Groundwater Vulnerability Assessment and Mapping

Editors: Andrzej J. Witkowski, Andrzej Kowalczyk, Jaroslav Vrba
GROUNDWATER VULNERABILITY ASSESSMENT AND MAPPING
SELECTED PAPERS ON HYDROGEOLOGY

11

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Groundwater Vulnerability Assessment and Mapping

Selected papers from the Groundwater Vulnerability Assessment and Mapping International Conference, Ustroń, Poland, 2004

Edited by

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Preface

The papers in this volume cover the main issues and topics pertaining to the assessment of groundwater vulnerability:

- Factors affecting the selection of vulnerability assessment methods.
- Uncertainty in vulnerability assessment methodologies.
- Designing general (intrinsic) and specific vulnerability maps.
- Applications and limitations of vulnerability maps.
- Data needs, processing and presentation using a GIS format.

This volume has been divided into three main parts. The first part is a keynote introductory paper by Stephen Foster (the present IAH President). The second part covers aspects of the European approach to groundwater vulnerability assessment and mapping. Many of these papers refer to the Water Framework Directive (2000/60/EEC), which is currently being implemented by member states of the European Union, and a number of European funded programmes (e.g. COST Action 620), and some national solutions (Chapters 1–4). The third and most extensive part of this volume comprises case studies dealing with a wide range of issues concerning the assessment of intrinsic and specific vulnerability of different aquifers located in various geological and hydrogeological environments (coastal aquifers, shallow and deeper Quaternary aquifers, carbonate aquifers).

Increasing interest in the most vulnerable aquifers and specifically in karst aquifers has been confirmed by the large number of contributions on that topic. Because of the frequent application of the vulnerability assessment methodologies the case studies have been divided into two separate groups depending on the type of aquifer. The first group incorporates the porous-type aquifers (Chapters 5–15), whereas the second one deals with the karst-type aquifers (Chapters 16–22).

The papers were selected from those presented at the IAH Conference “Groundwater vulnerability assessment and mapping” which was held in Ustron, Poland on 15–18 June 2004. The Conference was organized 10 years after the first book about groundwater vulnerability assessment and mapping was published by UNESCO and IAH. Within the fourth phase of the IHP the international working group, composed mainly of members of the IAH Groundwater Protection Commission, published the manual “Guidebook on Mapping Groundwater Vulnerability” (J. Vrba and A. Zaporozec, editors, 1994).

The Conference was organized by the IAH Commission on Groundwater Protection, the Polish National Chapter of IAH, UNESCO and the University of Silesia. A total of 81 papers were presented during the oral and poster sessions during the conference and 23 of them have been selected for inclusion in this volume. We would like to express our particularly warm acknowledgments to the authors for their contributions as well as for their patience and understanding with regard to the delay in publication which has been caused by editorial and technical reasons. We thank the numerous reviewers (Brian Adams, Alistar Allen, Colin Both, John Chilton, Antonio Cimino, Donal Daly, David Drew, Stephen Foster, Edmund Gosk, Ricardo Hirata, Travis Hudson, Robert Kleinmann, Neven Kresic, Philip LaMoreaux, David Lerner, John Moore, Nick Robins, Ramiro Rodriguez, Andrzej...
Preface

Różkowski, Thomas Rude, Andrew Skinner, Jaroslav Vrba, Natalya Wiliams, Guido Wimmer, Alexander Zaporozec and Francois Zwahlen for their careful reviews and for their tremendous efforts in the linguistic correction of some manuscripts. We are very much obliged to Series Editor, Nick Robins, for his valuable suggestions and very kind help in editorial work. We would also like to express our special thanks to colleagues at the University of Silesia, particularly Dorota Grabala, Pitr Siwek and Jacek Wróbel for their valuable help with editing this publication.

Finally, we would like to express our special thanks to IAH and to UNESCO for their crucial financial support, without which the attendance at the conference as well as some contributions to this book by several experts from Eastern Europe and the Developing Countries, would not have been possible.

A.J. Witkowski, A. Kowalczyk & J. Vrba
March 2007
A picture speaks more than a thousand words and a map more than thousand pictures. Maps, therefore become an important tool for scientists, managers, policy and decision makers and the public. The art of groundwater vulnerability mapping based on groundwater vulnerability assessment has developed historically from geological and hydrogeological mapping.

The term vulnerability of groundwater to contamination was introduced by French hydrogeologist J. Margat in 1968 and the first vulnerability map was constructed in France by M. Albined in 1970. Since the early 1980s more complex methods of groundwater vulnerability assessment have been developed and a considerable number vulnerability maps of various scales and objectives have been produced throughout the world.

The concept of groundwater vulnerability assessment is based on the assumption that

1. the physical environment may provide some degree of protection to groundwater against natural and human impacts, and
2. some land areas are more vulnerable than others.

Groundwater vulnerability portrayed on a map shows various homogeneous areas, as cells or polygons, which have different levels of vulnerability. The differentiation between the cells is, however, arbitrary because vulnerability maps only show relative vulnerability of certain areas to others, and do not represent absolute values.

Vulnerability of groundwater is a relative, non measurable, dimensionless property. Aggregating a number of key vulnerability attributes to one vulnerability class (index), involves the various steps of selection, scaling (transforming attributes into dimensionless measures), rating and weighting. A final groundwater vulnerability class is a mathematical aggregation of individual attributes across different measurement units so that the final vulnerability output is dimensionless.

A generally recognized and accepted definition of groundwater vulnerability has not yet been developed. However, there are no significant differences in the formulation of groundwater vulnerability between individual authors. Groundwater vulnerability is mainly formulated as “an intrinsic property (characteristics) of the groundwater (aquifer) system that depends on the sensitivity of that system to human and/or natural impacts”, or “the sensitivity of the aquifer to being adversely affected by an imposed contaminant load”, or “the intrinsic susceptibility of an aquifer to contamination”.

There are generally two types of groundwater vulnerability assessments and maps: intrinsic and specific. Intrinsic vulnerability is based on the assessment of natural climatic, geological and hydrogeological attributes. Specific vulnerability relates to a specific contaminant, contaminant class, or human activity and is mostly assessed in terms of the risk of the groundwater system becoming exposed to contaminant loading. Recharge, soil properties, lithology and thickness of the unsaturated zone and depth to water table are the key attributes of both intrinsic and specific vulnerability. However, contaminants from point sources often enter the groundwater system beneath the soil profile (e.g. underground oil tanks, septic tanks) and the role of soil as an attenuation medium is then by-passed.
Some authors include the saturated aquifer in vulnerability assessment procedures, whilst other authors do not. However, the aquifer cannot be seen as a homogenous unit. Its vulnerability maybe significantly different at different places. The recharge area is always highly vulnerable and the discharge area, particularly in case of confined aquifers, is of low vulnerability. Aquifer hydraulic conductivity, does take a part in many groundwater vulnerability assessment procedures. Field and laboratory observations, however, demonstrate that the hydraulic conductivity of the aquifer may change significantly when fresh groundwater is replaced by polluted water.

The travel time of the contaminant should be included within specific vulnerability attributes. Some authors, however, state that the aquifer is equally vulnerable if contaminant travel time is one year or one hundred years and, therefore, the travel time attribute should be taken out of the vulnerability assessment concept.

The most important attribute in the assessment of specific groundwater vulnerability is the attenuation capacity of the physical environment (soil and rock) with respect to the properties of individual contaminants. However, the attenuation capacity will reduce with time, resulting in a changed vulnerability to the groundwater system. In the case of persistent and mobile contaminants, the contaminant travel time depends largely on the thickness and vertical permeability of the unsaturated zone. The amount of water stored in the aquifer and the net recharge, both control dilution of the contaminant in the aquifer.

Groundwater vulnerability maps are classified as problem oriented, specialized environmental maps derived from the basic hydrogeological map. Vulnerability maps are used for groundwater protection planning, management and decision making, for identification of areas susceptible to contamination and for public information and education. Basically two types of vulnerability maps exist. The intrinsic maps are used to evaluate the intrinsic groundwater vulnerability to a generic conservative pollutant. Single purpose and multi-purpose maps are the main categories of specific vulnerability maps. In single purpose maps the vulnerability is evaluated with respect to only one type of contaminant or group of contaminants of similar properties. The multi-purposed maps are focused on presentation of various groups of contaminants of different properties which have been identified in the mapped area. The GIS format is widely used to present various vulnerability scenarios on the vulnerability maps.

The overall utility of a vulnerability map is dependent on the scale at which the map has been compiled. Selection of the optimal scale to aggregate and present the groundwater vulnerability information depends on the data availability and its reliability, the information needed by the user and the aim of the map. The maps are only as good as the information and data upon which they are based and the knowledge and experience of the map makers. It is important that disclaimers appear on maps, informing the user:

1. about the level of accuracy of the presented information.
2. of the map limitations and any restrictions on the intended use.

Vulnerability maps are living documents. Without periodical updating, the degree of potential map misuse and misinterpretation increases.

Many hydrogeologists agree on which groundwater vulnerability attributes are relevant, but they use different methodologies for combining these attributes into a vulnerability statement. Neither terminology nor approach is standardized. Given the same data base, different authors will not arrive at the same conclusions.
Groundwater systems are much too diverse to be subjected to a standardized vulnerability assessment. However, it seems important and topical to start the process of formalization:

1. Formulation of a consistent and widely accepted definition of groundwater vulnerability.
2. Development, formalization and implementation of methods and procedures of groundwater vulnerability assessment.
3. Unification of vulnerability symbols and legends and standardization of vulnerability classes on the maps, and to make vulnerability maps internationally comparable.
4. Definition of the general content of vulnerability maps – both intrinsic and specific.
5. Development or improvement of groundwater monitoring networks to acquire data for more precise vulnerability assessment and mapping.

The “Groundwater vulnerability assessment and mapping” conference and the topics discussed in that forum have provided significant support to the new developments in groundwater vulnerability assessment and mapping. Allow me to express my appreciation and thanks to the organizers and sponsors for the preparation and organization of the conference and to Andrzej Witkowski, president of the organizing committee, my admiration to his personal effort and enthusiasm to make this conference a reality.

J. Vrba
Chairman of IAH Commission on Groundwater Protection
About the editors

Andrzej J. Witkowski (1950) received his MS (1973) and PhD (1983) from The University of Warsaw. He is Senior Lecturer at the University of Silesia, Poland, author and co-author of 90 scientific articles. He is certified professional hydrogeologist (American Institute of Hydrology and Polish Ministry of Environment), and consultant in many international projects. Since 2003 he serves as President of the International Mine Water Association (IMWA).

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Keynote introductory paper
Aquifer pollution vulnerability concept and tools – use, benefits and constraints

Stephen Foster
IAH President

ABSTRACT: A brief overview of the development, use and limitations of the aquifer pollution vulnerability concept and related mapping tools is given. While such approaches are essentially pragmatic simplifications, if appropriately formulated they are capable of providing a scientifically consistent input to formalised groundwater pollution risk assessment, which is required for advancing implementation of the provisions of the EC-Water framework Directive and for raising public awareness of groundwater pollution hazards.

1 EVOLUTION OF POLLUTION VULNERABILITY CONCEPT

In an ‘ideal world’, the groundwater hazard from each potentially-polluting activity would be investigated individually – but this is not realistic, cost-effective nor adequate to communicate concerns in the vast majority of cases. The expression aquifer pollution vulnerability thus started to be used intuitively to convey concerns about pollution from the land surface in a general way from the early 1980s – initially in France (Albinet & Margat 1970).

From the late 1980s there were various attempts to formalize the definition of the expression and to develop related mapping systems (DRASTIC, GOD, SINTACS, etc.) (Aller et al. 1987, Foster 1987, Foster & Hirata 1988, Civita 1994). These all attempted to represent complex processes in a simple fashion, which was scientifically based, but involved different ranges of contributing factors, varying degrees of simplification and subjective professional judgement (Figure 1 illustrates the GOD aquifer pollution vulnerability system).

The critical question that faces those attempting such simplification is the validity of using a single ‘integrated vulnerability index’. This bearing in mind that (in scientific reality) each class of potential groundwater contaminant will be influenced to different degree by various attenuation processes naturally operating in the soil and vadose zone (Foster & Hirata 1988). However, if we constrain use of the term ‘vulnerability’ to consider only potentially-polluting activities at the immediately-overlying land surface and use ‘smart definitions’ for vulnerability classes (Table 1), this problem can be largely overcome and the use of an integrated index justified. This then greatly favours the practical application of the concept.
2 CONTEXT FOR PRACTICAL APPLICATION OF MAPPING TOOLS

Although major simplification is involved, aquifer pollution vulnerability maps have become valuable tools in the following practical contexts:

- communicating concerns about the potential level of groundwater pollution hazard to civil society and the general public (in effect making groundwater more visible)
- providing a scientifically-based input to local land-use planning and effluent discharge control procedures
- as part of more formalized groundwater pollution risk screening procedures, especially where quality monitoring networks are still inadequate (e.g. for implementation of the EC–Water Framework Directive of 2000).

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Table 1. Pragmatic definition of the relative classes of aquifer pollution vulnerability at any given location from activities on the immediately-overlying land surface.

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<td>Extreme</td>
<td>Vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios</td>
</tr>
<tr>
<td>High</td>
<td>Vulnerable to many pollutants, except those strongly absorbed or readily transformed, in many pollution scenarios</td>
</tr>
<tr>
<td>Moderate</td>
<td>Vulnerable to some pollutants but only when continuously discharged or leached</td>
</tr>
<tr>
<td>Low</td>
<td>Only vulnerable to conservative pollutants in long-term when continuously and widely discharged or leached</td>
</tr>
<tr>
<td>Negligible</td>
<td>Confining beds present with no significant vertical groundwater flow (leakage)</td>
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For all of the above applications the most important factor in selection or design of an aquifer pollution vulnerability mapping system will be ‘fitness for purpose’ – such that the ‘vulnerability zones’ defined have strong resonance with environmental and land-use management decision-making.

In the latter of the above three applications, aquifer pollution vulnerability maps should preferably depict only the spatial variation of those intrinsic ground characteristics determining potential vertical contaminant pathways (Figure 2), since they have to be capable of interacting readily with:

- surveys of subsurface contaminant loading (or pressures upon the groundwater system).
- aquifer numerical modelling outputs delineating the area of groundwater capture or potential horizontal pollutant pathway for various receptors (Figure 2).

3 KEY FACTORS IN POLLUTION VULNERABILITY ASSESSMENT AND MAPPING

The central approach in all schemes of aquifer vulnerability assessment is to classify the (essentially intrinsic) characteristics of the strata overlying the saturated aquifer (vadose zone or confining beds) according to their:

- physico-chemical characteristics to retain and degrade potential water pollutants and consequently contribute to contaminant attenuation capacity.
- physical properties which can reduce the rate of vertical water infiltration.

It is recognised that much emphasis needs to be placed on the likelihood of preferential flowpaths developing in the vadose zone (usually as a result of fracturing) (Foster 1997, Foster et al. 2002), in view of their significance in increasing aquifer pollution vulnerability.
to certain of the most serious classes of pollution (e.g.: from pathogens and immiscible organic compounds) (Figure 3).

Certain other questions arise when selecting or designing systems of aquifer pollution vulnerability assessment, especially those relating to the inclusion of factors to take account of:

- **pollutant attenuation in the saturated zone** – the author is of the opinion that this tends to add unnecessary complexity and confusion since it is not appropriate to assume a ‘characteristic vertical travel distance to a typical receptor’, and it is thus better to include consideration of this parameter in other ways

- **attenuation capacity in the soil profile** – bearing in mind that in reality this can be highly modified or completely removed (especially in urban areas), the author is of the opinion that a soil profile factor reducing vulnerability should only be included in rural areas and where it is clear that any pollutants will be leached from the soil and not ‘injected’ deeper into the sub-soil

- **natural infiltration rates to aquifer** – despite the fact that most contaminant transport depends upon water flux the author considers it counter-productive to include such a factor in aquifer vulnerability and better to consider all forms of recharge as an integral part of the subsurface contaminant load (or pressure), since in reality recharge is a variable parameter depend greatly on human activity, such as irrigation returns and urban drainage.

4 Practical Limitations of Pollution Vulnerability Mapping

It has to recognised that any scheme of aquifer pollution vulnerability assessment and mapping is subject to inevitable limitations relating to difficulty in adequately
representing the complexity of field situations, particularly in the following instances (Foster et al. 2002):

- the **presence of semi-confined aquifer systems** – where considerable care will be needed to identify the aquifer horizon of interest for potable water-supply provision and assess the contaminant attenuation capacity of the overlying semi-confining beds bearing in mind that these may be geologically discontinuous.
- the **situation along surface watercourses** – which will often have complex influent relationships to underlying aquifers and unknown streambed attenuation properties.

Moreover, aquifer pollution vulnerability mapping schemes do not normally take into account large-scale man-made physical disturbance of the vadose zone (as may occur in mining areas or through intensive urban infrastructure development) – such situations need to be identified at an early stage and mapped accordingly. Despite the major research advances in understanding sub-surface contaminant transport and attenuation mechanisms, there is still considerable uncertainty over the behaviour of some important types of pollutant (e.g. MTBE, PCBs, etc.) in certain classes of porous media (Foster 1998).

5 FROM AQUIFER POLLUTION VULNERABILITY TO GROUNDWATER POLLUTION RISK ASSESSMENT

To move from aquifer pollution vulnerability maps to groundwater pollution risk assessment, a systematic inventory of the interacting subsurface contaminant load (both existing and potential future) is essential (Foster & Hirata 1988). In EC circles the cumulative load is known as the ‘**contaminant pressure on the groundwater system**’. This is the often-neglected complementary component of groundwater pollution risk assessment, and standardised desk and field techniques are helpful for the required survey work (Foster et al. 2002). Considerable experience and insight will be required for a balanced survey and diffuse pollution sources usually present more difficulty to estimate than potential point sources.

Another key facet of groundwater pollution risk assessment is the **delineation of flow and capture zones around public groundwater supply sources** (and other groundwater receptors), which in effect provide an additional priority focus for the risk assessment process (Figure 4). The delineation of such zones (known as **perimeters** in some EU countries) is considered the best way of dealing with the capacity of aquifers for contaminant transport, dilution and attenuation in the saturated zone (Foster et al. 2002). They also provide the scientific basis for **potable groundwater quality protection**, and are required for the implementation of the EC Water Framework Directive of 2000. But they also have their limitations as a result of unstable geometries where:

- aquifer pumping regimes are hydraulically unstable
- karstic aquifers with swallow holes and caverns occur
- multi-layered semi-confined aquifers are present.

6 FROM GROUNDWATER POLLUTION RISK ASSESSMENT TO GROUNDWATER QUALITY PROTECTION

Groundwater pollution risk assessment provides a clearer appreciation of the actions needed to protect groundwater quality, and internationally should become an **essential component**
of best practice in environmental management – the critical step being to ‘make visible’ the link between the use of given tracts of land and groundwater (resource and supply) quality (Foster et al. 2002). To protect aquifers against pollution it is necessary to constrain land-use and to control effluent discharge and waste disposal practices – and the process of land surface zoning will define a need to declare certain areas as especially critical for groundwater quality conservation and supply protection.

The legal feasibility of this approach will also have to be assessed. In certain legal codes it is possible to control land-use activities in the interest of groundwater quality, providing an overriding ‘public interest’ or ‘strategic need’ can be demonstrated – even without payment of compensation to affected land owners. But in some others powers will be more limited, and in some legal codes it will be more appropriate to use groundwater zoning information as an input to the land-use planning process, at least as far as controlling new sources of groundwater pollution is concerned.

Even where there is no quasi-legal basis for land-use planning to take account of groundwater interests, the procedures for groundwater pollution hazard assessment constitute an effective vehicle for mobilising involvement of the relevant stakeholders. The ultimate responsibility for groundwater pollution protection must lie with the relevant environment or water resource agency of national or local government, but given their responsibility to conform with codes of sound engineering practice, an obligation should also rest with water-service companies to be proactive in promoting pollution hazard assessments for all their groundwater sources (Foster et al. 2002), to provide a sound basis for forceful representations to be made for the implementation of necessary pollution control and aquifer protection measures.

7 CONCLUDING REMARKS

There is little doubt that the aquifer pollution vulnerability concept (and its practical manifestation in land surface mapping) is an extremely valuable tool for groundwater quality

Figure 4. Integration of aquifer pollution vulnerability mapping and delineation of source protection areas as the basis of a GIS system for groundwater quality protection.
protection, when ‘sensitively tuned’ to the specific needs of a given application. Aquifer pollution vulnerability maps will play an increasingly important role as a key component of empirical screening methods for groundwater pollution risk assessment, which are needed to allow the implementation of the EC Water Framework & Groundwater Protection Directives especially in areas where actual monitoring of groundwater quality is limited and/or the potential time-lags of pollution incident impact in groundwater are very large.

ACKNOWLEDGEMENTS

The author would like to thank the IAH Polish National Group for the original suggestion to provide this overview, his co-worker Dr Ricardo Hirata of the Universidade de Sao Paulo – Brasil for sustained interest and work on these topics, and his assistant Gill Tyson for work on the production of the paper.

REFERENCES


Examples of the European approach to groundwater vulnerability assessment and mapping
CHAPTER 1

The vulnerability paradox for hard fractured Lower Palaeozoic and Precambrian rocks

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ABSTRACT: The WFD criteria for chemical status require consideration of both the susceptibility of a groundwater body to pollution, and the susceptibility of the associated receptors to pollutants which have entered the groundwater body. Traditional concepts of aquifer vulnerability assess the groundwater body, but assessment of concentrations at specific points at the water table can better be undertaken by developing novel methodologies. One such approach is to remove recharge or aquifer productivity from the assessment and to focus only on transport and attenuation processes of pollution migration. When applied to fractured aquifer systems this reverses the vulnerability assessment from one of weakly permeable, low storage and, therefore, low vulnerability, to rapid transport, poor attenuation and high vulnerability. The new method provides assessment only of a single point at the water table but is only a part of the overall assessment process for a groundwater body. To help users of the maps, and avoid confusion, careful and clear definitions of vulnerability, including which receptors and pathways are addressed, are required at all times.

1 INTRODUCTION

One of the most significant pieces of European water legislation to be produced in recent years is the EU Water Framework Directive 2000/60/EC – “establishing a framework for Community action in the field of water policy” which was introduced in December 2000. The Water Framework Directive (WFD) expands the scope of protection to all waters (surface and groundwaters) with the aim of meeting specified environmental objectives, set out in WFD Article 4, by 2015.

In order to achieve the objectives and to manage surface and groundwater in an integrated way, the WFD introduces River Basin Districts (RBD) and requires that a River Basin Management Plan (RBMP) be produced for each District. The initial phase of the RBMP is the delineation of bodies of water within the RBD and their characterisation to assess their uses and the degree to which they are at risk of failing to meet the environmental objectives set for them. For groundwater bodies the Article 4 environmental objectives include the need to achieve good status. This has two components, quantitative and chemical status. The achievement of good chemical status involves meeting several criteria, including meeting quality standards and avoiding damage to receptors, of which associated surface waters and terrestrial ecosystems are specifically mentioned.