

Evaluation of Groundwater Vulnerability in the Lower Varuna Catchment Area, Uttar Pradesh, India using AVI Concept

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Abstract: Groundwater vulnerability assessments calculate the sensitivity of quality of groundwater to an imposed contaminant load which is essential element of the aquifer management plans. Seventy five groundwater samples have been analyzed for different chemical parameters to understand the groundwater quality of the lower Varuna river basin, Uttar Pradesh, India. The intrinsic groundwater vulnerability map of the lower Varuna catchment area in the north of the city of Varanasi (India) shows a high dependency on the depth to groundwater. The topmost layer of alluvial silty clay, protects the groundwater against contamination in this urban area, but the retention time in the unsaturated zone can be estimated to several months only. The input dataset is very sparse i.e. groundwater levels were measured twice (pre- and post-monsoon 2009) and the geological map shows only alluvium as the outcrop. Several boreholes in this area show, that the alluvium has a thickness of about 4 m and below that are fine grained sands. The surface information does not allow the development of a risk map since land use changes very fast and contamination areas can not be identified accurately. The vulnerability maps developed in this study have become important tools for environmental planning and predictive management of the groundwater resources in the fast urbanizing region in the Varanasi area.

Keywords: Groundwater quality, Aquifer Vulnerability Index, Varuna river, Varanasi, Uttar Pradesh.

INTRODUCTION

Water is essential component for our life support system. With rapid increase in population and growth of industrialization, groundwater quality is being increasingly threatened by disposal of agricultural chemicals and industrial wastes (Raju et al. 2011). Rate of depletion of groundwater levels and deterioration of groundwater quality is of immediate concern in major cities (Naidu et al. 1998; Babiker et al. 2007; Raju et al. 2009; Jain et al. 2010; Raju et al. 2011; Qian et al. 2012; Raju, 2012). Aqueous geochemistry is concerned with the chemical reactions and processes affecting the distribution and circulation of chemical species in natural water. Water chemistry describes the seasonal changes in the behavior of the major ions and catchment characteristics. Groundwater constitutes a basic resource where more than 80% of water supply for the population comes from groundwater resources. Fresh and clean water is crucial for the well-being of the society. Groundwater quality is a worldwide environmental issue which is influenced by various natural processes and anthropogenic activities (Ouyang, 2005; Shrestha and Kazama, 2007).

Margat (1968) first introduced the concept of aquifer vulnerability with reference to the potential for groundwater contamination by surface pollutant sources. There has been numerous attempts to define aquifer vulnerability (Vrba and Zaporozec, 1994; Qian et al. 2012) and countless methods have been devised for assessing vulnerability in a consistent and quantitative manner (Civita, 1993; Jimenez-Madrid et al. 2012). The term aquifer vulnerability tends to be defined in terms of the intrinsic properties of the groundwater system, consistent with the recommendation of Vrba and Zaporozec (1994). The term is sometimes referred to as 'intrinsic vulnerability' to distinguish it from 'specific vulnerability', a term that is generally preferred for situations where the role and behavior of a specific contaminant is explicitly considered in the analysis.

A relatively simple indexing method, DRASTIC, developed jointly by the US Environmental Protection Agency and the National Water Well Association (Aller et al. 1987) has emerged as the most popular and widely used technique for assessing the 'intrinsic vulnerability' of aquifers in eastern Algeria (Kachi et al. 2007), Nepal (Pathak et al. 2009) and northwest China (Wen et al. 2009). Despite

the apparent universality of the DRASTIC approach, the method has limitations. The method may also encounter problems in unusual hydrogeological environments such as karst where aquifer vulnerability is dominated by characteristics of the groundwater system that are inadequately represented in the basic DRASTIC model (Goldscheider 2005, Polemio et al 2009).

In this paper, the method of the Aquifer Vulnerability Index (Stempvoort et al 1993) and the concept of the German Geological Surveys (Hoelting et al 1995) was used. It is a GIS based assessment tool that has been used to perform a vulnerability assessment of groundwater underlying the alluvium in middle Ganga plain, a heavily populated region that relies heavily on groundwater for its potable water supply and there is great need of a reliable plan for resource management and protection. The applied method should give on the one hand a qualitative comparison and distinction within the catchment area and on the other it should also show a general estimation of the retention time in the unsaturated zone. The paper demonstrates the inherent value of AVI approach to vulnerability assessment but highlights the need to apply the method flexibly, incorporating changes that may better suit local hydrogeological conditions.

STUDY AREA, GEOLOGY AND HYDROGEOLOGY

The study area forms a part of central Ganga alluvial plain. The land surface, in general, has a blanket of clay followed at depth by sands of various grades, and clays at times admixed with kankar sands (Shukla and Raju, 2008). The lower Varuna river catchment area (Fig. 1) lies between the latitudes $25^{\circ}26'25''\text{N}$ and $25^{\circ}1'16''\text{N}$ and longitudes $82^{\circ}47'49''\text{E}$ and $83^{\circ}4'29''\text{E}$. The total study area of the lower Varuna river catchment area is around 315 km^2 . The drainage system is controlled by the river Varuna and its tributaries. The Varuna river is a tributary of the Ganga river and flows from west to east before finally joining the Ganga at the Mohan Sarai. The area receives rainfall from the southwest monsoon lasting from June to September with a mean annual rainfall of 102 cm. The study area enjoys tropical climate with short winter and long summer days. The temperature of the area varies from 5°C to 47°C .

Geologically, the lower Varuna river catchment area is a part of the Indo-Gangetic plain which is underlain by Quaternary alluvial sediments of Pleistocene to Recent. The unconsolidated sediments form a sequence of clays and sands of different grades. Nodular calcareous concretions at times intercalated with medium to fine grained sands form potential aquifers at various depths. Shallow aquifer occurs principally in clay kankar and meander river

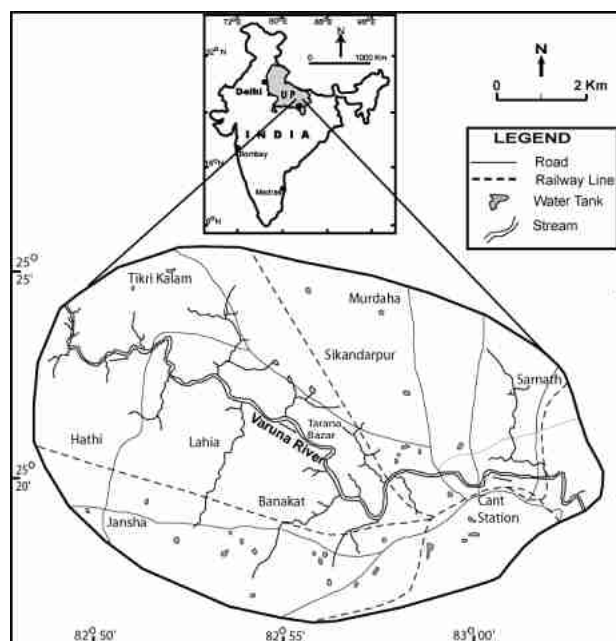


Fig.1. Location map of the lower Varuna river catchment area.

deposits. Deep aquifers occur in thick sand and gravel layers and have good potential. The sand beds with or without kankar in the study area forms the main aquifer zones of the multi-tier aquifer system. Near surface groundwater occurs under water table condition, while deeper aquifers occur in semi-confined to confined conditions. The hand pumps (bore wells) vary in depth from 40 to 60 m which mainly tap the unconfined aquifers. The general depth of deep bore wells ranges from 60 to 250 m bgl. From the well inventory, some perched water tables are also observed. The average hydraulic gradient is 0.35 m/km, which indicates porous formation at near surface of the area (Pandey, 1993).

The lower Varuna river catchment area is a traditional agricultural area. There are thousands of pumping wells for irrigation and drinking, and many of them are phreatic water wells. The dataset for the groundwater levels is taken from Ram (2010) and for the surface data the SRTM dataset (NASA 2005) is used. The surface data were proven according to data given in Ram (2010) for some measurement points and for the 80 m isoline. The resulting map of the depth to groundwater is shown in Fig.2, by applying the acquired data from wells and boreholes. Groundwater in the phreatic aquifer is relatively shallow (typically less than 4 m) such that flow directions are strongly influenced by surface topography. The general flow directions are towards central part of the river basin (i.e. Varuna river) which is in accordance with the general slope of the area and hence it is a effluent river system. The deeper water levels were recorded in the area adjacent to

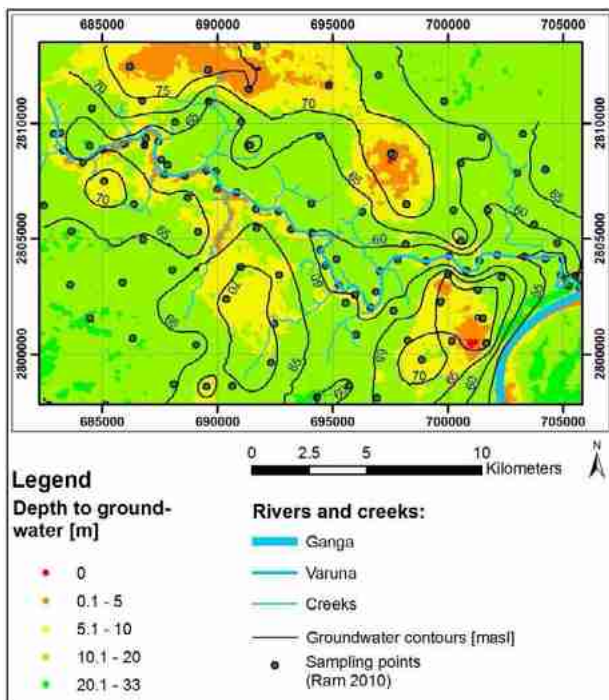


Fig.2. Depth to groundwater in the catchment area of the lower Varuna river

river Varuna due to gaining nature and in southwest, northern and northwest part due to overexploitation for irrigation use and effect of urbanization. It is obvious that the pumping in the pre-monsoon leads to a wide drawdown of groundwater levels even in the valley of the Varuna river. For the input data the pre-monsoon situation was taken because of the highest differentiation and the best groundwater protection can be outlined. The data for the surface geology and soil are uniform all over the area. Ram (2010) shows a map with coverage by alluvium and gives the profiles of three boreholes. These boreholes show the fine grained alluvium down to a depth of 4 to 5 m that consists of silty clay.

METHODOLOGY FOR AQUIFER VULNERABILITY ASSESSMENT

The basic data are especially the surface elevation and the groundwater surface to calculate the depth to groundwater. Both are interpolated on a 50 m x 50 m raster cell basis. Background of the approach was the need for an identification of areas with higher (or lower) groundwater vulnerability within the catchment of the lower Varuna river. The applied method should give on the one hand a qualitative comparison and distinction within the catchment area and on the other it should also show a general estimation of the retention time in the unsaturated zone. The geological situation is quite simple allowing an application of

techniques that are suitable for unconsolidated rocks. The groundwater vulnerability was estimated as intrinsic groundwater vulnerability since the land use changes are rapid in this area and, therefore, the specific vulnerability or a risk map for the groundwater is not appropriate.

According to these criteria two methods were chosen: The method of the Aquifer Vulnerability Index (AVI) (Stempvoort et al. 1993) and the concept of the German Geological Surveys (Hölting et al. 1995).

The AVI concept is very simple and suitable for the geological conditions of this area. It sums for all layers over the groundwater surface, the quotient of the thickness of the layers divided by the hydraulic conductivity. The thickness of the silty clay of the floodplains is given by a value of maximum 4 m according to the results of drilling in this area. In case of depth of groundwater, less than or equal to 4 m only is taken. The hydraulic conductivity of the silty clay was estimated as $1 \cdot 10^{-6}$ m/s. Below the silty clay of the floodplains follows a fine grained sand. The thickness was calculated as depth of groundwater minus 4 m for the silty clay of the floodplains. The hydraulic conductivity of this fine sand was estimated as $1 \cdot 10^{-5}$ m/s. In total the calculation of the AVI can be formulated mathematically as follows:

$$AVI = \begin{cases} \frac{gw}{k_1}, & gw \leq 4 \text{ m} \\ \frac{4 \text{ m}}{k_1} + \frac{gw - 4 \text{ m}}{k_2}, & gw > 4 \text{ m} \end{cases}$$

where gw = depth of groundwater; k_1 = hydraulic conductivity silty clay ($1 \cdot 10^{-6}$ m/s); k_2 = hydraulic conductivity fine sand ($1 \cdot 10^{-5}$ m/s).

The result is a value in [s], so it might be misunderstood as the retention time of the water in the unsaturated zone. In the description of the results the values are converted to days. This time is only a rough measure of the time shift of water pressure from surface to groundwater surface. The second concept applied to this map is the concept of the German Geological Surveys (Hölting et al. 1995) and is much more complex. It differentiates between:

- the influence of groundwater recharge,
- the protection by the soil zone (1 m),
- the protection by the unsaturated zone below the soil zone (1 m to depth to groundwater),
- the protection by perched aquifers, and
- the protection by confined aquifer conditions as shown by flowing wells.

The whole concept estimates the intrinsic vulnerability

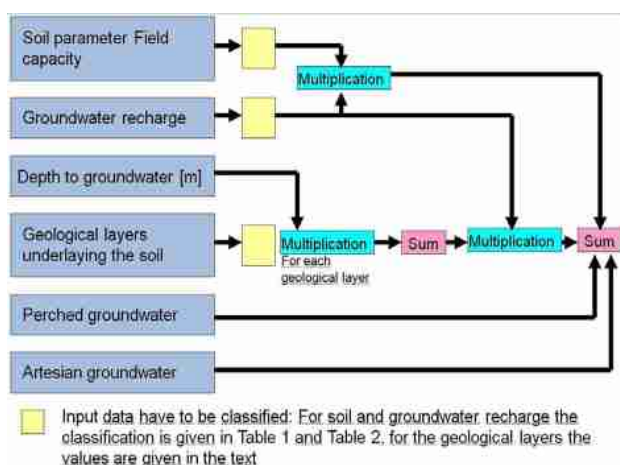


Fig.3. Structure of the calculation of groundwater vulnerability according to the concept of the German Geological Surveys (Hörling et al. 1995).

in a point scheme, therefore, also some of the parameters have to be classified. Compared to other classification methods, as used in the DRASTIC concept (Aller et al., 1987) this classification is very strict and is always bound to a defined parameter. The structure of the calculation system is given in Fig. 3. The influence of groundwater recharge is either classified according to recharge measurements or recharge modeling or it can be classified according to the climatic water balance. As an example, the groundwater recharge is modeled by a tool to be 250 mm/y. According to Table 1, the factor for the groundwater recharge is set to 1.25.

The reference parameter for the classification of the influence of the soil is the field capacity (see Table 2). The

Table 1. Factors for the groundwater recharge or the climatic water balance

Recharge	Climatic water balance	Factor
<100		1.75
>100-200	<100	1.5
>200-300	>100-200	1.25
>300-400	>200-300	1
>400	>300-400	0.75
	>400	0.5

Table 2. Points for the influence of the soil zone on groundwater protection

Field Capacity (mm)	Points
>250	750
>200-250	500
>140-200	250
>90-140	125
>50-90	50
<50	10

points for groundwater recharge and soil have to be multiplied to get a first value for the resulting sum of all points.

The protection by the unsaturated zone below the soil zone is higher differentiated according to unconsolidated rocks or hard rocks. The unconsolidated rocks are classified according to the substrates, i.e. silty clay gets 270 points/m and fine sand gets 25 points/m in case of the investigated area. These points have to be multiplied with the thickness of the layer minus the topmost 1 m of the soil zone. All layer values have to be summed and afterwards multiplied by the factor for the groundwater recharge. For perched groundwater and highly confined groundwater a predefined number of points should be added, but no perched groundwater or highly confined groundwater is reported in this area. The total sum of all these values allows for a rough estimation of the retention times of contaminants. The climatic condition was classified uniformly according to the climatic water balance. The mean annual precipitation is 1126 mm/a, and the potential evapotranspiration is calculated according to Thornthwaite (1948) to be 576 mm/a, so that a climatic water balance of 550 mm/a is the result (factor 0.5). The soil values are very uniform in the whole area (125 points). There are no further investigations of

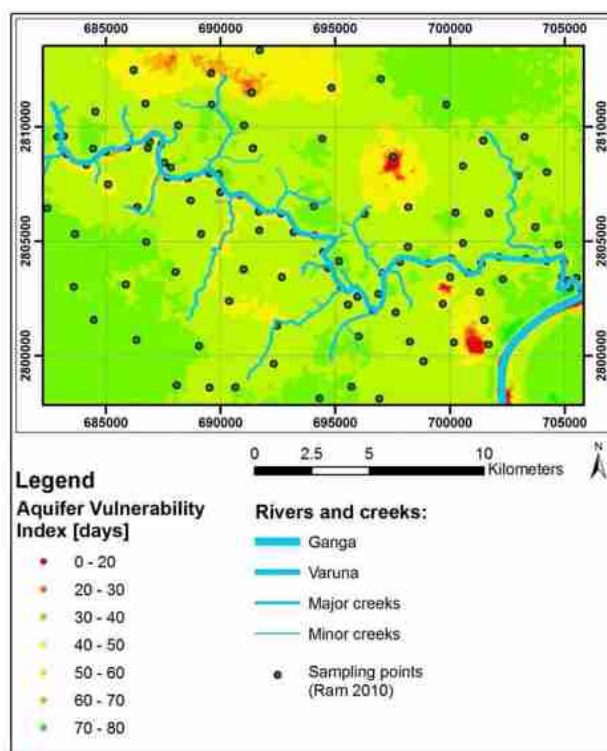


Fig.4. Vulnerability map of the lower Varuna river catchment area according to the AVI concept (Stempvoort et al. 1993). The classification in decades or days does not refer to a retention time of contaminants.

humic contents of the soils and, therefore, a single value according to the field capacity of silty clay is set. For the geological layers underlying the soil the first 3 m get the value for the silty clay and below that follows – if the depth of groundwater is more than 4 m – the fine sand.

RESULTS AND DISCUSSION

The results of the calculation of the aquifer vulnerability index (AVI) are shown in Fig. 4. A differentiation within the lower Varuna catchment area can be visualized. The distribution in the Fig. 4 with the classified AVI for the given number of hectares is dominated by the values between 50 and 70 days. Referring to the map, the distribution of lower values is restricted to agricultural areas which are at a wide distance from the river and the valley areas. The German concept shows no high differentiation. The point classification mainly yields values in the classes less than 500 points and 500 to 1000 points (s. hectares in Fig. 5), which results in a very high vulnerability (<500 points) to

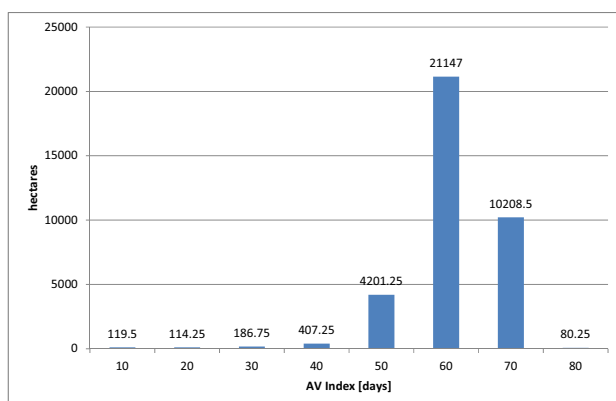


Fig.5. Probability distribution of the AVI in the catchment area of the lower Varuna River.

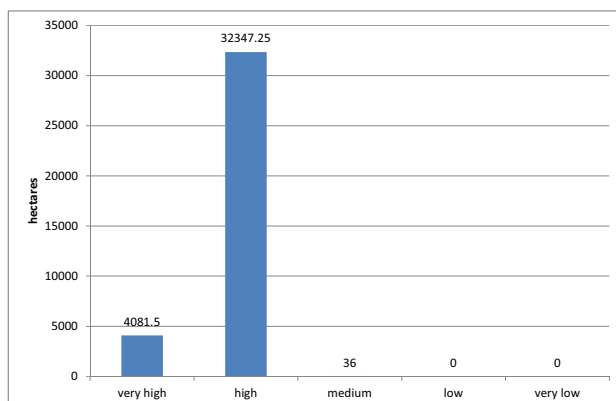


Fig.6. Probability distribution of the vulnerability according to Hölting et al. (1995) in the catchment area of the lower Varuna River. The classes are chosen according to the classification.

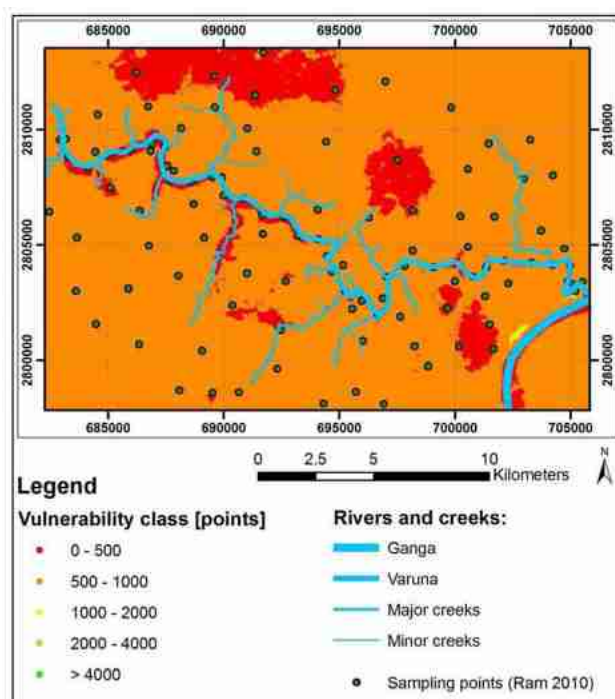


Fig.7. Vulnerability map of the lower Varuna River catchment area according to Hölting et al. (1995). The classification in decades of days does not refer to a retention time of contaminants.

high vulnerability (500-1000 points). The retention times of very high vulnerable areas is estimated to several days to several months and in highly vulnerable areas to several months to maximum 3 years. Figure 6 shows that the very highly vulnerable areas are located in the agricultural areas far from the river and the valley.

The calculations of the vulnerability were carried out based on the groundwater levels of the pre-monsoon whereas the groundwater levels of the post-monsoon are on an average 1.47 m higher than the pre-monsoon levels. This will only slightly change the indices in AVI and has no influence to the class values of the concept of Hölting et al. (1995). The seasonal aspect is, therefore, in this area not visible according to the concepts (Fig 7). Another aspect is the occurrence of mud cracks in the dry season. Due to preferential flow, mud cracks will decrease the retention time in the alluvium and, therefore, the indices have to be reduced. This question is not regarded in both concepts because they were developed mainly in humid climates.

CONCLUSION

Groundwater vulnerability assessments are an important component of groundwater resource protection plans and are essential for the development of reliable policies for

resource management and exploitation. The concepts show their applicability in India also although a number of conditions are not comparable. Soils and the top geological layers are different from soils in humid climates but this effect will have a higher influence on specific vulnerability values than on intrinsic vulnerability values. Uptil now the hard rock areas in India have not been regarded. In these

areas a more detailed analysis of the geology is necessary and this will possibly give a higher differentiation between the assessment values.

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