Asian Journal of Water, Environment and Pollution, Vol. 6, No. 2, pp. 31-42.

Assessment of Aquifer Vulnerability to Groundwater Pollution by Multi-criteria Analysis in and around East Calcutta Wetlands, West Bengal, India

Paulami Sahu and P.K. Sikdar*

Department of Environment Management, Indian Institute of Social Welfare and Business Management, Kolkata 700 073, India

✉ p_sikdar@hotmail.com

Received June 7, 2007; revised and accepted September 15, 2008

Abstract: The area lies between Hugli river in the northwest and Bidyadhari river in the east and includes the East Calcutta Wetlands, a Ramsar site. The area is flat in nature and a part of the lower deltaic plain of the Bhagirathi-Ganga river system. The sub-surface geology of the area is completely blanketed by the Quaternary fluviatile sediments comprising a succession of clay, silty clay, sand and sand mixed with occasional gravel. The Quaternary confined aquifer is made up of moderately well sorted sand and reflects fluviatile environment of deposition. Overlay analysis in GIS platform using multiple criteria such as height of piezometric surface above the base of top confining layer, hydraulic conductivity of the aquifer, groundwater velocity, thickness of top confining layer and water quality index have been utilized to understand vulnerability of the aquifer to groundwater pollution. The analysis indicates that 71% of the aquifer of the study area shows high to very high vulnerability to groundwater pollution. The aquifer below the sewage fed ponds and agricultural land shows high vulnerability to pollution. In these areas groundwater abstraction should be controlled to minimize surface water and groundwater interaction. Sensitivity analysis of the aquifer vulnerability assessment with the water quality indicates that in 70% of the total area vulnerability classes have matched with the present water quality distribution of the area. Artificial recharge to aquifer through roof top rainwater harvesting should be made mandatory for high-rise buildings and industries present in and around the wetlands.

Key words: East Calcutta wetlands, land use, piezometeric surface, multi-criteria analysis, aquifer vulnerability, groundwater quality.

Introduction

The study area consisting of 334 sq. km is bounded by latitude 22°25′ N to 22°40′ N and longitudes 88°20′ E to 88°35′ E and lies between Hugli river in the northwest and Bidyadhari in the east. The area consists of Salt Lake City and Rajarhat block in the north, parts of Bhangar-I and Bhangar-II blocks in the east and parts of Sonarpur block in the south and Kolkata City in the west (Figure 1). An important location within this area is the East Calcutta Wetlands, which occupy 125 sq. km area. This wetland has been declared as a Ramsar site on 19th August 2002 (Ramsar site no. 1208) and therefore has acquired an international status.

This wetland act as a sewage water treatment plant and treats about 800 million litres of wastewater flowing out daily from Kolkata. Wastewater of the city is a mixture of domestic and industrial effluent carrying high amount of heavy metals. This wastewater is fed into the wetland locally known as ‘bheries’. But the outlet water from the ‘bheries’ contain insignificant amount of these heavy metals. Scientists have also shown that there is a very low flux of metals from the sewage water to the fish (Ghosh, 1983, 1999, Chattopadhyay et al., 2002).

*Corresponding Author

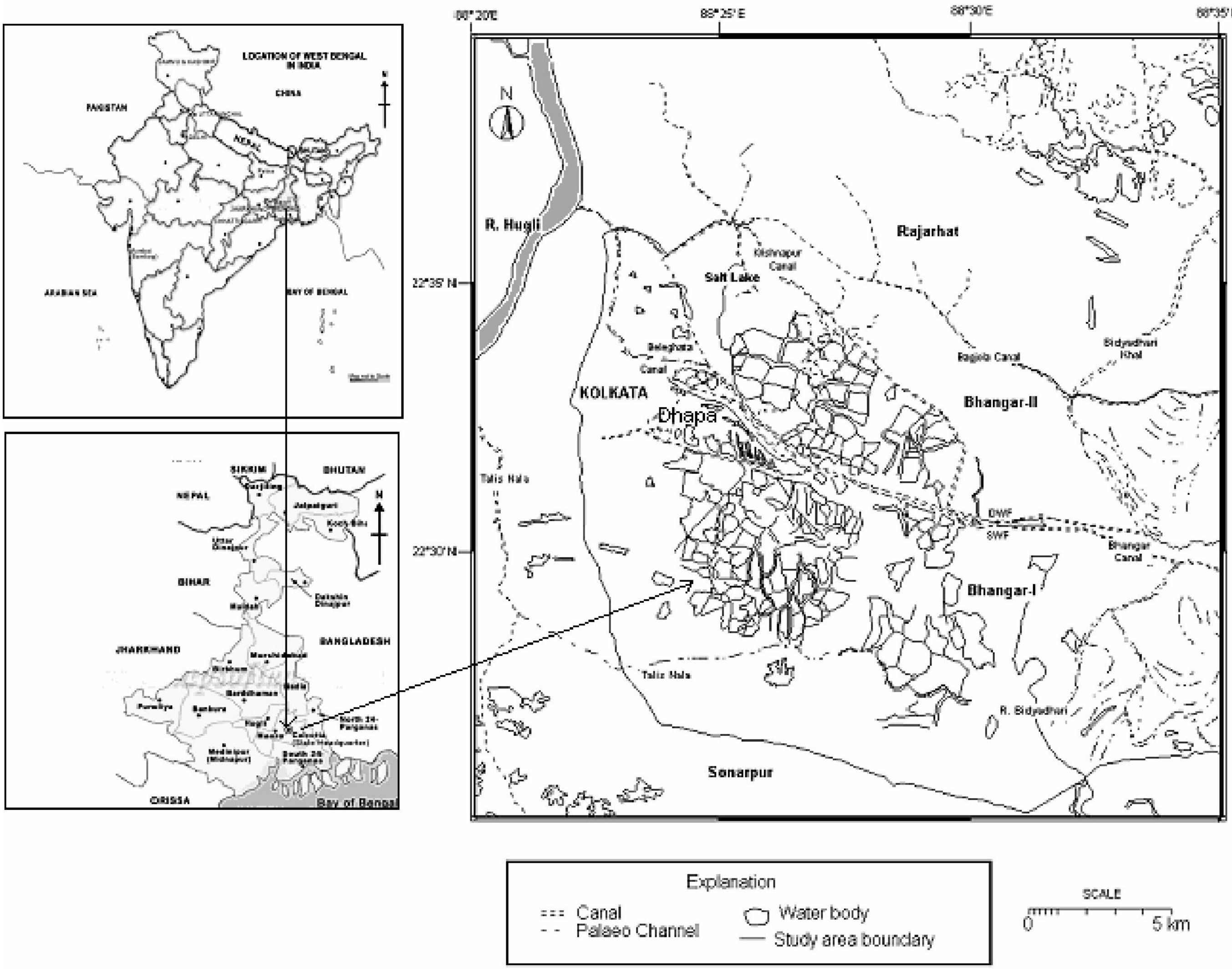

Figure 1: Location of the study area showing drainage and geomorphology.

Therefore, most of the heavy metals remain within the wetland system especially in the bottom sediments (Sikdar and Bhattacharya, 2003; Chatterjee et al., 2006). The wastewater of the city is also used for irrigation in the nearby farmlands and some heavy metals are trapped in the soil. These heavy metals can possibly leach from the soil and the bottom sediments of the sewage-fed farmlands and fisheries to the groundwater body. Leaching of pollutants may be accelerated due to over-withdrawal of groundwater for domestic, irrigation, industrial and commercial needs. The aquifer, therefore, might get contaminated and the east to west groundwater flow might transport heavy metals from the wetland aquifer to Kolkata aquifer.

Apart from this, excessive groundwater withdrawal may lead to change in groundwater flow pattern, depreciation of groundwater quality, land subsidence and increase the cost of pumping. The city solid waste dumping ground is at Dhapa (Figure 1). Solid waste dumping started in 1870 and at present more than 95% of the total waste generated in Kolkata is disposed here. This area may also act as an important source of contamination of ground water of the area.

Groundwater contamination is a major threat to the human health. In case of confined aquifer, due to presence of thick clay layer at the top of the aquifer, direct contamination from the surface is difficult. But the top clay layer is not uniformly thick everywhere and at some places they become very thin and even locally absent. These ‘stratigraphic shortcuts’ are very vulnerable to aquifer contamination. In the present study area, though a top clay layer of considerable thickness (average 40 m) is present above the aquifer; such ‘stratigraphic shortcuts’ are also present in the area in and around East

Calcutta Wetlands. The city solid waste dumping ground at Dhapa may also act as an important source of contamination of ground water of the study area. Thus, it is imperative to develop techniques for predicting areas that are more likely to become contaminated in near future due to activities at or near the land surface and to develop effective management strategies to protect the groundwater resource from future contamination.

An assessment on the aquifer vulnerability to pollution was carried out to delineate the areas where the aquifer is at potential risk of being polluted due to natural and anthropogenic activities. Aquifer vulnerability map is useful for future land use planning and groundwater quality monitoring. As far as the land use planning is concerned, the map provides information to lawmakers and developers regarding the spatial distribution of areas, which are more or less vulnerable to pollution. This map will help them to identify future areas suitable for urbanization, solid waste dumping and industrial activities. This map will also be helpful to water resource managers for identifying areas that need detailed analyses and assessment.

Hydrogeological Setting

The study area is a part of the lower deltaic plain of the Bhagirathi-Ganga river system and is generally flat in nature. The land surface with its elevation of 3 m to 6.5 m above the mean sea level, slopes gradually towards south and southeast. This elevation differs locally because of palaeo-levees, palaeo-courses, channels etc.

The climate of the study area is predominantly influenced by southwest monsoon. Hot lengthy summer with occasional nor'westers, prolonged monsoon from June to October, mild winter and a brief spring is characteristic features of the study area's climate. The average annual rainfall is about 1650 mm, 80% of which occur during June to October. The annual maximum and minimum temperatures are 42ºC and 10ºC, respectively.

River Hugli is the nearby river of this area. Past drainage is marked by another river known as river Bidyadhari. There are many small palaeo channels present in the area. Tali's nala and Bidyadhari khal are the two important palaeo-channels of the area. Two canals, namely Krishnapur Canal and Bagjola Canal are present along the northern boundary of the study area. The canals, which carry the dry weather flow and storm water flow of the Kolkata city, are known as DWF and SWF respectively. These two canals run parallel from west to east through the centre of the study area and divide the area into two halves. These two canals join together near Bantala from where it is known as Bhangar Canal (Figure 1).

Table 1: Land use pattern of the area in and around East Calcutta Wetlands (1998)

Land use type	*Total area covered (sq. km)*	*Area (%)*
Agricultural land	109.6	33.0
Fallow land	0.9	0.3
Canal	7.0	2.0
Dense settlement	71.0	21.0
Waste disposal ground	1.2	0.4
Less dense settlement	24.0	7.0
Less dense vegetation	56.0	17.0
Past channels	2.0	0.6
Road	0.3	0.1
Water body	40.0	12.0
Wetland	22.0	6.6
Total	334.0	100.0

The land use pattern of the study area was prepared from satellite imagery IRS ID LISS-III 1998 (Figure 2). The various land use classes, their total area and percentage of the area covered are given in Table 1. Agricultural land is the predominant land use class followed by dense settlement, vegetation and water bodies. Within the east Calcutta Wetlands the area occupied by wetlands is only 21.7 sq. km.

The sub-surface geology of the area is completely blanketed by the Quaternary fluviatile sediments comprising a succession of clay, silty clay, sand and sand mixed with occasional gravel. Lithologs of deeper exploratory boreholes, drilled by various agencies suggests the existence of underlying Tertiary clay at an average depth of 296 m (Chaterji et al., 1959). This clay bed continues up to a depth of at least 614 m below the ground surface.

The Quaternary aquifer of the study area is sandwiched between the silty clay/clay sequences. These two clay beds are dark grey in colour, sticky and plastic to semi-plastic in character and contain stringers of silt or fine sand. Clay beds are less plastic whenever they are admixed with silt or fine sand (Sikdar, 2000; Sikdar et al., 2002). The top fine grained clayey sediments is absent at places indicating scouring action of paleo channels with the deposition of fine sand. The top silty clay layer is underlain by a sequence of fine to coarse sand horizons mixed occasionally with gravel. The continuity of the sand layer that forms the aquifer material is broken by occasional clay lenses of limited lateral extent. The sand is often silty and highly micaceous.

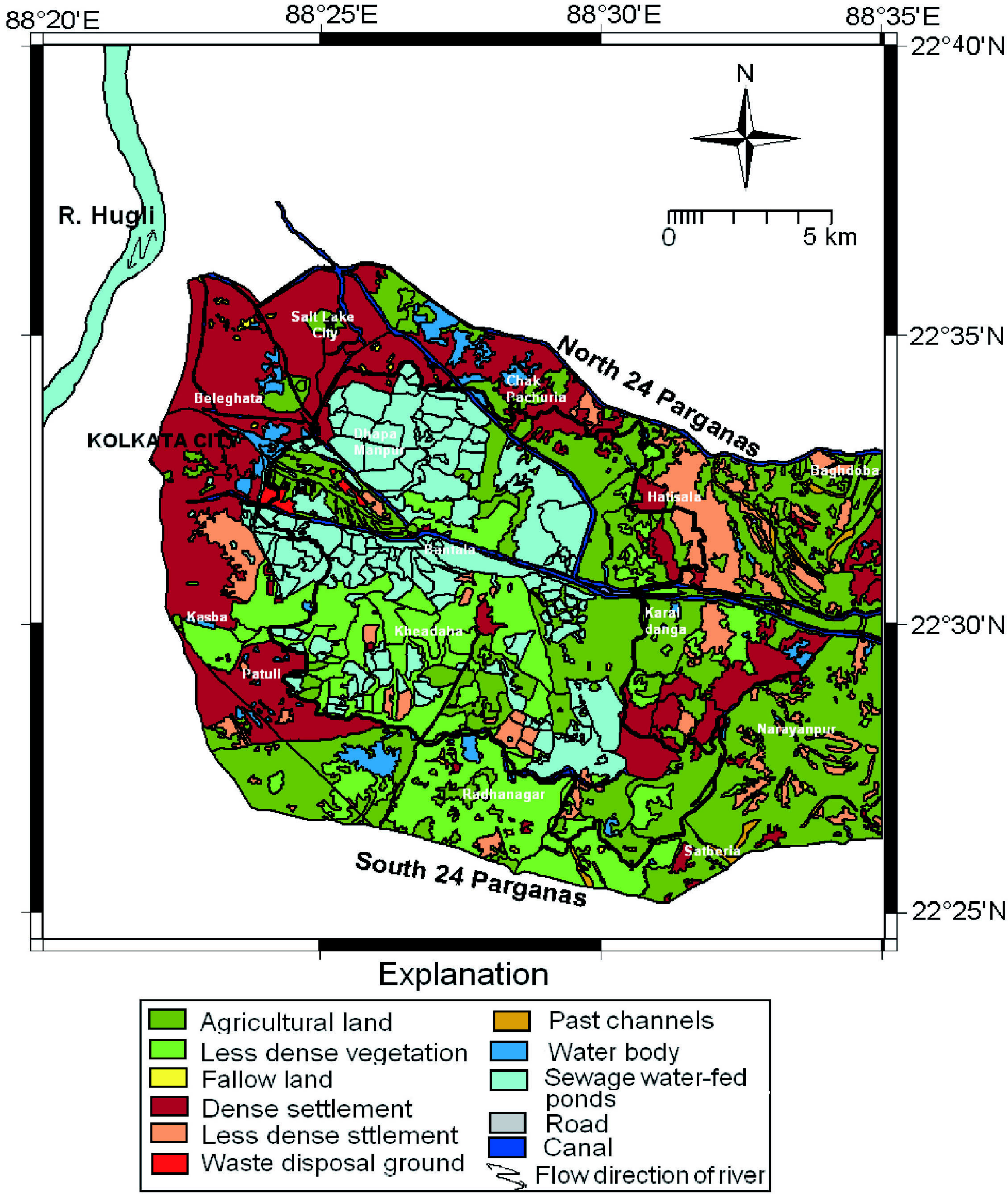

Figure 2: Land use map of the study area.

The sands are on average moderately well sorted and have an average graphic inclusive standard deviation of 0.98 that reflects fluvial environment of deposition. The fining upward sequence of the Quaternary sediments indicates a fluvio-deltaic depositional environment (Chatterji et al., 1964). Occurrence of peat in the upper horizons of the sediments and occurrence of marsh or salt lakes in the northern part of the study area indicate that bog and marshy conditions prevailed towards the close of sedimentation.

The yellow colour of the sand (at a depth range of 24 m to 76 m) is thought to be due to oxidation of the sediments derived from the Archean terrain of the Chotanagpur Plateau and brought down by the rivers flowing from the west. The grey to light grey colour of overlying sediments might indicate reducing condition of deposition and brought down from the Himalayan domain during the late Quaternary period (Sikdar, 2000).

The thick clay bed at the top of the stratigraphic column helps to hold water in the deeper sand sequence under pressure. During the present investigation, piezometric data were collected from 85 tubewells where strainers were placed at depths ranging between 40 m and 220 m. Here groundwater occurs in a confined condition within a sandy aquifer sandwiched between two clay beds. But at some places semi-confined to unconfined condition also prevails.

Methodology

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against the natural impacts, especially with regard to contamination entering the subsurface environment. Consequently, some areas are more vulnerable to groundwater contamination than others. The ultimate goal of vulnerability maps is to divide an area into several units, which have different levels of vulnerability. An exhaustive discussion on groundwater vulnerability mapping can be found in Vrba and Zaporozec (1994) and also in Zhang et al. (1996). For carrying out this assessment, data layers such as spatial distribution maps of piezometric surface above confining layer (Figure 3a), hydraulic conductivity (Figure 3b), groundwater velocity (Figure 3c) and isopach of top confining layer (Figure 3d) have been prepared using GIS software ILWIS 3.3 Academic Version.

Among a set of zones, choice of zones vulnerable to groundwater pollution depends on multiple criteria such as height of piezometric surface above the bottom of top confining layer, hydraulic conductivity of the aquifer, groundwater velocity within the aquifer and thickness of top confining layer. This process is most commonly known as Multi-Criteria Evaluation (MCE) (Voogd, 1983). Of several methods available for determining interclass/intermap dependency, a probability-weighted approach has been adopted that allows a linear combination of probability weights of each thematic map (Wi) with the individual impact value (IV) (Sarkar and Deota, 2000). The thematic maps have been ranked in scale of 1 to 5, depending upon their importance in spreading of groundwater pollution. The rank of each of these criteria has been converted to a probability map weight (Wi) using Bayesian statistics. The maps have been divided into ranges of values and rating has been ascribed to each of the range. These scores are again converted to capability values (CVi) using Bayesian statistics. These capability values (CVi) are then multiplied with the respective map weights of each thematic map (Table 2) to arrive at the final weight map (Figure 4). The procedure of weighted linear combination

Table 2: Thematic map weights and capability values of vulnerability analysis of the aquifer with respect to groundwater pollution

Thematic layer	*Rank*	*Map weight (Wi)*	*Range*	*Rating*	*Capability value (CVi)*
Piezometric surface above confining layer (m)	5	5/17 = 0.294	0-4	5	0.33
			4-8	4	0.27
			8-12	3	0.20
			12-16	2	0.13
			>16	1	0.07
Hydraulic conductivity (m/day)	2	2/17 = 0.118	>40	1	0.07
			40-30	2	0.13
			30-20	3	0.20
			20-10	4	0.27
			<10	5	0.33
Groundwater velocity (m/day)	2	2/17 = 0.118	>20	1	0.07
			20-15	2	0.13
			15-10	3	0.20
			10-5	4	0.27
			<5	5	0.33
Thickness of top confining layer (m)	4	4/17 = 0.235	0-20	5	0.33
			20-40	4	0.27
			40-60	3	0.20
			60-80	2	0.13
			>80	1	0.07

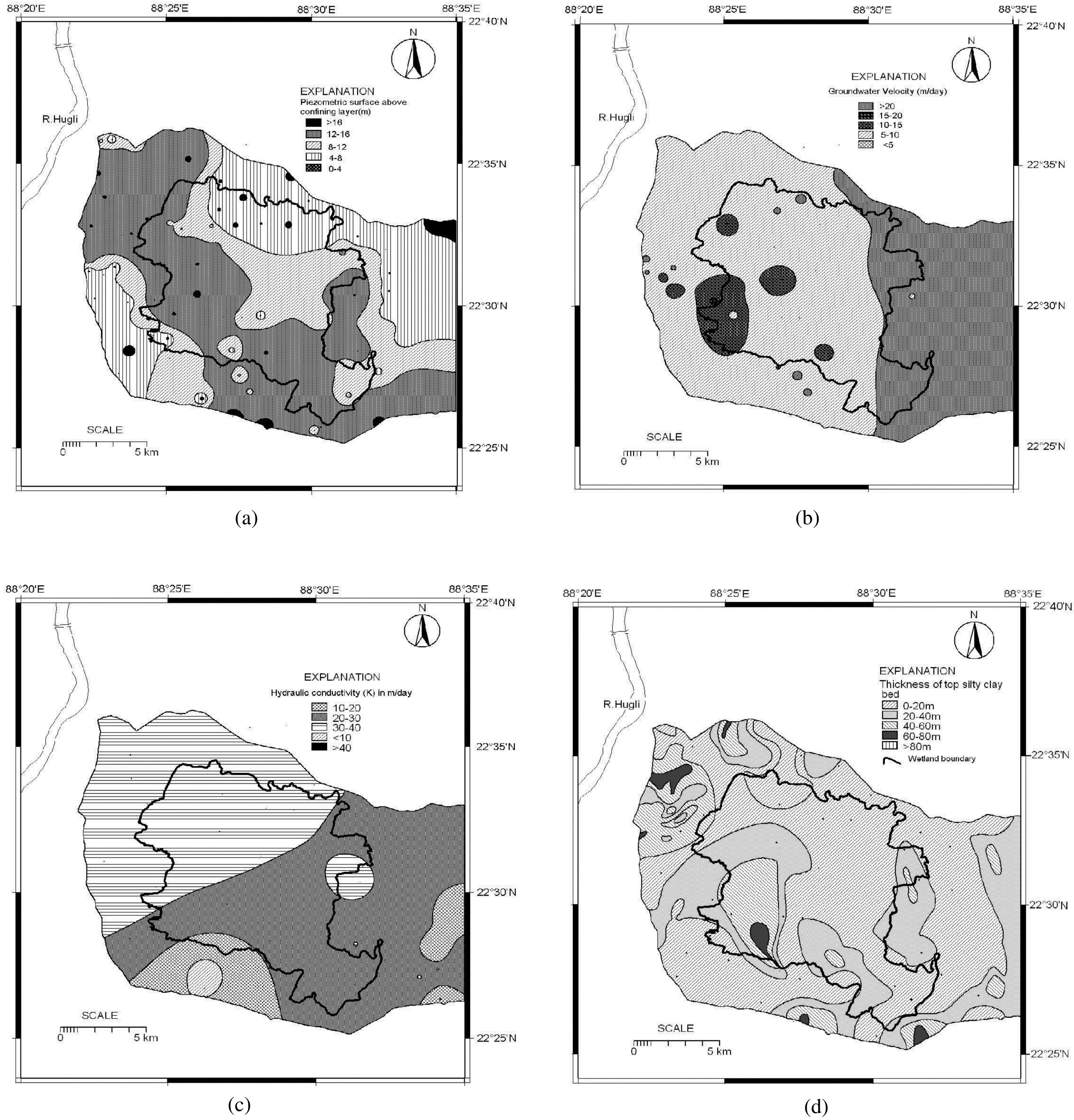

Figure 3: Spatial distribution of (a) height of piezometric surface above the bottom of top confining layer, (b) hydraulic conductivity, (c) groundwater velocity, and (d) isopach of top silty clay bed.

dominates in raster based GIS (Geographic Information System) software systems (Eastman et al., 1995; Eastman, 1996). Mathematically, this can be defined as:

$$GWp = f(Th, V, K, Ps)$$

where GWp = groundwater pollution, Th = thickness of top confining layer, V = groundwater velocity within the aquifer, K = hydraulic conductivity of the aquifer and Ps = height of piezometric surface above the bottom of top confining layer.

Groundwater pollution vulnerability map values can be expressed as

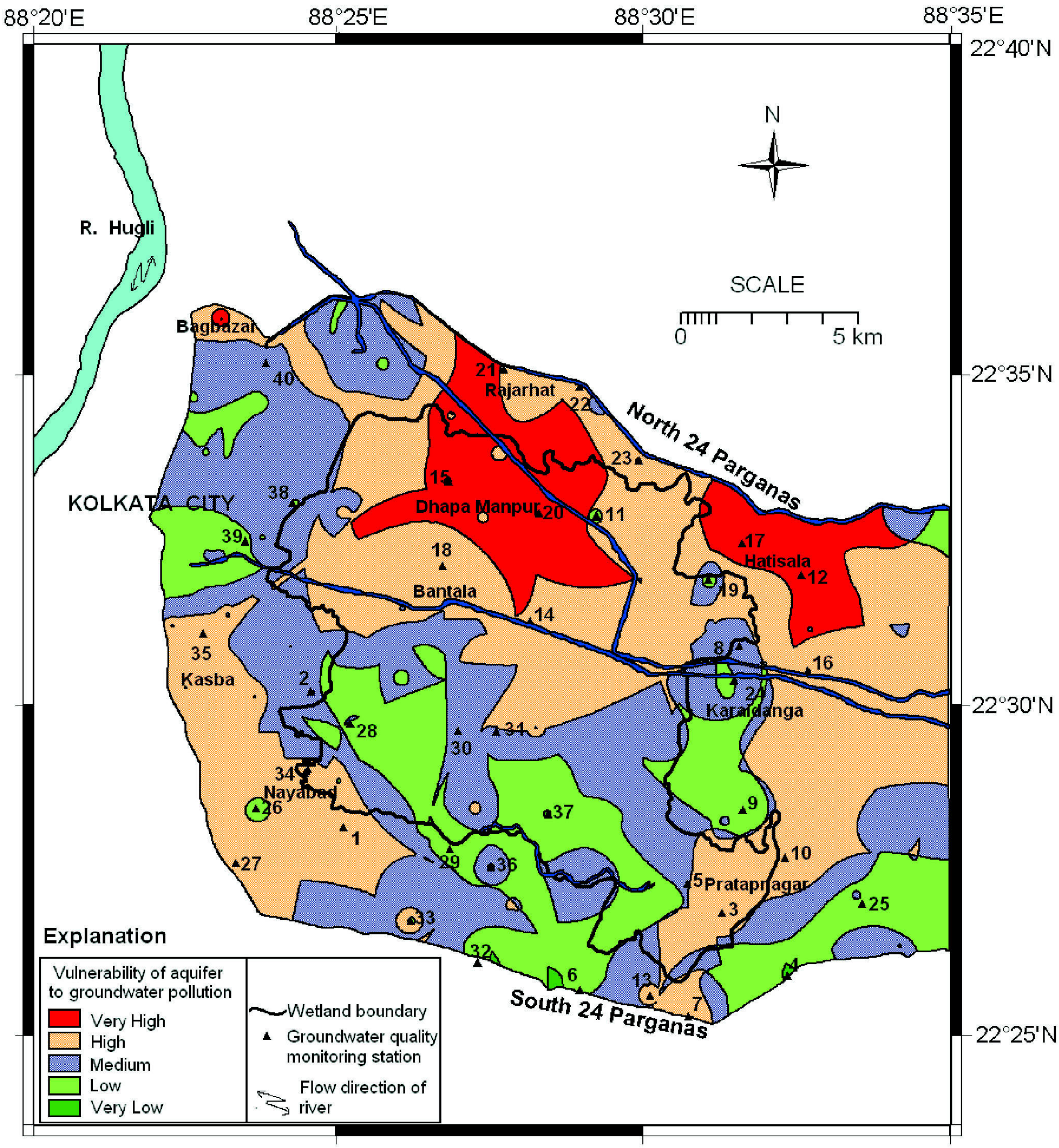

Figure 4: Aquifer vulnerability map of the area in and around East Calcutta Wetlands.

$$GpV = \sum Wi \times CVi$$

where GpV = groundwater pollution vulnerability, Wi = map weight and CVi = capability value.

The resultant final weight map will demarcate the areas vulnerable to groundwater pollution in and around East Calcutta Wetlands.

Data Layer Preparation

A. *Height of piezometric surface* above the bottom of top confining layer (Ps): This parameter gives an idea about the nature of the aquifer. If the piezometeric surface is above the base of the confining bed then the aquifer is definitely a confined one. On the other hand if the piezometric surface drops below the base of the confining bed then the aquifer will become an unconfined one. On lowering of the piezometric surface due to high abstraction of ground water, the hydrostatic pressure in the confining bed also decreases leading to an increase in the lithostatic pressure. The increased lithostatic pressure results in the decrease of the porosity of the confining bed material and release of water from the aquifer. This water from the overlying clay body may contain toxic material and hence will pollute the water present in the aquifer. A map (Figure 3a) has been prepared to delineate the areas where the aquifer is vulnerable to pollution from release of toxic water from the overlying aquiclude. A lower value of Ps has been given a higher vulnerability rating and vice versa.

B. *Hydraulic conductivity of the aquifer* (K): Hydraulic conductivity is a measure of the quantity of water that will flow through a unit cross sectional area of the aquifer in unit time under unit hydraulic gradient. The hydraulic conductivity values in and around the study area generated by various agencies such as Central Ground Water Board (CGWB), State Water Investigation Directorate (SWID), Government of West Bengal etc. were collected. Hydraulic conductivity values were also calculated using the predictive method of Masch and Denny (1966) for 223 samples, systematically collected during drilling operations at regular intervals from eight boreholes drilled in and around the study area. Using these K values a map has been generated using ILWIS 3.3 Academic Version Contour Interpolation (Figure 3b). Higher hydraulic conductivity helps to remove the pollutants from its point of origin. Therefore, higher value of K has been given a lower rating.

C. *Groundwater velocity* (V): Groundwater velocity at each network station has been ascertained using the following formula

$$V = Ki/S$$

where K = hydraulic conductivity, m/day, i = hydraulic gradient, dimensionless, and S = storativity, dimensionless.

Using the calculated 'V' values at each network station, a groundwater velocity map has been prepared (Figure 3c). Groundwater pollution is inversely related to groundwater velocity i.e higher velocity helps in quick removal of the pollutants from the source and hence results in less pollution. Therefore, higher value of V is given a lower rating.

D. *Thickness of top confining layer* (Th): Subsurface distribution of the top confining litho units occurring in and around East Calcutta Wetlands has been ascertained from one hundred nine lithologs of boreholes drilled by various government and private agencies. An isopach map (Figure 3d) has been prepared by joining points with equal thickness of top silty clay bed. High thickness of top clay prevents direct infiltration of pollutants into the aquifer. For this reason low rating is given to a higher thickness of silty clay.

Results and Discussion

The resultant final weight indicates the vulnerability of the aquifer to groundwater pollution in the area in and around East Calcutta Wetlands. The vulnerability value ranges from 0.10 to 0.30 and is classified into five categories, namely very low, low, medium, high and very high. About 71% of the total area falls under the category of high to very high vulnerable class. The area in sq. km and the percentage of the total area covered by each category are given in Table 3.

Table 3: Area covered by different zones vulnerable to groundwater pollution

Category	*Weight range*	*Area covered (sq. km)*	*Percentage of the total area*
Very high	0.25 - 0.30	55.1	16.5
High	0.20 - 0.25	180.6	54.1
Medium	0.15 - 0.20	97.1	29.1
Low	0.10 - 0.15	0.7	0.2
Very low	<0.10	0.5	0.1
Total		334.0	100.0

The spatial distribution of the aquifer vulnerability is shown in Figure 4. This map depicts that the regions with very high to high vulnerability are present at the northern, south-western and eastern parts of the study area. Within the East Calcutta Wetlands, very high to high vulnerable zones are present along the entire north and south-eastern parts.

Sensitivity Analysis

The vulnerability analysis is subjective in nature. Therefore, to avoid subjectivity, sensitivity analysis was carried out. Sensitivity analysis characterizes the distribution of both individual variables and input parameter on the resultant output. Many factors influence the result such as the type of overlay operation performed, the value of the weights, the number of data layers and map units in each layer, the error or uncertainty associated to each map unit, and so on. For the sensitivity analysis, firstly Water Quality Index (WQI) map (Figure 5a) was prepared. The sensitivity analysis has been carried out by crossing the aquifer vulnerability map (Figure 4) with the WQI map (Figure 5a) by cross operation under GIS platform.

Preparation of WQI Map: In order to get a comprehensive picture of the quality of groundwater, water quality index is one of the most effective tools

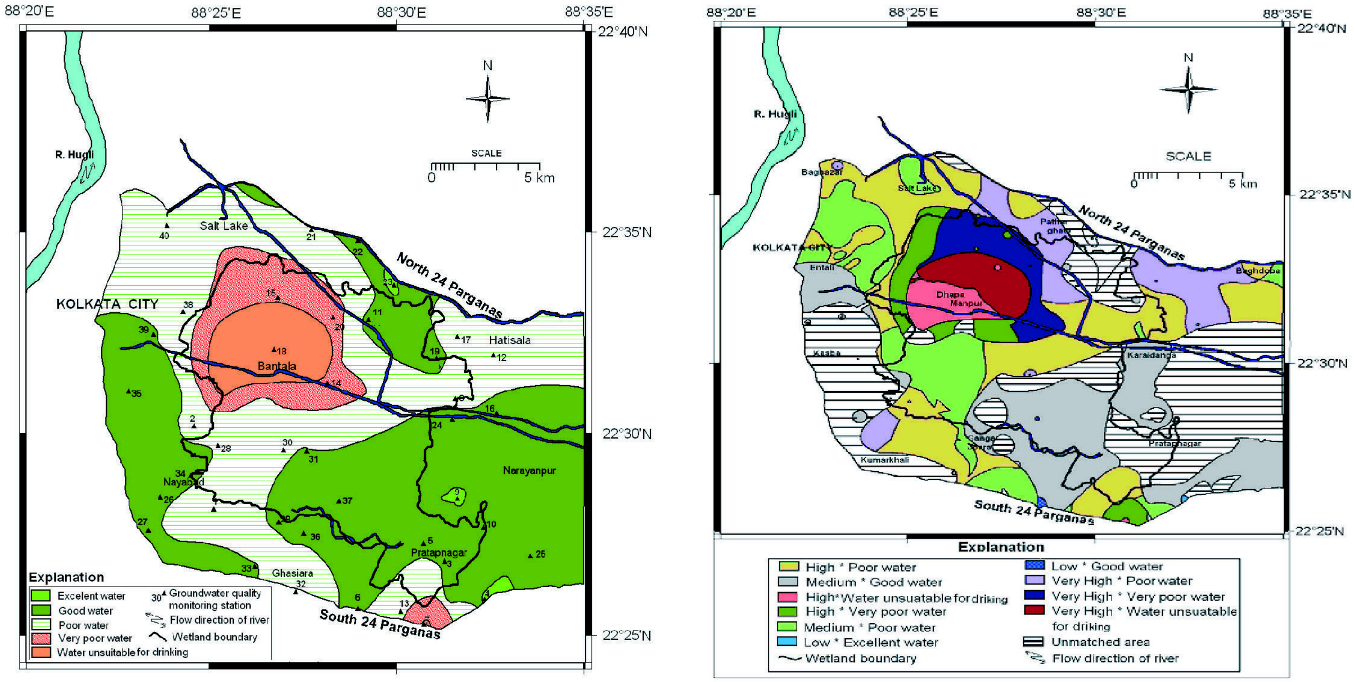

Figure 5: Spatial distribution of (a) water quality index and (b) cross map between aquifer vulnerability and water quality index.

(Tiwari and Mishra, 1985; Singh, 1992; Subba Rao, 1997; Mishra and Patel, 2001; Naik and Purohit, 2001; Sahu and Sikdar, 2008). WQI is defined as a rating reflecting the composite influence of different water quality parameters on the overall quality of water.

For assessment of water quality, nineteen parameters were selected from the twenty six parameters which were analyzed for forty groundwater samples. The nineteen parameters are pH, total dissolved solids (TDS), total hardness (TH), bicarbonate, chloride, sulphate, nitrate, fluoride, calcium, magnesium, iron, manganese, copper, arsenic, zinc, lead, chromium, cadmium and selenium. WQI is calculated from the point of view of the suitability of ground water for human consumption. An exhaustive discussion on WQI of the study area can be found in Sahu and Sikdar (2008).

Five classes have been attributed to the WQI. They are <50 = Excellent water, 50-100 = Good water, 100-200 = Poor water, 200-300 = Very poor water, >300 = Water unsuitable for drinking. In the present study, the computed WQI values ranges from 48.7 to 605.9 and can be categorized into five types, 'excellent water' to 'water, unsuitable for drinking'. The spatial distribution of the water types is shown in Figure 5a. A perusal of Figure 5a reveals that 'Excellent water' covers only 1.8 sq. km of the total area. Majority of the area is occupied by 'good water' and it covers about 153.5 sq. km. The area covered by 'poor water' and 'very poor water' is 132.2 sq. km and 28.3 sq. km respectively. In about 18.2 sq. km area the water is 'unsuitable for drinking'.

In the next step, the vulnerability map and the Water Quality Index map have been crossed to generate a map (Figure 5b) showing the areas where the various vulnerability classes have matched with the water quality distribution. This covers 233.29 sq. km which is about 70% of the total study area (Table 4). In the rest of the

Table 4: Cross operation table showing areas where vulnerability of the aquifer and Water Quality Index correspond to each other

*Vulnerability * Water Quality Index*	*Area in sq. km*
High * Poor water	69.1
Medium * Good water	56.2
High * Water unsuitable for drinking	8.1
High * Very poor water	12.1
Medium * Poor water	37.8
Low * Excellent water	0.1
Low * Good water	0.3
Very high * Poor water	25.5
Very high * Very poor water	14.2
Very high * Water unsuitable for drinking	10.3
Total area	233.7
Percentage of total area	70

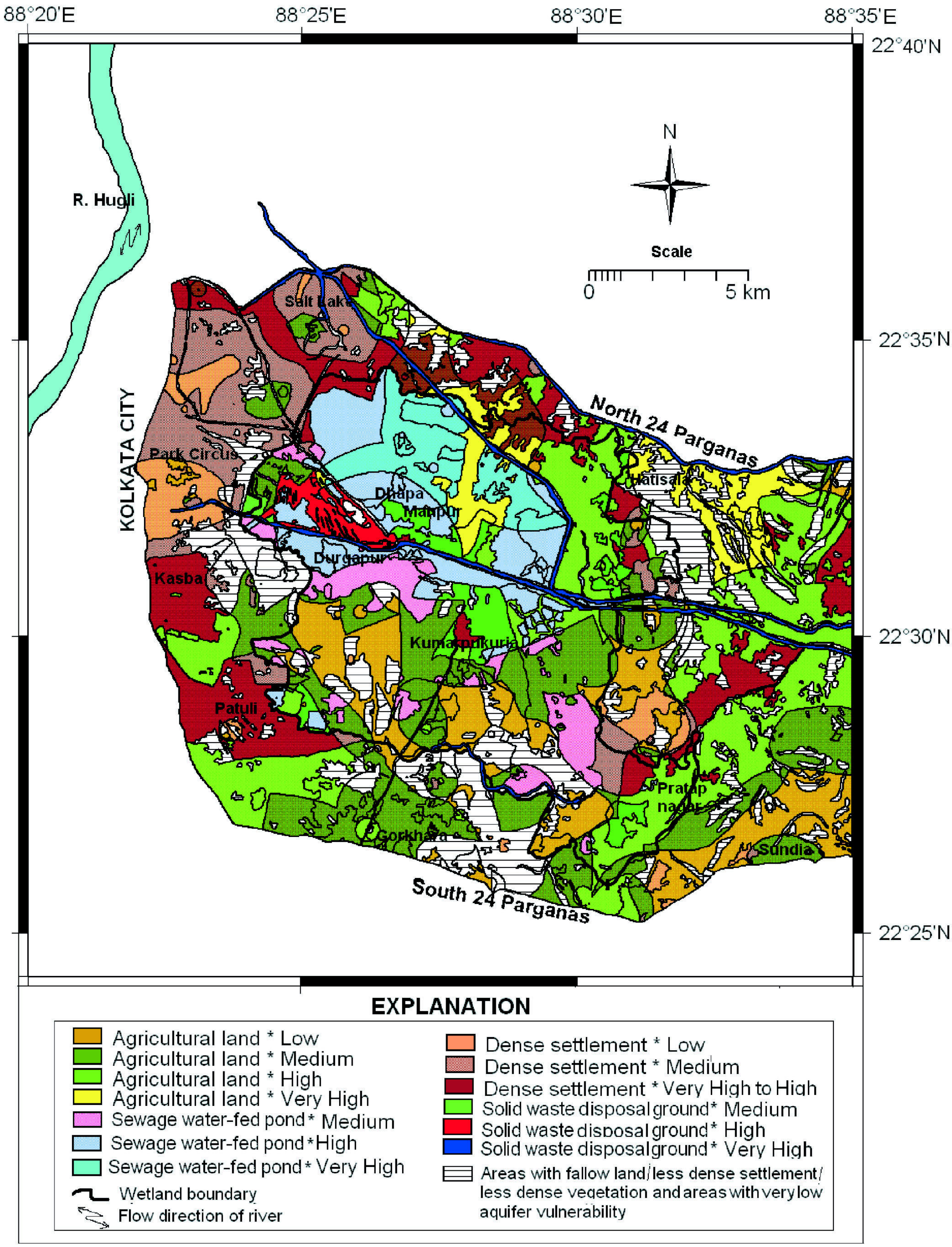

Figure 6: Cross map between land use pattern and aquifer vulnerability of the study area.

area the present water quality and aquifer vulnerability to groundwater pollution do not match with each other (Table 5). Therefore, it can be said that the aquifer vulnerability analysis is more or less reliable.

Conclusion

The land use map (Figure 2) and the aquifer vulnerability map (Figure 4) of the area have been crossed using the

Table 5: Cross operation table showing areas where aquifer vulnerability and water quality index do not correspond to each other

*Vulnerability * Water Quality Index*	*Area in sq. km*
High * Excellent water	0.5
High * Good water	91.8
Medium * Excellent water	1.2
Medium * Very poor water	1.7
Very high * Good water	4.9
Low * Poor water	0.1
Total area	99.3
Percentage of total area	30

Table 6: Cross map of present land use pattern and the final vulnerability map (area in sq. km)

Landuse class \ Vulnerability	*Very high*	*High*	*Medium*	*Low*	*Very low*
Agricultural land	13.00	64.16	50.63	36.69	0.32
Water body including sewage-fed ponds	14.04	23.61	17.75	6.31	-
Canal	0.76	3.57	2.09	0.38	-
Dense settlement	4.57	31.96	24.73	9.64	-
Less dense settlement	3.67	9.98	5.18	4.72	0.03
Solid Waste Disposal ground	0.0014	0.64	0.59	-	-

Cross Operation of ILWIS 3.3 Academic Version. The resultant map (Figure 6) shows the areas with low to very high vulnerability of dense settlement, agricultural land, sewage water-fed ponds and waste disposal ground land use classes. Table 6 shows the area occupied by various land use class with respect to different vulnerability classes. A perusal of Figure 6 indicates that within East Calcutta Wetlands, aquifer vulnerability to groundwater pollution is very high to high near the sewage water-fed ponds or 'bheries' and the present solid waste dumping ground located in the eastern part of the wetland. Therefore, surface water and groundwater interaction should be minimized in these areas. This can be achieved by regulating groundwater withdrawal from the shallow aquifers within a depth of 100 m. The areas with dense settlement also fall under the category of high vulnerability. In these areas, especially in eastern part of the study area, groundwater abstraction should be minimized by regulating tubewell operation time and treated surface water supply system should be introduced. The aquifer is also vulnerable to pollution from agricultural land. Therefore, it is recommended that in very high to high vulnerability areas, use of chemical fertilizers, insecticides, pesticides etc. be minimized and modern methods of irrigation be practiced to reduce the water use. In the medium vulnerability area with dense settlement or agricultural land, status quo should be maintained with respect to tubewell operation time. But in the low vulnerability areas with dense settlement or agricultural land, further development of limited number of tubewells is possible. It is also recommended that in the entire area roof top rainwater harvesting and artificial recharge to the groundwater body should be made mandatory for high-rise building and industries.

Acknowledgements

The authors convey thanks to Prof. Ashoke K. Dutta, Director, Indian Institute of Social Welfare and Business Management for his help and encouragement during the research work. The first author is thankful to Council of Scientific and Industrial Research (CSIR), India for their financial assistance.

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