CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

All aquifers and the ground water within are vulnerable to contamination. But, the ability of a contaminant, introduced at the land surface to reach the ground water, is not the same with regard to all aquifers. Globally and regionally, identification of aquifers, which are more vulnerable to contamination than others, is assuming significance, as it is a cost-effective measure for screening areas and to enact ground water protection measures.

Non-point source aquifer pollution by nitrate due to agricultural chemicals in the form of fertilizers is prevalent in most of the countries. Population growth demands higher yield per unit area leading to increased usage of fertilizers. From 1960 to 1985, the agricultural demand for nitrogen quadrupled to 12 M tonnes in USA (USDA 1987). At Indian level the situation is very similar. Ministry of Water Resources, Government of India, classifies Vellore district in Tamil Nadu, as having both non-point and point sources of pollution from agriculture and tannery industries. In Vellore district, India, coconut water contained 0.2% of residual chromium derived from chrome-tanning process-based tanneries that contaminated the ground water (Srinivas 1999).

The literature reviewed as part of this study is grouped distinctly under six major headings and discussed in this Chapter. The major headings are: (i)
Definition of vulnerability; (ii) Classification of vulnerability maps; (iii) Methods of aquifer vulnerability assessments; (iv) DRASTIC Model for intrinsic and specific aquifer vulnerability assessment; (v) Validation of DRASTIC model with water quality data; and (vi) Decision Support Systems (DSS) for vulnerability studies.

2.2 DEFINITION OF VULNERABILITY

Vulnerability of ground water contamination is assessed in variety of ways using different approaches and hence complete understanding of the formulation and definition of vulnerability is essential for the design, methods of cartographic representation and compilation of vulnerability maps. The historical overview of definition and evolution of aquifer vulnerability is presented below.

The concept of "vulnerability of ground water to contamination" was first introduced by Margat (1968) to create awareness of danger of ground water contamination. Villumsen et al (1983) defined ground water vulnerability as the risk of chemical substances - used or disposed on or near the ground surface-to influence the ground water quality. It is emphasized here that the chemical quality of ground water could be used as an indicator of vulnerability. Foster (1987) uses the term "aquifer pollution potential" and defines it as the interaction between the natural vulnerability of an aquifer and the contaminant loading that is, or will be, applied to the subsurface environment as a result of human activity. Palmquist (1991) defines vulnerability as "a measure of the risk placed upon the ground water by human activities and the presence of contaminants". He states that "without the presence of contaminants even the most susceptible ground water is not at risk, and thus, it is not vulnerable". The
U.S. Environmental Protection Agency (USEPA 1991) uses the term 'aquifer sensitivity' for intrinsic vulnerability and the term 'aquifer vulnerability' for specific vulnerability. According to National Research Council (NRC 1993) the ground water vulnerability is defined as the tendency or likelihood for contaminants to reach a specified position in the ground water system after introduction at some location above the uppermost aquifer. It also considers the inherent vulnerability (intrinsic) and anthropogenic impact in the form of specific vulnerability.

For the purpose of the present research, the latest vulnerability definition given by Jarsolav and Alexander (1994), for both intrinsic and specific assessment, is adopted. According to Jarsolav and Alexander (1994), aquifer vulnerability is defined as an intrinsic property of a ground water system that depends on the sensitivity of that system to human and/or natural impacts. There are basically two approaches to vulnerability mapping, intrinsic and specific. The general or intrinsic vulnerability maps are used to evaluate the natural vulnerability of ground water without context to a specific contaminant or a specific contamination source. Specific or integrated vulnerability maps are used to evaluate the impact of a particular landuse or a contamination source on ground water.

2.3 CLASSIFICATION OF GROUND WATER VULNERABILITY MAPS

The applicability of Ground Water Vulnerability Maps (GWVMs) as a planning tool for pre-emptive measure for ground water protection or for a detailed site-specific study for a contaminant depends on the scale, content and purpose of these maps.
According to Vrana (1984) the GWVMs are classified as extra large maps (1:5,000 and larger), large (1:10,000 to 1:50,000), intermediate (1:100,000 to 1:500,000), small (1:1,000,000 to 1:10,000,000) and extra small (1:10,000,000 and smaller). GWVMs together with land suitability maps were considered as subdivision of ground water protection maps by Zaporozec (1989), at local, regional and national levels. Vrba (1991) classified GWVMs into four categories: Specific-single purpose (1:50,000 and larger); Specific-multi purpose (1:100,000 to 1:500,000); Specific-general purpose (1:1,000,000 and less); and Basic, showing the intrinsic vulnerability of ground water (at various scales).

In this research study, the specific-single purpose assessment was attempted at 1:50,000 scale for the study area where the major contaminants are nitrate and chromium.

2.4 METHODS OF AQUIFER VULNERABILITY ASSESSMENTS

Aquifer vulnerability, not being a measurable quantity, involves high subjectivity in its assessment. Numerous approaches have been evolved ranging from sophisticated field scale models to models used in regional assessments. These models differ with each other in respect of parameters used; scale of assessment, areal extent and in the methodology. Based on the methodology, these models can be grouped into three major categories: (i) Overlay and index methods; (ii) Process based methods; and (iii) Statistical and probabilistic methods. These three categories of models are described and discussed below.
2.4.1 Overlay and index methods

Overlay methods of assessing vulnerability involve superposing a series of maps showing the spatial distribution of parameters considered important for characterizing the potential for aquifer contamination. The parameters are given equal weights and the zones with different vulnerability ratings are indicated by pattern, score or colour. Pettyjohn et al., (1991) used the simplest overlay method for underground injection control program in the contiguous United States on a state-by-state basis. However, the vulnerability assessment in this case was purely based on geologic classification of surficial or relatively shallow aquifers. In addition, several other attempts have been made by Hoyer and Hallberg (1991), and McKenna and Keefer (1991), with a specific emphasis on geology as the key factor influencing aquifer vulnerability.

The index method of assessing aquifer vulnerability assigns weights to the different themes used and has different ratings for the classes within the themes. The weighted rating is summed up to arrive at the vulnerability index. Among the several vulnerability indices developed, the DRASTIC index is the most widely used one (Aller et al., 1987).

Civita (1990,1994) has modified the DRASTIC method to suit the Mediterranean highly diversified hydro geologic conditions. One of the main differences between DRASTIC and SINTACS is in the values of the rating and in the selection of classes of weights. The SINTACS method is more flexible in assigning ratings and weights by encoding the input data as functions of local situations, but at the same time increases the subjectivity in the vulnerability assessment (Fabbri and Napolitano 1995).
System for Early Evaluation of Pollution Potential of Agricultural Ground Water System (SEEPAGE) was developed by Moore (1988). It considers various factors defining hydrogeologic settings and soil properties such as pH, drainage class, texture and permeability. The parameters are assigned rating in the range 1-50 and this model was developed to suit the needs of Natural Resources Conservation Service, USA.

Soil Pesticide Interaction Screening Procedure (SPISP) was developed for the Soil Conservation Service of the United States Department of Agriculture (Goss and Wauchope 1990, Goss 1992), using properties such as pesticide half-life, organic carbon partitioning coefficient, and solubility that interplay with soil properties such as organic matter content, erosion potential, and hydraulic properties. The SPISP was designed to be an initial measure in water conservation planning. The soil and pesticide properties are rated into potential classes of leaching and runoff. These groupings could then be combined into a matrix to give an overall potential rating.

Leaching Potential Index (LPI), developed by Meeks and Dean (1990), considers concentration of contaminant at source, solute velocity and attenuation characteristics to develop dimensionless number whose magnitude indicates the susceptibility of ground water to contamination. However, there are limitations associated with this model with respect to preferential flow, facilitated transport and migration of volatile chemicals.

The aquifer vulnerability assessment using Ground water-Overall lithology-Depth to water table (GOD) method (Foster 1987; Foster and Hirata 1988) lays emphasis on the occurrence of ground water (confined, semi-confined, over flowing, unconfined), overlying lithology (consolidation grade,
lithological character) and depth-to-water table if confined or strike if unconfined. The output consists of vulnerability index ranging from 0 to 1 with ranges from extreme vulnerability to low vulnerability. Gonzalez (1996) has demonstrated the GOD method of assessing vulnerability for Yaqui valley aquifer, Sonora, Mexico and prepared the pollutant hazard index for the sub aquifer units.

Overlay and Index methods have also been used by Kissel et al (1982), Cohen et al (1986) and Sacha et al (1987). These overlay and index methods for assessing vulnerability are based on data availability and expert judgement with less emphasis on processes controlling the ground water contamination. But at a regional scale, these models are immensely valuable as screening tools to focus efforts.

2.4.2 Process Based Methods

Process based models are developed to predict contaminant transport in both space and time. The emphasis in these models is on the factors influencing contaminant transport such as:

(i) Geochemical processes - (Adsorption-Desorption, Solution-precipitation and Oxidation-Reduction);
(ii) Biochemical processes - (Microbial reactions under aerobic and anaerobic conditions); and
(iii) Physical processes - (Advection, Dispersion, Retardation, Filtration and Gas Transport)
The complex simulation models for solving coupled and/or multiphase contaminant transport in two or three dimensions have been used to evaluate physical, biological and chemical controls in hypothetical settings or well-evaluated local incidences of contamination (NRC 1990).

Ground water Loading Effects of Agricultural Management Systems (GLEAMS) is a mathematical, continuous simulation, field scale model which was developed as an extension of the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel 1980) model (Leonard et al., 1987; Knisel 1993). The GLEAMS nutrient component incorporates processes to estimate surface and sub-surface fate of edge-of-field and bottom-of-root-zone loadings of plant nutrients nitrogen and phosphorous. The processes considered are mineralization from the crop residue, soil organic matter, and animal waste immobilization to crop residue, and crop uptake for both N and P (Knisel et al., 1992).

Pesticide Root Zone Model (PRZM) is a one-dimensional, dynamic, compartmental model that can be used to simulate chemical movement in unsaturated soil systems within and immediately below the plant root zone (Carsel 1984). The two principal components in this model are hydrology (and hydraulics) and chemical transport. The model was specifically designed to provide loadings to selected media, including air, water, ground water and plants. The results from the model include pesticide leaching depth, runoff volume, eroded sediment mass, pesticide movement with eroded sediment and runoff, and pesticide volatilization. Processes modeled include water movement through the soil profile, crop uptake, vapor phase transport and irrigation.
Leaching Estimation and Chemistry Model (LEACHM) consists of a group of simulation models describing the water and chemical regime in the soil root zone (Wagenet and Hutson 1987). The LEACHM consists of four models: LEACHW, LEACHP, LEACHN, and LEACHC simulating the water regime, pesticides, nitrogen-phosphorous, and calcareous soils respectively. LEACHM model has been used to derive relative risk of ground water contamination by pesticide leaching for the Levels Plain area in South Island, New Zealand (Webb and Lilburne 1999). He has compared the LEACHM results with DRASTIC indices and observed very similar results with high degree of correlation.

Bekesia and McConchieb (2000; 2000a) have considered the soil, unsaturated zone, rainfall recharge, and the aquifer medium, to be the four major factors influencing the aquifer vulnerability in Manawatu region of New Zealand. This work focuses on the spatial variability of sorption capacity of the unsaturated zone using bore log information and sorption values of various sediments. The derived map showing the unsaturated zone sorption has clear regional trend and is used to assess the vulnerability. Uncertainty ranking system was derived to indicate the reliability of the developed maps.

Ground water flow model with particle tracking to evaluate ground water vulnerability for Clark County, U.S.A. is described in detail by Synder et al (1996). Results of this work have shown that a single particle-tracking analysis simulating advective transport can be used to evaluate ground water vulnerability for any part of a ground water flow system.

Risk of Unsaturated/Saturated Transport and Transformation of Chemical Concentration (RUSTIC) model was developed by Environmental
Protection Agency, U.S.A (Dean et al. 1989). It consists of three models namely, PRZM, VADOFT and SAFTMOD and links these models to predict the fate and transport of chemicals to drinking water wells. Chemical Movement in Layered Soils (CMLS) (Nofziger and Hornsby 1985) was written to serve as a management tool and a decision aid in the application of organic chemicals to soils. The model estimates the location of the center of mass of non-polar organic chemicals as they move through a soil in response to downward movement of water. The model also estimates the relative amount of each chemical still remaining in the soil at any time. In addition PETSANS (Enfield et al., 1982), Behaviour Assessment Model (BAM) (Jury et al 1983), MOUSE-a management model for evaluating groundwater contamination from diffuse surface sources aided by computer graphics (Steenhuis et al., 1987), RF/AP (Rao et al., 1985) and RITZ/VIP (Nofziger et al. 1988) are the other process based models to predict the behaviour of chemicals in the saturated and unsaturated zones.

From the discussion above, it is evident that process based models for predicting vulnerability are mostly field scale and data intensive. Although, they offer the most sophisticated and potentially most accurate predictions of water quality, they are not widely used for regional ground water vulnerability analysis (GAO 1992). These models have the inherent limitations such as; for some parameters it may be impossible to measure physically; limited resources may preclude obtaining extensive measurements from the field for the scale at which the assessment is made; and the point measurements may not have sufficient well distributed coverage for suitability in regional scale assessments (NRC 1993).
2.4.3 Statistical and Probabilistic Methods

Statistical methods for the assessment of ground water vulnerability relate the occurrence of contaminants in ground water to explanatory variables. These methods incorporate the data of known contaminant spatial distribution and attempts to characterize the contamination potential of the location from where these data are collected. The explanatory variables describe either potential sources of these contaminants or the factors through which the contaminants could reach the ground water with differing difficulty/ease. The output from these models is usually in the form of maps indicating probability that a given area is having a high or low risk of contamination.

Chen and Druliner (1986) applied multiple linear regression to measurements of nitrate and herbicide concentrations in 82 wells tapping the High Plains Aquifer in Nebraska, USA. It was found that three variables (well depth, irrigation-well density and nitrogen-fertilizer use) explain 51% of the variation in nitrogen concentrations, and that two variables (specific discharge and well depth) explain 60% of the variation in triazine herbicide concentrations. Using nitrate concentration in combination with specific discharge explains 84% of the variation in triazine herbicide concentrations.

Teso et al (1988) has shown the utility of discriminant analysis, which is a statistical method for assigning objects to categories based on their location in a multi-dimensional data space. The methodology was to identify 835 sections of one sq. mile each in Fresno County, California, as susceptible to ground water contamination by 1,2-dibromochloropropane (DBCP) or not. As much as 511 sections out of the 835 evaluated were classified as contaminated. When
tested on an independent data set from nearby Merced County, the same function yielded a success rate of 0.573.

Evans and Maidment (1995) have statistically assessed the vulnerability of Texas ground water to nitrate using discrete and lognormal probability estimates. The exceedance values of nitrate in ground water samples are used as indicators of vulnerability. The nitrate data for the period 1962-1993 consisting of 62,692 records were used in this study.

Logistic regression analysis to relate the occurrence of elevated nitrate concentrations and the detection of atrazine to natural and anthropogenic variables in the Puget Sound Basin was reported by Tesoriero et al (1998). The form of the logistic regression model used is

$$P = \frac{(e^{(b_0 + bX)})}{(1 + e^{(b_0 + bX)})}$$  \hspace{1cm} (2.1)

where $P$ is the probability that the constituent of interest is present at a concentration above a specified level;

- $X$ is a vector of $n$ explanatory variable values;
- $b_0$ is a scalar intercept parameter; and
- $b$ is a vector of slope coefficient values, so that

$$bX = b_1X_1 + b_2X_2 + \ldots + b_nX_n$$  \hspace{1cm} (2.2)

The explanatory variables which best described the occurrence of elevated nitrate concentrations are well depth, surficial geology and the percentage of urban and agricultural land within a radius of 3.2 km of a well. In
addition, Eckhardt and Stackelberg (1995), Tesoriero and Voss (1997), Donato (2000) and Nolan (2001), have used the parametric and non-parametric statistical methods to relate contaminants in ground water to assess aquifer vulnerability.

Bates et al (1996) and Alberti et al (2001) have used Bayesian weights of evidence method to prepare the posterior probability maps indicating the vulnerable zones. The weights of evidence method (Bonham-Carter et al 1989) is the log-linear version of the general Bayesian model, where the evidence is binary. The binary evidence is the nitrate concentration exceeding a threshold value. Alberti et al (2001) has used the thematic maps such as rainfall, irrigation, soil, landuse, hydraulic conductivity of vadose zone, depth to ground water and ground water velocity as predictor maps to come out with a response map indicating the nitrate concentrations exceeding a particular value.

Huicheng et al (1999) developed a multi-objective fuzzy pattern recognition model for assessing ground water vulnerability based on the DRASTIC model. The model has been applied on five hydro geologic settings and the resulting membership degree is compared with the ranking of the above setting as per DRASTIC model. However, the proposed model did not take into account the variability within a hydro geologic setting.

2.4.4 Summary and comparison of vulnerability assessment models

The various models used in each of the category discussed above are listed in Table 2.1. As detailed in the table, most of the overlay and index methods are applied at small scale i.e. 1:50,000 or smaller, while the process based models are applied at a larger scale i.e. 1:24,000 or larger.
Table 2.1 Methods of Aquifer Vulnerability Assessments
(Modified from NRC (1993) and Improved)

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Model</th>
<th>Reference</th>
<th>Scale</th>
<th>Application</th>
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<tbody>
<tr>
<td></td>
<td><strong>(i) Overlay and Index Methods</strong></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>Kansas Leachability Index</td>
<td>Kissel et al., 1982</td>
<td>Small</td>
<td>Intrinsic</td>
</tr>
<tr>
<td>2</td>
<td>DRASTIC</td>
<td>Aller et al., 1987</td>
<td>Variable</td>
<td>Intrinsic, Specific</td>
</tr>
<tr>
<td>3</td>
<td>California Hot Spots</td>
<td>Cohen et al., 1986</td>
<td>Large</td>
<td>Intrinsic, Specific</td>
</tr>
<tr>
<td>4</td>
<td>Washington Map Overlay Vulnerability</td>
<td>Sacha et al., 1987</td>
<td>Small</td>
<td>Intrinsic, Specific</td>
</tr>
<tr>
<td>5</td>
<td>GOD</td>
<td>Foster 1987</td>
<td>Small</td>
<td>Intrinsic</td>
</tr>
<tr>
<td>6</td>
<td>SEEPAGE</td>
<td>Moore 1988</td>
<td>Variable</td>
<td>Intrinsic</td>
</tr>
<tr>
<td>7</td>
<td>SINTACS</td>
<td>Civita M 1990</td>
<td>Small</td>
<td>Intrinsic</td>
</tr>
<tr>
<td>8</td>
<td>LPI</td>
<td>Meeks and Dean 1990</td>
<td>Small</td>
<td>Specific</td>
</tr>
<tr>
<td>9</td>
<td>IOWA Ground Water Vulnerability</td>
<td>Hoyer and Hallberg 1991</td>
<td>Small</td>
<td>Intrinsic</td>
</tr>
<tr>
<td>10</td>
<td>EPA\UIC</td>
<td>Petty John 1991</td>
<td>Small</td>
<td>Intrinsic</td>
</tr>
<tr>
<td>11</td>
<td>SPISP</td>
<td>Goss and Wauchope 1990, Goss 1992</td>
<td>Small</td>
<td>Specific</td>
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<td></td>
<td><strong>(ii). Process Based Models</strong></td>
<td></td>
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<tr>
<td>12</td>
<td>PESTANS</td>
<td>Enfield et al., 1982</td>
<td>Large</td>
<td>Specific</td>
</tr>
<tr>
<td>13</td>
<td>BAM</td>
<td>Jury et al., 1983</td>
<td>Large</td>
<td>Specific</td>
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<tr>
<td>14</td>
<td>MOUSE</td>
<td>Steenhuis et al., 1987</td>
<td>Large</td>
<td>Specific</td>
</tr>
<tr>
<td>15</td>
<td>PRZM</td>
<td>Carsel et al., 1984</td>
<td>Large</td>
<td>Specific</td>
</tr>
<tr>
<td>16</td>
<td>RF/AP</td>
<td>Rao et al., 1985</td>
<td>Variable</td>
<td>Specific</td>
</tr>
<tr>
<td>17</td>
<td>CMLS</td>
<td>Nofziger and Hornsby 1985</td>
<td>Large</td>
<td>Specific</td>
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<tr>
<td>18</td>
<td>GLEAMS</td>
<td>Leonard et al., 1987</td>
<td>Large</td>
<td>Specific</td>
</tr>
<tr>
<td>19</td>
<td>LEACHM</td>
<td>Wagenet and Hutson 1987</td>
<td>Large</td>
<td>Specific</td>
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<tr>
<td>20</td>
<td>RTZ/VIP</td>
<td>Nofziger et al, 1988</td>
<td>Large</td>
<td>Specific</td>
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<tr>
<td>21</td>
<td>RUSTIC</td>
<td>Dean et al., 1989</td>
<td>Large</td>
<td>Specific, Intrinsic</td>
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<td></td>
<td><strong>(iii). Statistical and Probabilistic Models</strong></td>
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<tr>
<td>22</td>
<td>Discriminant Analysis</td>
<td>Teso et al., 1988</td>
<td>Small</td>
<td>Specific</td>
</tr>
<tr>
<td>23</td>
<td>Regression Analysis</td>
<td>Chen and Druliner 1988</td>
<td>Small</td>
<td>Specific</td>
</tr>
<tr>
<td>24</td>
<td>Weights of Evidence</td>
<td>Bates et al., 1996, Alberti et al., 2001</td>
<td>Small</td>
<td>Specific</td>
</tr>
</tbody>
</table>
The statistical and probabilistic methods discussed above have the advantage of being applied over a regional scale. But, they require extensive water quality data over considerably a long period, as the predictions are purely based on the known contamination distribution in the area using water quality data. And also, these methods are always applied for a specified contaminant and hence assessment of intrinsic vulnerability is not possible. Process based models are more sophisticated but are seldom used for regional scale vulnerability assessments owing to inherent limitations such as; cost of data acquisition, suitable spatial coverage of point measurements and usage of parameters which are not physically measurable. Overlay and index methods are most widely used for regional scale assessments on account of being less data intensive and simple in implementation. But, they lay less emphasis on processes controlling the ground water contamination and cannot be used as a replacement for site-specific assessment of ground water vulnerability. However, overlay and index methods are cost-effective for regional scale vulnerability assessments and are a valuable tool for relative evaluation of areas to screen out, focus and to enact ground water protection measures.

2.5 DRASTIC MODEL - INTRINSIC AND SPECIFIC VULNERABILITY

Merchant et al (1987) were probably the first to use the DRASTIC method for a 800 sq. miles area in Harvey and Kansas County, USA. The work was carried out in a raster based GIS with a cell size of 165 ft² and data required were collected from sources ranging from 1:500,000 to 1:24,000 maps. The output maps classified the area into low to high zones of vulnerability.
A number of authors, Regan (1990), Hickey and Wright (1990), Evans and Myers (1990) and Rundquist et al (1991), have carried out similar works but emphasized the means of use of GIS in the formulation of digital database required for DRASTIC model and in its implementation. However, most of these works highlighted the overlay concept used in GIS without capitalizing on the strengths of using GIS other than the overlay approach. Atkison and Thomlinson (1994) have used DRASTIC and Pesticide DRASTIC ratings and compared the DRASTIC intrinsic vulnerability rating with specific pesticide DRASTIC vulnerability. Canter et al (1994) reports that GIS enabled the merging of data obtained at different spatial and temporal scales, facilitating the organized characterization of regional-scale variability. And also, it is reported that visualisation of surface and sub-surface interactions is difficult as most of the current GIS softwares work only in two dimension.

Engel et al (1996) used DRASTIC methodology for Indiana State, USA, to evaluate ground water vulnerability to pesticide and nitrate pollution. The vulnerability maps for pesticide and nitrate are prepared at 1:2000,000, 1:1000,000, 1:500,000 and 1:100,000 scales and compared. Water samples were collected from 521 sites in the 35,870 sq. miles area and analysed for nitrate and commonly used herbicides such as alachlor, atrazine and metoalachlor. Secunda et al (1998) developed a composite DRASTIC model to a specific region of a coastal aquifer, at a scale commensurate with effective hydrological management needs. The methodology employs empirical means to integrate aquifer media and extensive agriculture landuse data covering the study area. The final assessment incorporates both the natural state of the vadose zone and aquifer media as well as the potential danger posed by the long-term effect upon the media of existing extensive land usage to the region’s ground water. The study estimates a composite index for each cell, enabling comparison
with a potential index of vulnerability to ground water pollution, which includes landuse impact and the empirical situation of ground water quality in the field. The results exhibit certain correspondence between the DRASTIC Index, the Composite DRASTIC-Agricultural Landuse Index, and high nitrate levels.

Hammerlinck and Arneson (1998) as part of Wyoming ground water vulnerability project used DRASTIC model for intrinsic and specific assessment. They have modified the model by assuming equal weight of one for all the seven parameters used in the model. For the purpose of specific assessment, they have used the landuse map of the state and ranked landuse classes irrigated cropland, dry land agriculture and urban areas depending on the inherent capacity to transport pollutants. The pesticide use intensity index is arrived at based on urban index, irrigated crop index and dry land index calculated using the pesticide loading rate and the areal extent.

George and Nagarathinam (1999, 2000) conducted vulnerability studies for Adyar watershed by combining DRASTIC and SEEPAGE models. In this study the sub-surface characterization was attempted using artificial neural network. Using process domain and terrain landscape intrinsic vulnerability assessment was made but specific vulnerability assessment was not attempted.

Johansson et al (1999) developed a framework for ground water protection for Managua, Nicaragua, using DRASTIC methodology for both point and non-point sources of pollution. The emphasis in this study is in characterizing the contaminant sources based on the contaminant class, relative contaminant concentration, mode of deposition, duration of contaminant load and remediation. The study area consisted of variety of activities ranging from tanneries to textile manufacturers consisting of point sources of pollution and
non-point sources of pollution from agricultural activities. The authors have given different rating for contaminants such as chromium and chlorinated solvents from tannery effluents and contaminants from textile effluents. The results obtained were represented as general vulnerability index map and sensitivity of vulnerability to ground water level changes and ground water abstraction.

Added and Hamaza (1999) have used DRASTIC method for a watershed in Tunisia and used surface water balance method for calculating the recharge parameter. The resulting DRASTIC index value ranging from 80 to 175 were reclassified into extremely high, very high, high, medium and low vulnerability category. Webb and Lilburne (1999) have reported that the results from the detailed process based model such as LEACHM has provided a similar rating as that of DRASTIC and indicated that DRASTIC model could be effectively used to the similar landscapes.

2.6 VALIDATION OF DRASTIC MODEL

Several investigators studied the impact of landuse related contamination. For instance; Mullen (1991) showed that the improvement to county level DRASTIC score could be achieved using intensity of atrazine use and occurrence of leachable soils. Spalding and Exner (1993) documented the association of nitrate contamination with irrigated cropland, especially when such cropland is situated on well-drained soils having permeable vadose zone. Erikson (1993) has used the landuse map to explore modifications on the vulnerability models, by modifying the DRASTIC method for nitrogen fertilizer applications using the fertilizer application rate based on the landuse themes.
Kalinski et al (1994) used the Nebraska state vulnerability map prepared by Rundquist et al (1991) and observed a positive correlation between ground water vulnerability as indicated by DRASTIC and the frequency of occurrence of Volatile Organic Chemical (VOC) contamination in ground water systems. The results suggested that the above link is the probable correlation between the DRASTIC scores and vadose zone time of travel.

Navulur and Engel (1996) have used modified ratings for DRASTIC model and compared the nitrate detections with the original and modified ratings. There was a 24% increase in the areas categorized as low vulnerability using the modified DRASTIC approach. The conventional DRASTIC and SEEPAGE models predicted 80% of the high and very high vulnerable areas correctly. There was a 20% increase in accuracy in predicting low vulnerability areas using the modified DRASTIC technique.

Melloul and Collin (1998) carried out an indexed assessment of ground water vulnerability in Sharon region of Israel and validated the model with chloride and nitrate values in ground water samples. They have suggested that the disagreement in chloride and nitrate values with DRASTIC index would help identify areas where lateral flow rather than vertical percolation is the major contributor to degradation of water quality.

Rupert (1999) has used nitrite plus nitrate as nitrogen (NO$_2$ + NO$_3$ - N) values in ground water samples collected during 1991-1994, to calibrate the probability map indicating ground water vulnerability. Three of the seven DRASTIC parameters namely, depth-to-water, recharge (landuse used as a surrogate for recharge) and soil map were used in this improved model. The probability ratings for each of the above themes were based on Wilcoxon rank
sum statistical test between the nitrate values and sub-classes in each of these themes. The developed probability map was correlated with the nitrate values using an independent set of ground water quality data.

Statistical methods and GIS were used to investigate potential indicators of ground water vulnerability to agricultural chemical contamination in an alluvial aquifer of Mississippi River (Lin et al 1999). A total of 47 wells were sampled for analysis of nitrate, phosphorus, potassium and 13 pesticides commonly used in the area. The background concentration of nitrate as nitrogen (values above back ground concentration indicate anthropogenic impact and considered as having elevated nitrate-N) adopted in this study is 0.4 ppm. Out of the 47 wells, 28 wells had elevated nitrate-N concentrations (i.e. above 0.4 ppm) and one well showed concentration above 10 ppm, which is the maximum contaminant level for drinking water purposes. Non-parametric statistical methods have been used to assess correlation between nitrate-N values and DRASTIC index. The generic DRASTIC index showed a spearman rank correlation coefficient of 0.426, while Pesticide DRASTIC index showed only 0.368. Envelope functions were developed between Generic DRASTIC index and nitrate-N values. The study concluded that nitrate concentration could be used as a variable in discriminating pesticide contaminated and non-contaminated wells. However, many wells with elevated nitrate concentrations did not have pesticide detections. The reason attributed to this observation is that the unequal retardation rate of pesticide and nitrate.
2.7 DECISION SUPPORT SYSTEM FOR VULNERABILITY STUDIES

Aquifer vulnerability assessment offers a high scope for use of multi criteria evaluation techniques, but contrary to that the literature is replete with use of such techniques. Reported literature using Analytic Hierarchy Process (AHP) and CLIPS-Expert System shell are summarised below.

Crowe and Mutch (1990, 1994) developed a model called Expert System for Pesticide Regulatory Evaluation Simulations (EXPRES), which accounts for the major physical, chemical, and biological processes affecting the transport and degradation of pesticides in the unsaturated zone. They have used the expert system approach for determining the potential for pesticide contamination of ground water in Canada.

Ta-oun (1998) developed an expert system for predicting the impact of intensive agriculture on ground water pollution potential using CLIPS expert system shell. The expert system predicts the ground water pollution potential under several conditions of agricultural activities and existing environments, based on the answers given by the user to the if-then questions. It also suggests appropriate mitigation and protection measures that can be applied efficiently. The ground water pollution expert system was mainly used to assess the ground water pollution potential from nitrogen fertilizer and pesticide applied to cropped area.

Giupponi et al (1999) developed a multi criteria analysis system for producing risk maps of agricultural pollution due to alternative cultivation systems in the Watershed of the Lagoon of Venice covering about 184,000 ha,
in Italy. Results of a field-scale simulation model for agricultural diffuse pollution were used to compile a matrix of environmental impacts, in terms of pollution indices. The authors have combined the risk of pollution of surface and ground water using the multi criteria approach. For the purpose of above study, four main risk factors were evaluated in terms of Drinkability index (ground water), Mammal toxicity index (ground water), Non-mammal toxicity index (surface water) and Eutrophication index (surface water). These pollution risk indices were evaluated for a 30-year period using GLEAMS model using two cultivation scenarios. The results have shown the impact of eco-compatible cultivation practices, which reduce the risk for surface and ground water pollution.

Analytic Hierarchy Process (AHP), a decision support tool proposed by Saaty (1980) is another method used in vulnerability assessment. The AHP is based upon the construction of a series of 'pair-wise comparison' matrices, which compare all the criteria to one another. This is done to estimate a ranking or weighting of each of the criteria that describes the importance of each of these criteria in contributing to the overall objective. Thirumalaivasan and Karmegam (2001) have used the AHP to modify the DRASTIC model in order to make it suitable for local conditions. However, in the above study sub-surface characterization of vadose zone was not included. Graphical User Interface (GUI) has been developed for the AHP model input using visual basic language and it has been seamlessly integrated with Arc View® GIS software.

As an improvement over this, the sub-surface characterization of vadose zone is attempted in this present study and incorporated in both the modified DRASTIC and AHP-DRASTIC model. Several other investigators namely,
Hickey (1997), and Jandric and Srdjevic (2000) have reported the use of AHP in the field of pollution and water resources.

2.8 SUMMARY

The process based models are the sophisticated methods focusing on the processes involved in contaminant transport, but depend too heavily on field data. The requirement of field data at the scale of assessment and its cost of acquisition are its major drawbacks. Similarly, the statistical methods rely on the known distribution of contaminants at a location and are reliable when long-term field data are available.

In this context, the DRASTIC model under overlay and index methods, is proposed to be used as a regional scale vulnerability assessment model in this study. The utility of DRASTIC model as a regional scale assessment model is well established and is fully compatible to be implemented in GIS environment.