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Spatial Assessment of Groundwater Over-exploitation in Northwestern Districts of Bangladesh

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Abstract: Groundwater demand in northwestern districts of Bangladesh is increasing rapidly with the growth of population and the expansion of irrigated agriculture. Development and management of groundwater resources are essential to supply the growing population with sufficient water for economic development as well as for the sustainable environment of the region. In the present study, groundwater recharge-abstraction balance method has been used for the spatial assessment of groundwater development potential. The abstraction of groundwater is estimated from irrigation and domestic water demands in the study area. The net recharge calculated from groundwater table fluctuation data, whereas the abstraction of groundwater is estimated from irrigation and domestic water demands in the study area. The study shows that out of twenty-six sub-districts, groundwater exploitation has reached to a critical condition in fourteen sub-districts. Development of surface water resources and water conservation are essential to reduce the stress on groundwater exploitation.

Keywords: Groundwater recharge, Groundwater development potential, Geographical Information System, Over exploitation, Bangladesh.

INTRODUCTION

Groundwater contributes to over 75% of the total consumptive uses of water in Bangladesh (Bhatti, 2002). Highly productive aquifers, near surface groundwater table, unconsolidated sediment, and easy to drill by hand to install tube-wells for groundwater exploration have made the groundwater as an attractive source in the northwestern districts, like many other parts of the country. Low river flow due to huge withdrawal of water in the upstream of Ganges river and high incidence of droughts due to unreliable rainfall also leads to high dependency on groundwater in the area. The National Water Policy of the government of Bangladesh encouraged groundwater development for irrigation both in the public and private sectors (Master Planning Organization, 1987, 1991; Water Resources Planning Organization, 2004). The poverty alleviation program of the government through the introduction of special groundwater-based irrigation project implemented through the Barind Multi-purpose Development Authority (BMDA) has accelerated the use of groundwater in the area in recent years (Faisal et al., 2005; Shahid and Hazarika, 2010).

Population of Bangladesh is growing by two million every year and may increase by another 24 million over the next 12 years. The country will require about 4.5 million tons of more rice to feed the increased population by 2020. A large portion of this increased production is expected to come from expansion of irrigated agriculture. From the present trend it is anticipated that the water required for irrigation will come from groundwater. Therefore, management of groundwater resource is essential in order to ensure sustainable supply of water in ever expanding irrigated land. The present study has been carried out to identify potential zones which are still to be developed to meet the growing water demands.

Groundwater in the study area is mainly used in irrigation of High Yield Variety (HYV) *Boro* rice fields during dry season as well as for domestic water supply throughout the year (Banglapedia, 2003; Shahid, 2011). So, water requirements for *Boro* rice field for irrigation and domestic consumption together is the total groundwater demand or total abstraction of groundwater in the study area. Spatial distribution of irrigation water requirements is calculated by using FAO-56 model (Allen et al., 1998) in a Geographical Information System (GIS). Soil map and long-term average climate data are used for this purpose. Spatial distribution of domestic water demand is calculated from population data at sub-district level. The volume of groundwater recharge is calculated by using water table fluctuation method (Rasmussen and Andreasen, 1959). The groundwater development potential zones are identified by comparing sub-district level maps of volumetric groundwater abstraction and groundwater recharge on GIS.

DESCRIPTION OF THE STUDY AREA

The study area comprises twenty-six upazillas (sub-districts) of northwest Bangladesh (Fig.1) covering approximately an area of 7625 km^2. The topography of the area is dome shaped with undulatory relief with elevation ranging from 15-45 m above the mean sea level. The dome shaped area of Pleistocene sediments is called as Barind tracts. The Barind tracts and surrounding areas underlie younger alluvial sediment at depths of 150–200 m or more (British Geological Survey and Department of Public Health Engineering, 2001). A number of hydrogeological studies have been carried out in the area (Jahan et al., 1994; Shwets et al., 1995; Jahan and Ahmed, 1997; Begum et al., 1997; Haque et al., 2000; Islam and Kanungoe, 2005; Faisal et al., 2005; Asad-uz-zaman and Rushton, 2006) which shows that upper aquifer in the region is unconfined to semi-confined in nature and that the thickness of exploitable aquifer ranges from 10m to 40m. The maximum depth to groundwater table from surface varies from 7m to 30m.

Climatically, the study area belongs to sub-humid zone with annual average rainfall between 1400 mm and 1800 mm (Shahid and Khairulmaini, 2009) and its seasonal distribution shows that almost 95% rainfalls occur during May to October (Shahid, 2010). Drought is a common phenomenon in the region (Shahid, 2008; Shahid and Behrawan, 2008). The economy of the area is mostly agro-based and about 84% population directly or indirectly depends on agriculture.

METHODOLOGY

Groundwater recharge-abstraction balance method is

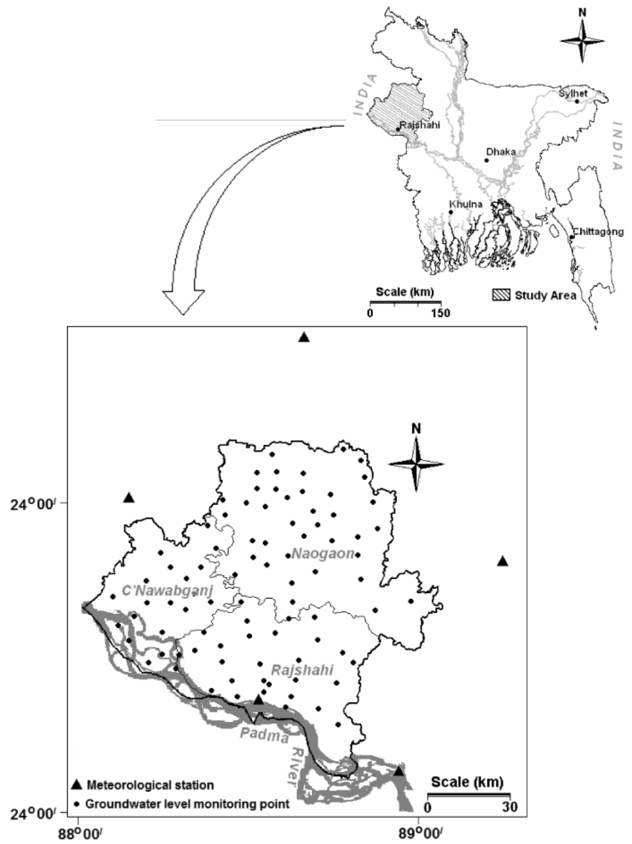

Fig.1. Location of the study area in Bangladesh.

used in the present study for the identification of potential zone for groundwater development. If groundwater abstraction in an area exceeds the net groundwater recharge, then it is considered as overexploitation. On the contrary if groundwater exploration is far less than the net recharge, then the area has development potential for groundwater resources. Total abstraction of groundwater is estimated from groundwater demands in the study area. Groundwater in study area is mainly used for irrigation of *Boro* rice cultivation in dry season and for domestic drinking. Therefore, in the present study groundwater requirements in dry season are estimated to get the total abstraction of groundwater resources. Details of the methods used for the calculation of water demands and groundwater recharge are discussed below.

FAO model (Brouwer and Heibloem, 1986) is used for the computation of water demand for irrigation. According to this model total irrigation water requirements can be calculated as,

$$W_{irr} = ET_{crop} + W_{lp} + W_{ps} + W_l - P_e \quad (1)$$

where, W_{irr} – Irrigation water requirements; ET_{crop} - Crop evapotranspiration; W_{lp} – Water for land preparation; W_{ps} – Percolation and seepage losses; W_l – Water to establish 'water layer'; P_e – Effective precipitation.

Evapotranspiration from crop is calculated as,

$$ET_{crop} = EC \times ET_{ref} \quad (2)$$

where, EC is the crop coefficient, and ET_{ref} is the reference evapotranspiration.

Penman-Monteith method is used to calculate the reference evapotranspiration. Due to lack of lysimeter data it is very difficult to compute the actual value of crop coefficient of *Boro* rice in the study area. In the present study, actual evapotranspiration data collected in an experimental field is used for the computation of crop-coefficient of *Boro* rice. Water required for land preparation is calculated from soil moisture deficiency data. The soil moisture deficiency is calculated using Thornthwaite's soil water balance method by comparing the water supply with the climatic demand for water (Komuscu et al., 1998). The amount of water required to replenish the soil moisture in the month of rice transplantation is considered as the water required for land preparation in the study area. Total water losses through percolation and seepage from the rice fields are calculated from soil data.

Following the FAO-56 method, the percolation and seepage losses for a sandy soil, clayey soil and loam soil are calculated which are 8, 4 and 6 mm/day respectively. Effective precipitation (P_e) is computed from Brouwer and Heibloem (1986) as:

$$P_e = 0.8\,P - 25 \text{ if Precipitation} > 75 \text{ mm/month}$$
$$0.6\,P - 25 \text{ if Precipitation} < 75 \text{ mm/month} \quad (3)$$

For the better yield of paddy, 50 to 70 mm standing water in the field is required during the growing stages of rice. In the present study 50 mm of water has been considered for establishing water layer in the paddy field throughout the study area.

For northwestern part of Bangladesh, the total length of HYV *Boro* rice growth period is 145 days (Mahmood, 1997) and the phenology of HYV *Boro* rice is given in Table 1. In the present study, irrigation water demands at different stages of *Boro* rice i.e., for 125 days is computed for the estimation of total irrigation water demand.

Sub-district scale map of domestic water use in the study area is prepared using equation:

$$W_{dom} = 365.4 \times Pop \times W_{pcw} \quad (4)$$

Where, W_{dom} - domestic water requirements; Pop - total population in a sub-district; W_{pcw} - per capita daily water requirement.

In the present study, 46 liter or 0.046 m^3 is considered as per capita daily water requirement as proposed by United Nations Development Program (2006) for Bangladesh. According to Banglapedia (2003) about 95% of domestic water supply in the study area comes from groundwater. Therefore, the total abstraction of groundwater in the study area is calculated as:

Table 1. Phenology of Boro rice in northwestern Bangladesh (after Mahmood, 1997)

Stage s(days)					
Initial	Vegetative	Flowering	Maturing	Total	Irrigation Days
25	60	40	20	145	125

$$GW_{total} = W_{irr} + (0.95 \times W_{dom}) \quad (5)$$

Groundwater recharge can be computed by various methods such as empirical methods, hydrological budgeting methods, water table fluctuations, etc. (Kasenow, 1997; Crosbie et al., 2005; Risser et al. 2005; Delin et al., 2007). In the present paper, water table fluctuation (WTF) or change in groundwater storage method is used for the estimation of net groundwater recharge. Agriculture in the study area during monsoon months mainly depends on rainfall, groundwater extraction is very negligible compared to dry season. It is assumed that sub-surface inflow and outflow is equal and uniformly distributed over the area.

WTF can reliably quantify groundwater recharge in alluvial sandy aquifer with shallow depth of water table (Koo and Lee, 2002). As the aquifer in the study area is unconfined and groundwater depth is very shallow, hence this method can give a reliable estimation of net groundwater recharge. The method is widely used in Indian subcontinent for groundwater recharge estimation (Sinha, 1988). In WTF method, groundwater recharge is estimated from the water-level rise in a well multiplied by the specific yield of the formation in the zone of fluctuation (Rasmussen and Andreasen, 1959). The recharge can be expressed by following relationship:

$$R = \Delta h \times S_y \quad (6)$$

Where, R is groundwater recharge; Δh is the change in water level; and S_y is the specific yield of the formation in the zone of fluctuation.

The specific yields recommended by Johnson (1967) for various geological formations of the study area (given in Table 2) are used in the present study for the computation of groundwater recharge.

Average HYV *Boro* rice cultivated area during the period 2008-2010 in northwestern districts of Bangladesh obtained from agriculture census data (Bangladesh Bureau of Statistics, 2011) is used in the present study for the

Table 2. Values of specific yield used for the estimation of groundwater recharge (after Johnson, 1967)

Geological Formation	Specific Yield (%)
Clay	3.0
Sandy Clay/Silt	8.0
Very find sand	20.0
Fine sand	23.0
Fine medium sand	25.0
Medium sand	28.0
Medium coarse sand	27.5
Coarse sand	27.0
Gravel fine	25.0
Gravel Medium	24.0
Gravel Coarse	23.0

calculation of water requirement for irrigation. Sub-district level population data is obtained from population census report 2011 (Bangladesh Bureau of Statistics, 2012) for the calculation of water demand for household. Long term averaged monthly climate data (1971-2010) at five stations situated in and around the study area is used for the mapping of effective rainfall and potential evapotranspiration during the irrigation period. Soil map of Soil Resources Development Institute of Bangladesh is used for the computation of seepage and percolation losses through the paddy field.

The network of water level monitoring stations in space needs to be adequate to smoothen the inconsistencies in observations which may arise due to varied hydrogeological and other factors. In the present study, 15-day averaged groundwater table fluctuation data for the time period 1998-2002 collected at 69 monitoring wells distributed over the study area and the lithological information of the wells are used for the calculation of groundwater recharge. Location of groundwater monitoring wells is shown by points in the location map of the study area (Fig.1). For the mapping of spatial extents from point data, kriging interpolation method (Isaaks and Srivastava, 1989) is used.

RESULTS AND DISCUSSION

Spatial Assessment of Groundwater Abstraction

Sub-district wise HYV *Boro* rice cultivated region in the study area as obtained from agriculture census data, is shown in Fig.2 where its density is higher in north-eastern part that comprise more than 80% of the cultivated area.

The deficiency of soil moisture in the area at the end of December is computed from soil moisture holding capacity (MHC) of different soil groups by Thornthwaite Water Balance Method considering that land is prepared at the end of December for the cultivation of *Boro* rice in January. The maps of land preparation, percolation and seepage losses, evapotranspiration, effective precipitation and water required for establishing water layer are integrated step by step using the Union tool of ArcMap 9.2. The irrigation water requirement in each polygon of the integrated layer is calculated by using equation (1). Polygons are classified according to the water requirement values to prepare the map of irrigation water requirement for HYV *Boro* rice in the area (Fig.3a) which shows water demand for irrigation varies between 900 mm and 1150 mm with an average value of 1035 mm. The water demand for irrigation is lowest (» 900 mm) in the eastern part with mainly clayey soil that prevents rapid percolation and seepage losses through the paddy field and precipitation is also higher than in other parts.

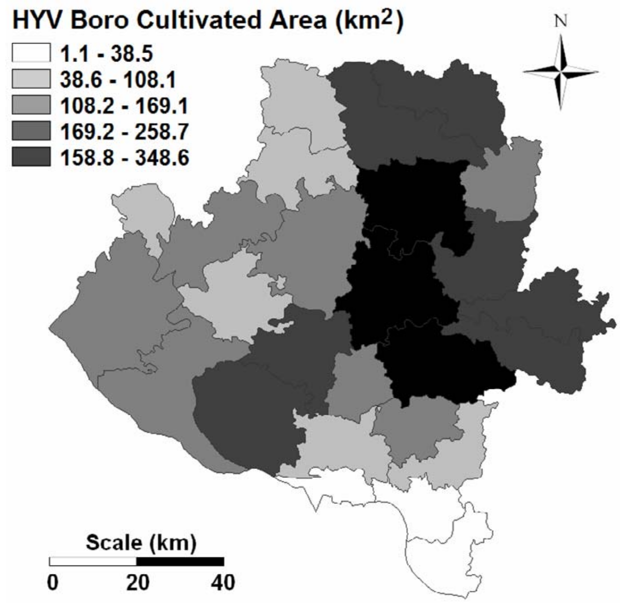

Fig.2. Sub-district wise *Boro* rice cultivated area.

The irrigation water requirement map is prepared by using Region Wide Overlay or "Cookie Cutter Approach" (Institute of Water Research, 1996) on a GIS. Finally, the irrigation water requirement map is multiplied by *Boro* rice cultivated area to get the sub-district scale map showing volume of water used for irrigation Fig 3(b).

Spatial distribution of population in the study area (see Fig.4a) is used to calculate the sub-district level volumetric domestic water demand using equation (5). Figure 4b which shows that the domestic water demand varies from 1.7 million-m^3 to 14.3 million-m^3. Total volume of groundwater used in each sub-district computed by using equation (6) where 96.3% of total exploited groundwater is used for irrigation and the rest for domestic purposes.

Spatial Assessment of Groundwater Recharge

Groundwater attains maximum level in the mid or end

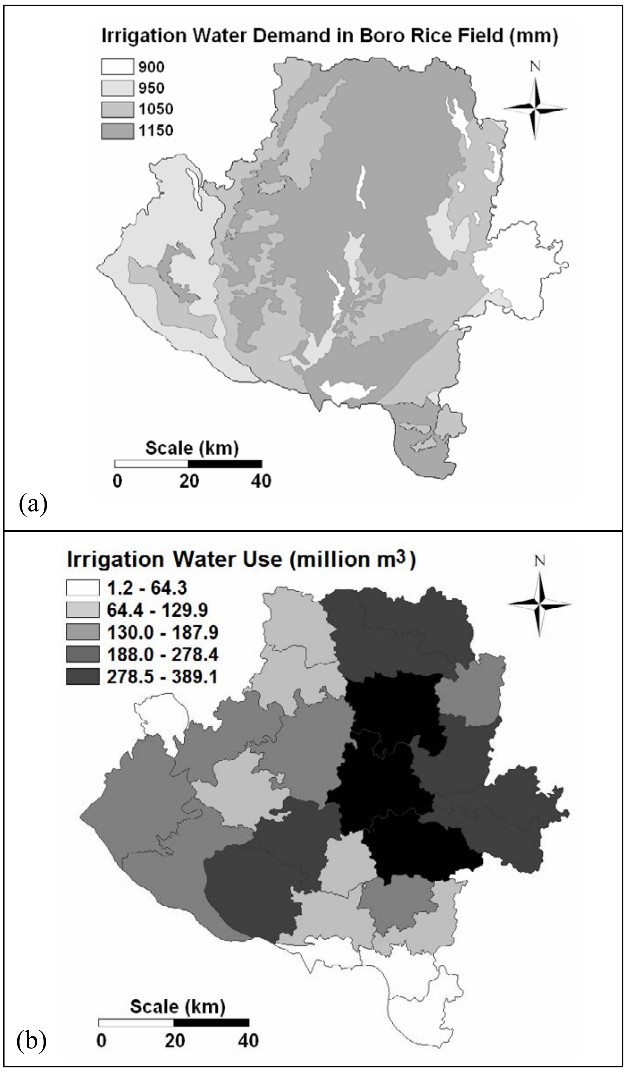

Fig.3. (a) Irrigation water demand in HYV Boro rice field in northwestern Bangladesh. **(b)** Sub-district wise volumetric irrigation water use in the study area.

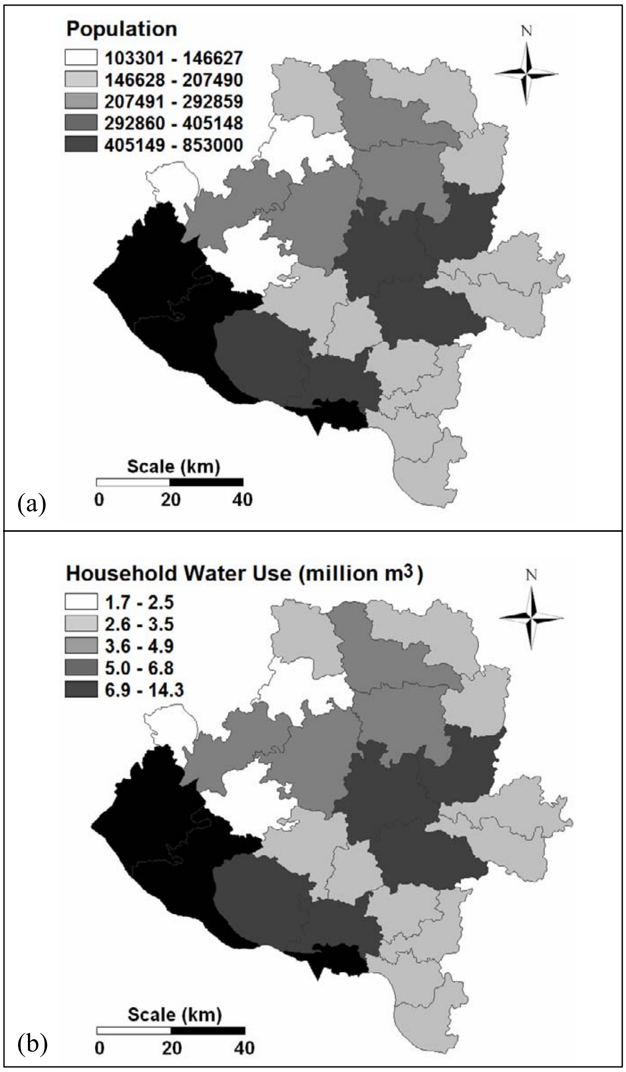

Fig.4. (a) Distribution of population in the study area. **(b)** Sub-district level map of volumetric water used for domestic purposes in the study area.

of October and minimum in the beginning or mid of May. In the present study, total recharge is estimated form five years (1998-2002) 15-day groundwater hydrographs. The average water table fluctuation is measured from the difference between pre-recharge (beginning or mid of May) average minimum water level to post-recharge (mid or end of October) average maximum water level. Groundwater recharge estimated at different points of the study area is krigged to prepare the groundwater recharge map (Fig.6a) and varies between 320 mm and 890 mm with an average value of 510 mm. Sub-district wise groundwater recharge is computed using region wide overlay method and then volumetric groundwater recharge map is prepared by multiplying the area of sub-district as shown in Fig. 6(b).

Identification of Groundwater Development Potential Zone

Groundwater abstraction is compared with groundwater recharge for identification of potential zones for groundwater development in the study area. The integrated groundwater abstraction and recharge map is shown in Fig.7 and is classified according to groundwater abstraction as: (a) less than 10 million-m^3 that of groundwater recharges and (b) higher than groundwater recharges. It reveals groundwater abstraction is far less than groundwater recharge in the western part of the study area. So, development of groundwater resources is still possible in large portion of the area. But groundwater abstraction in the remaining portion, in general, has exceeded the recharge hence, over-exploitation is going on. Development of surface water resources is essential in general to reduce the growing

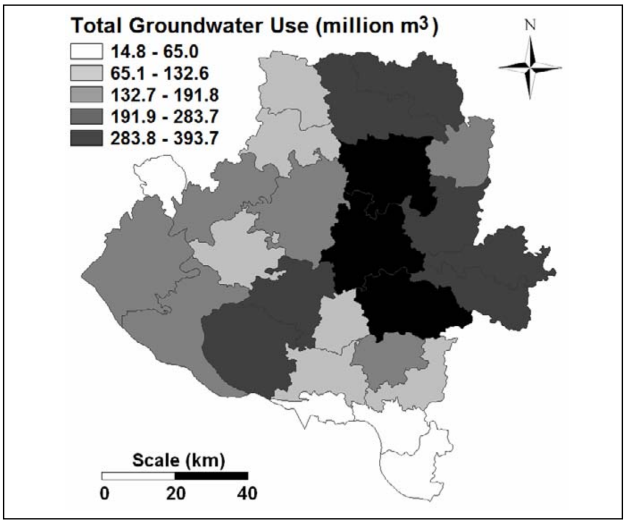

Fig.5. Sub-district wise volumetric groundwater use in the study area.

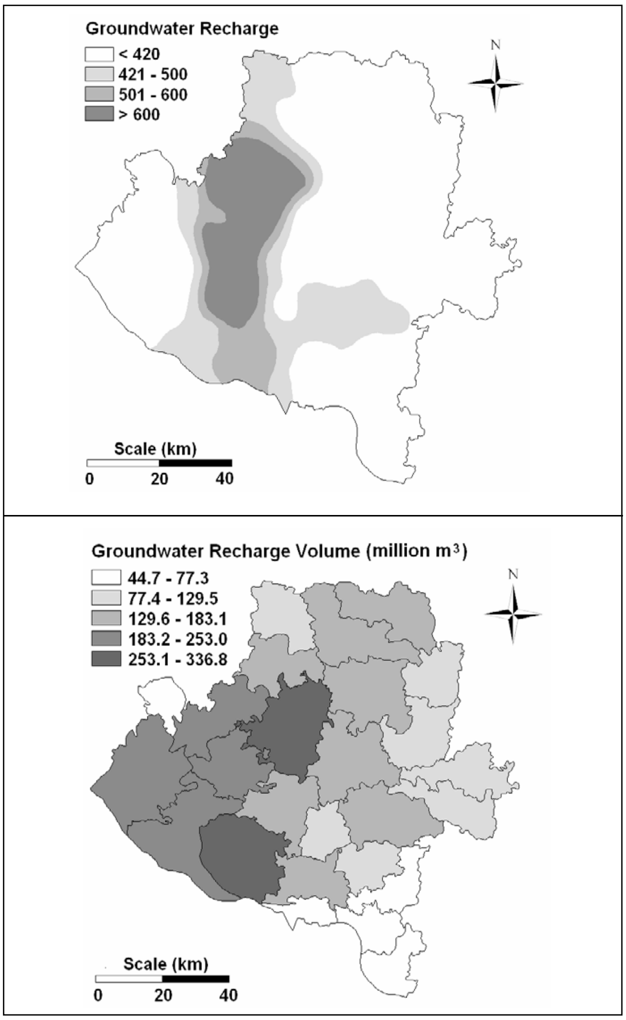

Fig.6. (a) Spatial distribution of groundwtaer recharge in the study area. **(b)** Sub-district wise volumetric groundwater recharge in the study area.

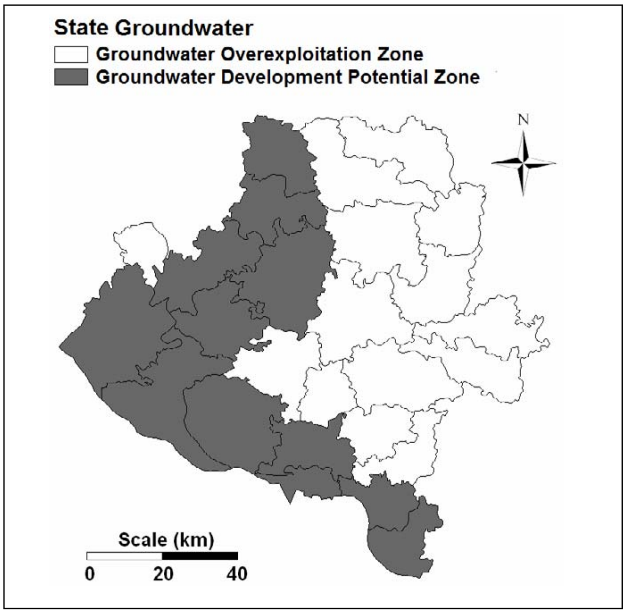

Fig.7. Map of groundwater development potential zone in the study area.

demand for groundwater. In addition, water conservation program is required which would contribute to the recharging of groundwater and steps are required to regulate the groundwater withdrawal for sustaining rechargeable aquifers.

CONCLUSION

The study has carried to assess the groundwater development potential of northwestern Bangladesh with a hope to help the stakeholders for better understanding about groundwater resources. Here, 96.5% of groundwater resource is exploited for irrigation and the rest for domestic purposes and the water demand for irrigation varies widely. The demand of water for irrigation in the central and northern parts of the study area is high due to high percolation and seepage losses and due to soil characteristics, high evapotranspiration and low precipitation. Spatial distribution of recharge also varies widely (from 320 to 890 mm). Groundwater exploitation is 10 million-m^3 less than that of recharge in twelve sub-districts in the study area and, therefore, suitable for future development of groundwater resource for expanding agriculture as well as for the growing population. But, groundwater abstraction is found higher than the average groundwater recharge in fourteen sub-districts. So development of surface water resources is essential, in general, to reduce growing demand on groundwater resources in the study area.

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