ISSN Print: 2394-7500
ISSN Online: 2394-5869
Impact Factor: 5.2
IJAR 2017; 3(5): 646-655
www.allresearchjournal.com
Received: 20-03-2017
Accepted: 21-04-2017

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Recent trends in groundwater vulnerability assessment techniques: A review

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Abstract
The concept of groundwater vulnerability to contamination is based on the assumption that the physical environment may provide some degree of protection to groundwater against natural and human impacts with respect to contaminants in the groundwater. It can be used as regional screening tool for groundwater quality risk assessment and managing groundwater sources, Groundwater vulnerability basically is the tendency or likelihood for the contaminants to reach a specific location in the groundwater system after release at some location above the uppermost aquifer. Various groundwater vulnerability assessment methods have been developed based on different approaches. These methods can be applied to a variety of hydrogeological settings, whether or not they contain specifically identified aquifers. Through this paper an attempt has been made to review some important groundwater vulnerability assessment techniques with main focus on overlay/index method and to present updated information by using comparative and evaluative analysis along with some recommendations.

Keywords: Groundwater; vulnerability assessment; overlay/index method; mapping

Introduction

Fresh water being one of the basic necessities for sustenance of life on the earth, the human race through the ages has striven to locate and develop it. Water, a vital source of life in its natural state is free from pollution but when man tampers the water body it loses its natural conditions (Asadi et. al 2007) [11]. Groundwater has been considered as an important source of water supply due to its relatively low susceptibility to pollution in comparison to surface water, and its large storage capacity (US EPA, 1985) [85]. The occurrence and movement of groundwater in an area is governed by several factors such as topography, lithology, geological structures, depth of weathering, extent of fractures, secondary porosity, slope, drainage pattern, landforms, land use/land cover, elevation, rainfall and other climatic conditions and interrelationship between these factors (Greenbaum 1992; Mukherjee et al. 2012) [31, 61] Being naturally filtered in their passage through the ground, groundwater is usually clear, colorless, and free from microbial contamination and requires minimal treatment. The excessive use and continued mismanagement of water resources to supply ever-increasing water demands to profligate users have led to water shortages, increasing pollution of freshwater resources and degraded ecosystems worldwide (Falkenmark and Lundqvist, 1997; Tsakiris, 2004; Jha et al. 2007) [27, 84, 38]. Rapid industrialization and consequent urbanization has led to several problems of water quality management (Katyal et al. 2012) [39]. Unfortunately, it seems that we can no longer take high quality groundwater for granted (Babiker et al. 2007) [14]. There are significant threat of diffuse and point pollution of groundwater from various activities such as release of soluble chemical from industrialization, urbanization and modern agricultural practices. The intrusion of pollutants to groundwater alters the water quality and reduces its value to the consumers (Melloul and Collin, 1994) [55].

Despite threats from potentially polluting activities, groundwater is often surprisingly resilient and water quality over large areas of the world generally remains good. In part this is because many aquifer systems possess a natural capacity to attenuate and thereby mitigate the effects of pollution. Though groundwater is not easily contaminated yet once this occurs it is difficult to remediate. The replacement cost of a failing local aquifer is generally high and its loss may stress other water resources looked to as substitutes.

Further, in the developing world, such remediation may prove practically impossible. Thus it is important to identify which aquifer systems and settings are most vulnerable to degradation. (Kaur and Rosin, 2011) [40]. It is now a well-recognized fact that water is a finite and vulnerable resource, and it must be used efficiently and in an ecologically sound manner for present and future generations. It is rightly said that groundwater will be an enduring gauge of this generation's intelligence in water and land management (Jha et al. 2007) [38].

2. Concept of aquifer vulnerability

In 1968 the French Margat first time used the term vulnerability in Hydrogeology, thereafter the concept was adopted worldwide (Albinet, M. and Margat, 1970) [6]. The concept of groundwater vulnerability to contamination is based on the assumption that the physical environment may provide some degree of protection to groundwater against natural and human impacts with respect to contaminants in the groundwater (Hallaq and Eliash, 2011) [33]. A common definition of groundwater vulnerability has not been agreed upon and various definitions of vulnerability have been proposed (Lindstorm, 2005) [48]. One mostly used definition is given by NRC that defined groundwater vulnerability as "the tendency or likelihood for the contaminants to reach a specific location in the groundwater system after release at some location above the uppermost aquifer" (NRC, 1993; Thirumalaivasan and Karmegam, 2001) [64, 80]. Later on Vrba and Zaporozec (1994) [90] defined groundwater vulnerability as "an intrinsic property of a groundwater system, depending on the sensitivity of that system to human and/or natural impacts". Foster and Hirata (1988) [29] aquifer pollution vulnerability as the "intrinsic characteristics which determines the sensitivity of various parts of an aquifer to being adversely affected by a imposed contaminant load".

Groundwater vulnerability may be intrinsic or specific. Intrinsic vulnerability refers to the aquifer being prone to contamination and is inherent to the geological and hydrogeological features of an area, regardless of the nature of the pollutants. Specific vulnerability defines the aquifer vulnerability for a group of pollutants or just a single particular pollutant (Vrba and Zaporec 1994) [90]. Specific vulnerability is produced by the properties of the pollutants themselves and their relationship with several intrinsic vulnerability components (Leal et al. 2010) [72].

Groundwater vulnerability is a function of the geologic setting of an area, as this largely controls the amount of time, i.e. the residence time of the groundwater that has passed since the water fell as rain, infiltrated through the soil, reached the water table, and began flowing to its present location (Prior et al, 2003) [69]. With the growing recognition of the importance of underground water resources, efforts are increasing to prevent, reduce, and eliminate groundwater pollution (Rahman 2008) [70].

Through this paper an attempt has been made to carry out review of important groundwater vulnerability assessment techniques with main focus on overlay/index method and to present updated information by using comparative and evaluative analysis.

3. Overview of methodology

According to National Research Council (1993) [64] groundwater vulnerability assessment method can be divided into three groups; subjective rating methods, statistical and process-based methods.

a. Subjective rating methods

Subjective rating method ranges from basic index and overlay methods to subjective hybrid methods. Index and overlay method are based on combining maps of various physiographic attributes (geology, soil, aquifer media, depth to water) controlling groundwater vulnerability of the region by assigning a numerical score or rating to each attribute. In all subjective rating methods relative degrees of ground-water vulnerability usually delineated in terms of low, medium, and high. DRASTIC (Aller et al., 1987) [7] is the most commonly used method other method includes, SINTACS (Civita, 1994) [17], GOD (Foster, 1987) [28], AVI (Van Stempvoort et al.1993) [78], EPIK (Doerfliger and Zwahlen, 1997) [23], SI (Ribeiro, 2000) [74] etc. Hybrid methods are defined as any methods that combine components of statistical, process-based, and (or) index methods. Subjective hybrid methods, which also include combinations of statistical, process based, or other objective components, incorporate subjective categorization and indexing of vulnerability. Subjective hybrid methods commonly do not rely on preconceived scoring systems such as DRASTIC or other index methods but instead produce project-specific categorizations (Focazio et al, 2002) [59].

b. Statistical method

Statistical method ranges from descriptive statistics of concentration of contaminant to more complex regression analysis. They incorporate data on known contaminant and their distribution areas and which provide information of contamination potential for the specific geographic area from the data. Additional information on factors affecting the intrinsic vulnerability of the resource can be obtained by using logistic regression. Evans and Maidment (1995) [26] examined the vulnerability of Texas groundwater to nitrate contamination by applying discrete probability and lognormal probability estimate methods and liner regression was used to assess the relationship between exceedence probability of nitrate and potential indicator parameters also tried to find out relation between the spatial patterns of nitrate contamination and the sale of nitrogen fertilizers. But result revealed no significant relationship. Troiano et al., (1999) [83] used CALVUL method in California to determine the groundwater vulnerability due to pesticide leaching. Teso *et al*. (1996) [79] applied a logistic regression model with GIS for predict groundwater vulnerability to pesticides.

c. Process based stimulation method

Process based methods examine vulnerability from a quantitative point of view by using equations governing water flow and solute transport. These models include the use of process simulating models that calculate the distribution of vulnerable areas based on the movement of water and solutes. These methods may be used to assess one or many underlying processes and can include direct field observations of environmental tracers place in the context o groundwater flow system. The most widely used numerical groundwater flow model is MODFLOW which is a three dimensional model, originally developed by the U.S. Geological Survey (McDonald and Harbaugh 1988; Kouli et al.,2008) [54, 46]. Rahman (2008) [90] applied MODFLOW model in muzzafarnagar to generate quantitative database on hydrogeological parameters and to study groundwater balance. Mechanistic models used for vulnerability assessment are most commonly one-dimensional NPS pollution models, such as LEACHM (Wagenet and Hudson, 1987) [91], MACRO (Jarvis, 1994) [36], WAVE (Vanclooster *et al*., 1994, 1995) [87], HYDRUS (Simunek *et al*., 1998) [76], PEARL (Tiktak *et al*., 2000) [81], MOC model (Konikow and Bredehoef, 1978, Konikow *et al*., 1994) [45, 44], The most used computer programme for groundwater modelling in three dimen-sions is MODFLOW (McDonald and Har-baugh, 1988) [54]. FEFLOW. Eliasson (2001) [25] applied the FEFLOW model for predicting the impact of de-icing salt and acci-dental spills from a large road to an important aquifer for water supply and results of model were used in the context of a Multiple Criteria Decision Aid System. Lindström (2006) [49] conducted a study in Sweden by using the one-dimensional unsaturated MACRO model and the two-dimensional MOC model to assess the groundwater vulnerability due to salt from road de-icing in a water supply area. Chloride was used as an indicator for determining the vulnerability for groundwater contamination from road.

4. Groundwater vulnerability assessment techniques

In Recent decades various methods of groundwater vulnerability assessment have been developed which are based on different approaches. They range from sophisticated numerical models simulating the physical, chemical and biological processes occurring in the subsurface, to techniques using weighting factors affecting vulnerability and also to statistical methods. (Gogu and Dassargues 2000) [30]. Various classical vulnerability methods like GOD, AVI and empirical vulnerability methods like DRASTIC, SINTACS, EPIK and SI can be used. Most often they are based on overlay and index techniques. Use of these methods depends upon the aquifer type, pollutant type and availability of data. Some of the main methods are discussed below:

a. GOD method

Foster (1987) [28] developed GOD method which is a rating based simple method. It is a classical system for quick assessment of the aquifer vulnerability to pollution. Three main parameters are considered: the groundwater occurrence, the lithology of the overlying layers, and the depth to groundwater (in unconfined or confined conditions). The vulnerability index is the result of the values assigned to these three parameters. The vulnerability index is computed by choosing first the rating of groundwater occurrence parameter and then multiplying by the overlying lithology rating as well as with the depth to water parameter rating. Rating values are given in table 1. The overlying lithology parameter contributes to the vulnerability index only in the case of unconfined aquifers. Because the parameters can only take values from 0 to 1, the computation result is usually a value less than the score assigned to each parameter (Gogu and Dassargues 2000) [30]. The Vulnerability index can be calculated by following formula GOD vulnerability index = Rating for groundwater occurrence x Rating for overlaying lithology of unsaturated zone x Rating for depth to groundwater

Table 1: Rating values of the vulnerability parameters for GOD method

Parameter	Ranges and Rates					
G (groundwater occurrence)	Range	none	overflowing	confined	semi confined	unconfined
	Rating	0	0.1	0.2	0.3	1
O (overall lithology of aquifer)	Range	Alluvial Fan	gravel and sand	sand	silt and clay, Silt and clay	clay
	Rating	0.8	0.7	0.6	0.5	0.4
D (depth to groundwater)	Range< 2 2 - 5	5 - 10	10 - 20	20 -50	50- 100	> 100
	Rating 1.0, 0.9	0.8	0.7	0.6	0.5	0.4

Source: Foster (1987) [28]

Khodapanah et al (2011) [43] applied GOD method with GIS to study alluvial aquifer in Iran and showed that GOD can provide good result for designing large area and GIS provided an efficient environment for analysis and handling of large spatial data.

b. DRASTIC Method

DRASTIC is a groundwater vulnerability model for evaluating the pollution potential of large areas using the hydrogeological settings of the region. This model was developed by the US EPA (US Environmental Protection Agency) in the 1980s (Aller et al. 1987) [7] as a standardized system for evaluating the intrinsic vulnerability of groundwater to pollution. This model employs a numerical ranking system that assigns relative weights to various parameters that help in the evaluation of relative groundwater vulnerability to contamination (Sinanh and Razack 2009) [77]. Weights are given in the table 2. Dixon (2005) [22] improved the DRASTIC index results by using fuzzy based model. The DRASTIC system considers seven parameters: depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity of the aquifer (C). The final vulnerability index (*Di*) is a weighted sum of the seven parameters and can be computed using the formula;

DRASTIC Index (*Di*) = $D_rD_w+R_rR_w+A_rA_w+S_rS_w+T_rT_w+I_rI_w+C_rC_w$

Where, w -Weight factor for parameter, r- Rating for parameter

Table 2: Weights of DRASTIC Parameters

Parameters	DRASTIC Weight	Pesticide DRASTIC Weight
Depth to water table	5	5
Net Recharge	4	4
Aquifer Media	3	3
Soil Media	2	5
Topography	1	3
Impact of Vadose Zone	5	4
Hydraulic Conductivity	3	2

Source: Aller et al. (1987) [7]

In india this method has been applied in different states by various researchers as by Rahaman (2008) in Aligarh, Nagar and Mirza (2002) [62] in Jammu, Ckakraborty et.al. (2007) [19] in north Bengal and Alam et al.(2012) [4] in central Ganga plains. Khan et al. (2010) [41] modified DRASTIC by introducing Land use as a parameter and applied to categorized Indo Gagnetic plains into vulnerability Zones. This method is also used worldwide in a number of studies. Babiker et al. (2005) [13] assessed groundwater pollution risk by applying the DRASTIC model along with sensitivity analysis to evaluate the relative importance of the model parameters for aquifer vulnerability in Kakamigahara Heights, central Japan. Generic DRASTIC has been applied by Hamza et. al. in Northern Tunisia (2007) [34], Anornu et al. (2012) [10] in Ghana, Breaban and Paiu (2012) [16] in Romania, and Varol and Devaz (2010) [88] in Turkey, Lobo-Ferreira and Oliveira (1997) [51] in Portugal, Lynch et al. (1997) [52] in South Africa, Melloul and Collin (1998) [56] in Israel while modified DRASTIC approached has been adopted by Al-Adamat et. al. (2003) [3] in Jordan, Javadi et. al. (2011) [37] in northern Iran, Al- Zabet (2002) [8] in Abu Dhabhi, Awawdeh and Jaradat in Jordan (2010) [12], and Pathak et al. (2009) [66] applied in Kathmandu valley and Remesan and Panda (2008) [73] employed DRASTIC and Pesticide DRASTIC to evaluate vulnerability of kapgarhi catchment, West Bengal.

Study considered socio-economic value of groundwater as a risk indicator and revealed interesting results which provide an adequate spatial tool for decision making at a municipality scale.

Guler et al. (2013) [32] conducted a study in coastal zone of Tunisia by employing both Generic and Pesticide DRASTIC method for assessing groundwater vulnerability to non point source pollution under conflicting land use pattern. Correlation analysis showed a significant association between high groundwater NO_3^{-}concentration and distance between LULC types.

Panagopoulos et al. (2006) [65] modified and optimized DRASTIC model by incorporating simple statistical and geostatistical techniques. These techniques were used for revising the factor ratings and weightings of all the DRASTIC parameters in a GIS environment. On the basis of correlation coefficient of each parameter with the nitrates concentration soil type and hydraulic conductivity were removed and landuse included as additional factor. After the modifications, the correlation coefficient between groundwater pollution risk and nitrates concentration found to be higher than the original method.

c. The Aquifer Vulnerability Index method

Van Stempvoort et al (1993) [78] developed AVI method which is a measure of groundwater vulnerability based on two physical parameters. i) thickness (d) of each sedimentary layer above the uppermost, saturated aquifer surface, and ii) estimated hydraulic conductivity (K) of each of these sedimentary layers. Based on the two physical parameters, d and K, the hydraulic resistance "c" can be calculated for layers 1 to I by using equation 1.

$\mathbf{c} = \sum \boldsymbol{d/Ki}$ ………… Eq. 1

This parameter c is a theoretical factor used to describe the resistance of an aquitard to vertical flow. The *c* or log (*c*) value is related to a qualitative Aquifer Vulnerability Index by a relationship table. The authors suggest calculating *c* for each well or test hole and then to generate the iso-resistance contour to classify the study area in AVI zones. (Gogu and Dassargues 2000) [30].

d. SINTACS method

The SINTACS method was developed by Civita (1994) [17] and Civita and De Maio (1997) [18] to assess the intrinsic vulnerability of groundwater. The method was adopted and modified from the DRASTIC method which has been widely used in the USA. The rate (R) and weight (W) of each variable are assigned a value from 0 to 10 or from 0 to 5. The weight of each variable will be different depending on the hydrogeologic scenario (Majandang and Sarapirome, 2013) [53] this method involves seven parameters and its name is derived from the initial of each parameter such as static level depth, net recharge, non-saturated zone, soil type, aquifer type, hydraulic conductivity and topographic slope. It can be calculated by usig following equation:

$$\mathbf{I_{SINTACS} = S_{r1}S_{w1} + I_rI_w + N_rN_w + T_rT_w + A_rA_w + C_rC_w + S_rS_w}$$

Where,
w -Weight factor for parameter,
r- Rating for parameter

Leal et al (2012) [71] applied SINTACS along with water quality index in mexico and established a cause and effect relationship between potential source of contamination and water quality indices. Majandang and Sarapirome (2013) [53] used SINTACS in thiland to evaluate intrinsic groundwater vulnerability. Amoush et al (2010) [5] conducted a study in Northern Jordan valley by using SINTACS. Result revealed a high correlated between measured concentration of nitrate and parameters of SINTACS. Senstivity analysis showed soil overburden attenuation capacity parameter (T) and the depth to the groundwater parameter (S) were the most sensitive parameters to SINTACS vulnerability model. Effective weights analysis was performed to revise the weights of the index.

e. Susceptibility Index (SI)

Susceptibility Index (SI), developed by Ribeiro (2000) [74], involves five layers which are: Depth to water, Net Recharge, Aquifer media, Topography and Land Use (LU). SI system contains three significant parts: weights, ranges and ratings. The ranges for water depth, net recharge, topography and aquifer media are identical to DRASTIC, while range for land use are based on CORINE Land-Cover classification (European Community 1993), (Anane et al, 2013) [9]. Weights for each parameters are given in table 3

$$\mathbf{SI\ Index= D_rD_w+R_rR_w+A_rA_w+T_rT_w+LU_rLU}$$

Where,
w -Weight factor for parameter,
r- Rating for parameter

Table 3: Weights of SI Parameters

Parameters	SI Weight
Depth to water table	0.186
Net Recharge	0.212
Aquifer Media	0.259
Topography	0.121
Land use	0.222

Source: Riberio 2000 in van Beynena et al. (2012) [86]

Van Beynena et al. (2012) [86] applied SI in karst region of Portugal and states that land use is a crucial and influencing factor on groundwater contamination through the pollution generated by anthropogenic activities and soil media is indirectly represented by land use. Himer et al. (2013) [24]

used SI method to evaluate a wetland watershed in morocco and founded low natural protection of wetland against pollution and suggested urgent management actions for preservation.

5. Overall methodology

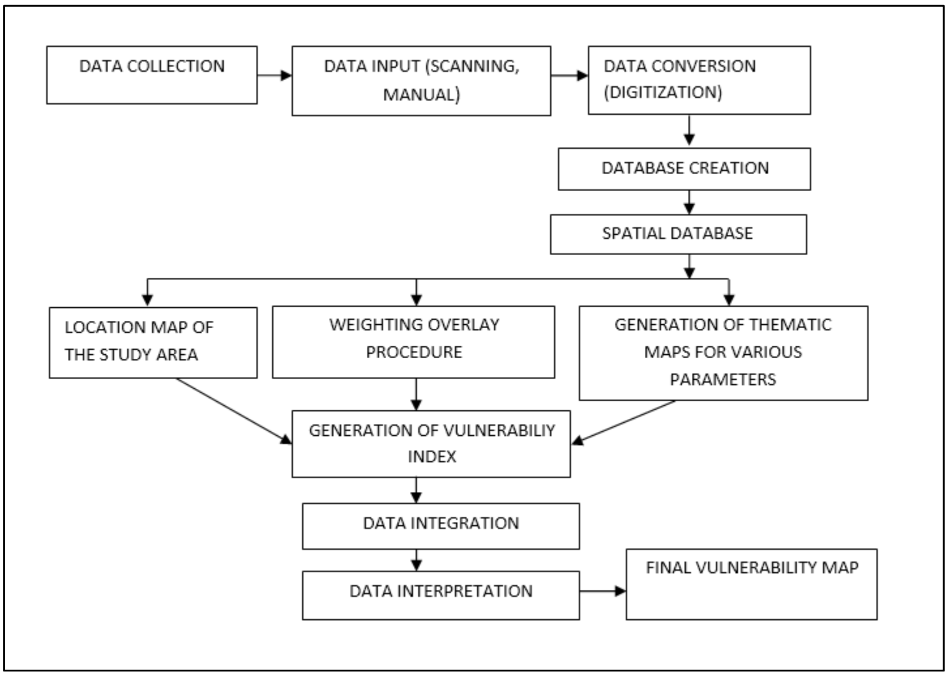

Fig 1: Flow Chart showing overall methodology for vulnerability indexing and mapping.

6. Review of some comparative studies

This paper presents some of important cases where an attempt has been made to compare several vulnerability methods. One of the cases is from mexico where Belmonte-Jimenez et al. compared three methods DRASTIC, AVI and GOD to evaluate zacchila valley aquifer. It was shown that GOD method generates some zones of this aquifer with medium to high vulnerability. The AVI method assigns to the valley a high to very high vulnerability. DRASTIC method assigned a high vulnerability to larger area. A sensitivity analysis of DRASTIC suggests that depth to water table is the key factor determining vulnerability, followed by impact to the vadose zone and soil type. It has been concluded that pesticide DRASTIC and GOD provide similar results, but DRASTIC may be considered more reliable since it is based on more hydrogeological parameters. However, for reconnaissance studies, the methods AVI and GOD provides good preliminary tools.

Vias et. al. (2005) [89] conducted another significant comparative study of four schemes GOD, AVI, DRATIC and EPIK to study a diffuse flow carbonate aquifer and to evaluate variations in the degree of vulnerability associated to the rainfall variations under Mediterranean climatic conditions in Spain. Result revealed that the GOD method could be adequate for vulnerability mapping in poorly karstified carbonate aquifers at least at small–moderate scales. For large scale and area with well developed it could be useful to compare the results of the GOD method with EPIK method, GOD method has found to be most adequate method out of four applied method for vulnerability mapping of study area.

Corniello et al. (1997) [20] tested four methods DRASTIC, SINTACS, GOD, and the AVI model to assess the vulnerability of the aquifer in "Piana Campana" region, Southern Italy. For qualitative comparison, specific aspects of vulnerability classes were considered. It was shown that the SINTACS method, compared with the others, generates "very high vulnerability zones in the areas concerned with surface waters and aquifer interactions. This result is strongly influenced by the aquifer identification and by different weight classification series used for the area affected by drainage.

Anane et al. (2013) [9] applied DRASTIC, Pesticide DRASTIC and Susceptibility Index method in Tunisia toassess pollution potential of shallow aquifer. In the study the SI layer was overlaid on DRASTIC and Pesticide DRASTIC to extract the area of agreement and divergence in vulnerability. Result of study revealed that DRASTIC identified low vulnerability and underestimate the pollution risk while Pesticide DRASTIC and SI identified three vulnerability categories represents better risk and recommended for future.

Mohammadi et al (2011) [60, 37] compared two vulnerability assessment method DRASTIC and GOD to predict more contamination prone area in central Labrador. DRASTIC used seven hydrological and hydrogeological parameters but the GOD rating system used only three parameters. Both the DRASTIC and GOD methods were compared qualitatively and statistically. It had been found that GOD method was relatively close to DRASTIC, therefore, a simpler method such as GOD can be used in areas with limited information.

Afonso et. al. (2008) [2] applied GOD and DRASTIC method to assess urban areas of northwest Portugal and concluded that GOD method is best suitable for designing large area such as land management while DRASTIC has good accuracy, flexibility and more effectively used in geoenvironmental detailed studies. Comparison of vulnerability methods can be used to estimate their efficiency for vulnerability of the study area. A method delineating more contrasted result for a specific area can be considered more accurate as giving higher sensibility.

List of some comparative studies conducted worldwide is given in table 4

Table 4: List of some comparative studies

Author	Study area	Year	Model used
Napolitano and Fabbri	Southern Italy	1996	Drastic,Sintacs
Ibe et al.	Southeastern Nigeria	2001	God,Drastic, Legrand, Siga
Ferreirea and Oliveira	Portugal	2004	God,Drastic,Sintacs,Avi, Si, Eppna
Tovar and Rodriguez	Mexico	2004	God,Avi
Mendoza and Barmen	Nicaragua	2006	God, Drastic
Polemio et al	Southern Italy	2009	God,Drastic,Sintacs, Cop,Epik, Pi
Khemiri et al.	Tunisia	2013	Drastic,Sintacs, God, Si
Abdelmadjid and Omar	Algeria	2013	Drastic,Sintacs, God, Si

7. Discussion

The general aim of groundwater vulnerability assessment is to support decision making procedures for monitoring and preservation of groundwater status by identifying sensitive areas, and prioritizing areas for further monitoring or protection. For this process based, statistical and overlay and index model can be utilized under different hydrogeological conditions.

In contrast to process based and statistical models, the overlay and index models are less constrained by data shortage and computation problems. There are numerous overlay and index methods that can be applied under different environment but a universal method that can applied to all hydrogeological environment is lacking.

Overlay and index methods probably will remain the main staple for vulnerability mapping. They are most suited for planning department. Process based models with computer models will work best if information about hydrogeology and unsaturated zone condition are well known along with data for building a groundwater model. Statistical models are usually region specific and useful for building prediction models for areas where widespread contamination of pesticide exist.

Vulnerability methods can be applied to a variety of hydrogeological settings, whether or not they contain specifically identified aquifers. However, some methods are best suited to assess groundwater within aquifers, while others assess groundwater above aquifers or groundwater in areas where aquifers have not been identified. Vulnerability maps are regional screening tool and can be used for groundwater quality risk assessment and managing groundwater sources, Guiding development and land use planning, Prioritizing contaminated area for clean up and groundwater monitoring. They could be used as meaningful tool in environmental decision making process, Educating the public and raising the awareness of need for groundwater protection (Liggett et al. 2011) [47]. They can be used to define areas with special regulations for agro-chemical application. Before using the intrinsic vulnerability maps, care should be taken for the areas of high vulnerability as these areas offer the least amount of natural protection to the aquifer. Generally these areas require more comprehensive groundwater protection measures, especially if located in an area identified as a source water protection zone or an aquifer recharge zone.

Vulnerability assessment has several limitations as it is a relative, non-measurable property not in absolute term. Weighting are chosen arbitrarily and based on expert opinion. Some authors argued that vulnerability mapping methodologies cannot take into account all of the site specific heterogeneities that exist in the subsurface geological framework (Davidson et al. 2002) [21]. Systems based on indices do not capture the probabilistic nature or the uncertainty of groundwater vulnerability (Worrall, 2002) and uncertainties in the data themselves and in the actual relevance of each weighted factor question the reliability of the vulnerability maps (Merchant, 1994) [58].

Although there are some limitations of overlay/ index method but they can be improved by integration of overlay/index with process based method and improvement in GIS software for effective integration of assessment methods with spatial attribute database can be more useful. Prediction capabilities of DRASTIC models can be improved by incorporating land use/ land cover data into them. Use of hydro-chemical data with vulnerability data can give more realistic results. Additional research should be focused on the determination of the relative importance of and possible interdependencies among parameters considered in the overlay/ index model. Numerous aspects that affect groundwater vulnerability assessment like climate, vegetation, data access etc. along with hydrogeological data need to be studied further. The utility and reliability of these methods depends upon the availability, nature and quality of data used for the assessment, skill, knowledge and judgment of the individual selecting the method and the scale of resulted map.

8. Conclusion

GIS based Overlay and index methods will remain the most popular method for vulnerability mapping as they are simple and less constrained by data shortage. Integration of process-based models with overlay/ index methods could be more useful in future. Overlay and index method can enable informed management decisions and early warning of degradation. If regional aquifer vulnerability assessment properly conducted an effective strategy for sustainable ground water management can be devised. But success of these methods depends upon co-operative effort of local government, policy makers, natural resource managers, technical and scientific experts. Therefore it is required to develop an understanding of the interactions between the different roles of planners, politicians, policy makers and experts in groundwater management.

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