshadri K (2010). Groundwater - Remote Sensing Applications. NRSC e-books, Chapter 8:203-215. (Editor: P.S.Roy, et al. NRSC-ISRO, Hyderabad). Available online at: http://www.nrsc.gov.in/assets/doc/ebooks/Chap_8_GroundWr.pdf (Accessed June 2012).
- Surabuddin MD, Mondal, Pandey AC, Garg RD (2008). Groundwater Prospects Evaluation based on Hydrogeomorphological Mapping using High Resolution Satellite Images: A Case Study in Uttarakhand. *J. Indian Soc. Rem. Sens.* 36(1):69-76.
- Treidel H, Martin-Bordes JJ, Gurdak JJ (Eds.) (2011). Climate change effects on groundwater resources: A global synthesis of findings and recommendations. International Association of Hydrogeologists (IAH) – International Contributions to Hydrogeology. Taylor & Francis publishing, p. 414.
- WHOINDIA (2010). Water Quality in India. http://www.WHOINDIA.org/LinkFiles/SDE-Workshop_Water_Quality_In_India_MOH.pdf (Accessed December 2011).
- WHO (2006). Available online at: http://www.who.int/water_sanitation_health/monitoring/jmpfinal.pdf (Accessed December 2011).

