

# Groundwater Vulnerability Assessment Using a Common Index Model Adapted to Urban Conditions

T. Wolters, M. Koch & M. Rahimian

*Department of Geohydraulics and Engineering Hydrology, University of Kassel, Germany*

**ABSTRACT:** An index model based on DRASTIC and the related SINTACS is applied for groundwater vulnerability assessment in the highly urbanized area of Chennai City, India. In index models, empirical indices are allocated to certain intrinsic, physical parameters defining the underground and the land surface with regard to their capability to protect the aquifer against surficial contamination. Different from numerous former DRASTIC vulnerability studies, the specific site conditions as well as the monsoon-driven rainfall pattern are considered by adapting certain input parameters and their scores and weights to obtain a more realistic spatial distribution of the groundwater vulnerability. The adapted parameter maps are 'Depth to water table', 'Groundwater recharge', 'Aquifer media + Vadose zone', 'Soil media + Land cover', 'Topography', and 'Hydraulic conductivity', which are weighted and overlain to one composite map displaying mostly medium groundwater vulnerability. Fuzzy logic is then applied as an additional approach, wherefore four suitable parameters with continuous data sets are fuzzified first and, after defuzzification, combined with the two remaining parameters. The resulting map shows a slight increase of groundwater vulnerability compared to the classic approach. The two vulnerability maps can be used as a preliminary estimation tool to prevent further groundwater quality deterioration in the study region.

*Keywords: Vulnerability, DRASTIC, Groundwater, India, Urban, Index Model, Fuzzy Logic*

## 1 INTRODUCTION

Metropolitan areas of emerging and developing countries, with their high and dense population, often suffer from a large variety of intensive anthropogenic impacts. Many of the associated processes and structures, like sewer disposal, urban runoff, landfills, storage tanks, etc. pose contamination hazards to groundwater, as the effluent pollutants can be transported to the aquifer by surface infiltration. Therefore, groundwater protection strategies are urgently needed. However, remediation of aquifers, once they are contaminated, is time-consuming and costly, also the success is often uncertain. Therefore, the use of sustainable prevention measures of groundwater contamination is indispensable. A first step to do so may be the application of a groundwater vulnerability model that can provide valuable information on the planning of appropriate measures to prevent further groundwater quality deterioration. Among the three basic model types (physical, statistical and index) used for vulnerability assessment, index models are the most widely used as they allow the inclusion of complex hydrogeological properties in a rather comprehensible manner and their results are easily interpreted and implemented in the decision-making process of land-use planners and water resources managers (Focazio et al., 2002).

One of the most renowned index models are DRASTIC and SINTACS which, despite their widespread use, are still being criticized for having too many input parameters (Merchant, 1994) - which often are correlated to each other (Foster et al., 2002) -, for lacking validation (Nobre et al., 2007), or for not enough validation studies (Garrett et al., 1989). No wonder that many hydrogeologists argue about the often unconsidered applications of these models, due to oversimplification of complex geological conditions, hydrological processes or the neglect of human-caused changes of the land surface (Foster et al., 2013). On the other hand, by crucial adaptations within these index models, such as the addition and re-

removal of single input parameters, and assigning them different weights (Bai et al., 2012), or applying fuzzy logic (Dixon, 2005), a more realistic model to assess groundwater vulnerability can be created.

In this study, an adapted model based on DRASTIC and the related SINTACS is applied for groundwater vulnerability assessment in Chennai City, India, considering specific conditions of the highly urbanized area. Additionally, a similar vulnerability assessment based on fuzzy logic is applied by fuzzifying four parameter maps and combining them subsequently with the two remaining maps.

## 2 STUDY AREA

Chennai City (formerly Madras) is the capital of the state of Tamil Nadu in southeast India. The coastal megacity is the fourth largest in India, inhabiting 4.7 million people on an area of 176 km<sup>2</sup> which makes it one of the most densely populated areas in the world. This study focuses only on the urban area of Chennai City rather than the metropolitan area<sup>7</sup>.

Monthly averages of potential evapotranspiration collected from a weather station from 1901-2011 range from 144.1 (December) to 218.7 mm/month (May), whereas precipitation at this station averages 1183 mm/yr (Table 1). The southwest monsoon from June to September, which is the major monsoon for most parts of India, contributes in Chennai only about 35% to the annual rainfall, whereas its major proportion is measured during the northeast monsoon from October to December (60%). Since 2005, another weather station (KEA) additionally delivers data for the number of rain events, revealing an average of 58 days per year with rain. This results in high rain intensities of 17 mm and 30 mm for an average rainfall event during the southwest and northeast monsoon periods, respectively (KEA, 2012), which often leads to water stagnation in the streets of the city during these seasons.

Table 1. Mean of monthly measured precipitation of Chennai City (1901-2010); Chennai KEA weather station data for mean precipitation (2000-2011), rainy days (2005-2011) and calculated rain intensity.

Season Month	Dry Season			Summer		Southwest-monsoon				Northeast-monsoon			Year
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1901-2011 [mm]	17,6	11,9	5,8	15,4	42,1	50,9	96,1	139,1	138,3	248,9	283,9	132,9	1182,9
KEA 2000-2011 [mm]	20,3	16,4	36,7	10,3	44,9	76,2	106,8	133,5	131,6	307	382,5	167,7	1433,9
KEA 2005-11 [d]	2	<1	<1	<1	<1	4	7	8	7	11	11	5	58
Rain intensity [mm/d]						19,1	15,3	16,7	18,8	27,9	34,8	33,5	

## 3 MATERIALS AND METHODS

### 3.1 Data collection and processing

Climatic, hydrological, geological and land use data, as explicitly described below, was acquired on site from responsible state authorities and institutions. Additionally, online maps and information from scientific journals were used. The collected data was digitized and pre-processed in ArcGIS version 10.1 which was also used for the interpolation of point data, reclassification, weighting and overlaying of the parameter maps. For the fuzzy approach, the fuzzy toolbox of Matlab R2012a was employed.

### 3.2 Groundwater vulnerability models

In a hydrogeological context, vulnerability which can be intrinsic or specific describes the sensitivity of groundwater to contamination. Intrinsic vulnerability only considers the inherent geological, hydrological and hydrogeological characteristics and is valid for every type of contaminant, whereas specific vulnerability takes into account varying transport processes of different contaminants (Sinreich, 2009). Specific vulnerability was not investigated here, due to a lack of information on the groundwater chemicals.

Well suitable for intrinsic vulnerability assessment are index models, also referred to as parametric or overlay models. They are easy to use and operate with mostly readily available data (Liggett & Talwar, 2009). Basically, scores are subjectively assigned to different hydrogeological parameters, whose magnitudes depend on the parameters' effects to facilitate groundwater contamination.

Since the late 1980's numerous index models have been developed for vulnerability assessment, namely, GLA, AVI, DRASTIC, SINTACS, GOD, ISIS, EPIK, PI and more (Neukum *et al.*, 2008), wherefore. DRASTIC (Aller *et al.*, 1987) is the most frequently one used. Parameters, ratings and weights determined for this model arise from several field studies across the US. Physical properties of each parameter are assigned rating scores, ranging from 1 (low) - 10 (high vulnerability), each multiplied by a specific weighting factor (1 - 5). The overlay of the weighted maps results in a vulnerability map with five classes (Figure 1). The SINTACS model, developed by Civita & De Maio (1997), uses the same parameters as DRASTIC, only with slight adaptations of groundwater recharge for Mediterranean conditions and the implementation of various weighting systems, representing different hydrogeological scenarios.

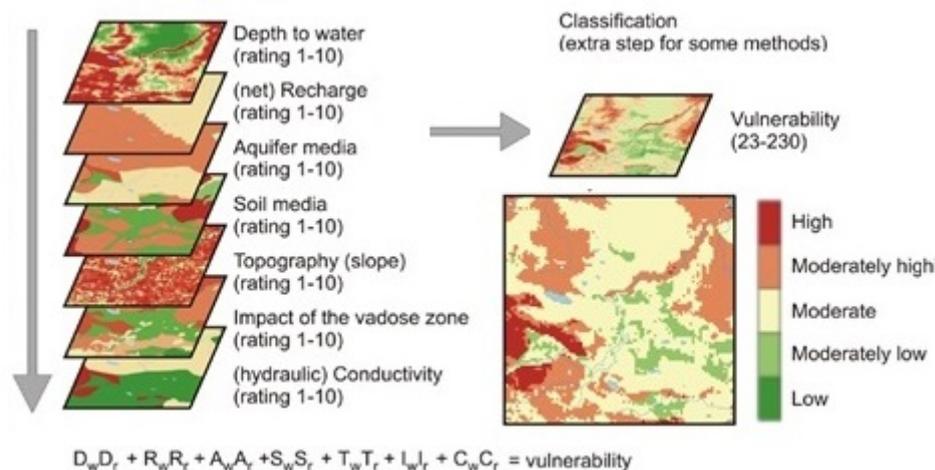


Figure 1. Creation of a groundwater vulnerability map using overlaying method DRASTIC (Liggett *et al.*, 2009)

### 3.3 Adapted approach

For Chennai City a modified version of DRASTIC and SINTACS is applied. Originally, DRASTIC and SINTACS were designed for rural areas and, thus, do not incorporate urban conditions with its anthropogenic influence on the land surface and the subsurface due to groundwater abstraction. However, some of the many DRASTICS studies have been some carried out in urban environments which take into account these special conditions (Kim & Hamm, 1999; Nobre *et al.*, 2007; Rahman, 2008) by appropriately modifying relevant factors, such as the Ground Water Recharge and the Soil Media factor. The advantages of SINTACS are its specific weighting system for different scenarios to detect the relevance of single parameters more precisely and the incorporation of the dilution effect in the classification of groundwater recharge. In fact, studies in Chennai show a decrease of solute concentration after heavy monsoon rains, as the aquifer is diluted with fresh precipitation water (Shanmugam *et al.*, 2007; Sathish & Elango, 2011), i.e. the illuviation of contaminants is outweighed by this process over a short time period.

## 4 GROUNDWATER VULNERABILITY MODEL

### 4.1 Depth to groundwater table

One of the most significant factors in DRASTIC is the depth to groundwater table, as the latter directly affects the vertical travel time of contaminant from surface impoundments (Stigter *et al.*, 2006). The DRASTIC model has been developed basically for temperate climate zones with little seasonal variations of the precipitation which results in small annual water table fluctuations, i.e. the depths to water tables are more or less constant. In Chennai, however, the precipitation amount strongly depends on the dry- and monsoon seasons which, together with the extensive groundwater abstractions, lead to extreme annual groundwater fluctuations. In this study, water levels from the beginning of October are selected, as this is the time right before the major northeast-monsoon, when heavy rainfall will carry most of the pollutants underground. The depth-to-water-table map is interpolated by universal Kriging from a total of 88 groundwater levels measured for year 200 by several Chennai local authorities.

The shallow groundwater level implies high groundwater vulnerability over the area. Following the original rating scheme of Aller *et al.* (1987), the scores of this parameter range from 7 to 10 (Table 2).

Table 2. Vulnerability scoring for parameter ‘Depth to Water Table’

Depth to water table [m]	< 1.5	1.5 – 4.5	4.5 – 6.75	> 6.75
Score	10	9	8	7

#### 4.2 Groundwater Recharge

As outlined above, DRASTIC was developed for temperate climate with uniform temporal rainfall distribution and natural land surfaces, both of which do not apply to the Chennai City study area. Therefore, an adapted approach is used for groundwater recharge estimation, wherefore monsoon- and non-monsoon seasons are segregated and the specific land cover is considered.

For estimating the recharge  $R_m$  [mm] in the monsoon-season, the ‘Water-Table Fluctuation Method’ (WTF) (Healy & Cook, 2002) is used:

$$R_m = \Delta h \times S_y + D_G \text{ [mm / 5 months]} \quad (1)$$

where  $S_y$  is the specific yield of the rocks,  $\Delta h$  [mm] is the net water level rise, and  $D_G$  [mm] is the groundwater draft during the monsoon-season.

Water level rises between 0.6 to 4.2 mm are calculated from the 88 measurement wells for a period of five months (October 2009 to February 2010), taking into account an extra month for base flow after the end of the monsoon rains in January. Specific yields, determined mainly from rock samples in the study area (Sivakumar *et al.*, 2006) and supplemented by empirical coherences of unconsolidated material and specific yield (GWREC, 2009), range between 0.04 and 0.23. A value of 135.8 mm is calculated for the groundwater draft in this period, based on assumptions of the groundwater extraction from 2002-2006 (Srinivasan *et al.*, 2010b), and then adapted to Chennai City area and its population in 2009, and the more up-to-date study of Dayamalar (2011).

For the remaining seven months, the water level is decreasing, thus a water balance approach for calculating the groundwater recharge is used,

$$R_{nm} = P - ET - Q + R_{Pipe} \text{ [mm / 7 months]} \quad (2)$$

wherefore the precipitation  $P$  and the evapotranspiration  $ET$  are taken from local weather station measurements (Table 1). The runoff  $Q$  is calculated with the SCS Runoff Curve Number method, where curve numbers represent certain soil and cover conditions which affect its infiltration potential (USDA, 1986). According to this approach, Chennai City is segregated in four land cover types (vegetation, roads, urban, water), resulting in four unique runoff values, ranging between 300 and 540 mm. In addition to natural recharge by precipitation, urban recharge is estimated by recharge from leaking pipeline recharge  $R_{Pipe}$  from leakage of Chennai City’s water supply and sewer systems. Srinivasan *et al.* (2010) estimate leakage rates of 100,000 m<sup>3</sup>/d, whereas GWEMC (2009) proposes to multiply area of underground canals in Chennai City (2,930,000 m<sup>2</sup> (CMWSSB, 2010b)) with the empirical seepage factor of 0.05 m/d, which results in a pipeline recharge of 146,500 m<sup>3</sup>/d. Thus, an average rate of 123,250 m<sup>3</sup>/d has been assumed, which is an aerial recharge 152 mm during the non-monsoon season. Adding up the two recharges  $R_m$  and  $R_{nm}$ , results in a total recharge between 344 and 751 mm/y.

In many index vulnerability models, like the original DRASTIC, vulnerability is enhanced by increased groundwater recharge. Since water is the main transport media for contaminants, this assumption is generally right. However, for very high volumes of introduced fresh water, like during a monsoon event, the concentration of most of the pollutants is diminished, due to the dilution effect of the water. Unlike the other methods, SINTACS takes this dilution effect into account, so that for low recharge rates (<250 and 300 mm/a), the transport of contaminants is the dominant process, whereas for higher recharge, the dilution effect gains relevance, i.e. vulnerability rates decrease. The relevance of this dilution effect for Chennai City has been justified by two local groundwater studies (Shanmugam *et al.*, 2007; Sathish & Elango, 2011) Based on this discussion, the vulnerability scores of, as indicated in Table 3, have been attributed to the groundwater recharge.

Table 3. Vulnerability scoring for parameter ‘Groundwater Recharge’

Groundwater Recharge [mm]	< 400	400 – 500	500 – 600	600 – 700	> 700
Score	8	7	6	5	4

### 4.3 Aquifer Media + Impact of Vadose Zone

The shallow aquifer of the study area and its covering layers consist almost exclusively of unconsolidated material from the recent alluvium. Its importance to groundwater vulnerability is rooted in its grain size. Soils with smaller grain sizes, like clay and silt, result in less space for the contaminants to move vertically through the vadose zone or along the hydraulic gradient in the aquifer, i.e. the vulnerability decreases (Hearne et al., 1995). Contrary to other DRASTIC studies, where the vadose zone and aquifer are usually considered as two independent zones, here the local conditions allow the combination to one layer. This is due, firstly, to the shallow groundwater surface, i.e. a thin vadose zone; secondly, to strong seasonal water table fluctuations and groundwater abstraction which induce a permanent boundary shift of saturated and unsaturated zone; and, lastly, to the fact that the two zones consist of the same alluvial material.

Three geological maps are overlaid in ArcGIS to create an intersecting map. Additionally, stratigraphic profiles of 67 boreholes, as well as three cross-sections are used to validate those maps. Out of these input data four different rock types are derived for the study area. These rocks are each allocated to different vulnerability scores (Table 4), based on the proposed ratings from DRASTIC and SINTACS.

Table 4. Vulnerability scoring for parameter ‘Aquifer Media + Impact of Vadose Zone’

Rock type	Medium Sand	Clayey Sand / Sand	Sandy Clay / Silt	Weath. hard rock
Score	7	6	4	3

### 4.4 Soil Media + Land Cover

The uppermost soil layer acts as a filter, buffer and decomposer of contaminants and is thereby integrated in the vulnerability method. Similarly to the aquifer rocks, scores are low for clayey and high for coarser material (Aller et al., 1987). The soil media data is based on a soil map of the Chennai Metropolitan Area (Dayamalar, 2011) and fitted by borehole data and a geological map (CMWSSB, 2012b). Five soil types (Sand, coarse loam, clayey sand, sandy clay, clay) are assigned to four hydrologic groups (A-D), according to their infiltration rate (USDA, 1986).

In extensive parts of urban environments the soil layer is altered and sealed due to human development. Therefore, the original soil layer is combined with a land cover layer generated with the aid of aerial images. Polygons of surface water are created and divided into canals, lakes, tanks, rivers and marshes. Greater pervious areas like lawns, parks or cemeteries are spotted and marked as ‘Non-urban’, whereas the rest of Chennai City is considered to be urban development, i.e. roads, residential and other built-up areas. For combination of the soil and land cover map, a vulnerability rating system with 8 scores is developed (Table 5), which is based on another urban DRASTIC study (Nobre et al., 2007).

Table 5. Vulnerability scoring for parameter ‘Soil Media + Land Cover’

Land Cover + Soil Group	Lakes	Marsh	Non-urban + A	Non-urban + B	Non-urban + C/D	Urban + A	Urban + B	Urban + C/D	Rivers /Canals
Score	8	7	6	5	4	3	2	1	

### 4.5 Topography

The surface slope determines potential surface runoff of water and contaminants. A flat topography retards the drainage of an area, thus increases the chance of contaminants to infiltrate into the ground, which, eventually, enhances groundwater vulnerability (Aller et al., 1987). Chennai City has maximum slopes of only 1.4 to 1.7% along the major rivers. This results in maximum vulnerability scores of 10 for almost the entire area and only two small areas along the Adyar River receiving a value of 9 (Table 6).

Table 6. Vulnerability scoring for parameter ‘Topography’

Slope [%]	< 1.5	> 1.5
Score	10	9

#### 4.6 Hydraulic Conductivity

Higher hydraulic conductivities accelerate contaminant transport, i.e. the vulnerability is increased (Hearne et al., 1995). Hydraulic conductivity is obtained from pumping tests carried out in the study area (CGWB, 2004; Elango *et al.*, 2006). For areas not covered by these tests, conductivity is derived from a specific yield map, outlined above. An empirical logarithmical formula relating the effective porosity and hydraulic conductivity of sands is also used. The hydraulic conductivity of the shallow aquifer ranges from 0.8 to 78 m/d and the vulnerability scores as shown in Table 7 are attributed, following the method of Aller *et al.* (1987), modified by adding intermediate classes.

Table 7. Vulnerability scoring for parameter ‘Hydraulic Conductivity’

Hydraulic conductivity [m/d]	> 61.3	40.8 – 61.3	34.6 – 40.8	28.6 – 34.6	20.4 – 28.6	12.2 – 20.4	4.1 – 12.2	< 4.1
Score	8	7	6	5	4	3	2	1

#### 4.7 Weighting and Overlaying

Finally, the six vulnerability maps are overlaid after weighting each parameter by a factor ranging from 1 to 6 which determines its importance to the overall vulnerability (Figure 2). DRASTIC by Aller *et al.* (1987) proposes a fixed weighting system, whereas recent DRASTIC studies claim modifications to better fit the local conditions (Zhong, 2005; Nobre *et al.*, 2007; Rahman, 2008). The SINTACS approach furthermore proposes five weighting systems for different hydrogeological scenarios (Civita & De Maio, 1997). Problems in assigning appropriate weights are overestimating the importance of recharge, weakening the importance of soil media and the aquifer ability to dilute the pollutants (Bai *et al.*, 2012). For this reason some adaptations to the original DRASTIC, as will be discussed later, have been made.

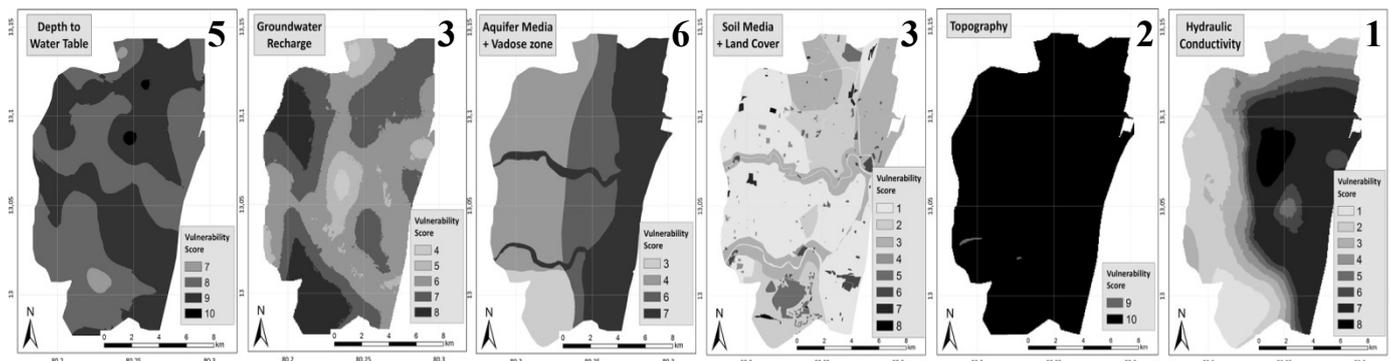


Figure 2. Six vulnerability parameter maps with respective weighting factor

Merging the two factors of Aquifer Media (AM) and Impact of Vadose Zone (IVZ) means to add their weights, which in the original DRASTIC are set to 3 and 5, respectively, resulting in a total weight of 8. In DRASTIC the layer thickness is neglected, in favour of IVZ, in contrast to other index models, such as GLA (Hölting et al., 1995) where it plays a major role. In Chennai City shallow groundwater levels result in a very thin vadose zone, which limits the effect of attenuation within this layer. For this reason the IVZ weight is decreased from 5, so that a total weight of 6 is now assigned to AM+ IVZ. Many DRASTIC studies assign low weights of 2 to the rather thin soil layer. By introducing the Land Cover as an additional factor in this study, however, Soil Media (SM) + Land Cover (LV) gain importance, considering the level of imperviousness for different types of land surfaces. Therefore an increased weight of 3 is assigned to SM+LC. The Topography is a minor factor in DRASTIC, representing the amount of precipitation being discharged or infiltrated. Extremely low slopes and the deficient drainage system lead to water stagnation in many parts of the area, which leads to a higher probability of infiltration. Accordingly, an increased weight of 2 is assigned. Since hydraulic conductivity (K) does not include the hydraulic gradient, the former does not reflect the actual flow velocity, which is the determining factor for contaminant spreading (Stigter et al., 2006). Therefore, the minimum weight of 1 is used for the K-factor.

#### 4.8 Fuzzy logic approach

DRASTIC method is based on the Boolean algorithm classifying with discrete thresholds. This classification causes uncertainties because of uncertainties in the choice of the threshold values. Using a method to specify more precisely the classification and to fine-tune the vulnerability map may be useful. Thus,

Fuzzy logic, at first proposed by Zadeh (1965), is applied in this study. Dixon (2005) used fuzzy logic, combining selected parameters from the DRASTIC index, to modify vulnerability maps in the Mississippi Delta region. Also land-use data was added for further adjustment. Niknam *et al.* (2007) combined fuzzy logic with the DRASTIC method to evaluate the Teheran-Karaj aquifer vulnerability.

Four vulnerability layers (parameters), namely, Depth to Water Table, Groundwater Recharge, Topography and Hydraulic Conductivity, have been used to modify the vulnerability map by fuzzy logic. The remaining two layers (Aquifer Media + Vadose Zone and Soil Media + Land Cover) are not suitable for fuzzy logic analysis, as they are defined by crisp borders, rather than by continuous values. MATLAB fuzzy toolbox has been used for this operation. Membership functions used are ‘II shape’ for hydraulic conductivity, groundwater recharge and depth to water and Gaussian for topography (Figure 3).

‘II shape’ is a product of a S-shape and a Z-shape membership function and is defined by Eq. 3. It is examined at the points determined by the value of the variable  $x$ . Factor  $a$  and  $d$  locate the bottom,  $b$  and  $c$  the top of the curves. The Gaussian function includes parameters  $\sigma$  and  $c$ , as given by Eq. 4, where  $c$  is the mean and  $\sigma$  is the standard deviation (width) (Mathworks, 2014).

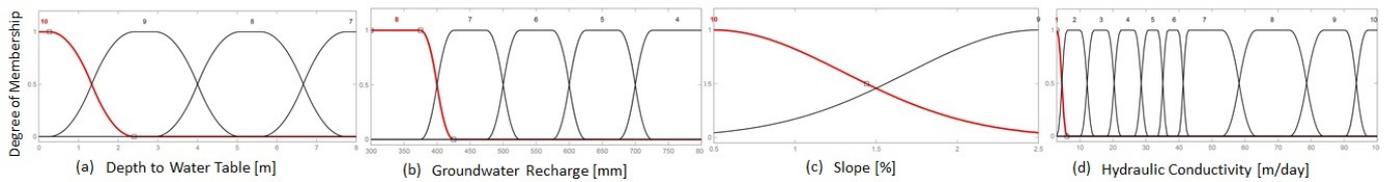


Figure 3. Membership functions for parameters modifying vulnerability scoring

$$f(x; a, b, c, d) = \left\{ \begin{array}{l} 0 \rightarrow x \leq a; 2 \left( \frac{x-a}{b-a} \right)^2 \rightarrow a \leq x \leq \frac{a+b}{2}; 1 - 2 \left( \frac{x-b}{b-a} \right)^2 \rightarrow \frac{a+b}{2} \leq x \leq b; 1 \rightarrow b \leq x \leq c; 1 - 2 \left( \frac{x-c}{d-c} \right)^2 \rightarrow \\ c \leq x \leq \frac{c+d}{2}; 2 \left( \frac{x-d}{d-c} \right)^2 \rightarrow \frac{c+d}{2} \leq x \leq d; 0 \rightarrow x \geq d \end{array} \right\} \quad (3)$$

$$f(x; \sigma, c) = e^{-\frac{(x-c)^2}{2\sigma^2}} \quad (4)$$

The priory-developed rating and weighting system was applied for the fuzzification. Thus, overall 400 rules have been defined for the four parameters. Defuzzification has been conducted, using the centroid method and, finally, the four maps have been overlaid in ArcGIS, together with the two remaining weighted maps to obtain the final groundwater vulnerability map.

## 5 RESULTS AND DISCUSSION

The final groundwater vulnerability maps obtained with the classic and fuzzy logic are shown in the left and right panels of Figure 4, respectively. The classical vulnerability map, obtained from the overlaying of the weighted single maps of Figure 2, displays predominantly medium (4 to 6) and scatteredly high values (7) throughout Chennai City. Comparing this map with the single parameter maps (Figure 2), it is obvious that the slightly increased vulnerability towards the coast in the east is mainly a consequence of the rock material in the vadose zone and the aquifer. This is a consequence of the high weight of 6, as well as of the clear formation of four discrete vulnerability areas. Also, the high vulnerability along the two rivers Adyar and Cooum is only representative for the river bank area, as the rivers themselves serve as outlet channels to the sea in the east.

The fuzzified groundwater vulnerability map (Figure 4, right panel) shows only little changes compared to the classic one. More specifically, the overall groundwater vulnerability index is slightly increased, particularly in the central, west and southwest, where the index goes up from 4 to 5 and 5 to 6, respectively. This is due to the uneven distribution of the four antecedent variables used in the analysis. For instance, for the parameters depth to water table and groundwater recharge, the majority of values are rather close to the threshold of the next higher vulnerability level. Consequently, while in the classic approach these values are considered solely to be at the lower vulnerability level, in fuzzy logic they are at the same time at a lower vulnerability level and partly at a higher vulnerability level.

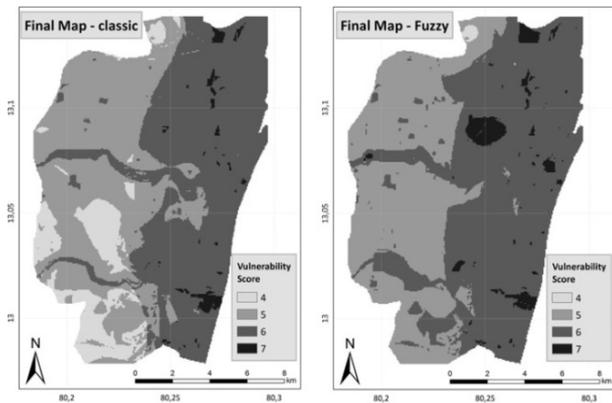


Figure 4. Final groundwater vulnerability maps for classic (left) and fuzzy logic approach (right)

In face of the study area's complexity and subjectivity of the rating systems, a set of uncertainties, concerning model assumptions, input parameter and numerical approximations remains, which should be kept in mind, when using these maps as management tools. To that regard, one important remark refers to the maps' intrinsic nature, where the attenuation processes that operate differently depending on the specific substance, as well as the layer properties, have been neglected. For remedy, the determination of the specific vulnerability should be a future task.

## REFERENCES

- Aller, L., Lehr, J. H., Petty, R., Bennett, T., Hackett, G. (1987). DRASTIC: A Standardized System to Evaluate Ground water Pollution Potential Using Hydrogeological Settings. Washington D.C.: U.S. Environmental Protection Agency.
- Bai, L., Wang, Y., Meng, F. (2012). Application of DRASTIC and extension theory in the groundwater vulnerability evaluation. *Water and Environment Journal*, 26 (3), 381-391.
- Civita, M., De Maio, M. (1997). SINTACS. Un sistema parametrico per la valutazione e la cartografia della vulnerabilità degli acquiferi all'inquinamento. Bologna: Pitagora Editrice.
- CGWB (2012). Central Ground Water Board. Aquifer Systems of Tamil Nadu and Puducherry. Ministry of Water Resources. Chennai: Government of India.
- CMWSSB (2010). Chennai Metro Water Supply and Sewerage Board. Water Supply System. Accessed at 12th December 2012 from <http://www.chennaiwater.tn.nic.in/departments/operation/developwss.htm>
- Dayamalar, D. (2011). Ground Water Scenario in Major Cities of India. Faridabad: Central Ground Water Board.
- Dixon, B. (2005). Applicability of Neuro-Fuzzy Techniques in Predicting Ground-Water Vulnerability: A GIS-Based Sensitivity Analysis. *Journal of Hydrology*, 1-4 (309), 17-38.
- Focazio, M. J., Reilly, T. E., Rupert, M. G., Helsel, D. R. (2002). Assessing Ground-Water Vulnerability to Contamination: Providing Scientifically Defensible Information for Decision Makers. Denver: U.S. Geological Survey Circular 1224.
- Foster, S., Hirata, R., Gomes, D., D'Elia, M., Paris, M. (2002). Groundwater Quality Protection - a guide for water utilities municipal authorities and environment agencies. Washington, D.C.: The World Bank
- Foster, S.; Hirata, R.; Andreo, B. (2013). The aquifer pollution vulnerability concept: aid or impediment in promoting groundwater protection? In: *Hydrogeology Journal* 21 (7), S. 1389–1392.
- Garrett, P., Williams, J., Rossoll, C., Tolman, A. (1989). Are ground water vulnerability classification systems workable? Columbus: National Ground Water Association.
- GWEMC (2009). Ground Water Estimation Methodology Committee. Detailed Guidelines for Implementing the Ground Water Estimation Methodology. Central Ground Water Board. Ministry of Water Resources. Government of India.
- GWEMC (2009). Ground Water Estimation Methodology Committee. Ground Water Resource Estimation Methodology. Ministry of Water Resources. Government of India.
- Healy, R., Cook, P. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal* (10), 91-109.
- Hearne, G., Wireman, M., Campbell, A., Turner, S., Ingersoll, G. (1995). Vulnerability of the uppermost ground water to contamination in the greater Denver area, Colorado. U.S. Geological Survey. Denver: U.S. Government Printing Office.
- Hölting, B., Haertle, T., Hohberger, K.-H., Nachtigall, K., Villinger, E., Weinzierl, W., et al. (1995). Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung. (B. f. Rohstoffe, Hrsg.) *Geologisches Jahrbuch*, C (63), 5-24.
- KEA (2012). KEA Weather Station Chennai. Accessed at 27th August 2013 from <http://www.kea.metsite.com/rainfall.htm>
- Kim, Y. J., Hamm, S.-Y. (1999). Assessment of the potential for groundwater contamination using the DRASTIC/EGIS technique, Cheongju area, South Korea. *Hydrogeology Journal* (7), 227-235.
- Liggett, J., Talwar, S. (2009). Groundwater Vulnerability Assessments and Integrated Water Resource Management. *Watershed Management Bulletin* 13 (2), 18-29.
- Mathworks (2014). pimf – II-shaped membership function. Fuzzy Logic Toolbox. R2014a Documentation Center. Accessed at 01st June, 2014 from <http://www.mathworks.de/de/help/fuzzy/pimf.html>
- Merchant, J. W. (1994). GIS-Based groundwater pollution hazard assessment: A critical review of the DRASTIC model. *Engineering & Remote Sensing*, 60 (9), 1117-1127.
- Niknam, R., Mohammadi, K., Majd, V.-J. (2007). Groundwater Vulnerability Evaluation of Tehran-Karaj Aquifer Using DRASTIC Method and Fuzzy Logic. *Iran-Water Resources research* 3 (2), 64-72.

- Neukum, C., Hötzl, H., Himmelsbach, T. (2008). Validation of vulnerability mapping methods by field investigations and numerical modelling. *Hydrogeology Journal* (16), 641-658.
- Nobre, R., Rotunno Filho, O., Mansur, W., Nobre, M., Consenza, C. (2007). Groundwater vulnerability and risk mapping using GIS, modeling and a fuzzy logic tool. *Journal of Contaminant Hydrology* (94), 277-292.
- Rahman, A. (2008). A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India. *Applied Geography* (28), 32-53.
- Sathish, S., Elango, L. (2011). Groundwater Quality and Vulnerability Mapping of an Unconfined Coastal Aquifer. *Journal of Spatial Hydrology*, 11 (1), 18-33.
- Shanmugam, P., Neelamani, S., Ahn, Y.-H., Philip, L., Hong, G.-H. (2007). Assessment of the levels of coastal marine pollution of Chennai city, Southern India. *Water Resource Management* (06).
- Sivakumar, C., Elango, L., Gnanasundar, D. (2006). Numerical modelling of Groundwater Flow in South Chennai Coastal Aquifer. *MODFLOW and more - Managing Groundwater Systems* (2006), 506-510.
- Sinreich, M. (2009). Konzept der Vulnerabilität im Grundwasserschutz. *gwa*, 89 (2), 109-117.
- Srinivasan, R., Balaji, R., Abdul Gaffar, P., Rama Murthy, V., Srinivas, S. (2010a). First Level Seismic Hazard Microzonation of Chennai Metropolis. Geological Survey of India, Hyderabad: Government of India.
- Srinivasan, V., Gorelick, S., Goulder, L. (2010b). A hydrologic-economic modeling approach for analysis of urban water supply dynamics in Chennai, India. *Water Resources Research* (46)
- Stigter, T. Y., Ribeiro, L., Carvalho Dill, A. M. (2006). Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. *Hydrogeology Journal* (14), 79-99.
- USDA (1986). *Urban Hydrology for Small Watersheds - Technical Release 55*. Natural Resources Conservation Centre. Conservation Engineering Division. Washington D.C. United States Department of Agriculture.
- Zadeh, L. A. (1965). Fuzzy sets. *Information and Control* 8 (3), S. 338–353.
- Zhong, Z.-S. (2005). A Discussion of Groundwater Vulnerability Assessment Methods. *Earth Science Frontiers* (S1), 3-13.