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County-Based Priority Assessment Methodology for Phasing of Wellhead Protection Programs

H. O. Pfannkuch
University of Minnesota

M. E. Campion

D. C. McCaa

J. M. Palenberg

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H. O. PFANNKUCH, M. E. CAMPION, D. C. McCAA, and J. M. PALENBERG

ABSTRACT—Setting priorities to schedule and implement wellhead protection programs for municipal and community drinking water supplies is presented in the framework of a general risk assessment approach. This includes a hazard identification procedure representing the likelihood of contaminants being released to the surface environment, a hydrogeologic vulnerability assessment representing the risk of contaminants entering the groundwater supply, and an impact assessment, strongly linked to the population at risk. A methodology was developed to aggregate information on a county basis for Minnesota. The resulting composite risk index map shows a number of counties in the central part of the state roughly following a line from the Twin Cities Metropolitan area along two major transportation axes to the St. Cloud and Fargo-Moorhead area, and toward the south to the Rochester-Austin area to which a high priority for phasing-in of the program is recommended. These counties emerge in addition to those in the southeastern karst area of Minnesota that traditionally have been identified as vulnerable areas.

Wellhead Protection Program

The wellhead protection program (WHP) is a preventive measure intended to safeguard the quality of municipal and community drinking water supplies. It derives its legal status from the Federal Safe Drinking Water Act (Section 1428, as amended 1986) and, at the state level in Minnesota, from recently passed legislation (Groundwater Protection Act, Chapter 326 of Minnesota Session Laws, 1989). The lead agency in Minnesota to implement the provisions of the act is the Minnesota Department of Health. The basic idea behind the WHP program is to designate areas around producing wells or well fields as protection zones in which land-use activities that might endanger the water supply will not be allowed. The boundaries of the protection areas are determined by hydrogeologic methods and drawn so that potential contaminants entering the groundwater resevoir at or beyond the boundary line probably will degrade or become innocuous before reaching the well. In developing the wellhead protection program the lead agency is faced with a number of technical issues that need to be resolved. These include the actual delineation procedures, identification of potential contaminant sources and their inventory in the different protection zones, development of scientifically-based management control options for land use in the protection zones, and criteria for phasing of management controls.

This paper describes a basis for phasing-in of the implementation of wellhead protection programs in the State of Minnesota. It addresses the question of temporal scheduling of various plan elements as, for example, delineation and source control options. It is intended to be a pilot project to develop preliminary priorities to guide the process as to what areas of the state should receive priority attention for implementation of WHP programs for existing supply systems.

In particular, a method of ranking priorities based on risk assessment is developed on a county basis, so that efforts and finances can be allocated where they are needed most urgently and where they will provide the greatest effect. The work is based on the evaluation of land-use information, hydrogeologic sensitivity, and population statistics. This paper focuses on the risk assessment and hazard identification part of the problem. It needs to be recalled that besides purely technical vulnerability evaluations and risk assessments, other public policy concerns such as political and economic feasibility may enter the ultimate development of WHP programs.

Groundwater Contamination and Risk Assessment

Risk Assessment Framework

A complete risk assessment procedure has three basic components: risk determination, risk evaluation, and risk management. Risk determination involves: (i) hazard identification, which is the recognition of a hazard or threat by methods of research, screening, monitoring, and diagnosis, and the construction of causal sequence scenarios; (ii) risk estimation, which deals with the estimation of the threat potential of the hazard, the likelihood of occurence, and magnitude of the consequences by methods of probability analysis. Risk evaluation is the social evaluation of the importance of the risk, its relative ranking, acceptability, and integration into the environmental decision-making process. Risk management develops strategies to modify the system or procedures for the reduction of risks and assesses their cost effectiveness (Figure 1).

H. Olaf Pfannkuch is a professor in the Department of Geology and Geophysics at the University of Minnesota, Minneapolis. Moira Campion, David McCaa, and Janice Palenberg were students in petrology, hydrology, and earth science/geology.

Causal Sequence of Hazard Model and Groundwater Protection

For manufactured systems Hohenemser *et al.* (1) have developed a causal sequence of hazards in the form of a block flow diagram. The different blocks or components represent needs and wants that drive the technology and initiate events that produce outcomes with consequences and exposures to hazard. In natural geologic systems many components and their role in the sequence cannot be controlled, nor can their physical-geological characteristics be fully described. An adaptation of the general causal sequence of the hazard model to the particular conditions of a hydrogeologic wellhead protection system in its simplest form has at least two parallel causal sequence strings (Figure 2). One is directly related to drinking water production and supply, the other to agricultural production activities (as an example). In the first the demand block starts with the need for drinking water, the desire (or "want" in Hohenemser's terms) to meet this need with groundwater production, through a technology of pumping wells. The initiating event for the consequences is the creation of a drawdown cone around the well defining a zone of contribution (ZOC) to the pumped well. The outcome is the release and entry of contaminants into the groundwater body, the exposure is their movement through the aquifer towards the producing well using the pathway model. The consequence block is the impairment of drinking water and ingestion of the contaminated water, and whatever adverse health effects are produced.

The second parallel causal sequence string is somewhat more general. It represents the want to increase agricultural productivity through the application of agrichemicals which are released into the environment, from which outcomes, exposures, and consequences are similar to the first string. Note that the linkage between the two strings is through the release module, triggered by a natural initiating event, namely precipitation and recharge.

Groundwater Contaminant Pathway and Compartment Model

For a more effective description of the transport and fate of contaminants in the subsurface a simple pathway model has been proposed where the total migration path is subdivided into separate compartments that have common characteristics with respect to transport and fate of the pollutants. It accounts for migration and modification of anthropogenic hazards (contaminants) introduced at the land surface. The groundwater contamination pathway model describes the vertical distribution of water in a cross-sectional view, follows the bulk water movement, and identifies significant sites along the path and relevant processes within the different compartments that alter the chemical composition of the water. These compartments are the land surface, the soil zone, the vadose zone, the capillary fringe and water table, and the groundwater flow zone.

Aquifer Vulnerability Assessment

Definition in Risk Analysis Context

From a risk assessment viewpoint, hydrogeologic sensitivity or vulnerability represents the likelihood that a contaminant molecule attached to a fluid particle of water will pass through any given segment of the pathway in a given time and at a given concentration. The basic hydrogeologic problem is to answer the question: "What is the concentration of a given contaminant at a given location and time after its entry into the system?;" namely, $C = f(x,y,z,t)$. The hydrogeologic vulnerability assessment is an expression of the conditional probabilities that a contaminant sequentially traverses all compartments in a pathway model. The basic idea is to assign a score or rating value to each of the compartments of the pathway model according to the hydrologic properties and the flow and dispersion regime represented by the aquifer materials. The scores are weighted according to the relative importance accorded each compartment, the weighted

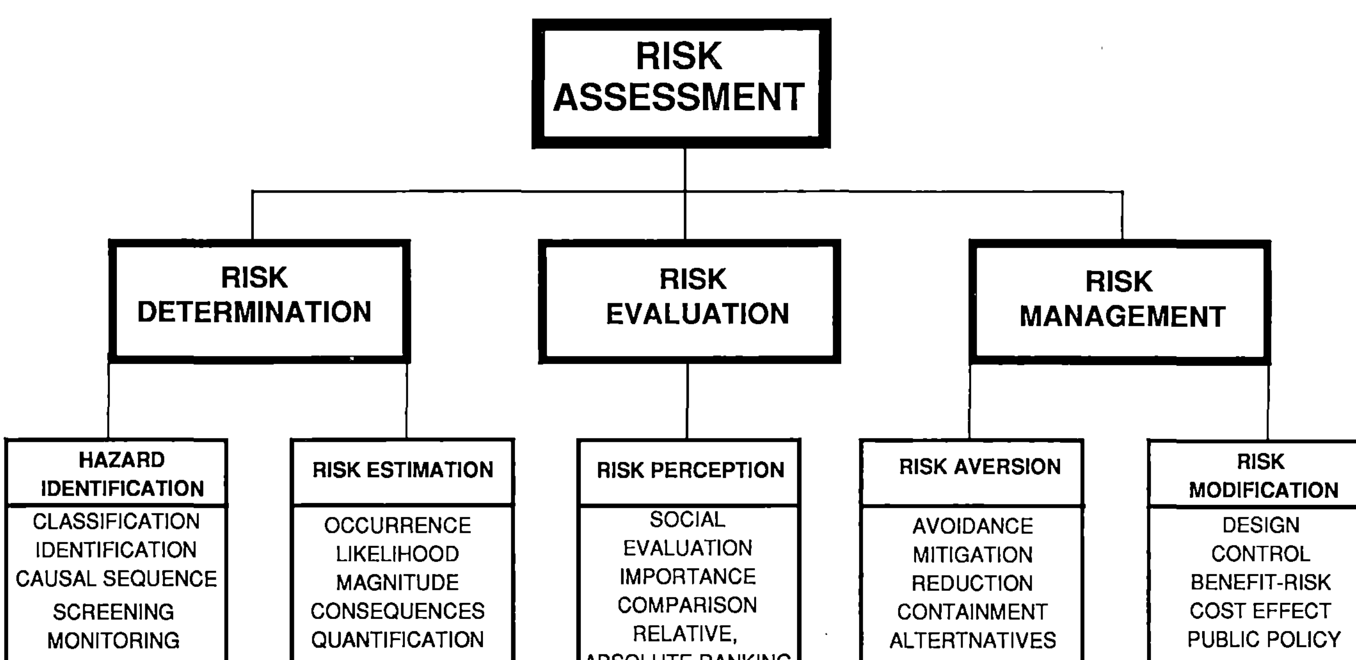

Figure 1. Components of risk assessment procedure.

scores are summed, and the total score is a relative measure of the likelihood that the contaminant will enter the aquifer and move with the groundwater flow.

A more accurate assessment of sensitivity would involve the characterization of the different compartments in the pathway model with respect to the expected fate of each specific compound, because flow properties, physicochemical characteristics, and reactivity depend on the paired characteristics of both the contaminant and the transport medium in each one of the compartments, and on the ambient environmental conditions. However, the hydraulic approach should be sufficient for the first approximative ranking of areas where the program should be implemented. In established assessment methods, like DRASTIC(2), the main emphasis is on quantification of those factors that contribute mainly to travel time such as depth to water, aquifer materials, hydrologic characteristics of the aquifer materials, and on those factors that describe the opportunity of water to enter the system, namely recharge and topography. These assessment methods account for sorption and and attenuation properties in a somewhat more implicit way in the soil and vadose zone factors.

Rating Systems

Rating systems are most frequently used to delineate sensitive hydrogeologic areas, allocate resources for groundwater protection, plan monitoring systems, permit specific land use, and set priorities for certain activities such as selection of priority areas for implementation of wellhead protection programs.

A large number of rating systems exist; the U.S. Environmental Protection Agency's (EPA) DRASTIC is a prime example (2). Porcher (3) has modified a rating system for Minnesota in close analogy to DRASTIC, and Trojan and Perry (4) have developed a rating and weighting system especially applicable on the county scale. Both publications give an overview and bibliography of existing rating systems. Most systems deal only with the definition of an intrinsic or generalized vulnerability based on bulk movement of water. None explicitly takes into account the contaminant specific vulnerability which involves retardation, sorption, or reaction in a given pathway compartment or aquifer environment. Another system to priority setting of municipal well sampling and analysis was developed by LaMalva (5). He described options for priority monitoring of organic chemical contamination in Minnesota's community wells most likely to be contaminated based on three criteria: population density, industrial activity, and proximity to known hazardous waste dump sites. This approach differs from previously discussed ones in that risk of contaminant release and impact are included explicitly in the assessment.

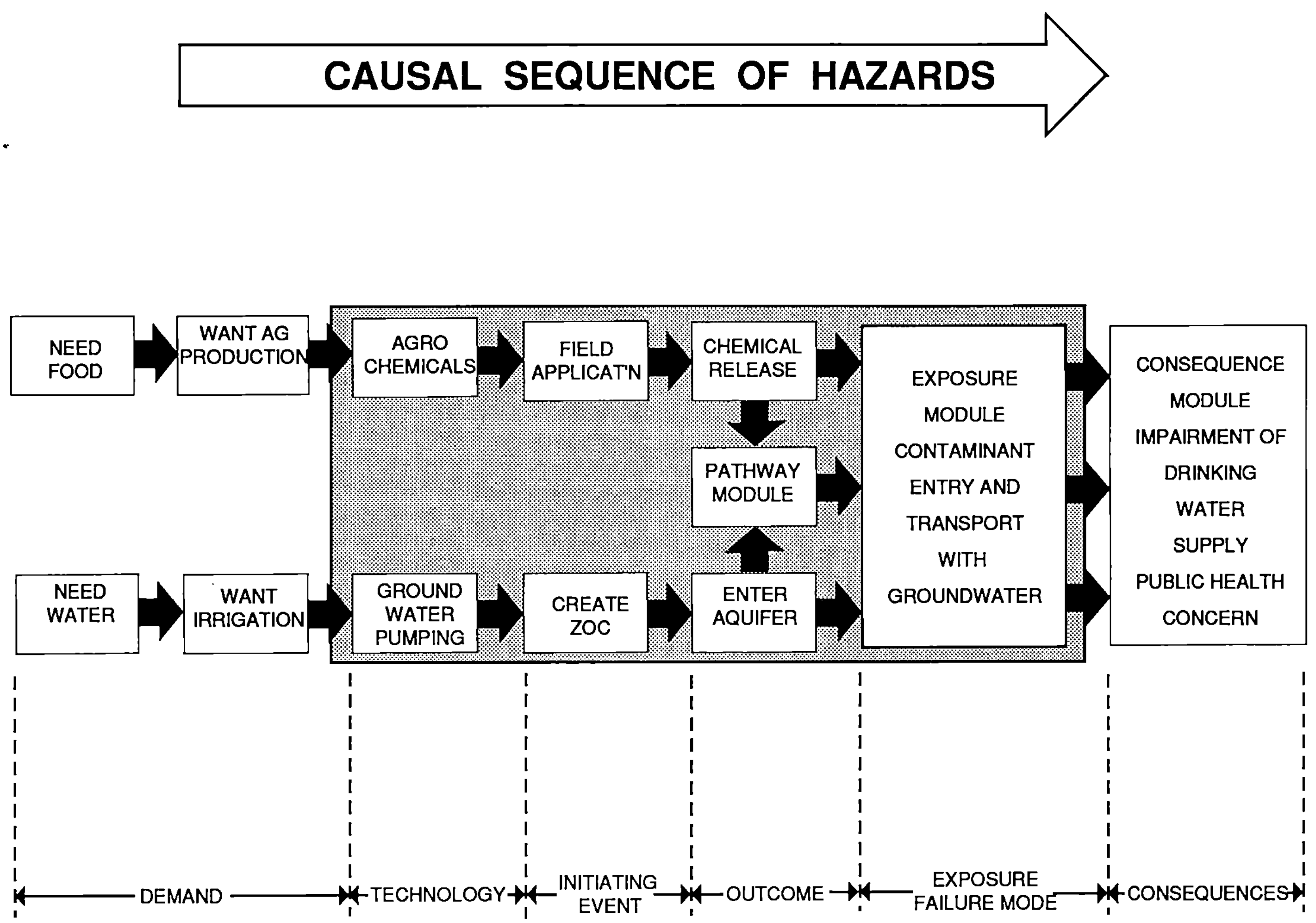

Figure 2. Causal structure of hydrogeologic hazards.

Priority Assessment Methodology for Wellhead Protection Phasing

General Approach

County-Based Approach

This paper uses an information processing and presentation approach based on counties. They are first of all the basic accounting unit for different kinds of statistical data, dealing with population, agrichemical use, public health data and surveys, and more. They are the most common scale of aggregation of specific information small enough to provide useful differentiation on the state level, but large enough to avoid fragmentation and incompleteness of relevant data. They are also the basic political subdivision in which decisions are made and carried out.

Presenting relevant information on a county base offers little difficulty for the land-use model of hazard identification and the impact module. Transforming hydrogeologic vulnerability data from a continuous vulnerability map to a county base presents more of a problem in having to areally weight and average the vulnerability units over the county.

Elements in Hazard Sequence Appropriate for Wellhead Protection

For our present purposes only the central blocks of the causal hazard sequence need to be considered, as outlined by the broken line in Figure 2. The demand for pumped groundwater is accepted as a given, and the modules involving human exposure and health consequences can only be addressed adequately through toxicological risk assessments, not considered in the present context. The three elements to which the approach can be reduced are sequential and interrelated: hazards generated at the land surface representing an outcome, intrinsic hydrogeologic vulnerability expressed as an exposure in the pathway model, and impact which is a consequence with severity measured by population density.

Hazard Identification/Land-Use Approach

The intent of a land-use assessment is to identify and inventory the hazards that are generated at the land surface or the immediate subsurface by use, storage, or transfer of hazardous substances and potential pollutants. In addition, the likelihood of mobilization through dissolution and release into the surface and subsurface environment has to be made by expressing the risks associated with the land use. For this particular study, considered preliminary, no explicit attempt has been made to differentiate between the weight of point and nonpoint sources of contamination. Implicitly this was done by using an areal normalization approach. This may, however, be too simplistic and needs to be addressed in further studies.

Hazard Categories by Source and Risk Factors

The hazard categories used in this study are ordered according to a decreasing likelihood that contaminants will become a problem:

- Identified contamination (Class I): This category accounts for the contaminants or indicators that have already been found in a county. In this paper the following were included in the list: identified well contamination (e.g. pesticides, nitrate, and volatile organic carbon), and identified locations such as state and federal superfund sites and priority listings. The figures are based on contaminants detected, not on the level of contamination. The logic for this first category is the concept that the likelihood to find more contamination in an area that already shows pollution is higher than in one where none has been detected yet. It needs to be pointed out that this assumes even and consistent groundwater quality data coverage for the entire state. If this is not the case, an error proportional to the degree of imbalance in the coverage can be expected.
- Potential pollution-direct indicators (Class II): These include activities and land use with high risk factors to produce hazards. This is not to say that they unescapably will result in contamination, but the likelihood that release will take place is proportional to the land area or the intensity of application. Categories in this list for which information was available include: number of waste generators and transfer points; hazardous waste generators; hazardous waste handling, storage, and treatment facilities; railroad transportation of hazardous wastes; roads and traffic volume; landfills, municipal and individual sewage lagoons; number of pesticide applicators.
- Potential pollution-indirect indicators (Class III): These comprise the low risk categories with some potential for release of contaminants through inappropriate application or handling, although the land-use activities themselves are not primarily implicated in producing hazards. These comprise agricultural activities represented by crop acreage, livestock and poultry production and transformation facilities, industrial and manufacturing sites, mining (minerals and aggregate), and major transportation routes, railroads, interstate highways, and pipelines.

In order to normalize and to make the county level information comparable, the county specific data were divided by the area of the county unless otherwise specified. This approach is justified because the purpose of this study is a relative and serial ranking of the counties to identify those of similar risk intensities for inclusion into descriptive risk classes. In a resource allocation scheme, which this study is not, the absolute quantities or amounts need to be used since they determine the level of funding needed.

Weighting Factors

Weighting factors are an additional means of improving the estimate of the likelihood of release, entry, and migration to the groundwater body and of comparing this likelihood between different pathway modules and settings. Two basic schemes were used: (i) the more general one uses relative rankings between the categories where class I has the greatest weight (x3), class II has (x2) and class III has (xl). This reflects in a relative way the pollution potential and likelihood of release into the environment of the three respective categories; (ii) a specific weighting system was applied where it was scientifically justified. In determining the final weighted crops total, the following method was used: the average rate of application of herbicides per acre was 36 quarts for corn, 29.9 quarts for soybeans, 6.1 quarts for wheat. Other small grains used an average of 4.4 quarts. This represents a ratio for corn:soybeans:wheat:other grains of 8.2:6.8:1.4:1. This ratio determined the weight factor of each crop by which the original ranks based on production area were multiplied. The ranks generated by these factors were then added together to yield a weighted crops average. The underlying hypothesis is that, in general, the counties which use the larger percentage of their area to grow or produce pesticide intensive crops will have a greater potential for pesticides to appear in their groundwater, assuming similar soil characteristics and climatic conditions.

Scoring Process and Ranking

In the present study a serial ranking approach was used. For each county the absolute value of the hazard factor in question was established and normalized according to the area of the county. Then the 87 counties are ranked serially from the highest value to the lowest in the respective category, a score of 87 being the highest and representing the highest priority, 1 representing the lowest priority. To obtain the overall score for each county, the individual scores were added over the group of weighted categories. The counties were then serially ranked according to this final score and ranges were established as the basis for the map representations. The rankings ranged from 1 to 83, and were grouped into these intervals; [1-20], [21-41], [42-62], [63-83], which were used to display the relative potential for pollution with four graphic patterns (Figure 3). A distinctive trend of high to moderately high rankings can be seen from the southeast towards the northwest along a line following the Mississippi in the southeast through the Twin Cities Metropolitan Area and the St. Cloud area towards Fargo and Moorhead.

The serial ranking process has the initial advantage of an accurate relative ranking of counties, but it cannot take into account cases where there is a large difference in the underlying absolute hazard factor between two adjacent serial ranks. This disadvantage can be overcome by more thorough statistical analyses such as the construction of a cumulative frequency diagram for each category. Significant breaks in the curve would indicate natural range boundaries. For the present study the raw summation of ranked values over all categories at least in each group is a sufficient approximation to demonstrate the methodology.

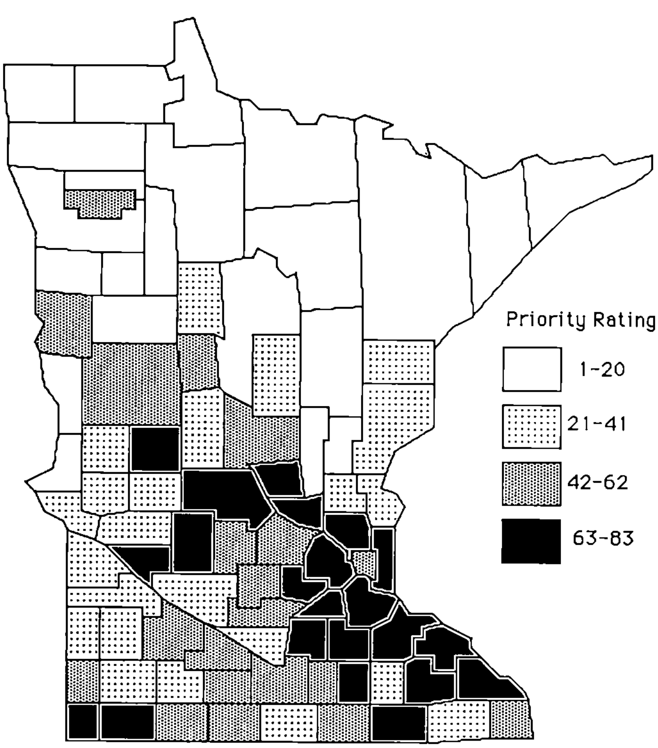

Figure 3. Composite land-use hazard index map.

Hydrogeologic Vulnerability Map

The present study concentrates on aspects of specific interest to the wellhead protection program and the use of priority setting methods to determine the phasing sequence to select the counties at highest estimated risk for first implementation of the program; it is not intended to be used for site specific studies.

General Assumptions and Approach

The characterization of hydrogeologic vulnerability or sensitivity of an area is viewed in this paper as part of the entire risk assessment process. The hydrogeologic environment provides the link between the step of hazard identification and impact assessment. It is the compartment of the sequence where the actual processes of contaminant dispersal and attenuation or other changes occur.

Hydrologic Factors

The choice of the hydrologic factors for the present study was in part dictated by the availability of information. The different categories are:

Climatic Assessment: This factor evaluates the availability of water for infiltration and entrainment of contaminants and recharge to the aquifer. It is the difference between precipitation (P) and evapotranspiration (ET). Isolines connecting points of equal values of P — ET trend roughly in a north-south direction in Minnesota for average annual conditions. The metropolitan area and the southeastern karst region of the state fall to the east of the neutral line (P — ET = 0). This indicates that on the average these regions are slightly more likely to provide the necessary recharge for entrainment, while the western portion of the state is slightly less likely to do so. For the level of resolution of the present study, this information was only used in an indirect way to ascertain that no excessive gradients exist across the state. In a more detailed study available water would have to be estimated on a county by county basis.

Soil Assessment: This factor evaluates the opportunities for the available water to infiltrate into the subsoil and the capacity of the active soil material to attenuate contamination through sorption processes and through biochemical activity in the organic layer. The most important controls for the soil's attenuating capacity are its texture, the amount and mineralogic nature of the clays present, and its exchange capacity. Palenberg (6) constructed a soil vulnerability map for Minnesota based on soil types, percent area used as cropland, known pesticide contamination, and number of pesticide applicators. The results are shown on Figure 4. Some of the parameters included in this evaluation were also used in determining the overall hazard index shown on Figure 3. Therefore the results of Palenberg's study were only incorporated qualitatively in the final composite priority map for this project. Otherwise it could increase their weight unduly, but the general trend shown on the map confirms the one already established in the hazard ranking scheme.

Surficial Geology: The factors controlling the vulnerability of surficial aquifers are hydraulic conductivity which, in conjunction with the gradient, determines the spreading of contaminants in the aquifer system. Most of the surficial aquifers in Minnesota are Quaternary glacial deposits or alluvial sediments. Their hydrologic properties are closely linked to their depositional environment. For a more detailed study a depositional facies model could be used to estimate hydrologic properties of the material in question. For the present study, however, a sustained yield map was used as the information base. The underlying idea is that sustained yield embodies in some way most of the parameters that characterize the hydrologic behavior of an aquifer system.

Bedrock Geology: Considerations of bedrock hydrogeologic sensitivity are in part based on the work of Porcher (3) and DRASTIC (2). For Minnesota the igneous and metamorphic crystalline bedrock units are essentially considered as not being aquifers except for some local conditions due to heavy fracturing. For this study they get the lowest rating in the ranking scheme. More important are the Paleozoic sedimentary rock sequences of sandstones, shale, and limestones alternating according to transgressive-regressive conditions at the time of deposition in the southeastern part of the state. Here the karst-forming carbonate sequences result in some of the intrinsically vulnerable areas. Little information about exact values of hydraulic conductivities is available statewide for the aquifer units, and even less about the hydrologic properties of the intercalated aquiclude or aquitard units. Most of the rationale for ranking aquifers is therefore based on textural information of the units and on their petrographic and lithologic description. Large depths to bedrock and numerous thick aquitards between the aquifer units mitigate the vulnerability rating.

Overall Hydrogeologic Vulnerability Ranking

For a final composite hydrogeologic sensitivity map, surficial and bedrock maps are combined. Some new concepts deal with the degree of protection. In general, great thickness of unconsolidated materials over bedrock aquifers, large numbers of aquitards above and great absolute depth to the applicable aquifer result in a higher degree of protection and a lower rating. Two other concepts relate

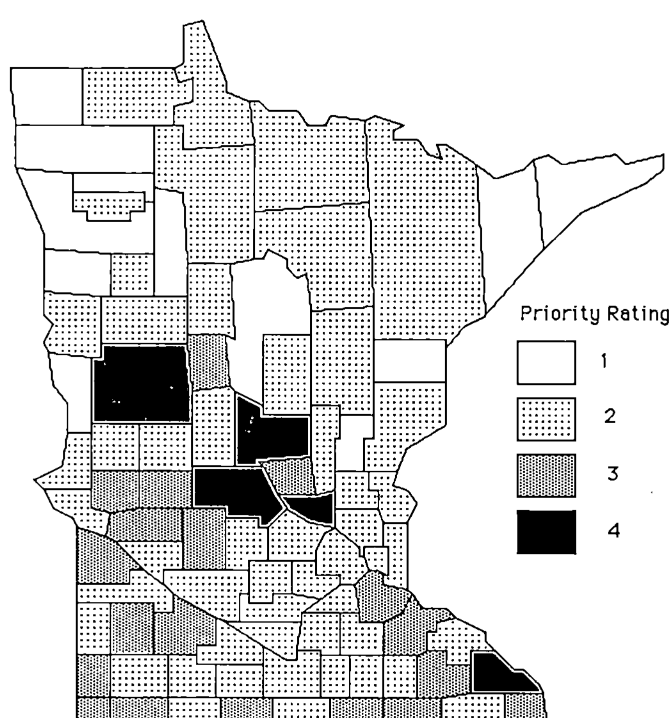

Figure 4. Soil vulnerability map.

alternative sources for municipal water and the economic and technological feasibility to produce water from alternative sources to the wellhead protection scheme.

Alternative Source and Feasibility Concept

The objective of wellhead protection is to assure the quality of drinking water supplies. Therefore, if more than one aquifer exists at one location, the vulnerability rating of any one of the aquifers in the system decreases. This concept was developed in more detail by Wallen (7) who applied a stack function to a series of aquifers after a scheme for ranking the pollution susceptibility was established for individual aquifers in the system or stack. The algorithm accounts for the position of each aquifer under the assumption that the aquifers closest to the surface are the most vulnerable. A viability factor is added to the equation by multiplication, where 0 is a non-viable aquifer and 1 is a high quality aquifer that is within economic and technical reach of being exploited.

The composite map takes into account the vulnerabilities established for the surficial and bedrock aquifers, including the viability functions applied to each region or hydrogeologic sequence. It uses a weighting scheme that accords the surficial aquifers twice the importance of bedrock aquifers. This reflects the fact that, in general, the important bedrock units already are protected by the overlying unconsolidated sediment.

On the original hydrogeologic vulnerability map the sensitivity units follow the outlines of the hydrogeologic units. In order to transform this information to a county base the areal extent of each rated unit was estimated as an areal percentage. The areally-weighted scores were added and rounded up to the nearest unit between a score of [1 to 1.5]; [2 to 2.5]; [3 to 3.5]; and [4 +] to form four sensitivity classes (Figure 5). The map does not show any dramatic trends. The northern and northeastern parts of the state have a low priority ranking (1), mostly because of the absence of any large surficial aquifer units and the underlying mostly impermeable crystalline basement. The counties around the Twin Cities area show a moderately high (3) to high (4) priority ranking.The higher ratings shown in the metropolitan area are due largely to overrating the alluvial aquifers in the Mississippi and Minnesota River valleys. This is an artifact of the scoring method which weights heavily high transmissivities and near-surface aquifers. This bias will be dealt with in subsequent studies, but had to remain on the present map for consistency. The southern half, central and west central parts of the state are of moderate priority (2) This presents a more uniform priority ranking in the southern and central part of the state than had previously been assumed. The reason for this is that the outcome of the present rating system assigns a relatively high hydrogeologic vulnerability score to the aquifers in the central part of Minnesota. These are mostly sole source near-surface water table aquifers with no alternative bedrock supplies in the underlying crystalline bedrock. Aquifer vulnerability for purposes of municipal water supply protection in the southeastern karst region is not as dramatic as the hydrologic vulnerability of such a region might imply due to the fact that within the sedimentary basin deeper aquifers exist that can serve as alternative drinking water sources.

Impact Assessment

The third component in a risk assessment procedure is to estimate the magnitude and likelihood of the impact. In the context of wellhead protection this risk is best represented by the number and density of population potentially affected. Within the limitations of this project the most meaningful and accurate available data for a first approximation is population density. Figure 6 shows a population density map with four ranges of densities (in persons per square mile). It indicates a southeast to northwesterly trend in population density starting from the southeastern corner of the state along the Mississippi through the Twin Cities-St. Cloud area and on to Fargo-Moorhead. The pattern for absolute numbers of population remains about the same.

Composite Risk Index Map

The emphasis of this study has been on hazard and risk analysis by source and impact. This approach had not been used in previous sensitivity assessments for Minnesota to the extent applied here. As discussed above four maps representing the different aspects of risk assessment were prepared with four levels of sensitivity (Figures 3 through 6). The hazard index map is based on a rigorous serial ranking scheme, the soil vulnerability and hydrogeologic sensitivity maps on a somewhat arbitrary, but internally consistent scoring procedure closely related to the DRASTIC ranking scheme, and the potential impact map on population densities from census estimates.

For this study a straight additive ranking procedure was chosen: the present level of accuracy of the data that form the basis for scoring considerations does not warrant further manipulations lest an impression of unwarranted precision and reliability be created. The maps were combined into a composite map with three levels of sensitivity scores: the highest for the values of 12 to 14+ (approximately representing the upper quartile), the next for values 9 to 11 (approximately representing the next lower quartile), and the third any value 8 or lower (approximately representing the lower half of the values). The results (Figure 7) indicate that the counties with the primary and secondary priorities for phasing in the wellhead protection program follow a southeast to northwest trending band through the state.

Discussion and Conclusions

The results of the present work show the emerging of a new grouping of priority regions in the state besides the southeastern karst region of traditional concern. The counties contained in this group are aligned along a band that follows major transportation corridors along the trace of Interstate 94 to St. Cloud and the Fargo-Moorhead region, and US 52 towards Rochester and Austin. These corridors contain other means of transportation such as railway lines and major product and crude pipelines and are the sites of other major agricultural and industrial land use. They introduce additional potential for pollution, but they are also axes along which increased economic activity takes place. Increased economic activity in turn leads to increased population density, thereby increasing the likelihood of potential impact. Since the newly identified corridor is mostly concentrated in the central part of the state, the groundwater supply is most often furnished from a single near-surface glacial drift or alluvial aquifer, whereas the underlying bedrock units usually are low volume yielding or non-productive crystalline rocks, or Cretaceous sediments producing low quality water. This makes the corridors more vulnerable than a simple hydrologic sensitivity analysis might suggest.

It should be stressed that the county-based vulnerability assessment presented here is primarily a discussion of methodology and the results are of an approximative nature.

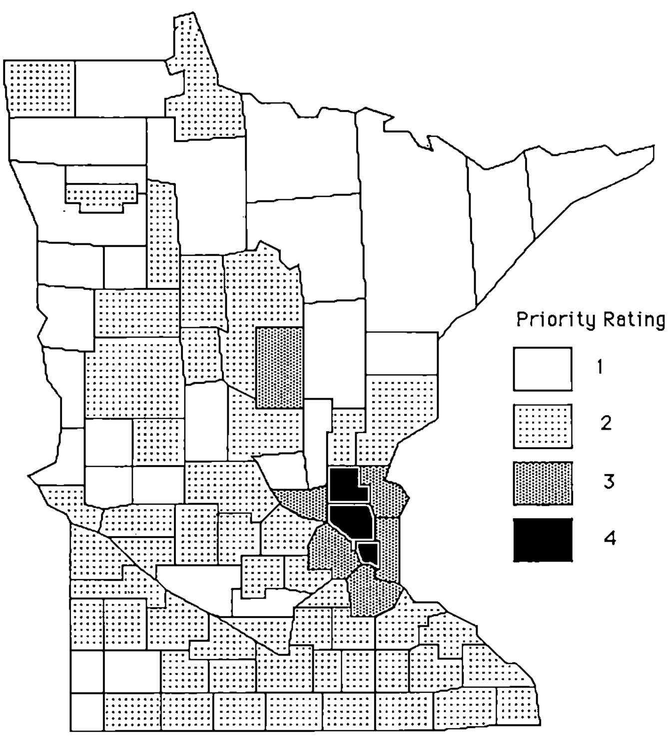

Figure 5. Composite hydrogeologic vulnerability map.

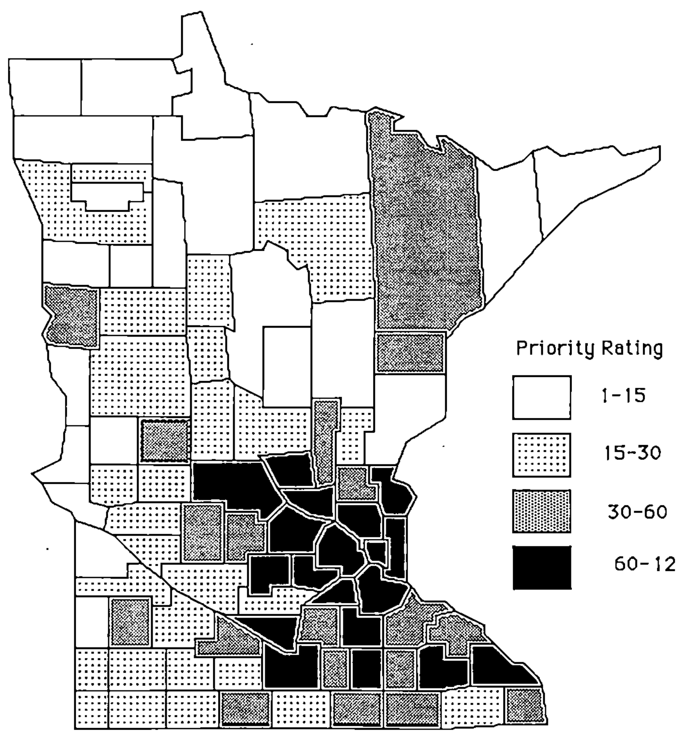

Figure 6. Population density map.

Nevertheless they can be useful to guide the selection of counties in which to initiate implementation of wellhead protection programs in the state. A more intensive development of the methodology and adaptation to other objectives would make it useful to construct vulnerability maps of a more general purpose. For this the ranking schemes should be put on a sounder statistical footing, the ranking procedures between the four categories need to be unified, and weighting and transformation functions must be found to furnish an improved basis for the final composite risk index and map. To this end, the introduction of geographical information systems (GIS) and the use of such information display and gathering systems such as Minnesota Land Management Information System (MLMIS) would be of great help.

Acknowledgements

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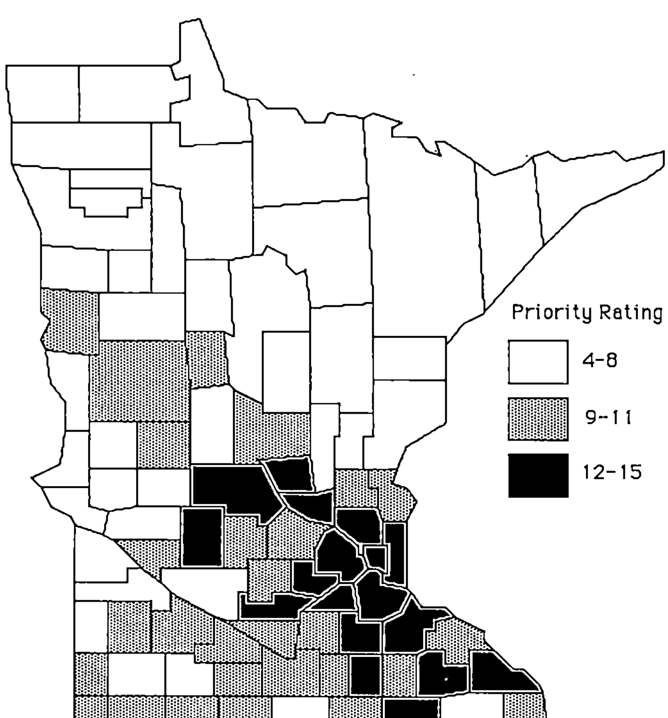

Figure 7. Composite priority index map for scheduling of wellhead protection program.

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