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Spatially explicit groundwater vulnerability assessment to support the implementation of the Water Framework Directive – a practical approach with stakeholders

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Abstract. The main objective of the study presented in this paper was to develop an evaluation scheme which is suitable for spatially explicit groundwater vulnerability assessment according to the Water Framework Directive (WFD). Study area was the Hase river catchment, an area of about 3 000 km^2 in north-west Germany which is dominated by livestock farming, in particular pig and poultry production. For the Hase river catchment, the first inventory of the WFD led to the conclusion that 98% of the catchment area is “unclear/unlikely” to reach a good groundwater status due to diffuse nitrogen emissions from agriculture.

The groundwater vulnerability assessment was embedded in the PartizipA project (“Participative modelling, Actor and Ecosystem Analysis in Regions with Intensive Agriculture”, www.partizipa.net), within which a so-called actors’ platform was established in the study area. The objective of the participatory process was to investigate the effects of the WFD on agriculture as well as to discuss groundwater protection measures which are suitable for an integration in the programme of measures.

The study was conducted according to the vulnerability assessment concept of the Intergovernmental Panel on Climate Change, considering sensitivity, exposure and adaptive capacity. Sensitivity was computed using the DRASTIC index of natural groundwater pollution potential. Exposure (for a reference scenario) was computed using the STOFFBILANZ nutrient model. Several regional studies were analysed to evaluate the adaptive capacity. From these studies it was concluded that the adaptive capacity in the Hase river catchment is very low due to the economic importance of the agricultural sector which will be significantly affected by groundwater protection measures. As a consequence, the adaptive capacity was not considered any more in the vulnerability assessment.

A groundwater vulnerability evaluation scheme is presented which enjoys the advantage that both exposure and sensitivity can be operationalized in a spatially resolved manner (500×500 m grid) by the two models mentioned above. The evaluation scheme was applied in the Hase river catchment. 21% of the catchment was classified as highly vulnerable, another 73% as medium vulnerable. Only 6% of the Hase river catchment has low vulnerability. Grid cells of the high vulnerability class are considered as priority areas for groundwater protection measures in the programme of measures of the WFD. Measures will be particularly effective in the north-eastern part of the catchment where groundwater vulnerability is mainly due to high nitrogen emissions.

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1 Introduction

The Water Framework Directive (WFD) requires that all surface waters and groundwater must reach good status by the year 2015. In 2004, a preliminary inventory of the present status of surface waters and groundwater was drawn up for the Article 5 report. The Article 5 report, delivered to the European Commission in 2005 by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU, 2005), is a first inventory of the status of surface and groundwater bodies in each river basin district. By the year 2006, the next step of WFD implementation was completed: the establishment of a monitoring programme. Subsequently, a programme of measures will have to be implemented by the year 2009. According to the WFD, not only environmental aspects but also socio-economic impacts of measures need to be considered. The findings of the WFD implementation steps described above will be included in the River Basin Management Plan (RBMP). The RBMP is required under Article 13 of the WFD by the year 2009 for the first time, and has to be reviewed every six years. In addition, the

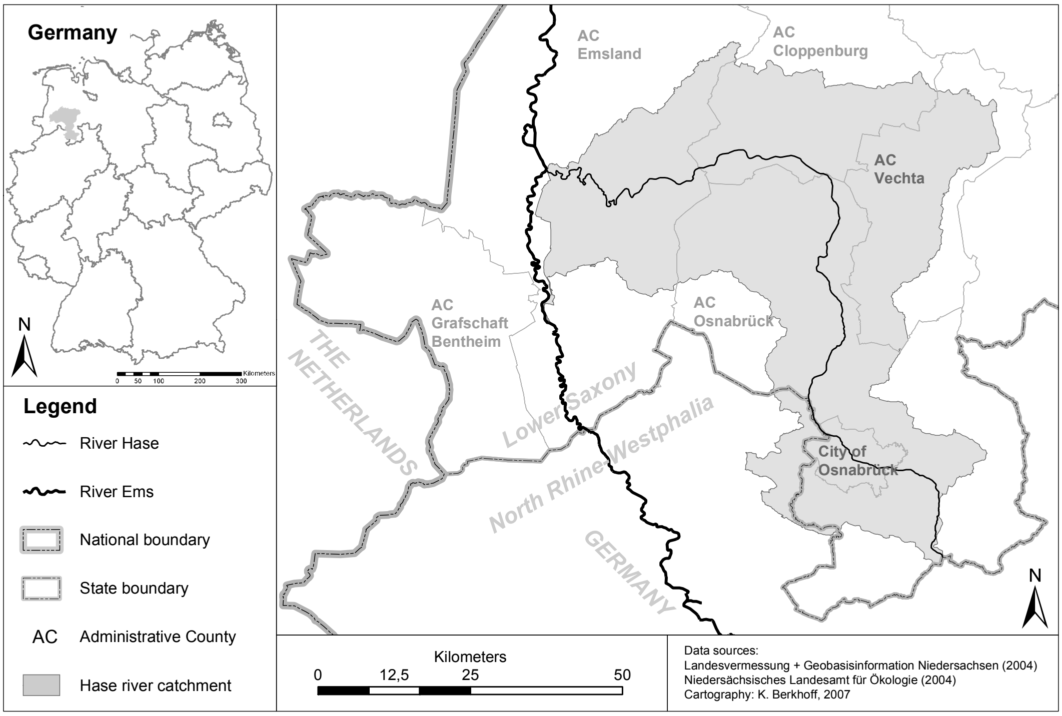

Fig. 1. Overview map of the Hase river catchment.

WFD requires under Article 14 public information and consultation throughout the implementation process. The programme of measures of the WFD currently is under development; it requires to identify areas at risk more specifically than in the Article 5 report. In the Article 5 report, whole sub-catchments of the study area were assigned the rating “unlikely to reach a good groundwater status”; there was no spatial differentiation within them. Thus, the main objective of the study was to develop an evaluation scheme which is suitable for spatially explicit groundwater vulnerability assessment according to the WFD. Furthermore, by model application in the project’s participatory process, the demand of the WFD for stakeholder integration should be met.

Study area is the Hase river catchment in Northern Germany, which is a sub-catchment of the river Ems and covers an area of 3112 km^2 (Fig. 1). Around 1 100 000 people live in the five administrative districts covered by the catchment, resulting in a mean population density of 135 inhabitants per square kilometre (NLS, 2001). Agriculture is the most important economic sector, nearly 50% of the persons employed work directly in the agricultural sector (3%) or in markets related to agriculture (46%) (NLS, 2003b). 81% of the catchment area is utilised as field and grassland. Agriculture in the catchment is dominated by livestock farming, in particular pig and poultry production. Mean animal numbers per farm are 628 pigs and 20 795 chickens (NLS, 2003a). In contrast, mean farm area is low, only 5% of the farms manage more than 100 hectares (NLS, 2003b).

The county district of Vechta, most parts of which are located in the study area, has the highest chicken density of the world; 13 million chickens are kept there (Blasberg, 2006). Furthermore, parts of the study area have the highest pig density in Germany (NLS, 2003a; Statistical Offices of the Länder and the Federal Statistical Office, 2006). The mean value of livestock density in the region is 2.1 livestock units per hectare, which is significantly higher than the German average of 0.9 livestock units per hectare. The maximum value in the study area is 3.9 livestock units per hectare (NLS, 2003a). Nitrogen emissions from intensive livestock farming have been a major point of discussion in the region for many years, both in research (Gerlach, 1990; Forschungszentrum Jülich, 1991; Raderschall, 1995; Berlekamp et al., 2000; Klohn et al., 2001; Klohn et al., 2003) and among the public (Streck et al., 2001; Küster, 2005; Busse, 2006; Rohwetter, 2006b; Rohwetter, 2006a). For the study area, the Article 5 report led to the conclusion that 98% of the catchment area is “unclear/unlikely” to reach a good groundwater status due to diffuse nitrogen emissions from agriculture (NLWKN, 2005). The main source of agricultural nitrogen emissions is organic nitrogen from livestock. Groundwater pollution is a particular severe problem due to long residence times of groundwater prevalent in many regions. The improvement of its quality is a process that can take up to several decades. Berding et al. (1999) calculated for the study area that the reduction of the nitrate concentration in groundwater from a mean value of 60 mg/l to a value of 25 mg/l will take almost 50 years, assuming a reduced nitrate input of 10 mg/l per year. In addition, at least in Lower Saxony where the study area is located, groundwater is a main source of drinking water. Thus, a good groundwater status is a value of high priority in the region.

The paper proceeds as follows. In Sect. 2, the PartizipA project is described. In Sect. 3, the methodological approach of vulnerability assessment is outlined. Its Sect. 3.2 contains the groundwater vulnerability evaluation scheme, while in Sect. 3.3 the applied models (DRASTIC and STOFFBILANZ) are described. Sect. 3.4 includes the model results. Adaptive capacity is integrated in Sect. 3.5. The overall groundwater vulnerability in the study area is presented in Sect. 3.6. Finally, Sect. 4 is dedicated to model application in the participatory process. Conclusions on both model application in the participatory process and the vulnerability assessment are drawn in Sect. 5.

2 The PartizipA project

The modelling task was embedded in the PartizipA project ("Participative modelling, Actor and Ecosystem Analysis in Regions with Intensive Agriculture", www.partizipa.net), within which a so-called actors' platform was established in the study area. The objective of the participatory process was to investigate the effects of the WFD on agriculture in the administrative area of Osnabrück, located in the boundaries of the Hase river catchment. Further, groundwater protection measures were discussed which are suitable for an integration in the programme of measures. Model application in the participatory process was intended to serve the following purposes:

- integration of stakeholder knowledge into the STOFFBILANZ model, e.g. characteristic attributes of the agriculture in the study area,
- providing a common knowledge base for discussion on nutrient emissions in the study area.

The actors' platform consisted of 14 stakeholders each representing an institution from one of the following sectors: water management, agriculture, administration, forestry, nature conservation. The Agricultural Chamber of Lower Saxony acted as partner with practical experience in the PartizipA project. A total of seven stakeholder meetings took place in the time period from September 2004 to March 2006. Each of the meetings lasted three to four hours. During the first meetings, there was an introduction to the WFD, including a presentation of the results of the first inventory for the Hase river catchment (Fig. 2). The next step involved a discussion of the stakeholders' cognitive maps concerning nitrogen load. This was followed by a discussion on measures, focusing on the topics of agriculture and consumer behaviour. Meetings 5 and 6 were dedicated to the STOFFBILANZ model. The actors' platform was closed in March 2006 with the completion of the final document (http://www.partizipa.uni-osnabrueck.de/docs/Schlussdokument20final_web.pdf (in German)) in the seventh meeting, edited by both the research team and the stakeholders.

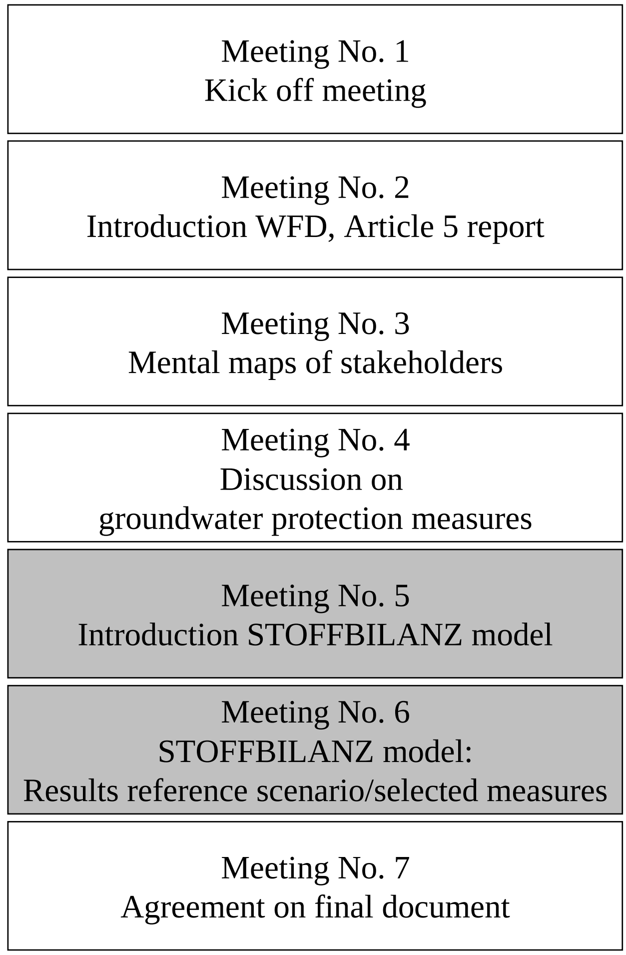

Fig. 2. Model application in the actors' platform.

3 Vulnerability assessment approach

3.1 Theoretical background of vulnerability assessment

According to the WFD, not only environmental aspects but also socio-economic impacts of measures need to be considered in the programme of measures. Thus, the programme of measures describes the ability of a region to mitigate groundwater pollution taking into account these aspects. In order to be able to integrate not only ecology into the vulnerability assessment but also the human dimension, the definition of vulnerability of the Intergovernmental Panel on Climate Change (IPCC, 2001) was chosen for the study. Vulnerability here is defined as a function of

Table 1. Evaluation scheme for groundwater vulnerability assessment (Berkhoff, 2007). (Numbers in brackets: Original threshold values from the evaluation scheme of Lower Saxony).

Groundwater vulnerability	N load in seepage water [kg N/(ha*yr)]	Total runoff [mm/yr]	DRASTIC index	N concentration in seepage water [mg N/l]
high	>90 (20–40)		>159	
			>159	>33 (9)
	>90 (20–40)			>33 (9)
	> 10	< 150	> 119	
low (DRASTIC-Index <120)	< 10		< 120	
			< 120	< 9
	< 10			< 9
	< 20	< 250	< 120	
	< 30	≥250−350	< 120	
	< 40	> 350	< 120	

– exposure

– sensitivity and

– adaptive capacity

The IPCC approach relates to vulnerability due to changes in climate, but it is extended in this study also to other changes of natural conditions. Metzger (2005) proceeds in a similar manner. Exposure means a system's degree of exposure to external impacts (IPCC, 2001). In the case of the study presented in this paper, exposure is the nitrogen load caused by land use. It is computed using the STOFFBILANZ nutrient model (Gebel et al., 2005). To use this method, a reference scenario was characterised which represents the current state of agricultural practice in the study area (Berkhoff, 2006). The output parameters of the STOFFBILANZ model are nitrogen load [kg/(ha*yr)] and nitrogen concentration [mg/l] in the seepage water and nitrogen load [kg/(ha*yr)] in the receiving stream. Sensitivity is the degree to which a system responds to external impacts. It is described here by the natural groundwater pollution potential, which can be estimated by the DRASTIC index (Aller et al., 1987). The DRASTIC index is based on seven parameters: depth to water, groundwater recharge, aquifer media, soil media, topography, influence of the vadose zone media and conductivity. Therefore, the DRASTIC index provides a method to describe the intrinsic characteristics of a groundwater body. Applying the DRASTIC index results in an index of groundwater pollution potential ranging from 23 (very low pollution potential) to 230 (very high pollution potential). Adaptive capacity is defined as "the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate" (IPCC, 2001). As mentioned above, the programme of measures of the WFD gives information on the ability of a region to mitigate groundwater pollution by conducting measures and thus can be referred to as the adaptive capacity of a region.

The demands of the WFD and those of the chosen theoretical approach (IPCC) result in the proposal of a three steps approach for the implementation of the programme of measures:

1. spatially explicit assessment of the current groundwater status on catchment level

2. in-depth analysis of the current groundwater status in priority areas as identified in step 1

3. joint evaluation of the ecological and socio-economic consequences of the measures on farm level

Step 1 is supported by the vulnerability assessment approach presented in Sect. 3.2. Steps 2 and 3 are not an integral part of the study, but are necessary to finally come up with a programme of measures. The stepwise approach is an alternative to the existing approach of using one complex coupled model system, which has been applied in Lower Saxony in several projects. There, an agricultural sector model (RAUMIS) (Henrichsmeyer et al., 1996), a runoff model (GROWA) (Kunkel et al., 2002) and a model of groundwater residence times (WEKU) (Kunkel et al., 1997) are combined to evaluate measures based on ecological and socio-economic criteria. Projects that use this model system in Lower Saxony are e.g. REGFLUD (Gömann et al., 2005) and AGRUM Weser (Henneberg et al., 2007). This well proven approach perfectly meets the requirements of the WFD if there are enough data and resources available for applying the model system in the area under study. On the other hand, the stepwise approach is advantageous in that it allows for concentrating resource-intensive tasks on the areas at risk. The regional model requires only input data which are generally available for larger areas. Local models requiring detailed input data then only need to be applied in areas classified as highly vulnerable before. With respect to stakeholder participation as demanded in article 14 of the WFD, the three steps approach is more suitable than the complex model system. It is difficult to apply very complex models in participatory processes because stakeholders usually are not experienced in modelling and would not be able to understand them (Borowski et al., 2007). The same is true for models operating on regional scale because their working scale differs from the local perception of the stakeholders. The three steps approach allows for stakeholder participation in step 2 and 3. Despite the fact that the regional scale is not optimal to involve stakeholders, stakeholder participation in the PartizipA project took place as soon as step 1 of the three steps approach and is described in Sect. 4.

3.2 The groundwater vulnerability evaluation scheme

The evaluation scheme presented here is designed to deliver spatially explicit results of the current status of groundwater. It is clearly focused on an assessment of whole catchments. The approach is model-based and uses only data which are generally available for larger areas. Both the STOFFBILANZ model and the DRASTIC index were calculated on a 500×500 m grid. The vulnerability assessment approach chosen for the study enjoys the advantage that both exposure and sensitivity can be operationalized in a spatially resolved manner by the two models. Each grid cell of the catchment is assigned a certain value of exposure (nitrogen load) and sensitivity (DRASTIC index). The scheme for the evaluation of groundwater vulnerability is based on the Lower Saxony approach of groundwater assessment used in the WFD (NLWKN, 2005, Appendix 1, Sect. 1.2.3.1). The advanced groundwater vulnerability evaluation scheme is shown in Table 1 and consists of four columns:

- nitrogen load in seepage water [kg N/(ha*yr)]
- total runoff [mm/yr]
- DRASTIC-Index
- nitrogen concentration in seepage water [mg N/l]

Nitrogen load and nitrogen concentration are both computed using the STOFFBILANZ model for the reference scenario. Furthermore, total runoff is calculated in the water balance module of the STOFFBILANZ model. The evaluation scheme distinguishes between two classes: “high vulnerability”’ and “low vulnerability”. Grid cells that are not assigned to one of these classes are grouped in the class “medium vulnerability”. For the nitrogen load in seepage water, a threshold value of 90 kg/(ha*yr) was defined for the high vulnerability class, which reflects the high level of pollution in the study area. In order to be able to identify priority areas in a region, the threshold value had to be increased due to high emission levels in the study area. The threshold value of 90 kg/(ha*yr) is also included in the German fertilizer regulation. A threshold of 10 mg N/(ha*yr) has only been defined for grid cells with a very low total runoff of below 150 mm/yr. For the low vulnerability class, threshold values of 10 to 40 kg N/(ha*yr), depending on the total runoff, were taken from the Lower Saxony approach. Referring to Aller et al. (1987), three groups were established for the DRASTIC index:

- low groundwater pollution potential (<120)
- medium groundwater pollution potential (120–159)
- high groundwater pollution potential (>159)

Grid cells can only be assigned to the low vulnerability group if their DRASTIC index is below 120. There are two threshold values for the nitrogen concentration. 33 mg N/l corresponds to 150 mg nitrate/l; as in the case of nitrogen loads, it was necessary to choose this high threshold value to identify priority areas. 9 mg N/l corresponds to 40 mg nitrate/l and was taken from the evaluation scheme used in Lower Saxony. Threshold values of nitrogen load and nitrogen concentration needed to be increased in comparison to the threshold values of the Lower Saxony approach (cf. Table 1). This was due to the high level of exposure in the study area. But in general, the values of the Lower Saxony approach serve as reference values defining nitrogen values of high risk.

3.3 Description of applied models

3.3.1 DRASTIC

DRASTIC is a well established method used in many regions of the world (Al-Adamat et al., 2003). It is often applied in the United States (e.g. Rupert, 2001) and Canada, but also in Europe (Stigter et al., 2006), Australia (Piscopo, 2001), New Zealand (McLay et al., 2001), South Korea (Kim et al., 1999), South Africa (Lynch et al., 1997) and Jordan (Al-Adamat et al., 2003; El-Naqa, 2004). It was already applied in the study area of the Hase river catchment before (Berlekamp et al., 2000). The model was chosen because it is the most proven model available for calculating groundwater pollution potential on regional scale. Further, the DRASTIC input data are generally available. The DRASTIC model consists of

- ranges
- ratings (1–10)
- weights (1–5)

Determination of the DRASTIC index number is done by multiplying each parameter rating by its weight and adding together the resulting values. The higher the calculated sum values the greater is the according groundwater pollution potential. Each parameter is rated on a scale from 1 to 10, a rating of 10 indicating a high pollution potential of the parameter for the study area. In the next step, the parameters are weighted (numbers in brackets below) to express their relative importance with respect to each other:

- D: depth to water (5)
- R: groundwater recharge (4)
- A: aquifer media (3)
- S: soil media (2)
- T: topography (1)
- I: influence of the vadose zone media (5)
- C: conductivity (3) (El-Naqa, 2004)

As can be seen from the enumeration above the first letters of the DRASTIC parameters form the acronym DRASTIC. Finally, the DRASTIC index number can be calculated as follows:

$$\text{DRASTIC index}=D_R D_W+R_R R_W+A_R A_W+S_R S_W+T_R T_W+I_R I_W+C_R C_W \quad (1)$$

where R=rating and W=weight.

The weights were constituted in a Delphi approach. They form the framework of the DRASTIC index, hence, they are fixed and may not be changed (Aller et al., 1987).

3.3.2 STOFFBILANZ

The STOFFBILANZ model (Gebel et al., 2004; Gebel et al., 2005) is based on an Access database. It computes nutrient emissions from agriculture on catchment scale. It was developed for the application on the mesoscale (up to approximately 2500 km^2), in particular to support the implementation of the WFD. A model comparison done by Kunst et al. (2003) showed that STOFFBILANZ is more suitable for the implementation of the WFD than the other models of the study (i.e. MOBINEG,www2.hydrotec.de/vertrieb/mobineg/), MODIFFUS (Schmid et al., 2000) and MONERIS (Behrendt et al., 2002). This is only true for the nitrogen part of the STOFFBILANZ model, the phosphorus part was not considered to be suitable for the implementation of the WFD. In the study presented in the paper, only the nitrogen module of the STOFFBILANZ model was used, phosphorus emissions were not calculated. The STOFFBILANZ model consists of several modules:

- general data storage
- data storage nitrogen balance
- water balance
- soil erosion
- phosphorus balance
- nitrogen balance

Model outputs are nitrogen emissions from diffuse sources separated into the runoff paths surface runoff, interflow, drainage runoff, and baseflow. Furthermore, the model calculates nitrogen concentrations in the seepage water and nitrogen immissions in the receiving stream. Both the data storages require the following main input data:

- land use
- groundwater bearing aquifer
- soil texture, soil type
- climate (precipitation, number of rainy days, evapotranspiration, temperature)
- crop area, crop type
- organic and mineral fertilizer
- yield
- atmospheric deposition

Data generation for the STOFFBILANZ model was completely done in ArcGIS. The most important work steps were the reclassification of data according to the model requirements and their transformation to the 500×500 m grid which was selected as reference grid for the study. Grid data were exported to the Access database of the STOFFBILANZ model and were re-imported then to ArcGIS for a visualization of the model results after the model run. Data exchange was performed by assigning a unique ID number to each of the 12 476 grid cells in the study area which could be identified in both the GIS and the model data table. In the first step, the water balance is calculated in the STOFFBILANZ model, taking into account the following runoff pathways: surface runoff, drainage runoff, interflow, and baseflow. Interflow and baseflow are considered as seepage water the amount of which is determined on the basis of the relations given by Wessolek and Trinks (2002) for the different land use types. Baseflow is calculated from runoff ratio depending on soil type, slope and exposition. Surface runoff is computed according to the Curve Number method (US Soil Conservation Service, 1972). Drainage runoff is estimated from soil type, assuming that 50% of precipitation in winter and 10% of precipitation in summer runs off via the drainage system. Sensitivity analysis gave evidence that yield parameters and fertilization are the most important input data to be determined. Stakeholder knowledge of regional yields and fertilization has been considered in the modelling process (cf. Sect. 4.1). The amount of organic fertilizer is usually calculated from animal density using public statistical information (NLS, 2003b). STOFFBILANZ provides an interesting possibility to overcome the lack of data concerning mineral fertilizer application by assigning a total fertilizer need to each crop which first is satisfied by the available organic fertilizer. The lacking amount of fertilizer then is filled up with mineral fertilizer. It is obvious that the determining parameter is the total fertilizer need. In the study, it is (in terms of a best case scenario) assumed that the total fertilizer amount in the region is determined by the good farming practice. Data for nitrogen fertilizer needs of crops according to the good farming practice were provided by the Agricultural Chamber of Lower Saxony (LWK) (LWK, 2003). Uncertainties related to the use of organic fertilizer are taken into account by considering manure storage and application losses. STOFFBILANZ gives the possibility to define a discrepancy factor which increases the amount of mineral fertilizer subject to the real farming practice. This discrepancy factor has been defined by balancing stakeholder judgements against expert judgements and was identified as low for the investigation area. Another issue has been considered during modelling the current land use: since 2006, the German fertilizer ordinance (DüV, 2006), which implements the European Nitrates Directive, restricts the amount of organic fertilizer applied to field and grassland.

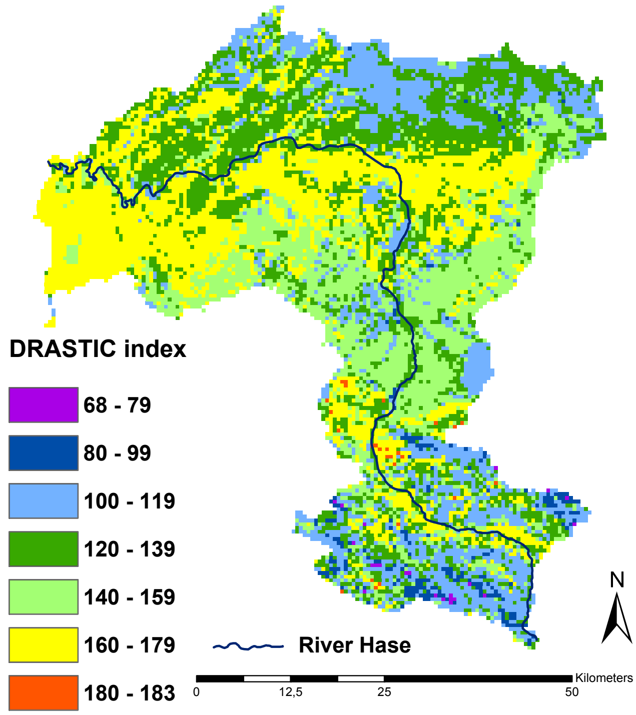

Fig. 3. DRASTIC index in the Hase river catchment.

3.4 Model results

DRASTIC values in the study area range from 68 to 183 (Fig. 3). Nearly one third of the study area shows DRASTIC values above 160, indicating a high groundwater pollution potential. These grid cells can be found in the lowland area in the centre of the study area, along the river Hase and also along the tributaries of the river. These areas are dominated by very permeable sand and gravel. The southern part of the study area, formed by a bedrock aquifer, has a lower groundwater pollution potential. As a result from the STOFFBILANZ model, nitrogen emissions in seepage water ranging from 0 to 147 kg N/(ha*yr) for the reference scenario were calculated (Fig. 4). Mean values of the different land use classes are: 81 kg N/(ha*yr) (field), 32 kg N/(ha*yr) (grassland), 26 kg N/(ha*yr) (coniferous forest), 18 kg N/(ha*yr) (deciduous forest), and 7 kg N/(ha*yr) (settlement, devastation). Nitrogen concentrations in seepage water range from 0 to 184 mg N/l. Mean values per land use class were highest in the field land use class (29 mg N/l). Grassland has a mean value of 19 mg N/l, coniferous forest 13 mg N/l, deciduous forest 7 mg N/l, settlement 4 mg N/l and devastation 2 mg N/l. Mean concentrations in seepage water cannot be compared directly to groundwater concentrations, but the threshold value of 50 mg nitrate per litre in groundwater (equivalent to 11 mg nitrogen per litre) as given in the Groundwater Daughter Directive (Groundwater Directive, 2007) can serve as loose reference point. It becomes obvious that it is difficult to meet the threshold value of 11 mg nitrogen per litre in case of agricultural land use. The STOFFBILANZ results were validated against water quality measurements on river gauging stations. Thus, the STOFFBILANZ output parameter “nitrogen immissions in the receiving stream” was used for comparison, because it considers denitrification processes and retention within the receiving stream. Six river gauging stations with attached catchment areas of 209 to 2974 km^2 were compared to modelled nitrogen loads resulting in a high model efficiency (Nash et al., 1970) of 0.95.

3.5 Adaptive capacity

The third parameter of the groundwater vulnerability assessment (besides sensitivity (Sect. 3.3.1) and exposure (Sect. 3.3.2)) is the adaptive capacity of the region. Unlike exposure and sensitivity, adaptive capacity cannot be identified within the groundwater evaluation scheme. To recapitulate, the programme of measures of the WFD gives information on the ability of a region to mitigate groundwater pollution by conducting measures and thus can be referred to as the adaptive capacity of a region. In the WFD, environmental and socio-economic aspects should be considered for the programme of measures. Generally, for a joint evaluation of the ecological and socio-economic consequences of the measures, farm level is the appropriate scale. On this scale, the measures have to be implemented. However, a first evaluation of the economic consequences can also be done on regional level. There are several ways of

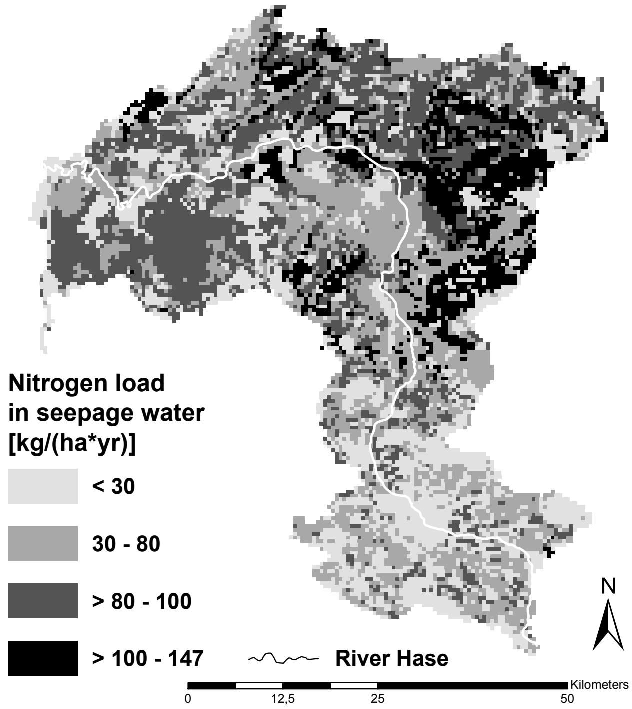

Fig. 4. Nitrogen load in the Hase river catchment as computed by the STOFFBILANZ model.

doing this evaluation. In the participatory process of the PartizipA project, measures were selected based on the criteria costs, acceptance, controllability and side effects. Ecological efficiency of the measures on regional scale was then computed by the STOFFBILANZ model (Sect. 4.2). On the other hand, in the REGFLUD project (Gömann et al., 2005) the RAUMIS model (Henrichsmeyer et al., 1996) was used to evaluate socio-economic impacts of groundwater protection measures on regional level in the Ems river catchment. RAUMIS is an agro-economic model which describes the whole of the German agricultural sector on the level of the German "Landkreise". It is designed for policy impact analysis of changes in agricultural practice which are introduced e.g. by the programme of measures of the WFD. RAUMIS follows the approach of profit maximisation of the agricultural production under the given constraints. Besides of the policy impact analysis RAUMIS also calculates a nitrogen balance following to the guidelines of the Paris Convention for the Prevention of Marine Pollution (PARCOM, 1995). A local assessment of groundwater protection measures is currently done in the WAgriCO (www.wagrico.de) project on "model farms" in three pilot study areas in Lower Saxony, one of which is located in the Hase river catchment. Both the regional studies mentioned, the own evaluation in the PartizipA project and the results from the REGFLUD project, indicate a low adaptive capacity of the region under study due to the socio-economic importance of the large animal husbandry farms. Gömann et al. (2004) give an example of the socio-economic effects of a measure aiming at the limitation of livestock density in the Ems river catchment. They found out that this measure would cause several thousand job losses and therefore is not feasible. Groundwater protection measures vary widely in economic and ecologic efficiency. Here, local studies are necessary to evaluate the effects of measures on the individual production process of farms. From the WAgriCO study, results are expected that identify the feasibility of measures on local scale in order to definitely determine the adaptive capacity of the region.

From the studies described above it was concluded that the adaptive capacity in the Hase river catchment is very low. This is mainly due to the economic importance of the agricultural sector which will be significantly affected by groundwater protection measures. Thus, the adaptive capacity was not considered any more in the vulnerability assessment. In case of regions with high adaptive capacity, it can be integrated into the groundwater vulnerability evaluation scheme in the following way: the STOFFBILANZ model is run for an "adaptation" scenario instead for the reference scenario. However, this is only possible if the adaptive capacity can be described within the model.

3.6 Groundwater vulnerability in the study area

Both the results of the DRASTIC model and the results of the STOFFBILANZ model were used to compute groundwater vulnerability according to Table 1. 21% of the catchment was classified as highly vulnerable. The areas of high vulnerability are concentrated in the north-eastern part of the catchment area, due to high nitrogen loads and high levels of nitrogen concentration in the seepage water there. Figure 5 shows the result of applying the evaluation scheme in the study area. In addition to the high pressure coming from exposure, the sensitivity of several municipalities in the north-eastern part of the study area is also rather high. In this region, the DRASTIC index reaches up to 158. Grid cells in the north which are assigned a low vulnerability are, without exception, those of the land use classes grassland, forest or settlement. Grid cells of the land use class field in this part of the catchment are mainly assigned to the high vulnerability class. In the north-western part of the study area, clusters of highly vulnerable grid cells can also be found. The high vulnerability in this part of the region, however, is caused by high DRASTIC indices of around 170 and only slightly increased levels of nitrogen load just above the threshold value of 90 kg/(ha*yr). In general, the northern part of the study area, which is characterised by unconsolidated sediments, is more vulnerable than the bedrock aquifer in the south of the study area. This is mainly due to the more intensive structure of agriculture there. Most of the grid cells in the low vulnerability class are located in the southern bedrock aquifer area. These are generally characterised by low DRASTIC indices of below 100 and low levels of nitrogen load and concentration. Only single grid cells in the south near the river

Hase are assigned to the high vulnerability class because of high DRASTIC indices existing at some sites there. In the bedrock aquifer area it has to be recognised that, due to the heterogeneous structure of the aquifer media and the potential occurrence of fractures, single hot spots of vulnerability are possible which are not grasped by the evaluation scheme. It can be taken from Fig. 5 that most of the catchment (73%) belongs to the medium vulnerability class.

4 Model application in the participatory process

To recapitulate, model application in the participatory process had the following purposes:

- integration of stakeholder knowledge into the STOFFBILANZ model, e.g. characteristic attributes of the agriculture in the study area,
- providing a common knowledge base for discussion on nutrient emissions in the study area

In the following sections, it is described if the objectives of model application were met.

4.1 Integration of stakeholder knowledge into the STOFFBILANZ model

In meeting 5 the stakeholders were given an introduction to the model. The required input data and their data sources were presented as well as the model's calculation modules and basic model equations. Further, a first model result was presented to the stakeholders. The model was run assuming that good agricultural practice is followed by the farmers in the region. This reference scenario was based on values provided by the fertilizer consulting department of the Agricultural Chamber of Lower Saxony for every field crop's yield, and mineral and organic fertilization. The standard values represent a fertilization practice according to "good agricultural practice". The reference scenario served as a starting point for the ensuing discussion of measures. From their knowledge of the agricultural practice in the region, the stakeholders made several suggestions for improving the calculation of the reference scenario:

- increasing the standard values of yield (and thus, also fertilizer) by 10%, due to a high level of yield in the catchment area
- defining yields separately for light (pure sand) and heavy soils
- accounting 70% of the organic fertilizer as plant-available due to the fact that organic fertilizer in the region is composed mainly of manure

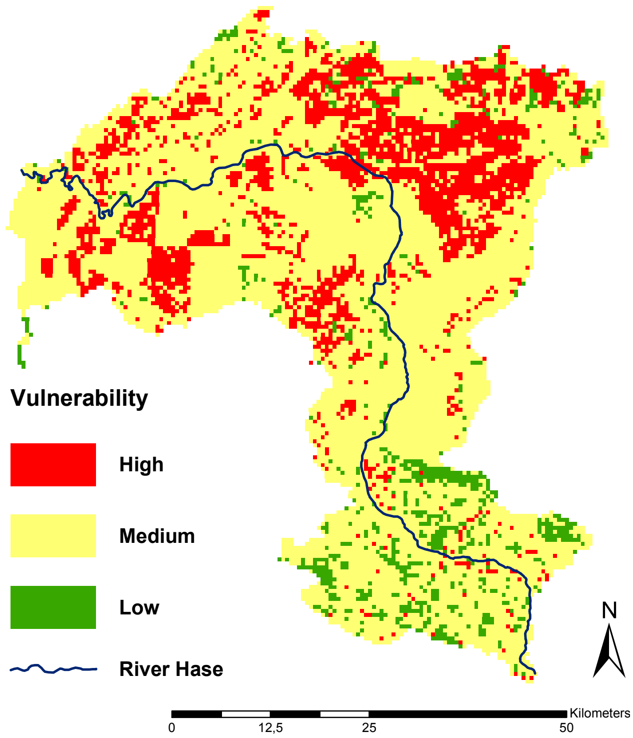

Fig. 5. Groundwater vulnerability map of the Hase river catchment.

Following the discussion of the reference scenario, the stakeholders selected a list of 14 groundwater protection measures based on recognized measures from the voluntary agreements in water protection areas and other cooperative approaches in Lower Saxony. Selection criteria were the costs, acceptance, controllability and side effects of the measures. Three of the 14 measures were selected to be modelled by STOFFBILANZ until the next stakeholders' meeting:

- transformation of field into grassland
- optimized fertilization
- afforestation

For the following stakeholders' meeting number 6, model runs of the three measures and the revised reference scenario were prepared. Before, the stakeholders' suggestions were validated against statistical information on yields and expert judgments of plant-availability of manure. Concerning the measures, STOFFBILANZ only estimates the ecological efficiency, socio-economic implications on farm level need to be evaluated subsequently.

4.2 Provision of a common knowledge base to the stakeholders

The result map of the revised reference scenario was presented in stakeholder meeting 6 whereas the validation against measurements on river gauging station was not yet finished at that point in time. For the calculation it was intended that the stakeholders should define areas suitable for the implementation of certain measures. This objective could not be met because the stakeholders had difficulties to allocate the measures. In exchange, each measure was computed on 2500 hectares (100 grid cells), selected randomly from the cells that were assigned high groundwater vulnerability in the reference scenario. The calculation of measures showed that the ecological efficiency varies widely. Transformation of field into grassland results in a mean value of nitrogen reduction of 58 kg/(ha*yr), optimised fertilisation in 21 kg/(ha*yr) and afforestation in 96 kg/(ha*yr). On regional scale, only rough estimations can be made of the costs of measures. Costs were calculated on the basis of cost estimates of the stakeholders for each of the measures, specified as Euro per hectare. Combination of the costs and the ecological efficiency as computed by the STOFFBILANZ model indicated that the cost efficiency (Euro per kilogram nitrogen reduction) also varies in a wide range (between 0.50 €/kg N-reduction and 260 €/kg N-reduction). A sound evaluation of the economic aspects can only be done using an agro-economic model like e.g. RAUMIS to be able to consider different farm types and production structures.

At meeting 6 it became clear that the 500×500 m spatial resolution of the model contrasted with the stakeholders' desire to have model results on a field scale. Only few stakeholders found the regional model results useful. In addition, the stakeholders criticised the modelling of nitrogen loads in seepage water despite modelling nitrate concentrations in groundwater. The model's way of including uncertainties related to organic fertilizer was particularly criticised. One stakeholder stated that by calculating numbers, the model makes out it is accurate, whereas in reality it is inaccurate, because it uses large-scale input data and imprecise equations. Even though some of the data came from the partner with practical experience, they were not accepted. Further, the stakeholders asked for validation of the model results, and for an expert opinion on them. The proof most accepted by the stakeholders turned out to be the validation of model results against field measurements. As a consequence of their disbelief in the regional model results, the stakeholders decided not to use them for their final document.

5 Conclusions

Three kinds of study results need to be distinguished. First, was stakeholder knowledge successfully integrated into the STOFFBILANZ model? Second, did the stakeholders benefit from the model results? And third, was the evaluation scheme suitable for identifying vulnerable areas according to the WFD?

As described in the previous section, application of the model in the participatory process led to a revised version of the reference scenario. The revised scenario is considered more specific as the first version. Even though the information given by the stakeholders in the case of the PartizipA case study could also have been generated from other sources (statistics, experts) and thus cannot be labelled as "unique", stakeholder participation gave valuable information for the modelling process. On the other hand, stakeholder participation in the modelling process can increase model acceptance by stakeholders. This was not the case in the PartizipA case study. Most of the problems the stakeholders had with the model refer to the regional scale of the STOFFBILANZ model. Therefore, it is expected that the application of a local scale model in a participatory process is more rewarding for the stakeholders. Besides the scale, also other aspects influenced the success of model application in the participatory process. They are referred to as the context of model application[1]:

- resources at disposal
- motivation of the stakeholder group to use the model results
- modelling purpose
- external factors
- intended utilisation level
- key stakeholder and
- method of visualisation

External factors influencing the modelling process have to be discovered. That can be the requirements of the WFD, as in the PartizipA case study, but also the scale on which information is supposed to be given. The intended utilisation level of the model results should be clearly described. It can range from a pure reception and cognition of the results to an adoption in reality (Knott et al., 1980). The partner with practical experience as a key stakeholder can support model application e.g. by data provision. He represents the link between project organisers (e.g. a research institute) and local stakeholders (e.g. farmers). Finally, the method of visualising the model results is important to communicate about the model results. In the PartizipA case study, only few stakeholders benefited from model application in the participatory process. Thus, it can be concluded, if stakeholder participation is the main objective of model application, local scale models should be preferred to regional scale models to support the stakeholders' local perspective.

The concept of vulnerability assessment was suitable for the identification of vulnerable areas on a regional scale.

[1] Berkhoff, K.: Modelling to support the implementation of the EC Water Framework Directive, in: Herrmann, S., Dabbert, S. and Krimly, T.: Flood protection with stakeholders in small catchments., in review, 2008.

Groundwater vulnerability was computed with a spatial resolution of 500×500 m. The vulnerability assessment resulted in the identification of priority areas of groundwater vulnerability, on which the planning of measures for the programme of measures of the WFD should be concentrated. Groundwater protection measures will be particularly effective in the north-eastern part of the catchment where groundwater vulnerability is mainly due to high nitrogen emissions. The applied models base on input data which are generally available for larger areas. Thus, the approach is considered to be transferable also to other regions. In relation to the programme of measures of the WFD the spatially explicit assessment of the current groundwater status on catchment level presented in this paper is only the first of three steps. It is essential to do the next steps subsequently. These are an in-depth analysis of the current groundwater status in the identified priority areas and the joint evaluation of the ecological and socio-economic consequences of the measures on farm level.

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