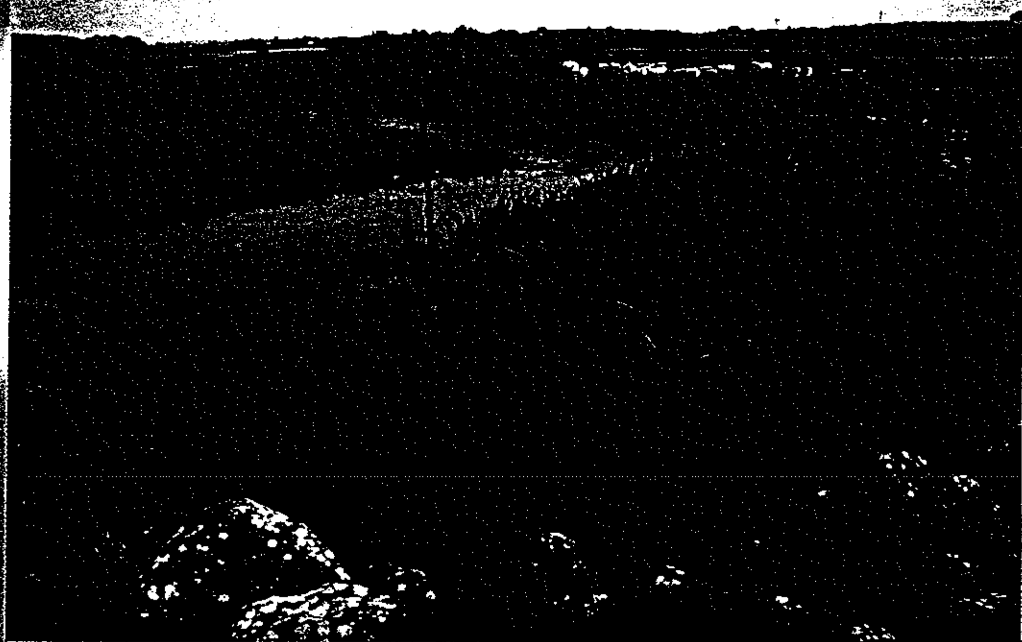
438

**COST**

European cooperation in the field of scientific and technical research

**Environment**

# Vulnerability and risk mapping for the protection of carbonate (karst) aquifers



*Final report*

**COST Action 620**

EUR 20912

5.4 References ... 105

6 Risk Assessment ... 106

6.1 Risk Definition ... 106

*Donal Daly, Heinz Hötzl & Dirk De Ketelaere*

6.2 Assessment concept ... 108

*Heinz Hötzl*

6.2.1 General approach ... 108

6.2.2 Risk intensity assessment ... 109

6.2.3 Risk sensitivity assessment ... 110

6.2.4 Aggregation of risk components ... 112

6.3 Risk Mapping ... 113

*Heinz Hötzl, Cyril Delporte, Tanja Liesch, Peter Malik, Christoph Neukum & Jaromir Svasta*

6.3.1 General Remarks and Mapping Techniques ... 113

6.3.2 Mapping procedure ... 114

6.4 References ... 120

7 From Data Collection To Map Validation ... 122

7.1 Overview ... 122

*Simon Neale*

7.2 Data collection using remote sensing ... 122

*Anna Spiteri*

7.3 Data processing using GIS ... 125

*Radu Constantin Gogu, Lorenz Hurni, Dirk De Ketelaere & James Petch*

7.4 Demonstrating the reliability of our maps ... 131

*Simon Neale*

7.5 Key Map Validation Tools ... 132

7.5.1 Hydraulics and spring hydrographs ... 132

*Michel Bakalowicz*

7.5.2 Natural Tracers ... 133

*Martin Kralik & Jacques Mudry*

7.5.3 Artificial Tracers ... 135

*Nico Goldscheider*

7.5.4 Analytical and numerical modelling ... 136

*Alain Dassargues & Ileana Cristina Popescu*

7.6 References ... 138

**Part B – Methods and Applications** ... 143

1 Mapping Methods ... 143

1.1 Overview ... 143

*Nico Goldscheider*

1.2 The PI method ... 144

*Nico Goldscheider*

1.2.1 Background and Overview ... 144

1.2.2 General Concept of the PI Method ... 144

1.2.3 Protective Cover (P factor) ... 146

1.2.4 Infiltration Conditions (I factor) ... 149

1.2.5 Construction of the Vulnerability Map ... 153

1.2.6 References ... 154

- The results also depend on the properties of the tracer. Conservative tracers are preferred for the validation of intrinsic vulnerability maps but most tracers are not completely conservative (Käss 1998).
- Tracer tests are practicable if the travel time is not too long and the dilution is not too high. They can thus be applied in highly vulnerable zones but not in zones where travel times of years are expected.
- As it is difficult to sample at the groundwater surface, the use of tracer tests for the validation of resource vulnerability maps is problematic.

There are only few examples on the validation of vulnerability maps using artificial tracer tests. Goldscheider et al. (2001) validated an EPIK vulnerability map by means of seven tracer injections. Six of the tracers were spread at the land surface with a watering can; one tracer was injected in a swallow hole. After the injections, an artificial rainfall of 20 mm was produced. The obtained travel time (in this case: time of maximum concentration!) was almost identical for the tracer injected in the swallow hole and the tracers injected on soils of low permeability. This was explained by the presence of macropores. However, there was a strong correlation between the assessed vulnerability, the recovery rate and the normalised maximum concentration. Perrin et al. (2002) used both artificial and natural tracers to assess and validated the intrinsic and specific source and resource vulnerability of different test sites in the Swiss Jura Mountains. They also showed the strong influence of the contamination scenario (type of release of tracers) on the resulting breakthrough at the target.

The use of toxic compounds in tracer tests to validate a particular specific vulnerability assessment is both unthinkable and often illegal. As a result only harmless substances can be used as tracers (Behrens et al. 2001). This presents some difficulty when trying to simulate the fate of toxic heavy metals, chlorinated solvents or pathogen viruses. In this case, we must select non-toxic substances that are known to behave in a comparable way as the respective toxic substances. As an example, some marine bacteriophages show similar transport characteristics in groundwater as particular pathogen viruses but are completely harmless for human beings and aquatic ecosystems. They can thus be used to simulate the behaviour of pathogen viruses (Rossi et al. 1998) and can also be used to validate a virus-specific vulnerability assessment.

### 7.5.4 Analytical and numerical modelling

Unfortunately, full validation of a vulnerability assessment using analytical and numerical models is an objective that is as yet out of reach. The principle of validating the results of a model (the chosen vulnerability assessment method is always a simplified model of the reality) using another model is a difficult concept. However, in practice a numerical model used in validation can increase the "degree of confidence" in the main assumptions made during the vulnerability assessment. With validation in mind, when utilising numerical models, sensitivity analysis can be used to examine the most uncertain and influential parameters used in the vulnerability method. Additionally, any validation of results requires clear criteria that are not easy to define (e.g. legal aspects or local agreements or regulations).

Numerical models can be chosen on their degree of complexity and data need, much like choosing a particular vulnerability assessment technique. These can range from black-box models (which are unlikely to add confidence in this particular context), to full physically based and spatially distributed models that can be used for accurately computing contaminant concentrations in groundwater. Whatever the degree of complexity of the numerical model used, a calibration using historical data and a validation on a remaining data set (not used during calibration) are needed. To summarise, four kinds of data are needed in order to proceed with accurate and reliable numerical modelling:

- Geometrical and geological data for the spatial discretisation of the modelled domain;
- Parameters or property values for characterising each of the discretised zones with respect to each simulated process. This is likely to provide most difficulty in terms of uncertainty of the parameters used in the modelled processes, due to scale effects and the lack of data that could be used to describe aquifer heterogeneity;
- Stress-factors influencing groundwater quantity (infiltration, pumping and re-injection rates) and groundwater quality (input/output of contaminant fluxes);
- Historical data (distributed both spatially and through time) relating to groundwater quantity (measured piezometric levels, water pressures, spring discharges, hydrographs, tracer tests) and groundwater quality (measured concentrations, chemographs, tracer tests).

Most vulnerability assessment methods were developed to avoid the need for extensive data sets and simplify description of the processes that may act on contaminants as they travel along a flowpath to either the groundwater table or source (spring or pumping well). In practice, only partial validations are feasible using numerical models, as they consider only some of the active processes. However in some instances a model may consider most of the active processes but only in a very limited and well-studied part of the area being assessed.

Trying to describe the main processes involved along the path of a contaminant, one can distinguish how numerical models, describing each of the main compartments of the water cycle, should be coupled in order to form an integrated numerical tool describing contaminant transport in a mechanistic way. As described in Fig. 41, it involves:

- Computation of water budget at the land surface in order to assess actual infiltration. This is not an easy task and many recently developed tools aim to simulate these processes accurately. On that particular topic, interesting and useful literature can be found in (among others): WILSON & LUXMOORE 1988, SMETTEM et al. 1991, LARSEN et al. 1994, MILLY 1994, SIMMERS et al. 1997, BEVEN 2000.
- Use of this modelled infiltration (and associated mass of contaminant) is then used as an input for modelling 1D vertical transport (in some particular cases a 3D approach is needed) of a dissolved contaminant through the different layers (porous, fissured or karstified) of the unsaturated zone. Recent developments in modelling the unsaturated zone take into account the possible influence of epikarst, macropores, and include bio-chemical reactions. However, in practice, huge uncertainties remain and are linked to the values given to each parameter and mostly in the highly karstified parts of the unsaturated zone. On these challenging topics interesting references are (among others): BEVEN & GERMANN 1981, CHEN & WAGENET 1992, CHEN et al. 1993, FORSITH et al. 1995, GWO et al. 1996, GERKE & VAN GENUCHTEN 1993, PERFECT et al. 1996, THERRIEN & SUDICKY 1996, DEMARCO 1998, GRIFFIOEN et al. 1998, BROUYERE 2001.
- Use of the computed fluxes of contaminated water at the base of the unsaturated zone can be used as input to a 3D groundwater saturated flow and transport model of the karstic aquifer. Depending on the scale of the study and the knowledge of the degree of heterogeneity, an equivalent porous medium approach may be adopted. Groundwater modelling in karstic systems is still a challenge. Useful references are the following (among others): KIRALY & MOREL 1976, CULLEN & LAFLEUR 1984, SAUTER 1993, SMITH & SCHWARTZ 1993, HUNTOON 1995, QUINLAN et al. 1996, DASSARGUES et al. 1997, DASSARGUES 1998,

JEANNIN & GRASSO 1997, DASSARGUES & DEROUANE 1998, HALIHAN & WICKS 1998, JEANNIN et al. 1999, WICKS & HOKE 1999.

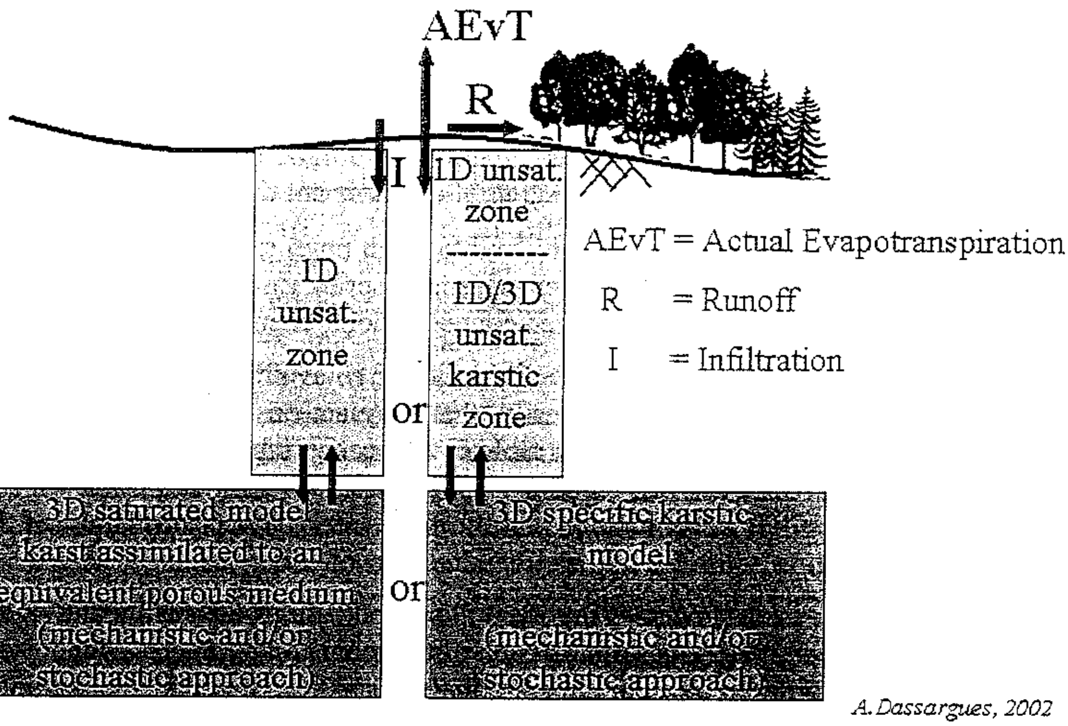



Fig. 41: Conceptualising the main processes affecting transport of dissolved contaminant from the soil surface until the spring or the pumping well: coupled numerical models forming an integrated numerical tool.

In conclusion, numerical models are useful as tools for consistently interpreting the results of field measurements and experiments. Calibration of numerical models using these measurements will ensure the optimum use of this information for validating (at least to some extent) the vulnerability assessment. They can also be considered as useful intermediate tools between field measurements and vulnerability assessments. After calibration, one can perform sensitivity analysis to check how results can vary in different stressed scenarios ('what if' simulations) or to consider the uncertainty of the parameters used. Results of this analysis allow the validation of the assumptions made in the adopted vulnerability assessment technique.

## 7.6 References:

BARRETT, E.C. (1995): Present trends and outstanding needs in satellite hydrology, pp. 355-360, in Progress in Environmental Remote Sensing Research and Apllication *Proceedings of the 15th EARSEL symposium, Basel, 4-6 September 1995*, pp. 484

BATIOT C., MUDRY J., BLAVOUX B & EMBLANCH C. – 2002 – Total organic carbon (TOC) variability at the outlet of karstic aquifers under different climatic and environmental contexts (south east and east of France). II simposio de Geologia Cueva de Nerja (Malaga, Espagne). In Carrasco F., Duran J.J., Andreo B. (Eds.) Karst and Environment. 131-137. 6 fig., 2 tabl.

BEHRENS H, BEIMS U, DIETER H, DIETZE G, EIKMANN T, GRUMMT T, HANISCH H, HENSELING H, KOSS W, KERNDORFF, H, LEIBUNDGUT C, MÜLLER-WEGENER U, RÖNNEFAHRT I, SCHARENBERG B, SCHLEYER R, SCHLOZ W, TILKES F (2001): Toxicological and ecotoxicological assessment of water tracers. Hydrogeology Journal (2001) 9: 321–325

BEVEN, K. (2000): Rainfall-runoff modelling. The primer. Wiley, 360p.

BEVEN, K. & GERMANN, P. (1981): Water flow in soil macropores. 2. A combined flow model. J.Soil Sci., 32, p.15-29.

BROUYERE, S. (2001): Etude et modélisation du transport et du piégeage des solutés en milieu souterrain variablment saturé. PhD Thesis, University of Liège, 572p.

CHEN, C. & WAGENET, R.J. (1992): Simulation of water and chemicals in macropore soils. 2. Application of linear filter theory. J. Hydrol., 130, p.127-149.

CHEN, C., THOMAS, D.M., GREEN, R.E. & WAGENET, R.J. (1993): Two-domain estimation of hydraulic properties in macropore soils, Soil Sci. Soc. Am. J., 57, p.680-686.

COPLEN T.B., HERCZEG AL, BARNES C (2000): Isotopic engineering – using stable isotopes of the water molecule to solve practical problems. In: Cook PG, Herczeg AL (eds): Environmental tracers in subsurface hydrology. 79-110, Kluwer Academic Publ., London.

COOK PG, HERCZEG AL (2000): Environmental tracers in subsurface hydrology. 529 p., Kluwer Academic Publ., London.

CORWIN LD (1996) GIS applications of deterministic solute transport models for regional-scale assessment of non-point source pollutants in the vadose zone. In: Corwin DL and Loague K (eds) Applications of GIS to the modelling of non-point source of pollutants in the vadose zone, Soil Science Society of America, Madison, USA. 48:69-100

CULLEN, J.J. & LAFLEUR, R.G. (1984): Theoretical considerations on simulation of karstic aquifers. – In: Groundwater as a geomorphic agent, LaFleur R.G. (Ed.), Allen and Unwin, p.249-280.

CURRAN, P.J. (1985): Principles of Remote Sensing, Longman Group Ltd., pp. 282

DEMARCO, D.T. (1998): On the parametrization of dual-porosity and equivalent-continuum theories describing mass transport in fractured rock: a stochastic analysis. MSc Thesis, University of Waterloo Dept. of Earth Sciences, 78 p.

DASSARGUES, A. (1998): Application of groundwater models in karstic aquifers. – In: Karst Hydrology, Leibundgut C., Gunn J. & Dassargues A. (Eds), IAHS Publication n° 247, p. 7-14.

DASSARGUES A. & BROUYERE S. (1997): Are deterministic models helpful to delineate groundwater protection zones in karstic aquifers ? In: Karst waters & environmental impacts, Günay G & Johnson I. (Eds), Balkema, p. 109-116.

DASSARGUES, A. & DEROUANE (1998): A modelling approach as an intermediate step for the study of protection zones in karstified limestones. – In: Karst Hydrology, Leibundgut C., Gunn J. & Dassargues A. (Eds), IAHS Publication n° 247, p. 71-79.

EMBLANCH C., BLAVOUX B., PUIG J.M. & MUDRY J. - 1998 - Dissolved organic carbon of infiltration within the authigenic karst hydrosystem. Geophysical Research Letters, 25, 9: 1459-1462, 1 fig.

FETTER, C.W. (1999): Contaminant hydrogeology, 2nd edition. – Upper Saddle River, N.J, Prentice Hall: 500 pp.

FORSITH, P.A., WU, Y.S. & PRUESS, K. (1995): Robust numerical methods for saturated-unsaturated flow with dry initial conditions in heterogeneous media. Adv. Water Resour., 18, p.25-38.

GERKE, H.H. & VAN GENUCHTEN, M.TH. (1993): Evaluation of a first-order water transfer term for variably saturated dual-porosity flow models, Water Resour. Res., 29(4), p.1225-1238.

GOGU C R, CARABIN G, HALLET V, PETERS V, DASSARGUES A (2001), GIS based hydrogeological databases and groundwater modelling, Springer - Verlag, Hydrogeology Journal, 9 (6) : 555-569.

GOGU CR (2000) Advances in groundwater protection strtegy using vulnerability mapping and hydrogeological GIS databases, PhD thesis, University of Liège, Belgium, 152 pp.

GOLDSCHEIDER, N., HÖTZL, H., FRIES, W. & JORDAN, P. (2001): Validation of a vulnerability map (EPIK) with tracer tests. – 7th Conference on Limestone Hydrology and Fissured Media, Besançon 20-22 Sep. 2001, Sci. Tech. Envir., Mém. H . S. n° 13, p. 167-170.

GOODCHILD MF (1996) The application of advanced information technology in assessing environmental impacts. In: Corwin DL and Loague K (eds) Applications of GIS to the modelling of non-point source of pollutants in the vadose zone, Soil Science Society of America, Madison, USA. 48:1-17

GRIFFIOEN, J.W., BARRY, D.A. & PARLANGE, P.-Y. (1998): Interpretation of two-region model parameters. Water Resour. Res., 34, p.373-384.

GWO, J.P., JARDINE, P.M., WILSON, G.V. & YEH, G.T. (1996): Using a multiregion model to study the effects of advective and diffusive mass transfer on local physical nonequilibrium and solute mobility in a structured soil. Water Resour. Res., 32(3), p.561-570.

HALIHAN, T. & WICKS, C.M. (1998): Modeling of storm responses in conduit flow aquifers with reservoirs. Journal of Hydrology, 208, p.82-91.

HARRISON, B.A., JUPP, D.L.B. (1990): Introduction to Image Processing, Part Two of the microBRIAN Resource Manual, Division of Water Resources Canberra, CSIRO Australia, pp. 256

HEUVELINK GBM (1998) Error propagation in environmental modelling with GIS. Taylor & Francis Ltd, UK

HUNTON, P.W. (1995): Is it appropriate to apply porous media groundwater circulation models to karstic aquifers? – In: Groundwater models for resources analysis and management, A.I. El-Kadi (Ed.), chapter 19, p.339-358.

HURNI L, CHRISTINAT R (1997) Hybrid "WYSIWYG"-Techniques for Updating the Swiss Topographical Map Series, Proceedings of the 18th International Cartographic Conference Vol. 2 , Stockholm

JEANNIN, P.Y. & GRASSO D.A. (1997): Permeability and hydrodynamic behaviour of a karstic environment. - In: Karst waters & environmental impacts, Günay G & Johnson I. (Eds), Balkema, p. 3359-342.

JEANNIN, P.Y., HAUNS, M. & ATTEIA O. (1999): Modeling breakthrough curves of tracing experiments in a karst environment. In: Karst Modelling, Palmer A.N. & Sasowsky I.D. (Eds), Karst Waters Institute, Special publication 5, p.173.

KÄSS, W. (1998): Tracing technique in geohydrology. – Rotterdam, Balkema: 581 pp.

KIRALY, L. & MOREL, G. (1976): Remarques sur l'hydrogramme des sources karstiques simulé par modèles mathématiques. Bulletin du Centre d'Hydrogéologie de Neuchâtel, 1, p.37-60.

KRALIK M (2001): Spring dynamics as a tool to evaluate Groundwater-Vulnerability. 7$^{th}$ conference on Limestone Hydrology and Fissured Media, Besancon 20-22 Sep. 2001, Sci. Techn. Envir., Mém. H. S. n° 13: 215-218, Besancon.

LARSEN, J.E., SIVAPALAN, M., COLES, N.A. & LINNET P.E. (1994): Similarity analysis of runoff generation processes in real-world catchments. Water Resour. Res., 30(6), p.1641-1652.

LEVENE M, LOIZOU G (1999) A guided tour of relational databases and beyond. Springer Verlag, London

MANGIN, A., (1970): Contribution à l'étude des aquifères karstiques à partir de l'analyse des courbes de décrue et tarissement. Annales de Spéléologie, 25(3): 581-610.

MARSAUD, B., (1996). Structure et fonctionnement de la zone noyée des karsts à partir des résultats expérimentaux. Doctorat Thesis, Paris XI, Orsay, 305 pp

MILLY, P.C.D. (1994): Climate, soil water storage, and the average annual water balance. Water Resour. Res., 30(7), p.2143-2156.

NATIONAL RESEARCH COUNCIL (1993) Groundwater vulnerability assessment, Contamination potential under conditions of uncertainty, Committee on Techniques for Assessing Ground Water Vulnerability, Water Science and Technology Board, Commission on Geosciences Environment and Resources, National Academy Press, Washington DC

NEW YORK STATE ARCHIVES AND RECORDS ADMINISTRATION (1997) Geographic Information System development guides. State Archives And Records Administration 9B38 Cultural Education Center Albany, New York, USA

PERFECT, E., MCLAUGHLIN, N.B., KAY, B.D. & TOPP, G.C. (1996): An improved fractal equation for the soil water retention curve. Water Resour. Res., 32(2), p.281-287.

PERRIN, J., POCHON,A., JEANNIN, P.-Y. & ZWAHLEN, F. (2002): Vulnerability assessment in karstic areas: validation by field experiments. – Proceedings of the 32$^{nd}$ IAH meeting, Mar de Plata, Argentina, October 2002 (in press).

PINAULT JL, PLAGNES V AND AQUILINA L (2001): Inverse modelling of the hydrological and the hydrochemical behavior of hydrosystems: Characterization of karst system functioning. Water Resources Res., 37: 2191-2204.

QUINLAN, J.F., DAVIES, G.J., JONES, S.W. & HUNTOON P.W. (1996): The applicability of numerical models to adequately characterize groundwater flow in karstic and other triple-porosity aquifers. – In: Subsurface fluid-flow (groundwater and vadose zone) modelling, Ritchey J.D. & Rumbaugh J.O. (Eds), American Society for Testing and Materials, Special Technical Paper 1288, p.114-128.

ROSSI, P., DÖRFLIGER, N., KENNEDY, K., MÜLLER, I. & ARAGNO, M. (1998): Bacteriophages as surface and groundwater tracers. – Hydrogeology and Earth System Sciences, 2(1), 101-110.

SAUTER M. (1993): Double porosity models in karstified limestone aquifers, field investigation and data provision. – In: Hydrologic processes in karst terrains, IAHS, publication n°207, p.261.

SIMMERS, I., HENDRICKX, J.M.H., KRUSEMAN, G.P. & RUSHTON, K.R. (1997): Recharge of phreatic aquifers in (semi-) arid areas, Balkema, 277p.

SMETTEM, K.R.J., CHITTLEBOROUGH, D.J., RICHARDS, B.G. & LEANEY, F.W. (1991): The influence of macropores on runoff generation from a hillslope soil with a contrasting textural class. J. Hydrol., 122, p.235-252.

SMITH, L. & SCHWARTZ, F.W. (1993): Solute transport through fracture networks. – In: Flow and contaminant transport in fractured rock, Bear J., Tsang C. & de Marsily G. (Eds), Academic Press, p.129-164.

SOLOMON DK, COOK PG (2000): $^3$H and /$^3$He. In: Cook PG, Herczeg AL (eds): Environmental tracers in subsurface hydrology. 397-424, Kluwer Academic Publ., London.

STEYAERT LT, GOODCHILD MF (1994) Integrating geographic information systems and environmental simulation models: A status review. In: Michener WK, Brunt JW and Stafford SG (eds) Environmental Information Management and Analysis: Ecosystem to Global Scales, Taylor & Francis Ltd, UK, 21: 333-355

STRUCKMEIER WF AND MARGAT J (1995) Hydrogeological maps a guide and a standard legend. In : Hannover, Verlag Heinz Heise GmbH&Co KG, International Contributions to Hydrology, v. 17, 177 p.

THERRIEN, R. & SUDICKY, E. (1996): Three-dimensional analysis of variably-saturated flow and solute transport in discretely-fractured porous media. J. Contamin. Hydro., 23, p.1-44.

WICKS C.M. & HOKE J.A. (1999): Linear systems approach to modelling groundwater flow and solute transport through karstic basins. – In: Karst Modelling, Palmer A.N. & Sasowsky I.D. (Eds), Karst Waters Institute, Special publication 5, p.97-101.

WILSON, G.V. & LUXMOORE, R.J. (1988): Infiltration, macroporosity, and mesoporosity distributions on two forested watersheds. Soil Sci. Soc. Am. J., 52,p.329-335.