Groundwater Quality and Vulnerability Mapping of an Unconfined Coastal Aquifer

S. Sathish and L. Elango

Abstract

Groundwater quality mapping is very essential to identify regions where groundwater is suitable for various uses. A study of the vulnerability of groundwater for pollution in a region is required as it will provide information for taking precautionary measures. Groundwater is being extensively used for domestic purposes in the region south of Chennai, India. The present study was carried out with the objective of preparing a groundwater quality map and vulnerability map of the south Chennai coastal aquifer. Groundwater samples from fifty representative wells distributed over the entire area were collected and analyzed for electrical conductivity and major ions. Based on the recommended limits of these parameters for domestic use the area was divided into different zones. A spatial index was assigned for these physio-chemical data layers showing groundwater with good, moderate and poor quality and these layers were integrated by overlay analysis using ArcGIS. From this overlay analysis, the groundwater quality and vulnerability map was prepared. By superimposing all the layers based on quality index, the vulnerability of groundwater was determined periodically. Finally, the periodic vulnerability index was overlaid and vulnerability map of this unconfined aquifer was represented by means of relative index value. The groundwater quality map of the region can be used as a tool for suitable and efficient management of groundwater by regulating pumping from the poor quality zone. The groundwater quality mapping should be periodically carried out as this aquifer is under stress and bounded by surface water bodies of poor quality on all sides.

Key words: hydrogeology, overlay analysis, special index, vulnerability index, Chennai, India

Introduction

Groundwater quality mapping is very essential to identify regions where groundwater is suitable for various uses. This will also assist in controlling or minimizing pumping from regions that are contaminated. Groundwater quality mapping will also assist the planners to take suitable action to improve the groundwater quality in contaminated regions. Aquifer quality mapping has been successfully used to access the extent of aquifer contamination due to seawater intrusion and it was used as a tool for management of the coastal groundwater resource (Melloul and Wollman, 2003). The spatial variation in chemical and physiochemical parameters of groundwater were used to identify suitable zone for pumping for both domestic and irrigation purposes (Srinivasarao, 2007). GIS was effectively used for the evaluation of groundwater quality by several researchers (Shahid and Nath, 2000; Phukon et al., 2004). The overlay/index approaches gained popularity particularly with the ease of usage of GIS technology (NRC, 1993; Bonamcartar, 1996; Corwin et al., 1997; Fuest et al., 1998). The spatial groundwater quality index and the procedure of weighing is widely used to identify the spatial characteristics of the aquifer by many researchers (Horton, 1965; Prati et al., 1971; Inhaber, 1975; Provencher and Lamontagne, 1979; Aller et al., 1987; Maha and AI-Dabbagh, 1989; Sinha and Shrivastava, 1994; Melloul and Collin, 1998; Secunda et al, 1998; Pradhan et al., 2001; Connell and Van den Daele, 2003; Babiker et al., 2005;
Chachadi and Lobo-Ferreira, 2005; Stigter et al., 2006a; 2006b; Chakraborty et al., 2007; Mamadou et al., 2010). Many approaches have been developed to extract aquifer vulnerability such as process based method, statistical methods and overlay/index methods (Zhang et al., 1996; Tesoriero et al., 1998). Ramakrishnaiah et al. (2008) used the spatial groundwater quality index was used for ranking, which reflected the influence of different parameters. The results obtained by such techniques was be used to point out the groundwater from a particular region is good or not (Rajankar et al., 2009). The vulnerability maps prepared were used to limit the pumping (Burkart et al., 1999; Thapinta and Hudak, 2003). Vulnerability maps have proved to be a popular tool in groundwater quality management throughout the world as documented by Worrall and Kolpin (2004). The present study was carried out in a coastal aquifer, south of Chennai City, India. As this aquifer is bounded by saltwater and this is being pumped to partially meet the domestic requirements of the Chennai City. Detailed geophysical investigation using electrical resistivity method was carried out earlier in this area to understand sub-surface geology by Gnanasundar and Elango (1999). Hydraulic conductivity of this aquifer formation was estimated using electrical resistivity methods (Senthilkumar et al., 2001). General groundwater quality of this region based on the major ion distribution was reported by Elango et al. (1992) and Gnanasundar and Elango (1998). Mohan and Pramada (2005) carried out a study on real time control of a well field with a groundwater simulation-optimization model to optimize a pumping strategy. In the recent years groundwater pumping has increased in this area due to rapid urbanization and each house or apartment have their own well to pump groundwater. Further, environmental and ecological imbalance is arising in this coastal area due to over exploitation of groundwater due to groundwater pumping from private wells of settlements, hotels, tourism center and industries. Hence, it is essential to identify the vulnerable zones to maintain the groundwater quality. The present study was carried out with the objective of preparation of groundwater quality map and vulnerability map of the south Chennai coastal aquifer by using overlay/index method. In the present study, index method was used based on the groundwater quality assessment carried out in different time periods, which will give better results.

Description of study Area

The study area is located in the southern part of Chennai which is the fourth largest City in India. This area is surrounded by salt water on three sides (Figure 1). It is bounded by the Adyar River in the North, by the Muttukadu estuary in the south, and the Bay of Bengal in the east. The Adyar River carries only the saline back water during most part of the year which is flushed out into sea only during times of very high rainfall. Muttukadu estuary in the south also has saline water. The Buckingham Canal forms the western boundary of the area. This canal originally established for navigation, but now it is used to collect storm water to moderate flood during monsoon. The Buckingham Canal dissipates the water into the sea through Adyar River which is the northern boundary of the study area and Muttukadu backwaters which is the southern boundary of the study area. This canal also carries domestic sewerage and hence it is highly contaminated.
The area has a humid and subtropical climate. The maximum temperature in this area is about 40°C and a minimum temperature of about 20°C. Summer (April-May) temperature varies from 35°C to 42°C and in winter (December – January) it ranges from 25 to 34 °C. The average annual rainfall is about 1200 mm. The southwest monsoon prevails from July to September and the northeast monsoon is active during October – December. The southwest monsoon, the northeast monsoon and the transition period contribute 40%, 51% and 9% of the annual rainfall respectively. The landuse and landcover pattern
(based on the data of Indian Remote Sensing (IRS) Satellite LISS III dated 24/02/2004) in the study area comprise of build up lands including settlements, theme parks, hotels and with small agricultural lands and industries. The human settlement in this region use groundwater for domestic purpose. The settlements and urbanization is comparatively high in the northern part than the southern part of the area (Figure 2).
Methodology

Field and Laboratory method

In order to identify monitoring wells for groundwater sampling in the study area, a well inventory survey was carried out during August 2008. During this survey measurement of groundwater level and electrical conductivity were carried out in the several wells located in this area. Based on this survey representative sampling wells were located covering the entire area. Thus, fifty sampling wells were identified for regular monitoring (Figure 1). Electrical Conductivity (EC) was measured in the field itself by using portable meter. The water level below ground level was measured by using a water level indicator and the water level converted to above msl with the help of digital elevation attribute data. Groundwater samples were collected once in three months from Aug 2008 to May 2009. The water samples were collected in clean acid washed polythene bottles by rinsing it two times with the samples. These bottles with samples were tightly packed without air bubbles and major ions like Ca\(^+\), Mg\(^+\), K\(^+\), Na\(^+\), Cl\(^-\), SO\(_4\)^\(-\), CO\(_3\)^\(-\) and HCO\(_3\)^\(-\) were measured in the laboratory by using titrimetry, spectrophotometric and flame photometric methods. The chemical analysis was checked by calculation of ion balance error, which was less than ±5%. The total hardness (TH) of the water sample collected was determined from the concentration of calcium and magnesium. The spatial quality index of groundwater and vulnerability of aquifer was obtained as by the procedure shown in Figure 3.
Overlay Analysis

The overlay analysis was carried out with selected parameters, which includes EC, TH, Sodium, Chloride, Sulphate and Alkalinity thematic layers, as they generally control the usability of water for domestic purpose. In ArcGIS, the spatial analysis tool was used to plot the variation of parameters. The zones were demarked for different spatial index by considering the importance of groundwater quality for domestic usage and recommended limits of Bureau of Indian Standards (BIS, 1992) and World Health Organization (WHO, 2004) (Table 1). GIS based overlay analysis as suggested by Xiugang et al., (1999) was used to obtain periodic vulnerability. The mean and sum of the periodic vulnerability index was used to find out the intrinsic vulnerability of the aquifer.

Table 1 The physio-chemical standards for domestic usage and their spatial distribution

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Classification based on quality</th>
<th>Standards by BIS &amp; WHO</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC (µS/cm)</td>
<td>&lt;780</td>
<td>780 – 3125</td>
<td>&gt;3125</td>
</tr>
<tr>
<td>(obtained by TDS/0.64)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH (Ca&amp;Mg) (mg/l)</td>
<td>&lt;300</td>
<td>300-600</td>
<td>&gt;600</td>
</tr>
<tr>
<td>Sodium (mg/l)</td>
<td>&lt;200</td>
<td>200-300</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Chloride (mg/l)</td>
<td>&lt;250</td>
<td>250-1000</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Sulphate (mg/l)</td>
<td>&lt;200</td>
<td>200-400</td>
<td>&gt;400</td>
</tr>
<tr>
<td>Alkalinity (mg/l)</td>
<td>&lt;200</td>
<td>200-400</td>
<td>&gt;400</td>
</tr>
<tr>
<td>Spatial Index</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Spatial analyst extension which is present in ArcGIS software of the International Geo-Information Science and Earth Observation was used to generate the raster output. Inverse Distance Weighing method was applied to generate the raster graphical output. The raster graphical output is suitable for the overlay analysis which gives high spatial variability of multi-attributes (Babiker et al., 2006). The decision criteria for the spatial quality index was categorized as 3 as good, 2 as moderate and 1 as poor based on equation (1) given below.

\[
\text{Spatial Index} = \begin{cases} 
1 & V_i \in [10 - 13] \\
2 & V_i \in [13.00001 - 16] \\
3 & V_i \in [16.00001 - 18] 
\end{cases}
\]  

(1)

The attribute of the periodic spatial index \(V_i\) is expressed by using the relationship obtained by method of Inverse Distance Weighing as follows (De smith et al., 2009).

\[
\text{Spatial index } V_i = \sum_{j=1}^{m} a_{ij} = 1, \quad 1, 2 \text{ and } 3
\]

(2)
where \( m \) is the number of factors (Saaty, 1980) whose spatial index maps overlaid, \( x_i \) the weight of the \( j \)th factor and \( l_{ij} \) the periodic vulnerability index. The vulnerability of the aquifer is estimated using equation (3).

\[
\text{Vulnerability of the aquifer} = \sum_{i=1}^{m} V_i
\]  

(3)  

Results and Discussion

Geology and Hydrogeology

Topographically this site is slightly elevated at the centre along north-south direction with gentle slope towards east and west, with a few sand dunes in between. The topographical elevation ranges from mean sea level 0 m msl to 12 m above msl (Figure 4).

The Precambrian gneiss of charnockitic composition is at the basement of this area, which is overlaid by unconsolidated quaternary sediments with thickness ranging between 10 m and 24 m. These quaternary sediments comprise of sand, clay, sandy clay and clayey sand. The sandy formation covers most part of...
the area and the clay is dominant in the western boundary i.e., along Buckingham canal. The clay, sandy clay and clayey sand are also present as patches in the quaternary formation (Figure 5). The upper unconsolidated formation and lower weathered/fractured rocky formations function as an unconfined aquifer. Rainfall recharge is the main source of aquifer replenishment. Wells that exist at the landward edge of the beach sand, in the dunes, supply significant amount of groundwater (Gnanasundar and Elango, 1999). Field observations indicate that only a few wells penetrate the weathered zone in the charnockite, whereas others tap only the upper Quaternary sediments. The average groundwater level fluctuation in a year is around 1.36 m. The maximum groundwater level fluctuation of 2.94 m occurred in the northern part of the area during the investigated period (Aug 2008 to May 2009) (Figure 6). The groundwater table in general follows the topography and flows towards the sea and Buckingham canal.

Figure 5 Fence diagram of area
Physio-Chemical Parameters

Electrical Conductivity (µS/cm) of groundwater ranges from 117 µS/cm to 13485 µS/cm. In general groundwater of the southern part had low electrical conductivity. The region was classified into three zones based on the values of EC and they were assigned spatial index from 1 to 3 as given in table 1. This classification is based on the desirable and permissible limits prescribed by the BIS and WHO. As 780 µS/cm (derived from TDS/0.64) is the desirable limit of BIS and WHO, the water with less than 780 µS/cm was classified as Good with the spatial index 3. Groundwater with EC between 780 µS/cm and

Figure 6 Spatial variations in groundwater level (in m above msl) in different months
3125 µS/cm, was classified as moderate with the spatial index 2. Groundwater with greater than 3125 µS/cm was classified as unsuitable with the spatial index 1.

The total hardness (TH) calculated using calcium and magnesium concentration ranges from 20 mg/l to 878 mg/l. The TH of water increases from southern to northern boundary of the study area. The region was classified into three zones based on the values of TH and they were assigned spatial index from 1 to 3. As 300 mg/l of TH is the desirable limit as per BIS and WHO, water with less than 300 mg/l is categorized as good with the spatial index 3. Groundwater which has TH between 300 mg/l and 600 mg/l, was classified as moderate with the spatial index 2. Water with greater than 600 mg/l of TH was classified as unsuitable with the spatial index 1. Similarly, the spatial index was prepared for all the other parameters include sodium, chloride, sulphate and alkalinity as given in table 1.

Vulnerability of the Aquifer

After preparing the spatial water quality index maps for various chemical parameters as explained earlier, overlay procedure was carried out and the periodic seasonal water quality index map of the region was prepared. The maps show the spatial variations in water quality index in different months.
prepared. These maps are shown in Figure 7.

The vulnerability index calculated using the equation 1 & 2, ranges from 11.3 to 18.0 by using the relationship \( \bar{v_i} \) and ranges from 45 to 72 by using the relationship \( \sum_{i=1}^{m} v_i \). The maximum value in both case was considered as good and the area having low value indicate that they are sensitivity to pollution (Figure 8).
The vulnerability index map of the study area indicates that the most of area contain groundwater with moderate quality. Even though this area is bounded by Buckingham Canal with poor quality water, moderate quality of groundwater is distributed in most part of the area. This is because of the fact that the western part of the region along the Buckingham canal predominantly comprise of clay, clayey sand and sandy clay which prevent the infiltration of contaminated water from the canal into the aquifer. Further, the influence of canal on the groundwater quality of this aquifer is also less pronounced as groundwater generally flows towards the canal. Because of the dominance of clay along the Buckingham canal the fresh groundwater from the central part of the aquifer is also not flowing rapidly into the canal thereby fresh groundwater is not lost by draining into the canal from this aquifer. Poor quality of groundwater was found in northern coastal part of the area. The poor quality of groundwater in this region is due to urbanization, which led to over pumping of groundwater. This has resulted in intrusion of seawater in this region. In general, throughout the year the quality of groundwater in this unconfined aquifer is comparatively good during the month of February (after rains in October-December and comparatively poor during the month of May (after dry periods of March-April). The amount of precipitation and amount of pumping of groundwater decides the groundwater quality in this region. That is the precipitation during northwest monsoon (October – December) results in fresh water recharge and improves the groundwater quality. Due to over pumping and less precipitation the groundwater quality is becoming poor during summer (March-April) until the beginning of monsoon.

Conclusions

The study indicates that the most part of the region contain groundwater of good quality, however the northern part of the region has comparatively poor quality of water. The periodic vulnerability index indicates that the groundwater quality is comparatively good during the month of February and comparatively poor during the month of May due to over pumping and less precipitation. The vulnerability of groundwater for degradation is high towards the north of the study area and marginal in south of study area. Groundwater quality mapping should be periodically carried out as this aquifer is under stress and bounded by inferior quality of water on all the sides. The quality index map of the region can be used as a tool for proper and efficient management of groundwater by regulating pumping from the poor quality zone.

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References


Horton, R.K. (1965) An index number system for rating water quality, Journal of Water Pollution Control Federation, 37, pp. 300-305.


