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EXPERT SYSTEMS FOR GROUND WATER MANAGEMENT*

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ABSTRACT

Ground water management via protection and remediation has been of special concern for several years due to the extensive usage of ground water resources as water supplies, and to impaired ground water quality resulting from a variety of societal activities and practices. Because of the complex and poorly understood mechanisms of subsurface transport and fate, subjective judgment or heuristic knowledge is often applied in ground water management; thus, this is a suitable domain for expert systems applications. Expert systems refer to computer programs that encode the knowledge and reasoning used by a variety of specialists to solve difficult problems in narrowly defined domains. They rely more on heuristic rules-of-thumb and pattern matching rather than numerical models and algorithms. Included herein is a delineation of thirty-nine such systems related to different facets of ground water management. Most of the systems are focused on hazardous waste site risk assessment and cleanup activities. Nine systems are briefly described to provide a range of illustrations; they include: 1) the RPI Site Assessment System to characterize hazardous waste sites, 2) DEMOTOX for the assessment of the contamination potential of organic chemicals at waste sites,

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3) HAWAMAX to assess and minimize risk from hazardous waste sites, 4) Defense Priority Model (DPM) for ranking of waste sites based upon their relative risk to human health and the environment, 5) WASES to identify and prioritize the contaminant sources in wellhead protection areas, 6) EXPRES to assess the potential for pesticides to contaminate ground water, 7) ESES to assist in designing a sampling plan, and selection of sampling techniques for soil and ground water contaminants, 8) CORA for remedial technology selection and cost estimation for cleanup of Superfund sites, and 9) SEPIC for issuing permits for on-site private sewage disposal systems. Validation is a critical step in the development of an expert system, with such validation enhancing its usage. Field applications and hands-on training opportunities are expected to lead to further refinements in existing systems and the development of new applications. Of critical importance in the development of an expert system are the numbers and types of involved experts, and the approach used to develop the knowledge base. This information, along with usage information, software costs, completeness of system documentation, and thoroughness of system rules, would be useful in selecting an expert system for meeting a particular need.

INTRODUCTION

An expert system generally refers to a computer software that has been developed to provide advice on solving problems in a topical area. The system is usually based on heuristic knowledge of facts in a particular problem domain. The complexity of ecosystems and environmental transport and fate concerns have made this a suitable generic domain for the development of expert systems. Also, because of the limited number of experts in many substantive areas, environmental problem-solving can be aided by the collective knowledge of a fewer number of experts. Expert systems can also be assembled for problems that can be solved heuristically, thus regulatory expert systems have been developed to improve management activities by saving time, and increasing consistency and efficiency.

Many expert systems for environmental management have been developed in recent years, and the number continues to increase. For example, a total of sixty-nine environmental expert systems was identified in a 1990 comprehensive review [1]. Although numerous expert systems have been developed, many are still at the prototype level and only a few are routinely used. Some reasons for such limited usage are presented later.

Among multiple environmental issues ground water quality protection and remediation is of special concern due to the excessive usage of ground water resources and to limitations which can result from quality impairment. Comprehensive ground water management can involve many activities, including resource protection, contaminant source control, contaminant site cleanup, and related monitoring and data management. Additionally, several environmental laws and regulations for protecting ground water have been enacted in the last few years at both the state and federal level in the United States. Due to these multiple concerns, management needs, and institutional requirements, specialized ground water management expertise is needed from such diverse fields as biology, chemistry, economics, engineering, geology, hydrogeology, law, mathematics, and statistics. Further, because of the complex and poorly understood mechanisms of subsurface transport phenomena, subjective judgment or heuristic knowledge can be useful. Therefore, ground water quality protection and remediation has been recognized as a suitable domain for expert systems applications. Accordingly, this article focuses on fundamental information related to expert systems, and on brief comparative reviews of nine systems related to ground water management.

BASIC ELEMENTS OF EXPERT SYSTEMS

An expert system consists of three major parts: a knowledge base, an inference engine, and a working memory. The knowledge base contains facts and heuristics associated with the application domain. This base is generally developed by knowledge engineers who translate the knowledge extracted from experts or published literature into rules or strategies. The knowledge base is usually incorporated in an expert system via the use of "If-Then rules."

The inference engine serves as the control mechanism. It organizes problem data, searches the knowledge base for applicable rules, and solves the problem in the working memory. During rules searching, the inference engine establishes its own reasoning and search strategies depending upon the imbedded knowledge in the knowledge base. In a typical rule-based system, the inference engine has a pattern matcher and rule applier. The pattern matcher searches for rules and determines which rules are relevant by comparing information in the working memory with the premises of every rule. If the rule applier finds no applicable rule(s), it does not act. Conversely, when multiple rules are relevant, the applier selects and applies the most specific one. New information is created in the working memory as the actions outlined in the selected rule's "then-part" are performed. The inference engine repeats this match-select-act cycle of interaction between the working memory and knowledge base until nothing more can be achieved for a specific problem [2].

The working memory of an expert system is used in the consultation process. As the inference engine searches and selects rules, new information is generated in the working memory; this information can then direct the inference engine to subsequent searching paths or strategies.

An expert system typically contains other components such as a user interface and explanation facility. The expert system user interface generally has more capability than conventional user interfaces, and the explanation facility can be used to respond to questions about the reasoning process used to develop a solution.

DEVELOPING AN EXPERT SYSTEM

The development of an expert system requires four basic elements: a knowledge engineer(s), experts or knowledge sources, software or development tools, and hardware. A knowledge engineer can also act as an expert, or vice versa. Generally, expert systems development includes the identification of the problem domain and selection of knowledge sources, knowledge acquisition, knowledge representation and programming, and testing. Each of these four stages are interdependent and can overlap in the system development process.

The first stage involves identifying the problem, defining the goal(s) or desired output(s) of the system, selecting sources of knowledge (e.g., experts and published literature), and determining required resources (e.g., time and computing facilities) for development of the system. Problems involving classification, interpretation, diagnosis, prediction, instruction, planning, and design are amenable to expert system development. These problem domains can be solved heuristically and/or require symbolic reasoning. If possible, the domain of an expert system should be relatively mature in terms of knowledge. A dynamic knowledge environment is not particularly suitable for system development; however, a system can be developed if it can be updated regarding changing knowledge. For example, expert systems based upon governmental rules and regulations will have to be modified as changes occur.

Knowledge acquisition (the second stage) refers to the process of extracting, organizing, and structuring knowledge for system input. Potential sources of knowledge include problem domain experts, published literature, and relevant informational databases. In any given expert system, one or a combination of knowledge sources can be used. Several approaches can be used to extract knowledge from human experts; examples include structured or unstructured interviews, use of questionnaires, brain storming meetings, the nominal group process technique, and the Delphi technique [3]. However, the relative success of these approaches are not well documented. Further, time and budgetary constraints may limit the utilized approaches. When inputs are received from a group of experts, one person (the knowledge engineer) must have the responsibility of making the final decision based on such inputs.

Knowledge representation (the third stage) involves expressing the concepts and relations of knowledge elements in a formal way, usually within a framework allowed by a selected building language or tool (expert system shell). Rule-based representation is the most commonly utilized technique in environmentally-oriented expert systems. The represented knowledge is then encoded using a computer language or expert system shell. Building languages can be classified into AI (Artificial Intelligence) languages such as Prolog and Lisp, and general languages such as Turbo Pascal, C, etc. Shells refer to complete applications development environments based on the languages mentioned above. Usually, commercially available shells incorporate one or more knowledge representation models (e.g., production rules, frames, and blackboard systems) and inference strategies (e.g., forward or backward chaining), debugging tools and software utilities, and a library of potentially usable functions. Selection of an appropriate shell is critical in the development of an expert system, and the choice can be complicated. For example, Badiru identified more than fifty commercially available expert system shells; their prices range from several hundred to several thousand dollars [3].

Once the programming is completed, in the fourth stage the expert system should be tested to verify and validate its applicability to the problem domain. Verification is required to determine if the system is working as intended, while validation is used to determine if the system's output is acceptable to problem domain professionals. Verification involves running the system with informal case studies to check the errors in the knowledge base, evaluate system performance in relation to its design objectives, and incorporate appropriate revisions. This stage may uncover problems such as missing concepts and relationships, conflicting or incomplete rules, or knowledge represented at the wrong level or detail. Once the system is verified, it should then be validated. Systems developed from "inflexible or hard knowledge," such as governmental rules or regulations, do not require rigorous validation; the accuracy of the system's output can be determined at the verification stage by running informal test cases. However, systems that include "flexible or soft knowledge" (professional judgment) in the knowledge base should undergo more rigorous validation. Such validation could be conducted by a third party evaluator or outside experts. For complete evaluation, input from a variety of potential users should be solicited.

SUMMARY OF THE REVIEWED EXPERT SYSTEMS

Several expert systems have been developed for ground water protection and/or management activities. A total of thirty-nine systems from the United States, Canada, and Europe have been identified; and summary information is presented chronologically in several specific categories in Table 1. Most of the listed expert systems are PC-based.

The majority of the expert systems listed in Table 1 apply to hazardous waste site risk assessment and cleanup activities. Prerequisite to cleanup and minimization of risks from waste sites is the assessment of risk and prioritization or ranking of sites; eleven of thirteen systems in the Contaminant/Source Risk Assessment category address such assessment and prioritization. Once waste sites are prioritized, the next steps include further problem investigation, remediation planning and remediation alternatives selection, and remediation system design. Six expert systems are included in the Remediation Planning and Investigation

Table 1. Expert Systems Related to Ground Water Protection and Management

System	Problem Domain	Reference(s)
	Vulnerability Mapping of Aquifers	
AQUISYS	Classification of aquifers according to vulnerability to contamination and importance	Hushon [4]
	Contaminant/Source Risk Assessment	
RPI Site Assessment*	System to characterize inactive hazardous waste sites	Law, Zimmie, and Chapman [5]
DEMOTOX*	Assessment of ground water contamination potential of organic chemicals at waste sites	Ludvigsen, Sims, and Grenney [6]
GEOTOX	Assessment of existing and potential waste disposal sites	Wilson, Mikroudis, and Fang [7]
HAWAMAX (Hazardous Wastes and Management Expert System)*	System to assess risk and provide advice about reducing health and environmental risks at hazardous waste sites	Shih and Bernard [8]
MEPAS	Prioritization of U.S. Department of Energy waste sites based on their potential hazard to human health, and facilitation of site specific remedial investigation and endangerment assessment	Droppo and Hoopes [9]
ALEXIS	Assessment of contaminated site for monitoring and remediation	Hushon [1]
XSAL	Identification, analysis, and evaluation of waste sites to provide assistance on remediation	Hushon [1]

	Contaminant/Source Risk Assessment (Cont'd.)	
Defense Priority Model (DPM)*	Used for ranking U.S. Department of Defense waste sites for cleanup based on the relative potential risk to human health and the environment	Hushon [10]
XUMA	Evaluation of contaminated sites in order to determine remediation alternatives	Page [11]
Risk Assistant	Provides assistance in conducting human health risk assessments at hazardous waste sites	Schaum et al. [12]
Risk Assessment System	Ranking and detailed risk assessment of industrial sites	Honert and Rohde [13]
WASES*	Identification and prioritization of contaminant sources in wellhead protection areas	Canter et al. [14]
EXPRES*	Assessment of potential for pesticides to contaminate ground water	Crowe and Mutch [15]
	Remediation Planning and Investigation	
WA/WPM (Work Assignment and Work Plan Generator)	Aids remedial planning activities for abandoned hazardous waste sites by generating draft-work plan	Paquette et al. [16]
SCEES	Helps in remediation of waste sites by providing an estimate of the cost and schedule	Hushon [4]

Table 1. (Cont'd.)

System	Problem Domain	Reference(s)
	Remediation Planning and Investigation (Cont'd.)	
Geophysics Expert System	Aids in the selection of appropriate geophysical monitoring techniques at Superfund sites	Greathouse, Clements, and Morris [17]
TSDSYS	System to identify facilities which treat or remove the waste from hazardous wastes or chemical incident sites	Greathouse, Clements, and Morris [17]; and Hushon [1]
FIESTA (Field Slug Test Analyzer)	Uses raw data from hazardous waste sites and evaluates field tests to compute hydraulic conductivity	Greathouse, Clements, and Morris [17]; and Hushon [1]
HASP	Assists in preparation of health and safety plans for Superfund sites	Hushon [1]
	Sampling, Analysis and Data Evaluation	
LABSYS	System to select appropriate analytical laboratores for environmental samples	Hushon [1]
Computer Aided Data	Evaluates laboratory analytical data for volatile and semivolatile organics and pesticides	Olivero and Bottrell [19]
ESES*	Assists in designing sampling plan, selection of sampling techniques, sample handling, and QA/QC procedures for sampling of soil and ground water contaminants	Olivero and Bottrell [19]
Smart Method Index	Selects appropriate laboratory analytical methods for particular waste site problems using several databases	Olivero and Bottrell [19]

	Remediation Technology Selection	
Toxic Waste Advisor	Selection of remediation technologies for cleanup of soil and ground water contaminated with solvents or hydrocarbons	Hushon [4]
TECHSCRN	System to assist in screening of remedial action technologies at Superfund sites	Greathouse, Clements, and Morris [17]
CORA (Cost of Remedial Action Model)*	Remedial action technology selection and cost estimation for cleanup of Superfund sites	Chenu and Crenca [20]
TSAR	Selection of remedial technologies during remedial investigation phase of waste site cleanup, and identification of additional required input data for final selection in feasibility study phase	Hushon [1]
	Permitting and Regulating Contaminant Sources	
SEPIC*	Permit issuance for on-site private sewage disposal systems, or recommendations for alternative systems	Hadden and Hadden [21]
Hazardous Waste Generator's System	Evaluation of hazardous waste generators for monitoring and regulating purposes	Knowles, Heaney, and Shafer [22]
Smart Reg	Provides assistance in interpreting underground storage tank regulations	Hushon [1]
HAZWASTE	System to assist EPA on regulating, under RCRA, the generation of new hazardous wastes	Anandalingam [23]

Table 1. (Cont'd.)

System	Problem Domain	Reference(s)
	Ground Water Modeling Assistance	
EXPAR	Assists users in estimating flow and transport parameters for ground water modeling	Schwartz, McClymont, and Smith [24]
Aquifer Classification System	Selection of the appropriate hydrogeologic setting for use in stochastic ground water modeling using relevant databases for the selected setting	Newell and Bedient [25]
INHEC-1	Helps users select input parameters for the HEC-1 ground water model	Hushon [1]
Expert ROKEY	Assists in preparing input data for a ground water transport model, and assists in planning monitoring strategy	Page [11]
	Other Systems	
FLEX (Flexible Liner Expert)	Selection of synthetic liners for landfills and surface impoundments based on their chemical compatibility	Rossman and Siller [26]
UTliner	System to aid in judging the quality of a compacted clay liner which may be placed over an abandoned landfill	Greathouse, Clements, and Morris [17]
LANDIS	Uses waste characteristics and the HELP (Hydrologic Evaluation of Landfill Performance) model in order to assess the leaching and disposal of solid wastes in a landfill	Constable [27]

*Systems that are described in brief detail herein.

category. Problem investigation involves activities such as sampling, sample analysis, and data evaluation. After completion of the remedial (problem) investigation, pertinent remediation alternatives are selected. In this step, remediation technology selection is a major task; and four expert systems are listed in this category in Table 1. Study activities ranging from risk assessment to cleanup require multiple experts, considerable professional judgment, interpretation of multiple environmental laws and regulations, and adequate information or data in the different problem solving processes; thus it is understandable why a large number of remediation-related expert systems have been developed.

A major issue in ground water protection is contaminant source control. Control-related activities involve permitting via regulating contaminants and contaminant sources. Several expert systems listed in Table 1 are related to permitting contaminant sources or regulating and monitoring hazardous waste generators. Table 1 also lists several expert systems for assisting ground water modeling efforts, and for evaluating engineering designs to minimize risk from contaminant sources.

EXAMPLES OF EXPERT SYSTEMS

Following a review of the features of the thirty-nine ground water-related expert systems listed in Table 1, nine were chosen as illustrations of a range of applications (six are related to Contaminant/Source Risk Assessment; and one each to Sampling, Analysis, and Data Evaluation; Remediation Technology Selection; and Permitting and Regulating Contaminant Sources). The selected systems include: 1) the RPI Site Assessment System to characterize hazardous waste sites, 2) DEMOTOX for the assessment of the ground water contamination potential of organic chemicals at waste sites, 3) HAWAMAX to assess and minimize risk from hazardous waste sites via cleanup, 4) Defense Priority Model (DPM) for ranking of waste sites based upon the relative risk to human health and the environment, 5) WASES to identify and prioritize the contaminant sources in wellhead protection areas (WHPAs), 6) EXPRES to assess the potential for pesticides to contaminate ground water, 7) ESES to assist in designing a sampling plan, and selection of sampling techniques for soil and ground water contaminants, 8) CORA for remedial technology selection and cost estimation for cleanup of Superfund sites, and 9) SEPIC for evaluation of permits for on-site private sewage disposal systems. Highlighted information from these nine systems illustrate the breadth of their potential use in ground water management.

RPI Site Assessment System

The RPI Site Assessment System was developed for inactive hazardous waste site investigations [5]. It can be used to characterize inactive sites so that risks to the environment and public health can be assessed. The knowledge base was developed using the U.S. Environmental Protection Agency's hazard ranking system (HRS) for Superfund sites. The HRS generates a hazard score once the site has been properly characterized. The RPI Site Assessment System enables a user to characterize a site by emulating the procedures an expert would follow. Production rules written in OPS5 language were used for knowledge representation. All numerical computations are performed using external functions written in COMMON LISP language.

The information contained in the knowledge base includes facts and rules of the HRS, as well as "rules-of-thumb" (professional judgment) an expert would use to characterize a hazardous waste site. The RPI Site Assessment System can be used in a tailored fashion to characterize two important site parameters: soil permeability levels and ground water flow direction and gradient. In the HRS, permeability levels are classified into four categories: very low, low, moderate, and high. Thus this expert system can be used to determine an HRS score for a site based on soil permeability and other information such as hydraulic conductivity, soil material type, soil stratification, and the position of the water table. Similarly, risk-based scores for the ground water flow direction can be determined by knowing the topography and the elevations of water bodies nearby the site [5].

DEMOTOX

DEMOTOX is a rule-based expert system developed as an aid for assessing the potential risk of ground water contamination by organic chemicals. The system uses soil and hydrogeological characteristics, as well as contaminant characteristics, in a prioritization scheme for organic contaminants. Developed using the M.1 expert system shell, the system contains more than 200 rules and 250 facts, and numerous helpful explanations [6].

The technical core of DEMOTOX is a pollutant ranking model which utilizes a mobility and degradation index (MDI). The index is defined as the ratio between the time required for a pollutant front to travel through a soil treatment zone, and the pollutant half-life due to degradation, assuming a first-order degradation rate. Smaller MDI values signify greater ground water contamination potential, while larger ones indicate a lesser threat.

DEMOTOX can be used to specify why a particular input is needed, check major assumptions, make estimations of source input parameters, access data bases, issue warnings, and offer explanations and advice. The data bases contain information on soil texture relationships with soil moisture and porosity, U.S. Soil Conservation Service permeability classifications, evapotranspiration relationships, organic chemical classifications, organic carbon partition relationships, chemical degradation rates, and corresponding data confidence factors [6]. Another feature of DEMOTOX is the incorporation of confidence levels in the inputs, outputs, and conclusions. Once the pollutant ranking model calculates the MDI, corresponding confidence factors based on the quality of available data, expert system estimations, and any confidence levels specified by the user are determined. A confidence adjusted MDI (CAMDI) is then calculated by multiplying the MDI value by the corresponding confidence factor. The CAMDI values can be used to rank organic soil contaminants at a site; these values provide a more conservative method for evaluating contamination potential than unadjusted MDI values.

HAWAMAX (Hazardous Wastes and Management Expert System)

The Hazardous Wastes and Management Expert System (HAWAMAX) was developed to assist site planners, managers, and other decision makers regarding hazardous waste site cleanup [8]. The system performs risk assessments and decision analyses based on scientific inferences and decision makers' judgment. HAWAMAX is a rule-based system which contains five interactive modules: a knowledge base of facts and rules module (KBFRM); an environmental and site description module (ESDM); an inference module (IM); a data bank module (DBM); and a risk/decision analysis module (RIDAM).

The KBFRM contains sets of rules and standards; planning, design, engineering, monitoring, and regulation information; and data on special considerations, functional relationships, and specifications in descriptive formats. The ESDM compiles all functional and coherent data and logical statements that describe potential site and environmental considerations to assist the user's understanding of the physical, chemical, geological, and biological interactions between sites, pollutants, and pathways; short and long term effects; socioeconomic effects; and legal and regulatory requirements. The IM extracts pertinent rules and facts and determines alternate feasible plans and designs subject to the identified specifications for hazardous wastes control and management. It can also organize data into files according to prescribed environmental and site characteristics. These are then fed into the data bank module (DBM) to create and enhance the bases of inferences. The IM also generates a series of output files, stochastic in nature, through an array of simulation models developed by experts [8].

The main component of HAWAMAX is the RIDAM module. Risks and decisions pertinent to hazardous waste management can be identified, quantified, analyzed, and evaluated. The actions in RIDAM start with user input on field and laboratory data and socioeconomic considerations. Initially, RIDAM begins with risk identification and quantification, moves through an evaluation of risk acceptability and generation of risk management alternatives, and concludes with a multiattribute decision analysis [8].

Defense Priority Model (DPM)

The Defense Priority Model (DPM) is another expert system designed to evaluate the relative risk to human health and the environment from hazardous waste sites. The DPM was developed based on the Hazard Assessment Rating Methodology (HARM), a weighting-scoring methodology used by the U.S. Air Force. DPM addresses the hazards associated with source materials, pathways that may result in exposure, and the presence of potential receptors. There are three pathways included in the model [10]: a surface water pathway, a ground water pathway, and an air/soil pathway. DPM considers both human and environmental receptors, with the former being more heavily weighted. Environmental receptors include both aquatic and terrestrial populations as appropriate. Each pathway score is computed by scoring a number of related factors; with different factors having different assigned weights. The weighted scores for all factors in a pathway are added and divided by the maximum possible score to obtain a normalized value. For each of the pathways, if a chemical release is observed in that pathway, a maximum score is assigned. PROLOG software language was used to develop the DPM [10].

DPM has several additional capabilities over the manual-calculation HARM model. The system requires the user to answer a question only one time even if it is used in several separate pathways and calculations. Additional features include automatic conversion of units, checks on the range of input data, and the use of alternate data if information is missing. DPM can also generate a report that includes, in addition to the scores, full documentation of the final score through comments and a certainty indication. The system has been evaluated and refined based on expert and public comments.

WASES (Wellhead Area Source Evaluation System)

The WASES expert system was developed to aid the user in prioritizing existing potential (or actual) sources of ground water contamination in wellhead protection areas (WHPAs), evaluating the relative risks of proposed new activities having the potential for causing contamination, and identifying potential countermeasures for preventing and/or minimizing the release of contaminants from existing sources and/or proposed new activities [14]. WASES consists of a three-level approach involving increasingly greater detail. Level I analysis allows the user to prioritize contaminant sources based on four general factors—the spatial release pattern, temporal release pattern, design condition, and release location of the source. Level II analysis includes the health effects of source-associated contaminants in addition to the Level I factors. Both of these levels can be applied where protection of an entire local ground water system is the emphasis. Level III analysis is focused on evaluating the likelihood of contaminants reaching a specific well. Factors considered in the source characteristics and health effects components are the same as for Levels I and II. Additional Level III factors include the planning period, depth to ground water, unsaturated zone hydraulic conductivity or unsaturated material types, contaminant mobility, distance to well, and ground water velocity or saturated zone material with the pumping rate. The results from applying any of the three levels consist of identified contaminant sources prioritized into high, medium, or low risk groups.

The knowledge base of WASES consists of rules, data, and text material. Declarative rules represent facts, assertions, and relationships of knowledge elements in the three levels of analysis. The rules were grouped into ten modules for efficiency and transparency for understanding and refinement. Nine modules are used in contaminant source prioritization, while one is used for the identification of source management options.

Module D1 includes the rules related to source characteristics and likelihood to reach the ground water system (four general factors) in the Level I analysis. Module D1′ addresses the same factors as Module D1; however, the evaluation differs because of the problem-solving method in the Level II analysis. Module D1″ includes the rules based on the three factors related to the source characteristics component of Level III analysis. The rules for classifying contaminants based on their health effects are in Module D2. Module D3 includes the rules based on the conclusions of the rules in Modules D1′ and D2. The rules used to evaluate the likelihood of contaminants reaching a well in the Level III analysis are in Module D4. This module includes submodules for evaluation of travel time through the unsaturated and the saturated zones for different planning periods. Module D5 encompasses the rules based on the conclusions of the utilized rules in modules D1″, D2, and D4. Module D6 incorporates rules for default contaminants for different sources types or source-associated facilities and wastes.

Level III analysis incorporates the mobility of contaminants in the evaluation of the likelihood of contaminants reaching the well. The mobility data for the contaminants are in an associated database file identified as Module D7; this module includes the rules that retrieve contaminant mobility values from the database. The database was developed using dBase IV©, a commercial database software.

The rules used for the identification of management options for different sources are in Module D8. Several text files were also generated to store management options for different sources. The rules in Module D8 retrieve management options for different sources by calling on the text files.

EXPRES (Expert System for Pesticide Regulatory Evaluations and Simulations)

EXPRES was developed as an aid for assessing the potential of pesticides to contaminant ground water [15]. Developed for usage in Canada, it includes a knowledge-based system, a graphically-based user-system interface, geographical databases for twenty-two agricultural regions (in Canada), an environmental properties database for 175 pesticides, and three solute transport models. The models are used for determining pesticide leaching and the consequences of subsurface transport and fate processes. The widely used models include LP/LI, PRZM, and LEACHM; the first one is a screening model which generates a relative ranking of the potential for a pesticide to leach to the water table. Four environmental properties of the pesticides are used as the basis for LP/LI. The latter two models mathematically simulate one-dimensional transport with degradation and attenuation within the unsaturated zone.

Users of EXPRES are expected to be knowledgeable, but not necessarily proficient, in subsurface pesticide transport modeling. Accordingly, EXPRES includes a set of introductory files consisting of operating instructions, an overview of the system and its data bases, an example input data set illustrating typical values required for a pesticide assessment using all three models, and displays of typical outputs from the models. Based upon the objectives of the user, as well as available data, EXPRES can be used as an aid in selecting the most appropriate model, constructing an input data set, and interpreting the modeling results.

ESES (Environmental Sampling Expert System)

Monitoring of remediation activities, and data quality assurance (QA) and quality control (QC), are important considerations for hazardous waste sites. The U.S. Environmental Protection Agency's Environmental Monitoring Systems Laboratory in Las Vegas, Nevada, has developed several expert systems to increase the accuracy, timeliness, and cost-effectiveness of field sampling, chemical analyses, and analytical data validation within the Superfund program. ESES is one of the expert systems which can be used to plan sampling activities at hazardous waste sites in an efficient, consistent, and coordinated fashion [19].

The rule-based ESES was developed using the KnowledgePro shell; and the features of the shell, such as hypertext and hypergraphics, were used extensively. The system contains several modules which address various aspects of sample collection and analysis. The data quality objectives (DQO) process is used in ESIS, with this process referring to a sequence of ordered steps that need to be followed to assure that the data generated is of known quality and appropriate for the intended use [19]. The user is expected to be familiar with the DQO process and to provide necessary information on site characteristics.

ESES has an explanation component which prints recommendations and related justifications. A comprehensive report of the expert system session can also be printed. Two versions of ESES are available—ESES-SM and ESES-GW. ESES-SM assists in designing a sampling plan for determining the extent of metal pollution in soil, and ESES-GW helps the user to decide what types of ground water sampling pumps and devices are appropriate for given site conditions. The ESES-GW also provides advice on proper sample handling, field determinations, QA/QC procedures, personnel safety measures, and program documentation.

CORA (Cost of Remedial Action Model)

The Cost of Remedial Action (CORA) model was developed for the U.S. Environmental Protection Agency (EPA) to use in determining remedial action costs for Superfund sites. This model includes two independent subsystems. One is a knowledge-based consultation program that develops remediation recommendations, and the other is a database management system that develops site-specific cost estimates for the technologies required to implement the recommendations [20].

The CORA expert system was developed using the Level 5 expert system shell, dBASE III+, and Nantucket Clipper software. The system is comprised of four knowledge bases that communicate with each other and update facts during execution. The first knowledge base, also called CORA, contains fifteen rules that require the user to specify the waste types for each contaminated area; then it calls on the second knowledge base, MAIN, to examine each waste type. MAIN has 492 rules grouped into the following categories: removal, treatment, containment, landfill, above-ground contamination, natural attenuation, and active restoration. The rules are used to examine the contaminants specified by the user and to identify remedial action technologies. The third knowledge base, LANDFILL, contains seventy-one rules exclusively focused on issues associated with landfilling of by-products generated by treatment or containment. The fourth knowledge base, WATER, has forty-three rules and addresses the treatment of liquids generated by the technologies recommended by MAIN or LANDFILL [20]. The knowledge bases of CORA have the capability to incorporate confidence levels related to the facts included in the rules. However, CORA was not structured to ask users for the degree of confidence in their answers. The system also has the capability to deal with uncertainty reasoning [20].

CORA has been used to develop both EPAs and the U.S. Navy's annual remediation budgets. It was also used for regulatory support for the Resource Conservation and Recovery Act (RCRA) and for analyzing corrective-action strategies and costs for the RCRA Location Standards Rule. Finally, it is being used to screen technologies and remediation strategies for the U.S. Department of Defense [20].

SEPIC

SEPIC was developed for permit application evaluation and issuance for private sewage facilities (PSFs) in Travis County, Texas. The system was designed to assist the Austin/Travis County Health Department (ATCHD) in assessing applications for installing PSFs and determining which of some twenty different forms of facilities is appropriate for the particular site while ensuring compliance with applicable ordinances [21]. SEPIC is a rule-based system which was developed using the Rulemaster expert system shell. Groups of related knowledge are agglomerated into modules that embody the metastructure of the expertise. The primary variables in SEPIC are: 1) location, which has so many ramifications that it is treated in several modules, 2) field data, including slope, percolation rate, core test data, soil conditions, and topographical and geological features, 3) size calculations, and 4) type of user. System outputs are focused on different types of PSFs that may be installed at a site [21].

In case a variety of PSFs are allowed for a site, SEPIC can use an economic module to determine which one would be most cost-effective based on user-supplied field data. Based on the type of PSF selected, SEPIC can then print appropriate inspection schedules and check sheets. When unexpected information is obtained during these inspections, SEPIC can be reinvoked employing the new data and used for new permit requirements [21].

SUMMARY AND CONCLUSIONS

Environmental expert systems have been developed for several topical areas, including media management (air, surface water, and ground water), problem assessment and remediation (e.g., air pollutant emission inventories, hazardous waste site evaluation, and treatment system design), and permitting programs. While some areas are well understood by scientific communities and have reached maturity, for example, municipal wastewater treatment, others are being still explored for understanding and new methodologies or technologies. One example of a dynamic topical area is ground water contamination evaluation and remediation. There are also areas characterized by differences in opinions among environmental professionals; for example, quantitative risk assessment approaches. Expert systems developed for mature topical areas where there is general consensus among professionals will have more application and success than systems developed for poorly understood and controversial areas. Usage of developed systems in less mature areas may tend to be limited.

The potential for successful use is relatively high when in-house expert systems are developed to facilitate managerial processes within an organization; examples including permitting, regulatory support, etc. Because most of the knowledge is procedural and/or inflexible, systems developed for these uses should be free of controversy and more easily acceptable to the user. Moreover, these systems can be well maintained within an organizational context [18].

The nature of ground water protection and remediation activities readily lends itself to applications involving knowledge-based expert systems. Ground water management is still developing in terms of concepts and technologies. Because expertise transfer can be crucial in many decision making processes, many ground water-related systems have been or are being developed. However, systems developed for problem domains in which solutions are not well recognized among professionals, such as ground water management, should be rigorously validated. The absence of such validation may limit usage of the expert system. Field applications and hands-on training opportunities should facilitate system refinement and further development.

One reason for the large number of ground water-related expert systems is that the ground water management field is highly dependent on empiricism. Complex chemical and microbiological processes in the subsurface environment cannot always be described via formal mathematical equations. Reliance on experience and intuition will continue, and expert systems can help transfer this knowledge to less experienced personnel. Expert systems can also assist the experienced engineer or scientist in dealing with uncertain, incomplete, or qualitative data. Traditional algorithmic solution methods are not well equipped to handle these types of data. Finally, ground water professionals often deal with numerous governmental rules and regulations. The rule-based nature of such regulations make them readily compatible with the rule-based representation of knowledge used in many expert systems. Thus, these systems can help decision-makers reconcile complicated regulatory requirements, and they can help regulators ensure compliance.

Still other problem domains in ground water management that could be explored for future expert systems applications include consideration of different contaminant sources for permitting, regulation, and monitoring purposes; selection of best management practices to minimize risk from contaminant sources; and multiple (different types) source prioritization or assessment. Some examples already exist of expert systems for these applications, and others are being developed.

In conclusion, several types of uses of expert systems for addressing ground water protection and remediation problems have been demonstrated via this cursory review of nine knowledge-based systems selected from a set of thirty-nine identified systems. Two reasons the ground water management field lends itself to the development and application of expert systems are: 1) it is a multidisciplinary field whose problems can require combined specialized expertise, and 2) the field requires individual contributions from different substantive areas such as biology, chemistry, economics, engineering, epidemiology, fluid mechanics, geology, hydrogeology, law, mathematics, statistics, and toxicology. Individual scientists or engineers will generally not be well versed in all of these areas. Therefore, expert systems can assist by providing solution-directed knowledge on unfamiliar subjects.

The review described herein was not focused on the actual or relative usage of the thirty-nine identified systems. Some are in the development stage, while others have existed for several years. Usage information would be valuable when considering the selection of an existing expert system for meeting a particular need. Other decision criteria could include software costs, completeness of system documentation, and thoroughness of system rules. Further, attention should be given to the number and type of experts who participated in the development of the knowledge base.

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