Using Geographical Information Systems (GIS) as an instrument of water resource management: a case study from a GIS-based Water Safety Plan in Germany

I. Wienand, U. Nolting and T. Kistemann

ABSTRACT

Following international developments and the new WHO Drinking Water Guidelines (WHO 2004) a process-orientated concept for risk, monitoring and incident management has been developed and implemented in this study. The concept will be reviewed with special consideration for resource protection (first barrier of the multi-barrier system) and in turn, for the Water Safety Plan (WSP) which adequately considers—beyond the current framework of legal requirements—possible new hygienic-microbiologically relevant risks (especially emerging pathogens) for the drinking water supply. The development of a WSP within the framework of risk, monitoring and incident management includes the application of Geographical Information Systems (GIS). In the present study, GIS was used for visualization and spatial analysis in decisive steps in the WSP. The detailed process of GIS-supported implementation included the identification of local participants and their tasks and interactions as an essential part of risk management. A detailed ecological investigation of drinking water conditions in the catchment area was conducted in addition to hazard identification, risk assessment and the monitoring of control measures.

The main task of our study was to find out in which steps of the WSP the implementation of GIS could be integrated as a useful, and perhaps even an essential tool.

Key words | GIS, hazard analysis, interpolation, risk assessment, Water Safety Plan

I. Wienand (corresponding author)
T. Kistemann
Institute for Hygiene and Public Health,
University of Bonn,
Sigmund-Freud-Str. 25, 53105 Bonn,
Germany
E-mail: *ina.wienand@ukb.uni-bonn.de*

U. Nolting
Stadtwerke Niederkassel,
Spicher Str. 32-34, 53859 Niederkassel,
Germany
E-mail: *boxman@ukb.uni-bonn.de*

INTRODUCTION

The worldwide provision of safe drinking water is critical. Despite the intensive efforts of many institutions at national and international levels, nearly 1.1 billion people still lack access to improved sources of water. As a consequence, 2.2 million people in developing countries die every year from diseases associated with a lack of safe drinking water, inadequate sanitation and poor hygiene (WHO 2004). This critical worldwide situation has been particularly associated with less developed countries, but in recent years drinking water quality concerns have also grown in developed countries, in particular with regard to microbiological parameters (Hunter 1997; Kistemann 1997; Bartram & Hueb 2000; Kistemann & Exner 2001). Ultimately it is the documentation of outbreaks of waterborne disease that lead the water industry and politicians to discuss the existing rules of quality assurance and risk management in developed and developing countries.

In the past many approaches have been developed in order to formalize principles of quality assurance and integrate elements of risk management for drinking water supplies. In order to organize and systemize the manifold management practices applied to drinking water and to ensure the applicability of these practices to the management of drinking water quality, the World Health Organization (WHO) has developed a comprehensive risk assessment and risk management approach–Water Safety Plans (WSP). These encompass all the steps in water supply from catchment to the consumer. This approach draws on

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many principles and concepts from other risk management approaches, such as the HACCP and the multi-barrier-approach (WHO 2004).

The objective of this study was the practical implementation of a WSP for one water supplier, emphasizing the protection of water resources and catchment management. The main focus of the WSP implementation included the application of Geographical Information Systems (GIS) in every step of the WSP. The development of such a GIS-based WSP in the context of risk, surveillance and incident management for a water supply includes hazard identification, risk assessment and effective operational monitoring as well as management and communication. Exposure assessment in the catchment area for the determination of critical limits is also conducted with the use of GIS. The result is an evaluation of the applicability of GIS-based spatial analysis techniques in the framework of the WSP which contributes to answering the following questions:

1. How can a GIS be integrated into the framework of the WSP? Which efforts have to be undertaken to integrate GIS-based spatial analysis techniques?
2. How can the use of GIS-based spatial analysis techniques be assessed in the framework of the WSP?
3. How can GIS-based spatial analysis techniques contribute to exposure assessment in the catchment area?

The study additionally provides practical experience in the development of a GIS-based WSP for a comprehensive resource and catchment management. The implementation of the WSP was conducted in conjunction with a groundwater supplier in the federal state of North Rhine-Westphalia in Germany.

METHODS

Study area

The catchment ($14.2\,km^2$) of the water supplier is situated in the densely populated area of Cologne-Bonn along the river Rhine. With groundwater production of $1.63\,Mio\,m^3$ per year, this water supplier provides water for more than 36,000 inhabitants. The groundwater aquifer mainly consists of quaternary sand and gravel with a thickness of 25 to 30 m. In the case of increasing river water levels in the river Rhine, bank filtrate infiltrates into the groundwater aquifer and changes the standard west-north-west groundwater flow to a south-easterly direction. Water treatment consists simply of reducing acidity for pH-regulation and, only if necessary, chlorination.

Principles of WSP implementation with GIS

The implementation of WSP with the main focus on resource and catchment management is comprised of the components shown in Figure 1.

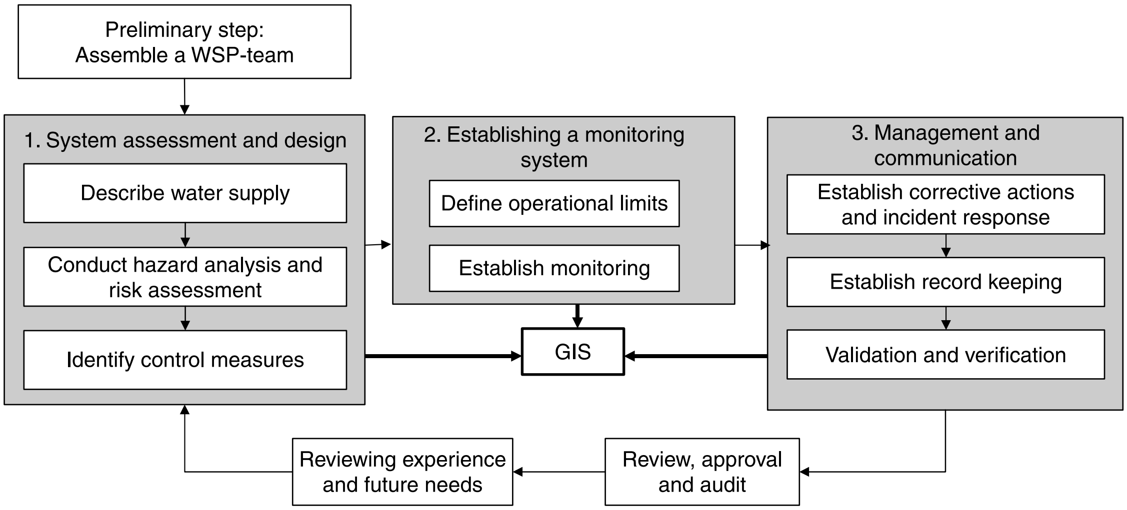


Figure 1 | Development of a WSP taking into account the application of GIS (according to Davidson *et al*. 2005).

System assessment and design (1) comprises data collection by the water supply company, the GIS-based description of the catchment area, as well as the GIS-based identification of vulnerable population groups or institutions. Furthermore, a hazard analysis for the catchment was conducted, which ultimately resulted in a semi-quantitative risk assessment based on the evaluation of groundwater vulnerability, the hazard potential of the groundwater and the experiences of the water supplier. Operational monitoring (2) comprises the determination of operational limits. For every control measure critical limits are assessed in the catchment area with the help of spatial analysis techniques. Management and communication (3), especially the establishment of record keeping as well as validation procedures are additionally supported by GIS.

Spatial analysis techniques with GIS for WSP implementation

The spatial examination is a constituent part and the fundamental specification of a GIS. In this study a variety of spatial analysis techniques are applied, comprising on one hand simple analytical techniques like clip, merge and dissolve or reclassification. On the other hand, spatial interpolation techniques are applied in order to predict the values of a variable distributed in space at unsampled locations from measurements made at regularly or irregularly distributed sample locations within the same area (Bourough & McDonnell 1998). The spatial analytical techniques used in the context of the WSP are described in Table 1. Nearly all GIS-software offers simple analytical techniques. With *overlaying, clipping, merging* and *dissolving* of spatial data, new information in the form of vector or raster data can be generated. Also *reclassification techniques* allow replacing input values with new output values for each grid cell. Generating new information with such techniques is very helpful in the context of hazard classification and risk mapping.

The idea of *kernel density estimation* is that a pattern has a density at any location in the study region, not just at locations where there is an event. This density is estimated by counting the number of events in the region (kernel) centred at the location for which a density estimate is required (O'Sullivan & Unwin 2003).

Spatial interpolation techniques are used for the prediction of values of a variable distributed in space at unsampled locations from measurements made at regularly or irregularly distributed sampled locations within the same area (Bourough & McDonnell 1998). The result of a spatial interpolation is commonly a discrete, continuous surface represented by a regular grid for mapping the spatial variability of the variable under study. This variable can be

Table 1 | Spatial analysis techniques within the WSP steps

General WSP step	Spatial analysis techniques
System assessment and design	*Overlay, Clip, Merge, Dissolve* vector and raster data of hydrological, geological, soil and land use characteristics
	Reclassification techniques for raster and vector data to conduct hazard analysis and risk assessment
	Spline interpolation for modelling of groundwater table heights
	Kernel density estimation to identify vulnerable population groups as well as hazards in the catchment area
Establishing a monitoring system	Presenting results in the form of *Thiessen polygons*
	Kriging interpolation of selected parameters (e.g. nitrates, chloride, boron) and for exposure assessment
	Probability kriging to estimate the probability of exceeding critical limits
	Implementation of *groundwater modelling* results in the GIS
Management and communication	*Cross validation* within kriging interpolation procedures for verification
	Comparative interpolation of different series of measurements
	Elimination of measurement errors through *standard error mapping*

continuously varying in space, such as in this study groundwater quantity and quality parameters. *Spline interpolation* estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smoothed surface that passes exactly through the input points. This method is best for gently varying surfaces, such as groundwater table depths.

Various types of *kriging techniques* as geostatistic interpolation methods have been widely used in the context of water management (Bardossy *et al.* 2003). In this study, ordinary kriging was used, based on a linear combination of the measured values. Ordinary kriging as a distance-oriented linear technique attempts to make the predictions unbiased, that is on average, the difference between the predicted values and the actual values should be near zero. Within the interpolation of a value only points which are in the vicinity of the location of interpolation are integrated. The weights are determined by variogram modelling, which describes similarly to a correlation function the spatial statistical correlation between measured values.

RESULTS

The results of the GIS-based WSP implementation for one water supplier are given as an example of the principle steps of WSP.

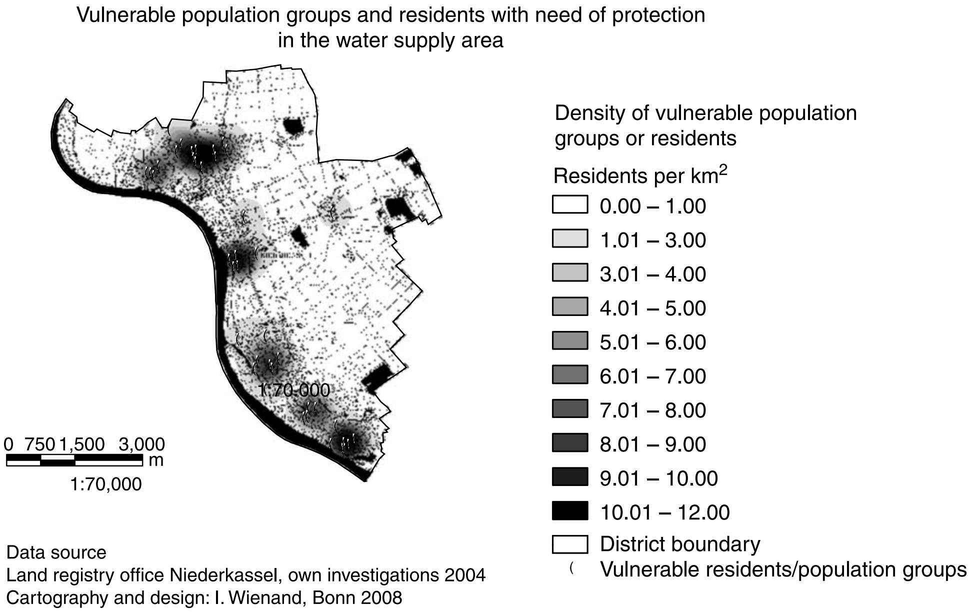
1. System assessment and design

According to the national guidelines of the German Drinking Water Directive (TrinkwV 2001), vulnerable institutions (schools, kindergartens, nursing homes etc.) have to be integrated into the countermeasure plan. Therefore, the data of all institutions which need protection are input into the GIS. The density of vulnerable institutions in the watershed is estimated with the *kernel* method.

In Figure 2, clusters of vulnerable populations and institutions can be detected in the urbanised area of the watershed. In the north of the area up to 12 institutions per square kilometre are found.

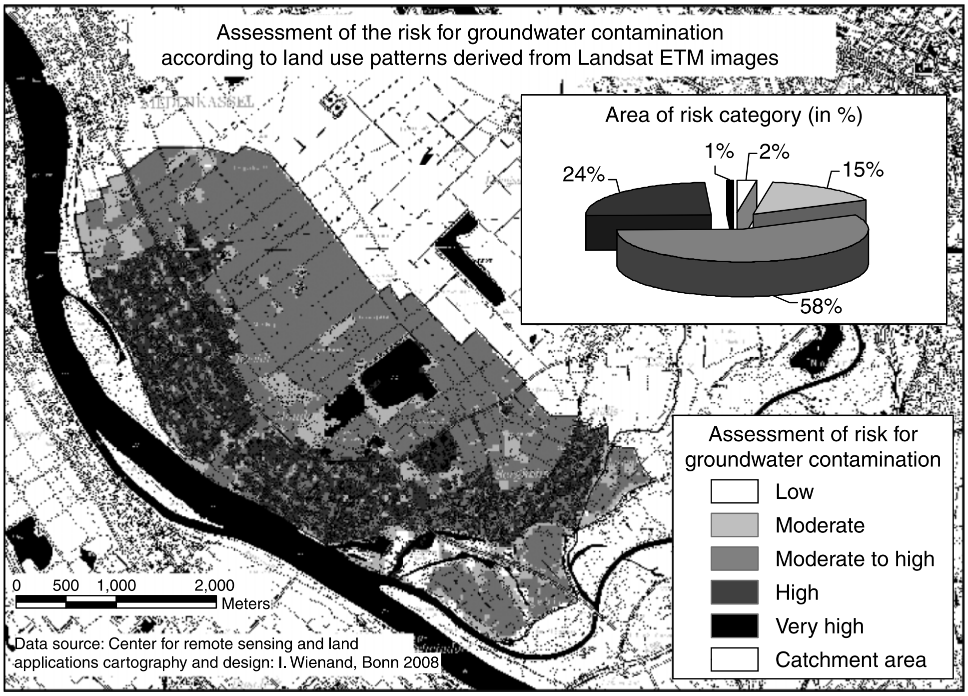
Another part of the description of the water supply is the characterisation of land use, which is done with classified Landsat-ETM images (30 m grid). With reclassification techniques the extent of groundwater contamination through land use patterns can be assessed (Figure 3).

Land use classifications of the Landsat ETM images (30 m raster) are allocated to the assessment categories, ranging from a low to a very high risk potential. These are agricultural areas as well as areas with a moderate to high site density, which include a number of activities which can be hazardous to water. About 58% of the protected area has a moderate to high, approximately 24% a high, and 18% (e.g. biotopes), a moderate or low ground water risk



Data source
Land registry office Niederkassel, own investigations 2004
Cartography and design: I. Wienand, Bonn 2008

Figure 2 | Vulnerable population groups and institutions with regard to drinking water contamination.


Assessment of the risk for groundwater contamination according to land use patterns derived from Landsat ETM images

Data source: Center for remote sensing and land applications cartography and design: I. Wienand, Bonn 2008

Figure 3 | Assessment of the potential for groundwater contamination according to land use patterns.

potential. A very high potential for groundwater contamination (1%) was estimated for mining activities in the catchment area.

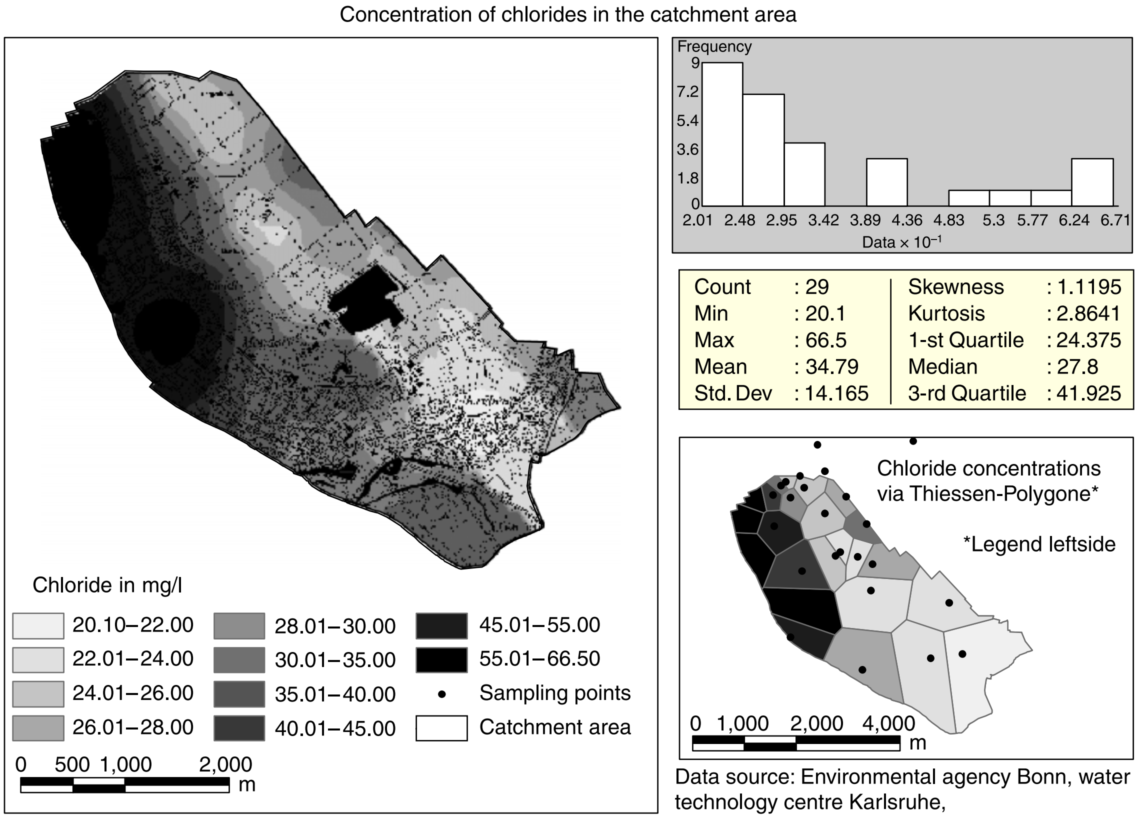
2. Establishing a monitoring system

Variable groundwater conditions in the protected area are considerably affected by the water levels of the river, i.e. when the aquifer is at a low level, groundwater infiltrates into the river, whereas by high aquifer levels–when the water level in the river exceeds that of the groundwater–river water infiltrates into the aquifer. Chloride is an important indicator for the interaction of groundwater and surface water and is examined extensively in the whole water protection area (Figure 4).

Both the results of the interpolation and the representation of the chloride concentrations using Thiessen polygons show river-laterally increased chloride concentrations. The influence on groundwater of the infiltration of surface water is further confirmed by a radiological investigation (with a contrast medium) which can be used as an indicator parameter for waste water and surface water influences. The results of the kriging interpolations presented here are verified by cross validation and standard error mapping, both showing the quality of this interpolation.

The assessment of limit values for the control measures is done by an identification of threshold values in the water protection area. On the basis of practice and experience, and in accordance with the Groundwater Memorandum 2004 (IAWR 2004), half of the drinking water limit values are defined to act as a safety margin. "These threshold values of maximal 50% of the drinking water limit also consider the long periods until actions are implemented and current long-term trends are broken." (IAWR 2004). Within the framework of the nitrate risk assessment, the environmental risk index (ERI) is calculated on the basis of threshold values (= 50 mg/l). According to the Groundwater Memorandum, 25 mg/l is the safety margin for nitrates. Control measures must be applied in the catchment area when ERI > 1 (Figure 5).

The ERI for selected years is calculated using kriging interpolation. The risk index varies from 0.52 to a maximum of 2.29 ERI. Owing to increased agricultural activity, the risk index is exceeded, especially in the northern part of the water protection area. The pollution of the groundwater by



Data source: Environmental agency Bonn, water technology centre Karlsruhe,
Institute for hygiene and public health Bonn
Cartography and design: I.Wienand, Bonn 2008

Figure 4 | Spatial trends of chloride concentration in the watershed.

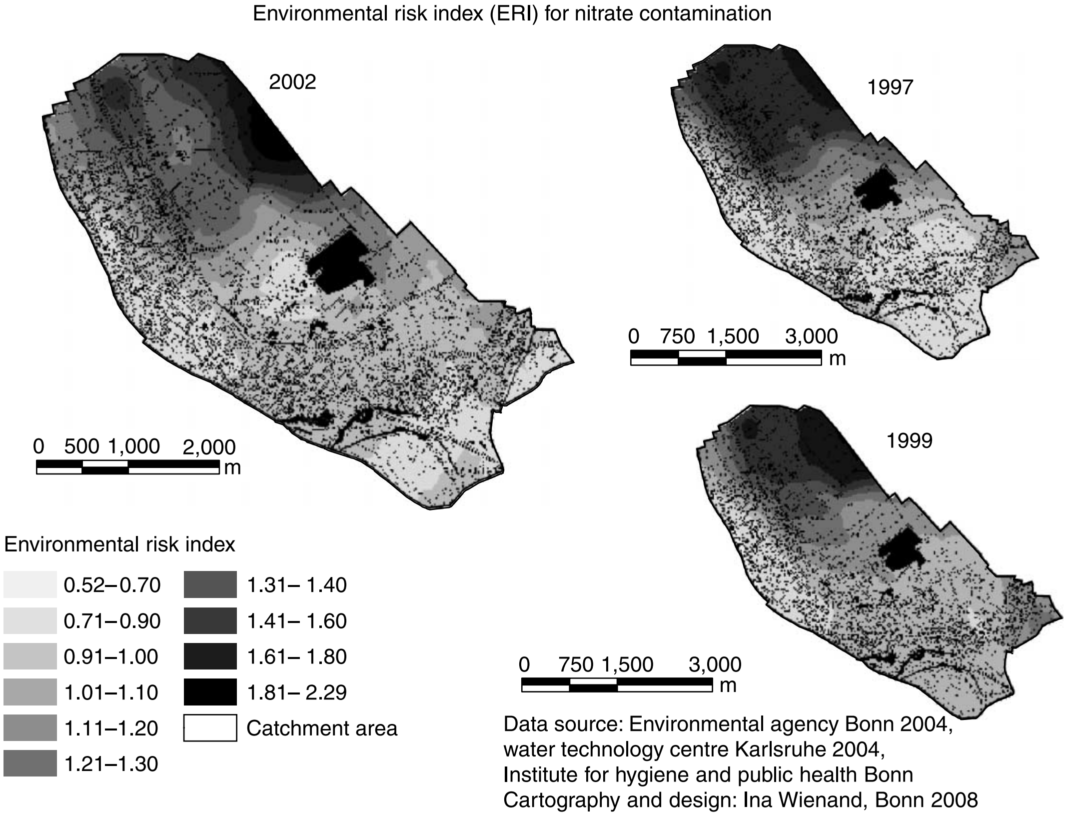
nitrates was reducing until 2002, due to cooperation between the agricultural and water supply sectors. This collaboration is shown to be an important measure which has in recent years led to a substantial reduction in the nitrate concentrations in groundwater.

DISCUSSION

The development and implementation of the WSP in the catchment area is supported effectively by the application of GIS-based spatial analysis techniques. The description of the water supply, especially the characterisation of the watershed bases resulting from the analysis of vector and raster data has in certain cases still to be digitalized. The greatest effort required for GIS implementation in a water supply company relates to data input and the plausibility check. From experience we can estimate that 80% of resources are allocated to this area (Kaupe *et al.* 2000). A substantial problem in this context is the quality of data, e.g. data heterogeneity, and the cost of data.

The data collected are captured and organised in a database and allow a comprehensive characterisation of the watershed. Point data of vulnerable population groups such as kindergartens, day care facilities etc. with need for more care and attention than others, can be localized by geocoding the addresses and visualized by generating clusters on the basis of density estimation. For the protection of drinking water, a spacious land use characterisation is vitally important. In this context, remote sensing technology makes an important contribution, especially if high resolution satellite images are available (Sawaja *et al.* 2003). The classification of satellite images facilitates the investigation of land use properties, e.g. housing density or vegetation types.

Hazard analysis and risk assessment build on the characterisation of the catchment area. In particular, the



Data source: Environmental agency Bonn 2004,
water technology centre Karlsruhe 2004,
Institute for hygiene and public health Bonn
Cartography and design: Ina Wienand, Bonn 2008

Figure 5 | Environmental risk index (ERI) of nitrate contamination.

reclassification of the collected raster data results in a semi-quantitative risk assessment, which allows the estimation of groundwater vulnerability as well as the need for groundwater protection and simplifies identification of risks for the water supplier. It is also possible to develop a modelling approach, calculating the need for groundwater protection from different selected pedological, geological, hydrological and land use data (Lake *et al.* 2003). Such risk-based modelling is advisable and worthwhile for big heterogeneous watersheds. Foster & McDonald (2000) developed a risk ranking regarding microbiological pathogens in drinking water catchments, emphasizing the potential use of GIS, in particular in pollution risk assessments for water resource protection.

For the identification of hazards in the framework of system assessment and especially the establishment of a monitoring system, spatial interpolation techniques, e.g. kriging interpolation, are vitally important (Bardossy *et al.* 2003). Using such geostatistical techniques, spatial trends can be identified in the catchment area, which contribute to the development of control measures. If the number of samples taken for one parameter, i.e. atrazine, is too small for interpolation, Thiessen polygons are created in order visualize a rough spatial trend for the sampling results. The interpolation of nitrate concentrations in the catchment area shows a spatial trend with higher concentrations in the north and lower concentrations in the south. This trend indicates the impact of very intensive agricultural activities in the northern part of the watershed. In order to reduce agricultural impact, cooperation between farmers and the water supplier has been facilitated, which includes control measures, such as the reduction of fertilizer use, the provision of expert advice for farmers and the investigation of soil samples. The regular monitoring of nitrate contamination and other pesticides with GIS proves the effectiveness of these control measures.

The definition of provisional threshold values for health-relevant parameters is an important element of environmental risk assessment in the watershed and is one precondition for the implementation of corrective actions. Thayer *et al.* (2003) uses probability mapping to estimate the probability of exceeding a specific threshold value in the context of exposure point concentrations in a limited data scenario performed at hazardous waste sites. Another possibility is the calculation of an environmental risk index (ERI), which is generally used in the context of health exposure assessments (Fehr *et al.* 2003; Mekel *et al.* 2004). The ERI is the quotient of actual to tolerable emissions in the catchment area and functions as a critical limit for the water supplier. It is a preventive value that indicates the necessity of corrective actions in the framework of water resource management. Thus an ERI of 25 mg/l for nitrates offers enough range for the effectiveness of corrective actions, e.g. intensified support of farmers which participate in the cooperation with the water supplier.

The manifold spatial analysis techniques of GIS, especially interpolation techniques, also enable the validation and verification of groundwater and raw water samples. With standard error mapping, sampling errors can be detected and cross validation is in turn an evaluation of the interpolation procedure. The comparison of interpolation results from different years proves the efficiency of control measures.

Documentation, as an important step in the framework of the WSP is indispensable. It can be supported by the use of GIS, for example in the shape of maps or by building up a web-based GIS approach, especially when communicating with external WSP-staff (e.g. local health authorities).

CONCLUSIONS

GIS have a very high value in the framework of a WSP. The characterization of land use activities can be supported by using spatial analysis techniques. Hazard analysis and risk characterization in the catchment area can be carried out with reclassification techniques, thus enabling a semi-quantitative risk assessment. Spatial interpolation techniques facilitate a spatial estimation of hazards in the catchment (e.g. nitrate contamination due to agricultural activities). They are vitally important in the context of environmental exposure assessments for the determination of critical limits. Although the initial implementation of GIS techniques involves a substantial effort, the continual use of GIS in the different WSP steps is definitely validated by this study.

The range of GIS applications varies between water suppliers and is dependent on human and financial resources. At present, GIS is primarily applied by water suppliers with large and complex watersheds. However, GIS spatial analysis techniques can also be of benefit to small watersheds, because they simplify the implementation of WSP steps, especially hazard analysis and risk assessment as well as monitoring procedures in the catchment area and also the documentation of the WSP. An important precondition is a sufficient number of samples of relevant parameters.

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