Ground Water Vulnerability Assessment – Challenges and Opportunities

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Abstract

Pollution of groundwater due to industrial and municipal wastes is of a rising concern in many cities and industrial clusters in India. 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. This can be achieved through several aquifer vulnerability assessment methods. These methods are primarily based on process models and statistical or overlay/index methods. Scanning of literature revealed limited application of such groundwater vulnerability assessment approaches under Indian conditions. Present manuscript attempts to illustrate the strengths and weaknesses of the existing groundwater vulnerability assessment approaches and the consequent opportunities and challenges associated with their wide scale application under Indian conditions.

1. Introduction

Groundwater is a globally important and valuable renewable resource for human life and economic development. It constitutes a major portion of the earth's water circulatory system known as hydrologic cycle and occurs in permeable geologic formations known as aquifers i.e. formations having structure that can store and transmit water at rates fast enough to supply reasonable amounts to wells. Its importance stems from its ability to act as a large reservoir of water that provides "buffer storage" during periods of drought.

Last 50 years have seen unprecedented development of groundwater resource. At a regional level groundwater is of huge importance in Africa, Asia and Central and South America. Nationally, countries from Palestine to Denmark are dependant on groundwater and examples of local reliance can be drawn from Mexico City to small villages in Ethiopia. An estimated 2 billion people worldwide rely on aquifers for their drinking water supply (Morris *et al.*., 2003).

In rural context, groundwater provides the mainstay for agricultural irrigation and will be the key to providing additional resources for food security. In urban centers groundwater supplies are important as a source of relatively low cost and generally high quality municipal and private domestic water supply. The annual utilizable groundwater resource of India is estimated as 396 km^3 per year. This accounts for about 80% of domestic water requirement and more than 45% of the total irrigation requirement of the country.

2. Major Groundwater Threats

Groundwater systems are dynamic and water is continuously in slow motion down gradient from areas of recharge to areas of discharge. In large aquifer systems, tens or even hundreds of years may elapse in the passage of water through this subterranean part of the hydrologic cycle. Such flow rates do not normally exceed a few meters per day and compare with rates of up to 1 meter per second for river flow. Velocities can be much higher where flow is through fracture systems, dependent on factors like aperture or fracture network density. In limestones with well-developed solution or in some volcanic aquifers with extensive lava tubes or cooling cracks, velocities can be measured in km/day. Thus supplies located in different aquifers, or in different parts of the same aquifer, can tap water of widely different residence time. This is an important factor for contaminants that degrade over time and in the control of disease-causing micro-organisms such as some bacteria, viruses and protozoa (Morris *et al*., 2003).

Despite its importance, groundwater is often misused, usually poorly understood and rarely well managed. The main threats to groundwater sustainability arise from the steady increase in demand for water (e.g., rising population and per capita use, increasing need for irrigation, etc) and increased use and disposal of chemicals to the land surface. For instance, in India about 40% of land area is irrigated through large canal water distribution systems. Between 1950 and 2001, the irrigated area in India increased from about 23 Mha to over 80 Mha (Chowdary *et al.*, 2005). In the same period, consumption of inorganic fertilizers also rose from less than a million tons to over 18 million tons. A large scale expansion of irrigated agriculture and a rapid growth in the use of chemical fertilizers in India during 1950s–1980s though contributed significantly to the green revolution and increased food security in the region, as evident from an increased food production from 50 million tons in 1950 to about 210 million tons in 2001, yet it also resulted into large scale degradation of soil and groundwater quality due to extensive seepage and percolation losses from canal network and agricultural fields particularly with rice cultivation (Ozha *et al*., 1993; Vijay Kumar *et al.*, 1993).

Pollution of groundwater due to industrial effluents and municipal wastes in water bodies is another major concern in many cities and industrial clusters in India. Disposal of treated and untreated industrial effluents on the land has become a regular practice in many countries. A 1995 survey undertaken by Central Pollution Control Board identified 22 sites in 16 states of India having ground waters degraded with industrial effluents. Shallow aquifers in the Ludhiana city have also been reported to be polluted by a stream which receives effluents from 1300 industries. Industries located in Mettupalayam taluk, Tamil Nadu (Sacchidananda and Prakash, 2006) are an excellent example of this practice. A study attempting to capture the environmental and socio-economic impacts of industrial effluent irrigation around different industrial locations in Mettupalayam taluk showed that continuous disposal of industrial effluents on the adjacent farm lands resulted in both groundwater pollution and increased soil salinization. In some locations even drinking water wells (i.e. deep bore wells) were degraded. It was observed that this greatly impacted the revenue from the banana cultivation in the area.

Disposal of solid wastes on land surfaces could be the other source of ground water contamination. Intensive use of chemical fertilizers in farms and indiscriminate disposal of human and animal waste on land result in leaching of the residual nitrate causing high nitrate concentrations in groundwater. It has been reported that nitrate concentrations in 95 districts of 11 states and two blocks of NCT-Delhi are beyond permissible limit of 45 ppm. Mor *et al.* (2005) studied the impact of leachate percolation from Gazipur landfill site on the adjacent groundwater quality. Concentrations of various physico-chemical parameters including heavy metals (viz., Cd, Cr, Cu, Fe, Ni, Pb and Zn) and microbiological parameters (total coliform and fecal coliform) were determined in both groundwater and leachate samples. The effect of depth and distance of the well from the pollution source was also investigated.

Modern agriculture practices reveal an increased use of pesticides and fertilizers to meet increasing food demand for rising population. Non-point pollution caused by fertilizers and pesticides used in agriculture, often dispersed over large areas, is a great threat to fresh groundwater ecosystems. Many of the pesticides and herbicides are cumulative poisons. A study conducted by Tariq *et al.* (2003) in Pakistan, evaluated pesticide contamination of ground water in four intensively cotton growing districts. Water samples were collected from 37 rural open wells in the Bahwalnagar, Muzafargarh, D.G Khan and Rajanpur districts of Punjab district and were analyzed for eight most commonly used pesticides. Information on the distance to the nearest pesticide mixing / application areas was also obtained for each site. From the eight pesticides analyzed, six pesticides were detected in the water samples. The study emphasized the need for monitoring pesticide contamination in rural water resources and developing a drinking water quality standard for specific pesticides in Pakistan.

Nalini *et al.* (2004) also conducted a similar study to investigate concentrations of both organo-chlorine and organ phosphorus pesticides in the surface and ground water samples of Kanpur district in northern India. In the ground water samples collected from the various hand pumps located in the agricultural and industrial areas, both γ-HCH (0.900 μg/l) and malathion (29.835 μg/l) and dieldrin (16.227 μg/l) were detected. Pesticide like DDE, DDT, aldrin, ethion, methyl parathion and endosulfan were not detected in the surface and groundwater samples. Jayasree and Vasudevan (2006) also undertook a study to know the levels of organo-chlorines in the groundwaters of Thiruvallur district in Tamil Nadu. It was observed that these groundwaters were highly contaminated with pp-DDT (14.3 μg/l), op-DDT (0.8 μg/l), endosulfan, HCH and their derivatives. Among the HCH and endosulphan derivatives, γ-HCH residues (9.8μg/l) were found to be highest in Arumbakkam open wells while the endosulfan sulfates (15.9 μg/l) were highest in the bore wells of Kandigai village. In fact DDT, BHC, carbamate, Endosulfan, etc., which are the most common pesticides used in India, have been widely reported in the ground waters (Kumar and Shah @ www.indiawaterportal.org).

The incidence of high concentrations of arsenic in drinking water has also emerged as a major public-health problem. Arsenic concentrations, above permissible levels of 50 ppb, have been reported in the alluvial plains of Ganges covering six districts of West Bengal. With newer-affected sites discovered during the last decade, a significant change has been observed in the global scenario of arsenic contamination, especially in Asian countries. A study conducted by Mukherjee *et al.* (2006) presents an overview of the current scenario of arsenic contamination in countries across the globe with an emphasis on Asia. Along with the present situation in severely affected countries in Asia such as, Bangladesh, India, and China recent instances from Pakistan, Myanmar, Afghanistan, Cambodia, etc. have also been elaborated.

Increasing incidence of fluoride concentrations (above permissible levels of 1.5ppm) have also been reported for 69 districts in 14 Indian states (e.g. Andhra Pradesh, Bihar, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal). It is estimated that about 65 % of Indian villages are exposed to fluoride risk (Kumar and Shah @ www.indiawaterportal.org). All these areas excepting West Bengal were also reported to be associated with high levels of salinity risks.

Other heavy metals have also been reported to be present in the ground waters of 40 districts in 13 Indian states (e.g. Andhra Pradesh, Assam, Bihar, Haryana, Himachal Pradesh, Karnataka, Madhya Pradesh, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh, and West Bengal) and several blocks of NCT-Delhi (Kaur and Rani, 2006) and Gurgaon and Mewat districts (**Kaur et al.,2008**). However, globally the biggest challenge to groundwater quality is not from high-profile contaminants like arsenic or toxic industrial chemicals but salinization.

3. Need of Groundwater Vulnerability Assessments

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.

The vulnerability studies enable assessment of how severe the likely consequences of pollutant loading may be. The severity of the consequences is measured in terms of water quality deterioration. Lobo-Ferreira and Cabral (1991) proposed that groundwater vulnerability to pollution be defined, in agreement with the conclusions and recommendations of the International Conference on Vulnerability of Soil and Groundwater to Pollutants (Duijvenbooden and Waegeningh 1987), as the sensitivity of groundwater quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer. Thus defined vulnerability is distinct from pollution risk, which depends not only on vulnerability but also on the existence of significant pollutant loading entering the subsurface environment. It is possible to have high aquifer vulnerability but no risk of pollution, if there is no significant pollutant loading or to have high pollution risk in spite of low vulnerability, if the pollutant loading is exceptional. It is important to clarify the distinction between vulnerability and risk. This is because risk of pollution is determined not only by the intrinsic characteristics of the aquifer, which are relatively static and hardly changeable, but also on the existence of potentially polluting activities, which are dynamic factors that can, in principle, be changed and controlled. The seriousness of the impact on water use will depend not only on aquifer vulnerability to pollution but also on the magnitude of the pollution episode, and on the value of the groundwater resource.

4. Groundwater Vulnerability Assessment Techniques

Many approaches have been developed to evaluate aquifer vulnerability. These include process based methods, statistical methods, and overlay / index methods (Zhang *et al*., 1996; Tesoriero *et al*., 1998). The process based methods use simulation models to estimate the contaminant migration (Barbash and Resek, 1996). Statistical methods use statistics to determine associations between the spatial variables and the actual occurrence of pollutants in the groundwater. While the overlay / index methods use location specific vulnerability indices based on the factors controlling movement of pollutants from the ground surface to the saturated zone. Of these major approaches, the overlay/index method has been the most widely adopted approach for large scale aquifer sensitivity and ground water vulnerability assessments.

Overlay/ Index Models

The overlay/ index models are based on combining maps of various physiographic attributes by assigning an index or score to each attribute (NRC, 1993). Qualitative or quantitative indices are derived, that bring together the key factors believed to determine pollutant transport processes (Connell and van den Daele, 2003). Thus overlay/ index-based ground water vulnerability mapping models essentially integrate ratings and attributes of important factors (viz., contaminant properties, depth-to-water table, recharge rates, soil / aquifer properties, land use and management practices) controlling pollutant transport from a ground surface to an aquifer (Hamerlinck and Ameson, 1998). Early examples of this type of assessment are the DRASTIC index (Aller *et al.*, 1985) and the GOD index (Foster, 1987). A number of similar index-based systems have been developed, sometimes extending the range of parameters included in the vulnerability assessment (Secunda *et al*., 1998). Vulnerability maps based on these methods have proved popular tools and are a common feature of groundwater quality management throughout the world, as documented by Worrall and Kolpin (2004). The main advantage of such approaches is that some of the factors such as rainfall and depth to groundwater are easily available over large areas thereby enabling regional scale assessments (Thapinta and Hudak, 2003).

Nitrate nitrogen (NO_3^-N) contamination of aquifers is an important global problem. Ceplecha *et al.* (2004) designed two tools to assess aquifer vulnerability to NO_3^-N contamination in Colorado. The first tool enables statewide aquifer vulnerability mapping (VM) for identifying regions vulnerable to ground water contamination. The VM approach uses five factors viz., aquifer location, groundwater depth, soil drainage class, land use, and recharge availability for assessing aquifer vulnerability on a regional scale. Validation of VM on 576 discrete ground water sample points across the study area showed that it could successfully ($r^2 = 0.78$) delineate aquifers with increased NO_3^-N vulnerability. The second aquifer assessment tool enables field scale vulnerability matrix (VMX) development and thereby helps practitioners determine relative field-scale aquifer vulnerability to NO_3^-N contamination and suggest any changes required in the management practices for reducing groundwater vulnerability. The VMX consists of a series of factors that are rated and combined for a particular field. The VMX can even be used in conjunction with the VM tool to determine NO_3^-N contamination potential from intensive agriculture.

The overlay/ index-based sensitivity and vulnerability mapping approaches have evolved considerably since their inception in the early 1980s, particularly with regard to the use of parameter weighting schemes and the utilization of GIS technology (Corwin *et al*., 1997; Fuest *et al*., 1998). An excellent example of this is the DRASTIC program of Aller *et al*. (1985). This program was originally developed for manual overlaying of semi-quantitative data layers (such as depth to water table, net recharge, aquifer media, soil media, topography and hydraulic conductivity) and thereby ranking regions with respect to their groundwater vulnerability to pesticides. This entire analysis has been recently shown to be feasible through the use of the GIS technology as well (Fabbri and Napolitano, 1995). Though DRASTIC has been successfully validated for the occurrence of a specific pollutants such as pesticides and nitrates in the groundwater system (Navulur and Engel, 1998). Yet it has been shown to be a poor predictor of general groundwater vulnerable regions (Maas *et al*., 1995; Barbash and Resek, 1996; Garrett *et al*., 1989; Koterba *et al*., 1993; USEPA, 1993).

Secunda *et al*. (1998) used composite models along with DRASTIC for the assessment of groundwater vulnerability in Israel. The methodology employed extensive agriculture land use data and empirical means to characterize aquifer vulnerability. Al-Adamat *et al*. (2003) also produced groundwater vulnerability and risk maps for Azraq basin of Jordan using GIS, remote sensing and DRASTIC. These maps were designed to show areas with greatest potential for groundwater contamination on the basis of their hydro-geological conditions and human impacts.

Lowe *et al.* (2003) applied a similar overlay/ index approach on the existing data for western United States to produce pesticide sensitivity and vulnerability maps using GIS methods. Hydro-geologic setting (vertical ground-water gradient and presence or absence of confining layers), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, and depth to ground water were the main factors used for determining ground-water sensitivity to pesticides. The study revealed that the irrigated lands with ground-water table closer to the land surface had higher potential for water quality degradation due to surface application of pesticides.

Babiker *et al.* (2004) also used a GIS integrated DRASTIC model to evaluate vulnerability of Kakamigahara aquifer in Central Japan. It was observed that net recharge has the largest impact on the intrinsic vulnerability of the aquifer. This was followed by the soil media, topography, vadose zone media and hydraulic conductivity. The integrated vulnerability map revealed high risk on the intensively vegetable cultivated (eastern) part of the Kakamigahara aquifer. Dixon (2005) also developed similar ground water vulnerability maps through the use of three newly developed indices based on the detailed land use, pesticide and soil structure information and the selected parameters from the DRASTIC model. GIS, GPS, remote sensing and fuzzy rule-based methods were used for generating groundwater sensitivity maps. It was observed that these three indices could compare well with the modified DRASTIC Index (DI, Al-Adamat *et al*., 2003) and the field water quality data.

Groundwater vulnerability and risk mapping assessment based on a source–pathway–receptor approach was also presented by Nobre *et al.* (2007) for an urban coastal aquifer in northeastern Brazil. A modified version of the DRASTIC methodology was used to map the intrinsic and specific groundwater vulnerability. The integration of fuzzy hierarchy methodology and numerical modeling provided the mechanism to assess groundwater pollution risks and identified areas with potential threats that must be prioritized in terms of groundwater monitoring and restriction on use. A groundwater quality index based on nitrate and chloride concentrations was also calculated.

A number of other alternative index methods based on a range of parameters such as land-use (Crowe and Booty, 1995), travel time (Maxe and Johansson, 1998), chronic toxicity (Britt *et al*., 1992) and attenuation and retardation factors (Rao *et al*., 1985; Kookana and Aylmore, 1994; Wooff *et al*., 1999) have been developed. For example, Shukla *et al*. (2000) applied an attenuation factor based method of Rao *et al.* (1985) to show that there was a general agreement between the vulnerability prediction and observed groundwater contamination. Zektser *et al.* (2004) used a Point Count System (PCS) to study the impact of pollution on Snake River aquifer system in eastern Idaho, United States. In this approach also the influence of each factor (e.g. depth to water, conduct properties of unsaturated medium and recharge) was ranked as per the expert assessment and the groundwater vulnerability was characterized by rank sum.

Stewart *et al*. (2004) applied a Type Transfer Function (TTF) approach to generate a regional-scale non point-source ground water vulnerability assessment for the San Joaquin Valley, California. The comparatively computationally inexpensive TTF approach could produce quantitative estimates of contaminant concentrations for large regional scales through characteristic functions based on different soil textures and their leaching properties. The TTF simulations employed an extensive soil and recharge database to estimate atrazine (1-chloro-3-ethylamino-5-isopropylamino-2, 4, 6-triazine) concentrations at a compliance depth of 3 m resulting from a surface application. Two different sets of TTFs with two different levels of up- scaling were used for spatially uniform and distributed recharge estimates. Results showed that estimated atrazine concentrations can be related to soil survey information. Sandy loam and loamy soils with low organic carbon contents were found to be associated with high vulnerability to atrazine leaching. Travel times for atrazine peak concentrations to the compliance depth ranged from 350 to 730 days. The extent of areas with estimated atrazine concentrations above the maximum contaminant level was less extensive when uniform annual recharge values were used. Simulated TTF concentrations were highest for eastern Fresno County. The TTF modeling approach was shown to be a useful tool for quantitative pesticide leaching estimates at regional scales. The so simulated vulnerability pattern was also supported by field observations.

Simplified pollutant transport models have also been used (Meeks and Dean, 1990) for assigning weights and ranks to the principal (indicator) variables. The development and application of a GIS based decision support framework that integrates field scale models for assessment of non-point-source pollution of groundwater in canal irrigation project areas was presented by Chowdary *et al.* (2005). The development and application of this framework was illustrated by taking a case study of a large canal irrigation system in India. Alternate strategies for water and fertilizer use could be evaluated using this framework to ensure long-term sustainability of productive agriculture in large irrigation projects.

However, the overlay/ index methods suffer from several flaws (Foster, 2002) thereby limiting their scope as only relative indices of aquifer sensitivity. One of the primary flaws in this approach is the arbitrary selection of parameter weights, based on some expert opinion (Fobe and Goossens, 1990). Worrall *et al*. (2005) calculated the vulnerability of groundwater to pesticide contamination based on a Bayesian method for the major aquifer units of southern England. The method was applied to the actually monitored data and hence did not rely on any expert opinions or pollutant transport models. The technique combined information from different sets of observations over periods of years and for a range of pesticide compounds and provided a measure of vulnerability on a continuous probabilistic scale (0 - 1). The resulting vulnerability map could show local and regional scales variations, both within and between major aquifer units. However, Troiano *et al*. (1997) in his overlay/ index approach assumed similar mobility rates for different pesticides for identifying regions vulnerable to pesticide contamination across several wells in California. Hence, unlike statistical approaches, the overlay/ index methods in general can not differentiate between contaminants and hence are applicable to the assessment of the intrinsic vulnerability only (Connell and van den Daele, 2003).

Some indices such as the UK ground water vulnerability index (Palmer *et al*., 1995) neither incorporate any aquifer properties nor account for any relative importance of the factors (in terms of their relative weights). Besides this, the UK system neither includes climatic factors nor depth to the water table (Palmer *et al*., 1995). Worral and Kolpin(2004) examined the validity of the UK vulnerability system (Palmer and Lewis, 1998) and found it to be in complete statistical disagreement with the actual groundwater contamination observations.

Besides this, the overlay/ index-based vulnerability systems are not probabilistic and hence have limited decision making capabilities (Merchant, 1994). Further most of these approaches have not been widely validated. Schlosser *et al*. (2002) developed a similar pesticide vulnerability index and showed a good agreement with the actual groundwater observations. However these observations were not supported with any statistical test of validation.

Process Based Simulation Models

Assessment methods in this category are usually more elaborated than simple overlay or index methods, and include different degrees of complexity from process-based indices to complex 3-D simulation models.

Simple models such as the Behavior Assessment Model (BAM; Jury and Ghodrati, 1989) or the Attenuation Factor (AF; Rao *et al*., 1985) can be used to map groundwater vulnerability, but they can also serve for screening purposes (i.e. to compare the environmental fate of a new compound with other pesticides). The AF is an analytical solution of the convection-dispersion equations. Indices can also be based on numerical solutions of the transport equations. For example, Meeks and Dean (1990) used a one-dimensional advection-dispersion transport model to develop a leaching potential index, which simulates vertical movement through a soil to the water table. Soutter and Pannatier (1996) expressed groundwater vulnerability as the ratio between the cumulative pesticide flux reaching mean water table depth and the total quantity of pesticide applied. The derivation of such indices is not necessarily a common feature of vulnerability assessments using process-based models. The selection of a single relevant variable can serve the purpose of estimating groundwater vulnerability. For example, Connell and van den Daele (2003) chose the maximum contaminant concentration at the water table as a proxy for groundwater vulnerability.

Vulnerability assessments can also be based on meta-models. A meta-model is basically a ‘model of a model’. It is a statistical significant response function that approximates outcomes of a complex simulation model (Wu and Babcock, 1999; Pineros Garcet *et al*., 2006). In environmental sciences, meta-models are usually based on multiple regression analyses, artificial neural networks, transfer functions, multidimensional kriging, etc. For example, Tiktak *et al.* (2006) mapped groundwater vulnerability at the pan-European scale using a combination of AF and a meta-model of GeoPEARL.

Statistical Inference Models

Statistical methods use response variables such as the frequency of contaminant occurrence, contaminant concentration, or contamination probability. These methods are based on the concept of uncertainty, which is described in terms of probability distributions for the variable of interest (NRC, 1993). One possible goal in applying statistical methods to vulnerability assessment is to identify variables that can be used to define the probability of groundwater contamination (Burkart *et al*., 1999a). Typically, one seeks to describe in mathematical terms (function or model) a relation ship between water quality and natural and/or human-induced variables in a discrete area.

For example, Teso *et al.*, (1996) developed a logistic regression model containing independent variables related to the soil texture. The dependant variable was defined as the contamination status of soil sections (uncontaminated vs. contaminated) and groundwater vulnerability was thus assessed through the estimation of a section's likelihood of its containing a contaminated well. Other statistical approaches, such as principal components analysis, discriminant analysis and cluster analysis, have been used to describe relationships between soil attributes and groundwater vulnerability (e.g. Teso *et al*., 1988; Troiano *et al*., 1997).

Worrall (2002) and Worrall and Kolpin (2003) used Bayesian statistics to measure the vulnerability of the catchment of a borehole to groundwater pollution, based on observation of contaminant occurrence in the borehole and the region. This vulnerability assessment is thus based solely on monitoring data and does not need explanatory variables. However, the application of this method requires extensive data sets (and hence is limited to large, intensively monitored areas) and appears to be less sensitive for boreholes with a low relative vulnerability (Worrall, 2002). Moreover, for regulation purposes, this approach implies that borehole catchments can actually be delineated.

Worrall and Kolpin (2004) developed a logistic regression model of ground water pollution that brings together variation in chemical properties with land-use, soil and aquifer properties. They found that vulnerability, as explained by the independent factors that produced the best regression fit, could be viewed as having two parts: an intrinsic vulnerability factor (consisting of variables related to the depth to groundwater, the organic matter and the sand content) and a molecular factor (consisting of variables related to molecular connectivity). However, the regression output is limited to the presence/absence of a compound, and hence limits the discrimination to vulnerable vs. invulnerable wells. Although the mapping of such a vulnerability assessment might prove to be problematic, this study is an excellent example of a statistical vulnerability assessment which explicitly accounts for the variability of both chemical and site properties.

5. Conclusions

Although, in contrast to the other process / statistical inference based models, the overlay/ index models are less constrained by data shortage and computational difficulties (Barbash and Resek, 1996) yet they have a number of conceptual flaws. Firstly, weightings are chosen arbitrarily and solely based on expert opinion (NRC, 1993; Worrall, 2002; Connell and van den Daele, 2003). Secondly, systems based on indices do not capture the probabilistic nature or the uncertainty of groundwater vulnerability (Worrall, 2002). Thirdly, uncertainties in the data themselves and in the actual relevance of each weighted factor question the reliability of the vulnerability maps (Merchant, 1994). Fourthly, the use of indices makes validation difficult. Merchant (1994) noticed that, apart from the use of 'visual validation', very few attempts have been made to validate the numerous DRASTIC applications. Worrall (2002) stressed that validation may be inherently impossible for this category of methods that assess vulnerability outside of a probabilistic framework. Finally, these methods have a greater focus on the distribution of environmental attributes rather than on processes directly controlling groundwater contamination by pesticides (Connell and van den Daele, 2003). These numerous limitations suggest that overlay and index methods will receive decreasing support in the future. However there are reports that suggest that overlay/ index methods could still be useful in combination with the process-based models (Gogu and Dassargues, 2000). Kaur et al. (Manuscript in preparation) successfully applied a similar methodology, based on an indigenously developed pre-validated (process-based) field scale decision support system named IMPASSE (Kaur, 2004), to assess salt and trace metal vulnerability of local ground-waters to the on-going agricultural practices in the peri-urban agricultural lands of the Faridabad block. A comparison of these salt and trace metal vulnerabilities with the actually observed ground water quality data for each test site confirmed that the presence of salts in the study area ground waters was geogenic and that on-going agricultural practices were not responsible for it.

Hence it is very evident that such regional aquifer vulnerability assessments, if properly conducted, can enable informed management decisions so as to afford early warning of degradation and devise an effective strategy for sustainable ground water management. This can ultimately increase the chances of closing the gap between policy enactment and enforcement – so often a stumbling block to achieving sustainable water use.

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