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Approaches to Groundwater Vulnerability to Pollution: A Literature Review

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Abstract: It is not feasible and perhaps impossible to formulate an universal technique for predicting groundwater vulnerability, one that considers all of the ways in which contamination occurs or that is appropriate for all situations. The intended use of the vulnerability assessment process is the most obvious and important factor to consider in selecting a vulnerability assessment approach. The three classes (Overlay and Index Methods, Process based Simulation Model Methods and Statistical Methods) of methods for assessing groundwater vulnerability range in complexity from a subjective evaluation of available map data to the application of complex transport models are available. Each class has its own characteristic strengths and weaknesses that affect its suitability for particular application. This paper attempts to review all the major approaches developed worldwide for groundwater vulnerability assessment.

Key words: Groundwater, vulnerability assessment, literature review, statistical method, overlay index, process based simulation.

Introduction

Groundwater is generally a safe source of drinking water. Certain problems have beset the use of groundwater to human use and to the environment due to its over-use or overdraft. Groundwater vulnerability refers to the sensitivity of groundwater to contamination. The seriousness of the impact on water use depends on the extent and magnitude of the pollution and the value of the groundwater resource. The importance of ground water has long been recognized, but the potential for ground water to become contaminated as a result of human activities at or near the land surface has only been recognized in recent years. Before 1980 it was thought that soils served as filters, preventing harmful substances deposited at the surface from migrating downward into ground water. Today it is known that soils and other intervening layers have a finite capacity to filter and retard, and so protect ground water. Despite this realization, a significant amount of contamination already had been released to the nation's soil and groundwater. Scientists have since realized that once an aquifer becomes polluted, it may become unusable for decades, and is often impossible to clean up quickly and inexpensively.

A major percentage of the population throughout the world relies to some extent on groundwater as a source of drinking water, and still more use it to supply their factories with process water or their farms with irrigation water. For those, who rely on ground water, it is critical that their groundwater be unpolluted and relatively free of undesirable contaminants.

A groundwater pollutant is any substance that, when it reaches an aquifer, makes the water unclean or otherwise unsuitable for a particular purpose. Sometimes the substance is a manufactured chemical, but just as often it might be microbial contamination. Contamination also can occur from naturally occurring mineral and metallic deposits in rock and soil.

Types of Groundwater Contamination

Groundwater contamination caused by human activities usually falls into one of two categories: point-source pollution and non-point source pollution.

Point-source pollution refers to contamination originating from a single tank, disposal site, or facility. Industrial waste disposal sites, accidental spills, leaking gasoline storage tanks, and dumps or landfills are examples of point sources. Chemicals used in agriculture, such as fertilizers, pesticides, and herbicides are examples of non-point source pollution because they are spread out across wide areas. Similarly, runoff from urban areas is a non-point source of pollution.

Many different definitions of groundwater vulnerability are now available in the literature, but all agree in the sense that vulnerability is a relative property (NRC, 1993). The National Research Council (1993) defined groundwater vulnerability to contamination, in the case of non-point sources or distributed point sources of pollution, as: the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer.

The reference location mentioned in the above definition is most often the water table (NRC, 1993; Connell and van den Daele, 2003). However, some authors argue that assessments of vulnerability of groundwater resources require analysis of not only the vadose zone, but also of the groundwater system itself (Fogg et al., 1999). Indeed, the choice of the reference location (e.g. the water table, wells intakes, recharge or discharge zones) can depend on the purpose of the study.

The above definitions tells that vulnerability differ across research disciplines. Kelly and Adger (2000) noted that some analysts regard assessment of vulnerability as the end point of any impact appraisal, others as the focal point, and yet others as the starting point. Depending on the field of study (e.g. natural hazards, food security, etc.), definitions of vulnerability may intrinsically include a social dimension. In this case, vulnerability is 'human' in nature and can be defined as the 'capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard' (Blaikie et al., 1994).

Factors Affecting Groundwater Vulnerability to Contamination

Various physical, chemical, and biological processes determine the environmental fate of pollutants. The rates and importance of each of these processes are, in turn, affected by different factors (Soutter and Pannatier, 1996). These factors are mentioned below.

Factors Affecting Geochemical Processes

Solubility

As water seeps through the soil, it carries with it water soluble chemicals. This process is called leaching. The more the water soluble a chemical is, it is more likely to leach.

Adsorption-desorption

Ion exchange can withhold, usually temporarily, cations and to a lesser extent anions, on the surfaces of clays or other colloidal-sized materials. Amounts of adsorbed metal cations will increase with increasing pH. Molecular species may be weakly retained on colloidal-size materials by physical adsorption. The much stronger binding forces due to chemisorption result in the formation of surface compounds involving metal ions and mineral grains. Adsorbed species may return to solution when more dilute moisture comes in contact with the colloidal material depending on the nature of the adsorption bond.

Degradation

Pollutants are degraded, or broken down by heat, sunlight, microorganisms, and a variety of physical and chemical properties. In most pollutants degradation takes place within the top few inches of soil. Pollutants that take a relatively long time to degrade are said to be persistent. The longer the compound persists in the soil, the longer it is available to leach into groundwater.

Volatility

Compounds that vaporise are said to be volatile. If a chemical is highly volatile and not very water soluble, it is likely to be lost to the atmosphere, and less likely to leach into groundwater. Highly volatile compounds may become groundwater contaminants, however, if they are also highly soluble in water.

Factors Affecting Physical Processes

Soil Texture

Texture affects movement of water through soil, and thus also movement of dissolved pollutants such as pesticides. The coarser the soil, the faster is the movement of percolating water, and the less opportunity for adsorption or evaporation. Textural and structural characteristics determine the hydrological behaviour of soils and hence the percolation rate of contaminants. Soil macroporosity is an important factor affecting pollutants movement to shallow groundwater in some cases (Shipitalo et al., 2000;

Haria et al., 2003). There is evidence that the effects of the initial water content on pollutants leaching depend on soil texture: under dry conditions, sandy soils tend to show less leaching, whereas loamy and clayey soils show more leaching when exposed to a strong rainfall shortly after pollutants application (Flury, 1996).

Soil Permeability

Soils that allow water to move downward very quickly are highly permeable. Dissolved chemicals are carried along with the water and thus more likely to reach groundwater in soils that are highly permeable.

Organic Matter Content

The amount of organic matter in a soil affects the adsorption capacity of a soil and the amount of water the soil can hold. Soils with high organic matter content tend to hold the water and dissolved chemicals in the root zone where they will be available to plants and to eventual degradation.

Depth to Groundwater

The shallower the depth to groundwater, the less soil there is to act as a filter, and the fewer opportunities there are for degradation and adsorption of chemicals.

Rainfall

If rainfall is high and soils are permeable, water carrying dissolved chemicals may take only a few days to percolate downward to the groundwater.

Geologic Conditions

The permeability of the geologic layers between the soil and groundwater also affects the probability of contamination. Highly permeable materials, such as gravel deposits, allow water and dissolved compounds to freely percolate down to groundwater. Layers of clay are much less permeable and thus inhibit the movement of water and chemicals. Karst, or limestone formations with sinks or separations in the rock can act as direct entryways for contaminants.

Subsoil, Vadose Zone

For aquifers with the water table deeper than the soil layer, the thickness and nature of the vadose zone may be important to evaluate groundwater vulnerability. In general, pollutants attenuation and degradation are slower below the soil layer (Robins et al., 1994), although in some cases small sites or horizons with a high degradation potential may occur in the vadose zone (Vanderheyden et. al., 1997).

It is recognized that vadose zone transport processes are very complex, and data on vadose zone parameters (e.g. retention curve and unsaturated hydraulic conductivity) are seldom available (Fogg et al., 1999). Therefore, vadose zone influence on groundwater vulnerability has often been estimated using weighting factors or vulnerability classes in index methods (Gogu and Dassargues, 2000).

Groundwater

If the vulnerability analysis is not restricted to contaminants reaching the water table, then the saturated zone properties can influence groundwater vulnerability estimates, e.g. at pumping wells. Fogg et al. (1999) argued that it is highly relevant to consider groundwater flow in the vulnerability assessment, particularly for groundwater resources at important depths, because of the significant time lag existing between the solute arrival at the water table and its presence in water supply wells.

Factors Affecting Biochemical Processes

Decay and respiration

Micro organisms can break down insoluble fats, carbohydrates, and proteins, and in so doing release their constituents as solutes or particulates to subsurface waters.

Cell synthesis

N, C, S, and P, and some minor elements that are required for growth of organisms, and can thus be retarded in their movement away from a waste disposal site.

Approaches to Vulnerability Assessment

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 and Index Methods

Overlay and index methods involve combining various physical attributes (e.g., geology, soils, depth to water table, well locations). In the simplest of these methods, all attributes are assigned equal weights with no judgment being made on their relative importance. These methods were the earliest to be used in assessing groundwater vulnerability and are still favoured by many state and local regulatory and planning agencies. These methods are based on combining maps of various physiographic attributes by assigning an index or score to each attribute (NRC, 1993). Early examples of this type of assessment are the DRASTIC index (Aller et al., 1985) and the GOD index (Foster, 1987). The factors that affect groundwater vulnerability vary from place to place, as does their relative importance. Therefore it is important that the attributes included in an assessment be appropriate for the specific situation and, if they are to be weighted, that their weights reflect the particular physical setting.

The overlay indices developed till date by different researchers are explained below.

DRASTIC

DRASTIC is a groundwater quality index for evaluating the pollution potential of large areas by using the hydrogeologic settings (factors) of the region. This model was first developed by US EPA in 1984. DRASTIC evaluates pollution potential based on seven hydrogeologic factors shown in Figure 1, which make up the acronym DRASTIC. They are: Depth of the water table, net Recharge, Aquifer media, Soil type, Topography, Impact of the vadose zone and hydraulic Conductivity.

Each factor is assigned a weight (1–5) based on its relative significance in affecting the pollution potential. Each factor is further assigned a rating value between 1 and 10 depending on local conditions. High values correspond to high vulnerability. The attributed values are obtained from tables, which give the correspondence between local hydrogeologic characteristics and the parameter value.

The DRASTIC Index, a measure of the pollution potential, is computed by summation of the products of rating and weights of each factor as follows.

$$\text{DRASTIC Index (DI)} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

where

Dr = Ratings to the depth to water table
Dw = Weights assigned to the depth to water table
Rr = Ratings for ranges of aquifer recharge
Rw = Weights for the aquifer recharge
Ar = Ratings assigned to aquifer media
Aw = Weights assigned to aquifer media

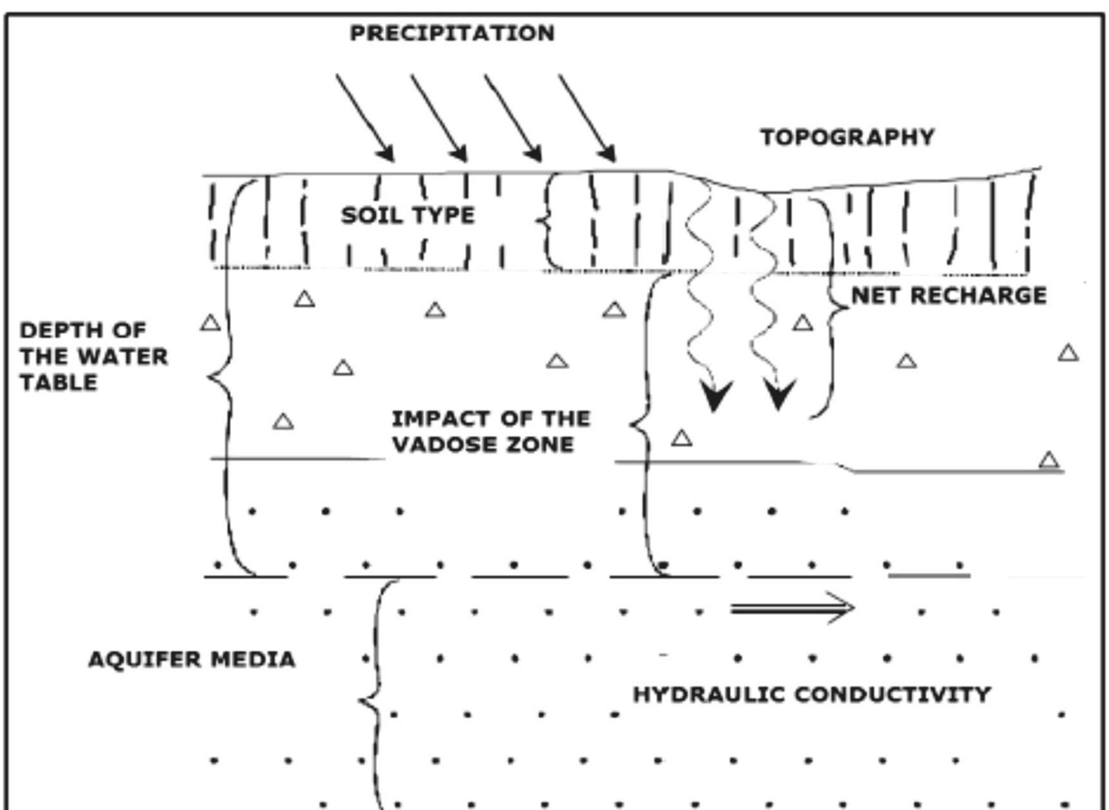

Figure 1: Hydro-geological Settings (Elements of DRASTIC model).

Sr = Ratings for the soil media
Sw = Weights for soil media
Tr = Ratings for topography (slope)
Tw = Weights assigned to topography
Ir = Ratings assigned to vadose zone
Iw = Weights assigned to vadose zone
Cr = Ratings for rates of hydraulic conductivity
Cw = Weights given to hydraulic conductivity

SEEPAGE

The System for Early Evaluation of Pollution potential of Agricultural Groundwater Environments (SEEPAGE) considers various hydrogeological settings and physical properties of the soil that affect the groundwater vulnerability to pollution potential. SEEPAGE model is a combination of three models that was adapted to meet SCS (Soil Conservation Service, recently renamed the Natural Resources Conservation Service) needs to assist field personnel (Richert et al., 1992). SEEPAGE considers soil properties in more detail than DRASTIC. The factor values and factor layers are assigned numerical weights which are multiplied and summed similar to DRASTIC.

SPISP

SPISP (Soil Pesticide Interaction Screening Procedure) is a technique developed by the Soil Conservation Service for use in water conservation planning (Goss and Wauchope, 1992). It considers pesticide properties and soil properties in predicting vulnerability of water. The properties/data considered are combined using algorithms to produce a vulnerability estimate.

GOD

GOD (Foster, 1987) is a rating system method that assesses vulnerability by means of three variables: groundwater occurrence (G), overall lithology of aquifer (O) and depth to groundwater table (D). This method uses fewer parameters than DRASTIC, although two of them (G and D) also depend on the lithology, and the range of values for each rating is short, varying from 0 (minimum vulnerability) to 1 (maximum vulnerability). The final index is obtained from the formula:

$$I = G . O . D$$

The value of the index may vary from 0 to 1 and five vulnerability classes are differentiated by the method.

AVI

Aquifer Vulnerability Index (AVI) is an analogical relation or numerical method that uses two parameters (Van Stempoort et al., 1993), viz., the thickness of each sedimentary layer above the uppermost saturated aquifer (d) and the estimated hydraulic conductivity (k) of each of these sedimentary layers. This method does not consider ratings and/or weights. The index is determined from the relation between the two parameters, taking into account variations of an order of magnitude, according to the following equation:

$$\mathrm{AVI} = \sum_i \frac{d_i}{k_t}$$

The AVI method also establishes five classes of vulnerability, which reflect the variations of the index equivalent to an order of magnitude.

EPIK

EPIK (Doerfliger et al., 1999) is a parameter weighting and rating method especially developed for karst aquifers to protect water supply sources (springs and wells). This method does not consider parameters depending on time (i.e. rainfall, recharge) but only the intrinsic parameters of the aquifer: presence of epikarst (E), the characteristics of the protective cover (P), the infiltration conditions (I) and the karst network development (K). A protection factor (Fp) is calculated by summing the values of parameters E, P, I and K (each between 1 and 4) and applying a weight varying from 1 to 3. In this case, unlike other methods, lower values of Fp correspond to higher vulnerability, because the vulnerability index is converse to the protection factor:

$$Fp = 3E + 1P + 3I + 2K$$

The protection factor is divided into four vulnerability classes, from ''low'' to ''very high''.

SINTACS

The SINTACS scheme of aquifer pollution vulnerability mapping was established for hydro-geological, climatic and impacts settings, typical for the Mediterranean countries (Civita, 1990). This assessment procedure incorporates seven parameters, relevant for the contaminant attenuation and vertical flow capacity. Elements normalized SINTACS index used for vulnerability assessment using SINTACS parametric methods (Civita and De Maio, 2000).

The assessment of the seven SINTACS parameters and three selected scenario enables the calculation of groundwater vulnerability. SINTACS index represents a sum of ratings and weights for all seven SINTACS parameters:

$$\mathrm{ISINTACS} = \sum_{j=1}^{7} Pj \cdot Wj$$

where, ISINTACS is vulnerability index and Pj and Wj are the ratings and the weights respectively of a particular grid.

P1: Depth to the groundwater table
P2: Effective infiltration
P3: Unsaturated zone attenuation capacity
P4: Soil/overburden attenuation capacity
P5: Hydrogeological characteristics of the aquifer
P6: Coefficient of hydraulic conductivity
P7: Topographic slope

A number of similar index-based systems have been developed, sometimes extending the range of parameters included in the vulnerability assessment. These are mentioned below.

Secunda et al. (1998) studied groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in Israel's Sharon region. This study has been to integrate the impact of extensive land use over long periods of time upon aquifer media as an additional parameter to the DRASTIC model to assess the potential level of groundwater vulnerability to pollution. An additional objective involved adaptation of this composite model to a specific region of a coastal aquifer, at a scale commensurate with effective hydrological management needs.

Groundwater vulnerability and risk mapping assessment based on a source–pathway–receptor approach was presented by Nobre et al. (2007) for an urban coastal aquifer in north-eastern Brazil. A modified version of the DRASTIC methodology was used to map the intrinsic and specific groundwater vulnerability.

Babiker et al. (2004) also used a geographical information system (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 (Al-Adamat et al., 2003) and the field water quality data.

Gemitzi et al. in 2006 assesses groundwater vulnerability to pollution in combination of GIS, fuzzy logic and decision making techniques. GIS was coupled with fuzzy logic and multi-criteria evaluation techniques in order to assess groundwater vulnerability to pollution. Twelve factors were analysed in the computation process, categorized into three main groups. Three intermediate groundwater vulnerability maps to pollution were produced that way and were combined in two ways, in order to produce the composite groundwater vulnerability map.

Massone et al. in 2010 proposed a methodology for groundwater vulnerability assessment in geological homogeneous areas. The methodology deals with the aquifer vulnerability where the homogeneity of the hydrogeological variables used by traditional methods (in this case, DRASTIC-P) causes vulnerability maps to show more than 80% of the territory under the same class. This absence of discrimination renders vulnerability maps of little use to decision-makers. In addition, the proposed methodology avoids the traditional vague classification (high, low, and moderate vulnerability) which is highly dependent on subjectivity in its association of each class with hydrogeological considerations. That traditional vulnerability assessment methodology was adapted using a geographic information system to reclassify classes, based on the Natural Breaks (Jenks) method. The pixel-to-pixel comparison between the result obtained by the DRASTIC-P and the reclassified classes generates the so-called operational vulnerability index (OVI), which shows four classes, associating each with different hydrogeological requirements to make decisions.

Advantages of overlay/index method

Overlay and index methods are often preferred because the data they require are easily available. In addition, these methods are relatively simple; while they include factors important in determining ground water vulnerability, they do not attempt to fully describe the processes that lead to contamination.

Limitations of overlay/index method

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 (NRC, 1993; Worrall, 2002; Connell and van den Daele, 2003; Fobe and Goossens, 1990). Unlike statistical approaches, the overlay/index methods in general cannot differentiate between contaminants and hence are applicable to the assessment of the intrinsic vulnerability only (Connell and van den Daele, 2003)

Besides these, the overlay/index-based vulnerability systems are not probabilistic and hence have limited decision making capabilities (Merchant, 1994). Systems based on indices do not capture the probabilistic nature or the uncertainty of groundwater vulnerability (Worrall, 2002). Moreover, uncertainties in the data themselves and in the actual relevance of each weighted factor question the reliability of the vulnerability maps (Merchant, 1994; Fogg et al., 1999).

No single set of factors or weights is suitable for all situations. Most methods use a single, average annual value for each attribute at each point location, but, attributes such as depth to ground water and recharge often vary in time, both seasonally and annually.

Finally, these methods have a greater focus on the distribution of environmental attributes rather than on processes directly controlling groundwater contamination by pesticides (Fogg et al., 1999; Connell and van den Daele, 2003).

These numerous limitations suggest that overlay and index methods will receive decreasing support in the future, although Gogu and Dassargues (2000) argued that they could still be useful in combination with methods using process-based models.

Process-based Simulation Models Methods

Process-based simulation models are used to predict groundwater flow and contaminant transport in both space and time. Process-based simulation models imitate the actual physics and chemistry of the contaminant transport in the subsurface, to make predictions about the amount of degradation, sorption, or remobilisation that a contaminant may experience as it travels through the subsurface. Computer models can be used to compute the travel time and the extent of contaminant plumes in the subsurface. Such computations are based not on generalized expert or expert knowledge, but on the fundamental scientific principles controlling the movement of water and contaminants in the subsurface.

Computer modelling codes for unsaturated zone and groundwater modelling abound, often serving very specific applications. Four computer model codes are particularly popular for computing the fate and transport of contaminants as those contaminants travel downward through the unsaturated zone to the water table: VLEACH (EPA), HYDRUS (International Groundwater Modelling Centre), SUTRA (Voss, 1984), PRZM (Carsel et al., 1985), LEACHP (Wagenet and Histon, 1987), and GLEAMS (Leonard et al., 1987).

The process based simulation model may employ the advective–dispersive solute transport approach along with different chemical reaction models that can describe the dynamics a pollutant may undergo. Several authors have combined GIS with process-based models.

Simple models such as the Behaviour 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.

Approaches using process-based simulation models require analytical or numerical solutions to mathematical equations that represent coupled processes governing contaminant transport. Methods in this class range from indices based on simple transport models to analytical solutions for one-dimensional transport of contaminants through the unsaturated zone to coupled, unsaturated-saturated, multiple-phase, two- or three-dimensional models. These approaches are distinguished from others in that many of them attempt to predict contaminant transport in both space and time.

Merits of Process Based Simulation Model Method

Groundwater vulnerability 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.

These models are excellent tools to predict water flow and contaminant transport under specific hydrogeologic conditions in the unsaturated zone, in particular those that are highly layered (heterogeneous), and for chemical process that undergo multiple chemical processes or chemical reactions.

Demerits of Process Based Simulation Model Method

The data these methods require often are not available and must be estimated by indirect means. In addition, these models do not account for flow and transport processes occurring at either smaller or larger spatial scales than those for which the models were developed, and they do not account for cases where preferential flow exists.

Statistical Method

Statistical approaches vary in complexity and generally include multiple independent variables and use a contaminant concentration or a probability of contamination as the dependent variable. These methods incorporate data on known areal contaminant distributions and provide characterizations of contamination potential for the specific geographic area from which the data were drawn. Statistical methods have been developed with the availability of data keenly in mind and are designed to deal with data of varying quality and types. These methods do not attempt to define processes or cause-effect relationships, and results are expressed as probabilities. These methods have been used in the assessment of vulnerability using probability models.

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 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.

A statistical method has been developed by the Department of Pesticide Regulations (DPR) to determine the specific vulnerability of groundwater to pesticide residues. The method is nicknamed CALVUL (California Vulnerability approach, Troiano et al., 1999).

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, using the results of Monte Carlo simulations, Morgan (2002) selected the pesticide mass loading at the 90% probability of non-exceedence as a means to map aquifer vulnerability. 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 metamodels. It is a statistical significant response function that approximates outcomes of a complex simulation model (Wu and Babcock, 1999; Piñeros Garcet et al., 2006). In environmental sciences, metamodels are usually based on multiple regression analyses, artificial neural networks, transfer functions, multidimensional kriging, etc. For example, Holman et al. (2004) used a meta-version of the leaching model MACRO (Jarvis, 1991) coupled with attenuation factor (AF) to assess the risk of groundwater contamination by pesticides. Tiktak et al. (2006) mapped groundwater vulnerability at the pan-European scale using a combination of attenuation factor (AF) and a metamodel of GeoPEARL.

Merits of Statistical Methods

Since, it is based on actually measured contamination; the statistical analysis lends the approach quantifiable credibility and validity that is not available with the index-and-overlay methods.

Demerits of Statistical Methods

Statistical methods are usually region specific and not suitable for transfer to other, geographically different region. Unlike index methods, the statistical method implies a certain degree of validation and quantifiable measure of vulnerability.

Summary

In recognition of the need for effective and efficient methods for protecting ground water resources from future contamination, scientists and resource managers have sought to develop techniques for predicting which areas are more likely than others to become contaminated as a result of activities at or near the land surface. Once identified, those areas could then be subjected to certain use restrictions or otherwise targeted for greater attention aimed at preventing contamination of the underlying ground water resources. The concept that some areas are more likely than others to become contaminated has led to the use of the terminology 'ground water vulnerability to contamination.' It is infeasible and perhaps impossible to formulate an universal technique for predicting vulnerability, one that considers all of the ways in which contamination occurs or that is appropriate for all situations. Key elements to consider in a vulnerability assessment for a particular application include the reference location, the degree of contaminant specificity, the contaminant pathways considered, and the time and spatial scales of the vulnerability assessment.

Several approaches for vulnerability assessments are available, and each has its own strengths, and limitations. All approaches combine uncertainty and should explicitly capture or reflect that uncertainty. Testing and evaluating these approaches is critical to producing a more justifiable, useful, and reasonable assessment.

References

Al-Adamat, R.A.N., Foster, I.D.L. and S.M.J. Baban (2003). Groundwater vulnerability and risk mapping for the basaltic aquifer of the Azraq basin of Jordan using GIS, remote sensing and DRASTIC. *Applied Geography*, **23:** 303–324.

Aller, L., Bennett, T., Lehr, H. and R.J. Petty (1985). 'DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings'. USEPA, Robert S. Kerr Environmental Research Laboratory, Ada, OK. EPA/600/2-85/0108, 163 pp.

Babiker, I.S., Mohamed, A.M., Hiyama, T. and K. Kato (2005). A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, Central Japan. *Science Total Environment*, **345:** 127–140.

Barbash, J.E. and E.A. Resek (1996). Pesticides in Ground Water: Distribution, Trends, and Governing Factors. Chelsea, Michigan: Ann Arbor Press, Pesticides in the Hydrologic System series, **2:** 590.

Blaikie, P., Cannon, T., Davis, I. and B. Wisner (1994). At Risk: Natural Hazards, People's Vulnerability, and Disasters. Routledge, London and New York.

Carsel, R.F., Mulkey, L.A., Lorber, M.H. and L.B. Baskin (1985). The pesticide root zone model (PRZM): A procedure for evaluating pesticide leaching threats to groundwater. *Ecological model*, **30:** 49–69.

Civita, M. (1990). Legenda unificata per le carte della vulnerabilita dei corpi idrici soutterranei (unified legend for the aquifer pollution vulnerability maps). *In:* Studi sulla vulnerabilita degli Acquiferi. Pitagora, Bologna.

Civita, M., De Maio, M., SINTACS R5 (2000). Quaderni di tecniche di protezione ambientale. Pitagora Editrice. Bologna, 72.

Connell, L.D. and G. van den Daele (2003). A quantitative approach to aquifer vulnerability mapping. *Journal of Hydrology*, **276:** 71–88.

Dixon, B. (2005). Groundwater vulnerability mapping: A GIS and fuzzy rule based integrated tool. *Applied Geography*, **25:** 327–347.

Doerfliger, N., Jeannin P.Y. and F. Zwahlen (1999). Water vulnerability assessment in karst environment: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). *Environmental Geology*, **39(2):** 165–176.

Flury, M. (1996). Experimental evidence of transport of pesticides through field soils – A review. *Journal of Environmental Quality*, **25:** 25–45.

Fobe, B. and M. Goossens (1990). The groundwater vulnerability map for the Flemish region: Its principles and uses. *Engineering Geology*, **29:** 355–363.

Fogg, G.E., LaBolle, Eric M. and G.S. Weissmann (1999). Groundwater vulnerability assessment: Hydrogeologic perspective and example from Salinas Valley, California. *In:* Corwin, D.L, Loague, K. and T.R. Ellsworth (eds), Assessment of non-point source pollution in the vadose zone, *Geophysical Monograph*, **108:** 45–61.

Foster, S.S.D. (1987). Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In TNO Committee on Hydrological Research, the Hague, Proceedings and Information, edited by van Duijvenbooden, W. and G.H. van Waegeningh, **38:** 69–86.

Foster, S.S.D. (2002). Groundwater recharge and pollution vulnerability of British aquifers: A critical overview. *In:* Robins, N.S. (ed.), Groundwater Pollution, Aquifer Recharge and Vulnerability. Geological Society, London, Special Publications, **130:** 7–22.

Gemitzi, A., Petalas, C., Tsihrintzis, V.A. and V. Pissinaras (2006). Assessment of groundwater vulnerability to pollution: A combination of GIS, fuzzy logic and decision making techniques. *Environmental Geology*, **49:** 653–673.

Gogu, R.C. and A. Dassargues (2000). Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. *Environmental Geology*, **39(6):** 549–559.

Goss, D. and R. Wauchope (1992). *The SCS/ARS/CES Pesticide Properties Database: II using it with Soils Data in a Screening Procedure.* USDA Research Article. USDA, Washington, DC.

Haria, A.H., Hodnett, M.G. and A.C. Johnson (2003). Mechanisms of groundwater recharge and pesticide penetration to a chalk aquifer in Southern England. *Journal of Hydrology*, **275(1–2):** 122-137.

Holman, I.P., Dubus, I.G., Hollis, J.M. and C.D. Brown (2004). Using a linked soil model emulator and unsaturated zone leaching model to account for preferential flow when assessing the spatially distributed risk of pesticide leaching to groundwater in England and Wales. *The Science of the Total Environment*, **318(1–3):** 73–88.

Jarvis, N. (1991). MACRO: A model of water movement and solute transport in macroporous soils. Reports and Dissertations 19, Swedish University of Agricultural Science, Department of Soil Science.

Jury, W.A. and M. Ghodrati (1989). Overview of organic chemical environmental fate and transport modelling approaches. *In:* Reactions and Movement of Organic Chemicals in Soils. B.L. Sawhney and K. Brown (eds), Madison, Wisconsin: Soil Science Society of America, Inc., Special Publication, **22:** 271–304.

Kelly, P.M. and W.N. Adger (2000). Theory and practice in assessing vulnerability to climate change and facilitating adaptation. Climatic Change, **47:** 325–352.

Leonard, R.A., Knisel, W.G. and D.A. Still (1987). GLEAMS: groundwater loading effects of agricultural management systems. *Transactions of the American Society of Agricultural Engineers*, **30:** 1403–1418.

Massone, H., Londoño, M.Q. and D. Martínez (2010). Enhanced groundwater vulnerability assessment in geological homogeneous areas: A case study from the Argentine Pampas. *Hydrogeology Journal*, **18:** 371–379.

Meeks, Y.J. and J.D. Dean (1990). Evaluating groundwater vulnerability to pesticides. *Journal of Water Resource Plan Management*, **116(5):** 693–707.

Merchant, J.W. (1994). GIS-based groundwater pollution hazard assessment – a critical review of the DRASTIC model. *Photogram Engineering Remote Sensing*, **60:** 1117–1128.

Morgan, L. (2002). Aquifer vulnerability analysis using the pesticide root-zone model (PRZM2), Washington (State). Department of Ecology. Watershed Management Section.

National Research Council (NRC) (1993). Ground water vulnerability assessment: Contamination potential under conditions of uncertainty. Committee on Techniques for Assessing Ground Water Vulnerability, Water Science and technology Board, Commission on Geosciences, Environment, and Resources. National Academy Press, Washington D.C.

Nobre, R.C.M., Rotunno, F.O.C., Mansur, W.J., Nobre, M.M.M. and C.A.N. Cosenza (2007). Groundwater vulnerability and risk mapping using GIS, modelling and a fuzzy logic tool. *Journal of Contaminant Hydrology*, **94:** 277–292.

Piñeros Garcet, J.D., Ordoñez, A., Roosen, J. and M. Vanclooster (2006). Metamodelling: Theory, concepts and application to nitrate leaching modelling. *Ecological Modelling*, **193**: 629–644.

Rao, P., Hornsby, A. and R. Jessup (1985). Indices for ranking the potential for pesticide contamination of groundwater. *Con Soil Crop Science Society Florida*, **44:** 1–8.

Richert, S.E., Young, S.E. and C. Johnson (1992). SEEPAGE: a GIS model for groundwater pollution potential. ASAE, St Joseph, Michigan. Paper no. 922592.

Robins, N., Adams, B., Foster, S. and R. Palmer (1994). Groundwater vulnerability mapping: The British perspective. *Hydrogéologie*, **3:** 35–42.

Secunda, S., Collin, M. and A.J. Mellou (1998). Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive land use in Israel. *Journal of Environmental Management*, **54:** 39–57.

Shipitalo, M.J., Dick, W.A. and W.M. Edwards (2000). Conservation tillage and macropore factors that affect water movement and the fate of the chemicals. *Soil Tillage Research*, **53:** 167–183.

Soutter, M. and Y. Pannatier (1996). Groundwater vulnerability to pesticide contamination on a regional scale. In Applications of GIS to the Modeling of Non-point Source Pollutants in the Vadose Zone. *Environmental Quality*, **25:** 439–444.

Teso, R.R., Poe, M.P., Younglove T. and P.M. McCool (1996). Use of logistic regression and GIS modelling to predict groundwater vulnerability to pesticides. *Journal of Environmental Quality*, **25:** 425–432.

Teso, R.R., Younglove, T., Peterson, M.R., Sheeks, D.L. and R.E. Gallavan (1988). Soil taxonomy and surveys: Classification of areal sensitivity to pesticide contamination of groundwater. *Journal of soil and water conservation*, **43:** 348–352.

Tesoriero, A.J., Inkpen, E.L. and F.D. Voss (1998). Assessing ground-water vulnerability using logistic regression. Proceedings for the Source Water Assessment and Protection 98 Conference, Dallas, TX; 157– 165.

Tiktak, A., Boesten, J.J.T.I., Linden, A.M.A. and M. Vanclooster (2006). Mapping Ground Water Vulnerability to Pesticide Leaching with a Process-Based Metamodel of EuroPEARL. *Journal of Environmental Quality*, **35:** 1213–1226.

Troiano, J., Nordmark, C., Barry, T. and B. Johnson (1997). Profiling areas of ground water contamination by pesticides in California: Phase II—evaluation and modification of a statistical model. *Environmental Monitoring and Assessment*, **45:** 301–318.

Van Stempoort, D., Ewert, L. and L. Wassenaar (1993). Aquifer vulnerability index (AVI): A GIS compatible method for groundwater vulnerability mapping. *Canadian Water Research Journal*, **18:** 25–37.

Vanderheyden, V., Debongnie, P. and L. Pussemier (1997). Accelerated degradation and mineralization of atrazine in surface and subsurface soil materials. *Pesticide Science*, **49:** 237–242.

Voss, C.I. (1984). SUTRA: A finite element simulation model for saturated–unsaturated, fluid-density dependent groundwater flow with energy transport or chemically reactive single species solute transport. US Geological Survey, National Centre, Reston VA.

Wagenet, R.J. and J.L. Histon (1987). Predicting the fate of nonvolatile pesticides in the unsaturated zone. *Journal of Environmental Quality*, **15:** 315–322.

Worrall, F. (2002). Direct assessment of groundwater vulnerability from borehole observations. *In:* Hiscock, K.M., Rivett, M.O. and R.M. Davison (eds), Sustainable Groundwater Development, Geological Society, London, Special Publications, **193:** 245–254.

Worrall, F. and D.W. Kolpin (2004). Aquifer vulnerability to pesticide pollution-combining soil, land-use and aquifer properties with molecular descriptors. *Journal Hydrology*, **293:** 191–204.

Wu, J.J. and B.A. Babcock (1999). The Relative Efficiency of Voluntary vs Mandatory Environmental Regulations. *Journal of Environmental Economics and Management*, **38(2):** 158–175.

Zhang, R., Hamerlinck, J.D., Gloss, S.P. and L. Munn (1996). Determination of nonpoint-source pollution using GIS and numerical models. *Journal of Environmental Quality*, **25:** 411–418.

Calendar of Events

2012 3rd International Conference on Environmental Science and Development (ICESD 2012)
5 to 7 January 2012
Hong Kong, China
Website: http://www.icesd.org/
Contact name: Conference Secretary
Sponsored by: CBEES

International Conference on Energy-Water-Waste Nexus for Environmental Management (ICEWWNEM - 2012)
28 to 30 January 2012
Sirsa, Haryana, India
Website: http://www.icewwnem.isgreat.org/
Contact name: Dr. Rani Devi
Organized by: Department of Energy and Environmental Sciences, Chaudhary Devi Lal University

Annual International Conference on Sustainable Energy and Environmental Sciences (SEES 2012)
13 to 14 February 2012
Singapore
Website: http://www.env-energy.org
Contact name: Shini
Organized by: Global Science and Technology Forum

Governance and Management of Drinking Water: Issues and Challenges
14 to 15 February 2012
Hyderabad, Andhra Pradesh, India
Website: http://www.ipeindia.org
Contact name: Institute of Public Enterprise
Organized by: Institute of Public Enterprise

International Conference on Environmentally Sustainable Urban Ecosystems (ENSURE 12)
24 to 26 February 2012
Guwahati, Assam, India
Website: http://www.iitg.ernet.in/coeiitg/ensure.html
Contact name: Prof. A.K. Sarma
Organized by: Centre of Excellence for Integrated Land-use Planning and Water Resource Management, Civil Engineering, Indian Institute of Technology Guwahati

2012 International Conference on Climate Change and Humanity (ICCCH 2012)
26 to 28 February 2012
Singapore
Website: http://www.iccch.org/
Contact name: Conference Secretary
Sponsored by: CBEES

2nd International Conference on Energy, Environment & Sustainable Development (EESD-2012)
27 to 29 February 2012
Jamshoro, Sindh, Pakistan
Website: http://www.muet.edu.pk/eesd2012
Contact name: Prof. Dr. Mohammad Aslam Uqaili
Organized by: Mehran University of Engineering & Technology

2012 3rd International Conference on Environmental Science and Technology (ICEST 2012)
10 to 11 March 2012
Chennai, India
Website: http://www.icest.org/
Contact name: Conference Secretary
Sponsored by: CBEES, EBSCO

Water & Environment 2012: CIWEM's Annual Conference
20 to 21 March 2012
London, United Kingdom
Website: http://www.ciwem.org/events/annual-conference.aspx
Contact name: Lauren Goozee
Organized by: CIWEM