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Standard Guide for Selection of Methods for Assessing Ground Water or Aquifer Sensitivity and Vulnerability[1]

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1. Scope

1.1 This guide covers information needed to select one or more methods for assessing the sensitivity of ground water or aquifers and the vulnerability of ground water or aquifers to water-quality degradation by specific contaminants.

1.2 This guide may not be all-inclusive; it offers a series of options and does not specify a course of action. It should not be used as the sole criterion or basis of comparison, and does not replace professional judgment.

1.3 This guide is to be used for evaluating sensitivity and vulnerability methods for purposes of land-use management, water-use management, ground-water protection, government regulation, and education. This guide incorporates descriptions of general classes of methods and selected examples within these classes but does not advocate any particular method.

1.4 *Limitations*—The utility and reliability of the methods described in this guide depend on the availability, nature, and quality of the data used for the assessment; the skill, knowledge, and judgment of the individuals selecting the method; the size of the site or region under investigation; and the intended scale of resulting map products. Because these methods are being continually developed and modified, the results should be used with caution. These techniques, whether or not they provide a specific numeric value, provide a relative ranking and assessment of sensitivity or vulnerability. However, a relatively low sensitivity or vulnerability for an area does not preclude the possibility of contamination, nor does a high sensitivity or vulnerability necessarily mean that ground water or an aquifer is contaminated.

1.5 The values stated in SI units are to be regarded as standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 5447 Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem[2]

D 5490 Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information[2]

D 5549 Guide for the Contents of Geostatistical Site Investigation Report[2]

D 5717 Guide for the Design of Ground-Water Monitoring Systems in Karst and Fractured-Rock Aquifers[3]

D 5880 Guide for Subsurface Flow and Transport Modeling[3]

3. Terminology

3.1 *Definitions*—Many of the terms discussed in this guide are contained in Terminology D 653. The reader should refer to this guide for definitions of selected terms.

3.1.1 *ground-water region*, *n*—an extensive area where relatively uniform geology and hydrology controls ground water movement.

3.1.2 *hydrogeologic setting*, *n*—a composite description of all the major geologic and hydrologic features which affect and control ground-water movement into, through, and out of an area (**1**).[4]

3.1.3 *sensitivity*, *n*—*in ground water*, the potential for ground water or an aquifer to become contaminated based on

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

[4] The boldface numbers in parentheses refer to a list of references at the end of this guide.

intrinsic hydrogeologic characteristics. Sensitivity is not dependent on land-use practices or contaminant characteristics. Sensitivity is equivalent to the term ″*intrinsic ground-water vulnerability*” **(2)**.

3.1.3.1 *Discussion*—Hydrogeologic characteristics include the natural properties of the soil zone, unsaturated zone, and saturated zone.

3.1.4 *vulnerability*, *n—in ground water*, the relative ease with which a contaminant can migrate to ground water or an aquifer of interest under a given set of land-use practices, contaminant characteristics, and sensitivity conditions. Vulnerability is equivalent to ″specific ground-water vulnerability.”

4. Significance and Use

4.1 Sensitivity and vulnerability methods can be applied to a variety of hydrogeologic settings, whether or not they contain specifically identified aquifers. However, some methods are best suited to assess ground water within aquifers, while others assess ground water above aquifers or ground water in areas where aquifers have not been identified.

4.1.1 Intergranular media systems, including alluvium and terrace deposits, valley fill aquifers, glacial outwash, sandstones, and unconsolidated coastal plain sediments are characterized by intergranular flow, and thus generally exhibit slower and more predictable ground-water velocities and directions than in fractured media. Such settings are amenable to assessment by the methods described in this guide. Hydrologic settings dominated by fracture flow or flow in solution openings are generally not amenable to such assessments, and application of these techniques to such settings may provide misleading or totally erroneous results.

4.2 The methods discussed in this guide provide users with information for making land- and water-use management decisions based on the relative sensitivity or vulnerability of underlying ground water or aquifers to contamination. Most sensitivity and vulnerability assessment methods are designed to evaluate broad regional areas for purposes of assisting federal, state, and local officials to identify and prioritize areas where more detailed assessments are warranted, to design and locate monitoring systems, and to help develop optimum ground-water management, use and protection policies. However, some of these methods are independent of the size of the area evaluated and, therefore, can be used to evaluate the aquifer sensitivity and vulnerability of any specific area.

4.3 Many methods for assessing ground-water sensitivity and vulnerability require information on soils, and for some types of potential ground-water contaminants, soil is the most important factor affecting contaminant movement and attenuation from the land surface to ground water. The relatively large surface area of the clay-size particles in most soils and the soils' content of organic matter provide sites for the retardation and degradation of contaminants. Unfortunately, there are significant differences in the definition of soil between the sciences of hydrogeology, engineering, and agronomy. For the purposes of this guide, soils are considered to be those unconsolidated organic materials and solid mineral particles that have been derived from weathering and are characterized by significant biological activity. In the United States, these typically include unconsolidated materials that occur to a depth of 2 to 3 m or more.

4.3.1 In many areas, significant thicknesses of unconsolidated materials may occur below the soil. Retardation, degradation, and other chemical attenuation processes are typically less than in the upper soil horizons. These underlying materials may be the result of depositional processes or may have formed in place by long-term weathering processes with only limited biological activity. Therefore, when compiling the data required for assessing ground-water sensitivity and vulnerability, it is important to distinguish between the soil zone and the underlying sediments and to recognize that the two zones have significantly different hydraulic and attenuation properties.

5. Description of Methods

5.1 *Hydrogeologic Settings and Scoring Methods*—This group of methods includes those that involve geologic mapping, evaluation, and scoring of hydrogeologic characteristics to produce a composite sensitivity map or composite vulnerability map, or both. The methods range from purely descriptive of hydrogeologic settings to methods incorporating numerical scoring. They can include descriptive information or quantitative information, or both, and the maps can be applied as a "filter" to exclude specific hydrogeologic units from further consideration or select sensitive areas for further study.

5.1.1 The concept of assessing ground-water sensitivity and vulnerability is relatively recent and still developing. Thus, the methods presented differ because they have been developed for different purposes by different researchers using various types of data bases in several hydrogeologic settings. These methods have been divided into three groups: assessments using hydrogeologic settings without scoring or rankings, assessments in which hydrogeologic setting information is combined with ranking or scoring of hydrologic factors, and assessments using scoring methods applied without reference to the hydrogeologic setting. The groups are not exclusive but overlap. Each of these methods produces relative, not absolute, results whether or not it produces a numerical score. Sensitivity analyses can be used as the basis for a vulnerability assessment by adding the information on potential point and non-point contaminant sources.

5.1.2 *Hydrogeologic Settings, No Scoring or Ranking*—Hydrogeologic mapping has been widely used to provide aquifer sensitivity information. This subgroup of methods includes those that generally present information as composite hydrogeologic maps that can be used for multiple purposes. The maps can be used individually to make a variety of land-use decisions or used as a basis for ground-water and aquifer sensitivity evaluations. Although derivative ground-water and aquifer sensitivity maps can be prepared, any geologic or hydrogeologic map could potentially be used to assess sensitivity. In settings where quantitative data are lacking, hydrogeologic maps can allow the same conclusions, with the same level of confidence, as scoring methods. Hydrogeologic settings were mapped in detail without scoring or ranking in the Denver Colorado, United States area by Hearne and others **(3)**.

5.1.2.1 Sensitivity assessments based on hydrogeologic settings with no scoring or ranking can be used to assess ground-water or aquifer vulnerability by overlaying information on potential point or non-point contamination sources. For example, the sensitivity map included in Ref **(3)** has been used in combination with a series of maps entitled "Land Uses Which Affect Ground-Water Management" **(4)** to conduct vulnerability assessments at specific sites within the greater Denver area.

5.1.3 *Hydrogeologic Settings with Ranking or Scoring, or Both*—This group of methods includes those which assess ground-water or aquifer sensitivity within or among various hydrogeologic settings using specific criteria to rank or score areas beneath which the ground water or aquifers have different potentials for becoming contaminated. The assessment is usually based on two or more hydrogeologic criteria. For example, material texture and depth to aquifer are parameters that are commonly used to establish criteria **(5-10)**. Criteria, once defined, can then be ranked or scored, or both.

5.1.3.1 Assessing vulnerability from point and non-point sources of potential contamination (for example, leaking tanks, waste generators, landfills, and abandoned hazardous waste sites) is accomplished by mapping their location on a sensitivity map (for example, numerous waste-generation sites in an area of low sensitivity would result in a relatively low vulnerability rank, all other factors being equal). This mapping method is particularly useful for evaluating the vulnerability of a large region. However, it can also be used to target smaller areas of particular concern where more detailed investigations may be needed. For example, Shafer **(11)** mapped regional aquifer vulnerability based on sensitivity analysis. Bhagwat and Berg **(12)** defined aquifer sensitivity according to depth to aquifers and the characteristics of the geologic materials. The sensitivity map was combined with information showing the distribution of waste-source sites per zip code per square mile. Highly vulnerable areas have aquifers at or near the surface and contain numerous point sources of potential contamination with mobile contaminants. Areas of low vulnerability have deep ground water or no aquifers and contain few potential contaminant sources or relatively immobile contaminants. This vulnerability information was then used to establish ground-water protection planning regions.

5.1.4 *Scoring, Without Hydrogeologic Settings*—This category includes those methods that use qualitative ranking or quantitative scoring with hydrogeologic information, but without subdividing the area on the basis of hydrogeologic settings. Methods were developed to have universal application and were intended to be used consistently to provide uniform results regardless of location. The methods are useful for applications that require a consistent approach over large areas, however, these methods can be complex and may require much unnecessary data preparation. Furthermore, because criteria selection and ranking are subjective, the final scores may be misleading.

5.1.4.1 These methods classify a site or region based on a ranking or a numerical score derived from hydrogeological information irrespective of the different hydrogeologic settings that may be present within the mapped area. Scores are calculated from equations based on criteria assumed to apply to different geographic areas and different hydrogeologic conditions **(1,13–14)**. For example, in South Dakota **(15)**, drilling logs and soil survey maps were used to prepare maps based on hydraulic conductivity which was inferred from the percent and thickness of surface organic matter. Attenuation potentials of soil in selected Wisconsin counties **(16)** were mapped based on soil depth, permeability, drainage class, organic matter content, pH, and texture.

5.2 *Process-Based Simulation Models*—These methods for assessment of ground-water sensitivity and vulnerability use a variety of models, each of which simulates some combination of the physical, chemical, and biological processes that control the movement of water and chemicals from land surface through the unsaturated zone to and through the saturated zone. These processes are formulated in terms of equations that are derived theoretically or empirically. Analytical or numerical techniques are used, usually within a computer program, to solve the equations. The solutions take the form of predicted rates of water and chemical movement as a function of location and time. Models differ greatly in the degree of complexity used to incorporate actual processes, the amount of data required, the intended scale of the application, and the domain simulated. The latter criterion is arbitrarily selected here to categorize different simulation models. The three categories are: Root Zone Models, which simulate water and chemical movement through the portion of the unsaturated zone that is affected by vegetation; Unsaturated Zone Models, which simulate transport through the entire thickness of the unsaturated zone; and Saturated Zone Models which deal with processes occurring beneath the water table. Within each category there can be a wide range of model complexity with some models overlapping between different categories. Unsaturated-zone and root-zone models have been cataloged by van der Heijde **(17,18)** and van der Heijde and Elnawawy **(19)**.

5.2.1 Model complexity, data requirements, and scale of application are closely related and should be considered in conjunction with each other. As models increase in complexity, it is expected that the accuracy of their predicted results would be improved. However, there would also be a commensurate increase in the amount of data required by the models. The lack of requisite data often limits the scale at which complex models may be applied, and many model codes are restricted to field-scale applications.

NOTE 1—The term "field-scale" as used here refers to the typical size of an agricultural field. In general, this is an area of 65 hectares (160 acres) or less that is planted to a single crop. "Local scale" refers to an area the size of a 1:24 000-scale quadrangle or the area of a typical county, while "regional scale" refers to an area of from several counties to one or more states.

5.2.2 *Root-Zone Models*—Models in this category were developed primarily for the agricultural industry to assess and compare the effects of agronomic best management practices (BMPs) on the management, protection, and enhancement of the chemical quality of ground- and surface-water resources. These simulation models provide a relative prediction of the fate and transport of sediments, salts, pesticides, fertilizers, and organic wastes applied to crop production systems. Because of the specificity of these models, they are generally applied at the scale of a single farm field although they can be used for areal management in combination with regional sensitivity maps.

5.2.2.1 Model components include the hydrology of the site (weather, surface runoff, return flow, percolation, evapotranspiration, lateral subsurface flow, and snow melt), erosion (water and wind), nitrogen and phosphorus cycling (loss in runoff, leaching, transport on sediment, mineralization, immobilization, and crop uptake as well as denitrification and nitrogen fixation), pesticide fate and transport, crop management factors (growth, yield, rotation, tillage, drainage, irrigation, fertilization, furrow diking, liming, and waste management), and economic accounting. Some models contain default values that allow them to be used for general planning, however, the user may supply site-specific values to improve the applicability of the result to the site of interest. These root-zone models usually calculate the amount of each pollutant of concern delivered out of the bottom of the root zone or unsaturated zone, but do not account for reactions in the saturated zone.

5.2.2.2 Examples of models in this category are the Pesticide Root Zone Model, PRZM **(20)**, the Groundwater Loading Effects of Agricultural Management Systems Model, GLEAMS **(21)**, the Chemical Movement in Layered Soils Model, CMLS **(22)**, and EPIC (Erosion Production/Impact Calculator) **(23)**. An application of the EPIC model is given in Williams **(24)**.

5.2.3 *Unsaturated-Zone Models*—Models in this category are capable of simulating processes throughout the entire unsaturated zone. Some models were developed specifically for agricultural applications, others were developed for more general problems of water and contaminant transport. In general, these models offer more sophistication in the treatment of the physical process of water movement than the root-zone models. Water movement through the unsaturated zone is usually described by Richard's Equation and the advection-dispersion equation is employed to describe solute transport. The equations are solved in one or two dimensions with primary consideration given to vertical water movement. Some models are capable of solving three-dimensional problems and others can account for both unsaturated and saturated movement of water and chemicals. Additional data are required for solving a more complex equation. For example, information on the relations between water and soil (that is, moisture-retention and relative permeability data) may be required.

5.2.3.1 Two problems limit the scale at which these models may be applied: the aforementioned lack of requisite data, and the fact that Richard's Equation is difficult to accurately solve for large regions. Application of these models is usually limited to areas less than or equal to the size of a single field. These models also require a certain amount of expertise to operate and to interpret results. Examples of these models include: LEACHM **(25)**, VS2DT **(26)**, RZWQM **(27,28)**, and SWMS_3D **(29)**. These models are used primarily for vulnerability assessment, although they can also be used for sensitivity analysis. A summary of commonly used unsaturated zone models, and their data requirements, is presented by Kramer and Cullen **(30)**.

5.2.4 *Saturated-Zone Models*—This category of models is limited to processes in the saturated zone. Effects of unsaturated zone processes such as recharge and evapotranspiration are often incorporated in an ad hoc fashion. For ground-water sensitivity studies, a ground-water flow model such as MODFLOW **(31)**, is often applied. Flow rates, position in the flow system, ground- and surface-water interaction, and recharge rates can be identified through model analysis. For example, regions with high simulated recharge rates may be considered to be highly sensitive to ground-water contamination. Data requirements are generally less stringent than for the previous category because Richard's Equation is not involved and chemical transport is often not addressed.

5.2.4.1 Ground-water modeling studies to evaluate sensitivity of a particular site should be developed in accordance with the procedures described in Guides D 5447 and D 5490. Ordinarily, these models are used to simulate primarily horizontal ground-water flow in two or three dimensions. These models have the advantage of also being applicable at large scales (regional analysis). A vulnerability analysis may be performed using a solute-transport model such as MOC **(32,33)** or MT3D **(34)** in conjunction with the guidance of Guide D 5880.

5.2.5 *Limitations*—Process-based simulation models are powerful and useful tools, but their application can be problematic. Uncertainty in simulation results can arise from two major causes: model-related errors and data-related errors. Modeling errors can arise from improper conceptualization of the problem or inappropriate application of a model on the part of the modeler. Also of concern is failure of the selected model to accurately and completely represent system processes. This matter is often a question of scale; while some very detailed processes can be addressed at the scale of a laboratory column experiment, it would not be practical to incorporate that detail into a regional-scale model. An example of such a process is preferential water flow through soils, such as flow through root or worm holes, desiccation cracks, and joints. The importance of this process is widely recognized, but because of the large amount of detailed data required to understand it, it is not practical to deterministically account for it in large-scale models.

NOTE 2—In karst or fractured-rock aquifers, velocity, turbulence, boundary conditions, directions of flow, and contaminant transport cannot be adequately simulated using currently available code **(50)**.

5.2.5.1 Data are needed in order to determine parameter values and to evaluate the accuracy of model results. A large constraint on model application is the availability of representative data. Representativeness refers to both the quality (all methods of data collection have some degree of error) and the quantity of data required to adequately represent the modeled region. Various approaches have been taken to study the effects of uncertainty in parameter values upon simulation results **(35)**. One approach is to use Monte Carlo techniques **(36)** and a large number of model simulations to assess parameters. Carsel and others **(36)** used this approach to assess leaching potential by applying PRZM in conjunction with probability distributions of soil properties in a simple screening procedure.