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Environmental risk mapping of pollutants: State of the art and communication aspects

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ABSTRACT

Risk maps help risk analysts and scientists to explore the spatial nature of the effects of environmental stressors such as pollutants. The development of Geographic Information Systems over the past few decades has greatly improved spatial representation and analysis of environmental information and data. Maps also constitute a powerful tool to communicate the outcome of complex environmental risk assessment to stakeholders such as the general public and policy makers. With appropriate cartography one can improve communication and thus bridge the gap between experts and users. Appropriate risk communication is pivotal to risk management, decision making and implementation and may prevent unnecessary concern about environmental pollutants. However, at present few risk maps are specifically tailored to meet the demands of such defined uses.

This paper presents an overview of the most important types of risk maps that can be distinguished using examples from the scientific literature: contamination maps, exposure maps, hazard maps, vulnerability maps and 'true' risk maps. It also discusses, in a general way, the most important issues that need to be addressed when making risk maps for communication purposes: risk perception, target audience, scale and spatial aggregation and visualisation such as use of colours and symbols. Finally, some general rules of thumb are given for making environmental risk maps for communication purposes.

1. Introduction

Environmental risk assessment of pollutants deals with the effects of hazardous substances that are present in the environment. Environmental risk assessment includes both human health risk assessment (effects on people's health) and ecological risk assessment (effects on ecosystems). Traditionally, results from environmental risk assessment are presented in a non-spatial way, but this has been changing rapidly over the past decade. The development of Geographic Information Systems (GIS) has greatly improved spatial representation and spatial analysis of all kinds of information and data. Geographical data (e.g. topology) and attribute data (environmental characteristics, land use, concentrations of contaminants, etc.) can be combined into maps using spatial models embedded in the GIS. Furthermore, these days GIS software can be easily obtained and used. This means that everybody can now make maps on their own personal computers, whereas map making used to be confined to specialist cartographers in the past. As a consequence of the development of GIS technology, environmental risk mapping of pollutants is a rapidly developing field as well (e.g., Pistocchi, 2006).

Environmental risk maps can be used for many purposes. However, there are perhaps two principal categories of use, analysis and communication. Risk maps help risk analysts and scientists to explore the spatial nature of pollutant concentrations, exposure and effects, but they also constitute a very powerful tool to communicate the outcome of complex environmental risk assessment. The map maker is also responsible for conveying the right message in the right way. This requires some knowledge of risk communication in addition to the technical aspects. Whenever environmental scientists produce maps to inform the general public, policy makers and other laypeople, they are entering the arena of social sciences, most notably that of communication science itself.

This review paper is written for environmental scientists, working in the area of risk assessment of environmental pollution, who make maps to present the results of their work. However, the paper may also help other people involved in environmental risk assessment to judge environmental risk maps critically and to interpret them more accurately. The goals of the paper are to give an overview of the different types of risk maps that can presently be distinguished, to explain the general principles of these different maps, to discuss examples of risk maps, and finally, to provide some general rules of thumb for making appropriate risk maps for communication purposes while avoiding some common pitfalls.

We searched for literature on environmental risk mapping of chemicals and for environmental risk assessment papers with examples of maps. Over one hundred and fifty scientific articles published between 1995 and 2009 were screened to write this paper. However, it is by no means a complete overview of the entire literature on environmental risk mapping. The number of publications

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with some sort of environmental risk maps in them is virtually endless and many of them cannot be traced with traditional literature research methods using keywords.

2. Types of maps

Before distinguishing different types of risk maps, it is important to define what we call risk in this paper. We use the definition by Van Leeuwen and Hermens (1995): "the probability of an adverse effect on man or the environment resulting from a given exposure to a chemical or mixture". We use the term hazard for "the set of inherent properties of a chemical or mixture which makes it capable of causing adverse effects in man or to the environment when a particular level of exposure occurs" (Van Leeuwen and Hermens, 1995).

There are many types of maps that can, very generally, be called risk maps. These range from maps showing contaminant levels in the environment to maps that show the outcome of complex risk assessment procedures. The principal categories that can be distinguished and their characteristics are given in Table 1. The categories and terminology used are in agreement with a recent report to the European Commission on risk mapping of various hazards to people (Wood and Jelínek, 2007). The different types of maps are discussed in the following sections using examples from the literature.

2.1. Contamination maps

The literature contains many examples of maps where levels of environmental pollutants in an area are measured or predicted and then mapped. These can perhaps be considered as risk maps in their most simple form because people, animals and plants may get in contact with the contaminants and be exposed to them.

Another type of contamination map is what may be coined a 'contamination risk' map. Contamination risk is the probability that a certain area becomes contaminated by polluting substances. The contamination has not yet taken place or the extent of contamination is unknown. Good examples of this are ground water pollution maps.

Table 1
Summary of current approaches used to map the distribution of risks and environmental stressors geographically.

Map category	How to make them?
Contamination	Display the distribution of measured or predicted (modelled) concentrations in a geographical area
Contamination risk	Use the physical and geographical features in an area to map the likelihood of (potential) contamination
Vulnerability	Use the presence and geographical distribution of sensitive receptors of environmental stress to map more and less vulnerable areas
(Potential) exposure	Combine (measured or predicted) contamination levels with the geographical distribution of (ecological or human) exposure receptors
Hazard	Divide measured or predicted pollutant concentrations in an area by a threshold value for effect (NOEC, LC_{50}, EC_{50}) or by an environmental quality standard and map the values of these Toxicity Exposure ratios (TERs)
Risk of single stressors	• Compare (measured or predicted) environmental concentrations to simple environmental threshold levels and map the results • Map results of extensive modelling/simulation of contamination, exposure and effects ('model train' approach) • Combine maps of vulnerability and maps of (potential) stress/environmental pressures (e.g., by overlaying)
Risk of multiple stressors	• Calculate combined risk from single stressors using cumulative stress principles and algorithms (e.g., concentration–addition) • Use multivariate statistical analysis to reduce dimensionality and map the resulting statistical parameter values • Present risk assessment results in more dimensions (e.g., a map with a matrix legend or visualisation in 3D or 4D)

The classification is based on the present survey of mostly peer-reviewed literature. The emphasis is on the risks of environmental pollutants.

There are dozens of publications that describe the results of mapping the probability that ground water in aquifers becomes contaminated by (agro)chemicals or macronutrients such as nitrate. These methods are rather well developed and to some extent apply a similar approach and methods, for instance the DRASTIC model (Ducci, 1999; Al-Adamat et al., 2003). Usually geological, hydrological or soil data are combined to determine places were the aquifers are more prone to contamination (Berg et al., 1999; Hirata et al., 1991; Tait et al., 2004; Worrall and Besien, 2005). These maps can be overlaid with maps for land use or sources of (agro)chemicals to produce a map of the actual ground water pollution risk (Ducci, 1999; Giupponi et al., 1999; Al-Adamat et al., 2003; Capri et al., 2009). The maps that are made this way are called vulnerability maps, sensitivity maps or risk maps by the authors. However, what is meant in these cases is the risk of contamination of an environmental compartment and not the risk to organisms or their vulnerability.

Other examples of maps that display the contamination risk of environmental compartments can be found in the articles by Huber et al. (1998) and Probst et al. (2005), who modelled and mapped the risk of pesticide losses through runoff in Germany using data on pesticide use patterns. Schriever and Liess (2007) made such pesticide runoff maps at the European scale. Zhu et al. (2001) drew a map of radon pollution risk in houses (and thus of potential exposure of inhabitants) for southern Belgium based on the relation between measured samples of indoor air and the geology of the region.

2.2. Exposure maps

Often there is not a straightforward difference between mapping pollutant levels in the environment and mapping potential exposure. We may speak of exposure assessment when (potential) contamination is compared to the presence and distribution of exposure receptors, either people, domestic or farm animals, or wild organisms. For instance, when the risk of contaminating crops with metals from soils is mapped (e.g., Barančíková et al., 2004) or the risk of ground and drinking water contamination (previous paragraph), one is implicitly mapping potential exposure of consumers to pollutants.

Dolinoy and Miranda (2004) modelled the release of toxic glycol ethers in the air and compared the results to the distribution of residential areas at the county level and to demographic data. This analysis revealed localized, neighbourhood-level exposure disparities by income and race. Gathering and presenting information in the context of environmental justice was also the objective of several other publications from the USA (Miranda et al., 2002; Sheppard et al., 1999; Maantay, 2002; Lejano and Smith, 2006).

Maps from literature showing (potential) exposure are mostly from the field of human health risk assessment. We found only one or two maps of exposure or potential exposure of receptors in ecosystems. However, this knowledge gap is presently being filled with the development of spatially explicit models, for instance BERISP (Cormont et al., 2006; also see www.berisp.org) and ECO-SpaCE (Loos et al., submitted) for the exposure of wildlife species to persistent soil pollution.

2.3. Hazard maps

One step further than mapping concentrations or exposure is to compare measured or predicted environmental concentrations of pollutants to threshold values for toxicity or to environmental standards and to map the result. This is may be called hazard mapping.

Korre et al. (2002), for example, constructed a risk assessment model to simulate and assess the risk associated with high Pb loads in soils in a mining area in Greece. In a GIS environment the spatial distribution of Pb concentrations was introduced in an exposure assessment model for adult and child populations. Exposure rates were compared with relevant reference dose levels providing hazard quotients which were presented in maps. In addition they mapped the probability of exceeding toxicological reference values.

De Vivo et al. (1998) and Boni et al. (1999) compared measured levels of various metals in river sediments in Sardinia to the Italian intervention criteria for different types of land use to build 'potential risk' maps. Markus and McBratney (2001) show a map of a Sydney neighbourhood displaying the probability of Pb in topsoil exceeding the Australian environmental investigation limit. Brus et al. (2002) and Brus and Jansen (2004) mapped the probability of cadmium exceeding thresholds for food quality (in beef and crops) for the whole territory of the Netherlands. Van't Zelfde and De Snoo (2003) and Vijver et al. (2008) mapped the exceedence of several environmental quality criteria by measured concentrations of several individual pesticides.

An example at the watershed level is presented by Verro et al. (2002) and Sala and Vighi (2008). These maps are based on the integration of relational and spatial databases, GIS, mass balance models and a pesticide toxicity exposure ratio (TER) risk indicator called PRISW-1 (Short-Term Pesticide Risk Index for Surface Water). Surface water pollution due to drift and runoff of the herbicide alachlor applied on corn in Lombardia region (northern Italy) was modelled. Worst-case simulation results were displayed in maps of the Predicted Environmental Concentration (PEC) and risk maps for polygons representing river subbasins in the region.

Hazard maps show how strong an impact in a given area may be, but they do not show the probability of an effect, i.e., the real risk. For this purpose one also needs to know where sensitive risk receptors are present and exposure does occur.

2.4. Risk maps

Almost one third of the papers screened contained maps with results of such 'true' risk assessment. These apply the classic approach by following the chain of events that leads from the release of chemicals through exposure and hazard assessment to risk characterisation. However, these publications and risk maps differ considerably with respect to the risk assessment methods applied, e.g., indicators, scale, underlying data and spatial operations applied. There is one thing, however, that most of these studies have in common; almost all studies include the use of one or more models to predict exposure and risks of effects, as illustrated below with some examples.

Gonzalez et al. (2002) modelled lead poisoning risk in children for the greater Tijuana area in Mexico and validated the modelling results by comparing these in GIS with the occurrence of lead poisoning cases. There was a good agreement. Hellweger et al. (2002) modelled the exposure to arsenic from a smelter facility in Bolivia with an air dispersion model and mapped the resulting lifetime excess cancer risk using a risk module in GIS. Bién et al. (2004) applied their own Health Index/Risk Evaluation Tool (HIRET) for the spatial and temporal mapping of the probability of cancer cases at an undisclosed locality with soils contaminated with benzene.

It is interesting to note that one can also map risk perception of people instead of calculated risks. Brody et al. (2004) used questionnaires to investigate the perception of air pollution in the Houston and Dallas metropolitan areas and mapped the results. The perception was not correlated with the true air pollution in the area. Setting (urban versus rural areas) and socioeconomic drivers were more important to explain perception.

There are also several examples of ecological risk maps. Clifford et al. (1995) mapped the risk of secondary poisoning of burrowing owls by dieldrin using a food chain model and spatial analysis. They also used this assessment to predict and map the effects of remediation. A similar approach was applied by Banton et al. (1996) for mapping the risks of organochlorine contamination in soil at the Rocky Mountain Arsenal (U.S.) to wildlife. The results of this modelling study were consistent with field observations on ecological endpoints and wildlife health at the same site. Kooistra et al. (2001) visualized the spatial risk of secondary poisoning by cadmium in little owls in a heterogeneously contaminated flood plain in the Netherlands using a combination of measured Cd concentrations, food web modelling, knowledge about foraging behaviour in different habitats and probabilistic risk assessment (Fig. 1). An analysis of the non-spatial variability and uncertainties in this risk assessment exercise was conducted later (Kooistra et al., 2005).

2.5. Hazard and risk indicators

All maps are simplifications of reality (Woodbury, 2003). An ordinary flat map can only display the values of a limited number of variables or parameters, usually one but up to three. Thus, even for complex cases, often a reduction to a single dimension must occur (Moen and Ale, 1998).

Just like there are many methods to construct risk maps there exists a plethora of different indicators that are used for mapping risks. Indicators used to display risks are often quotients (Toxicity Exposure ratios, TERs; Hazard Quotients, HQs) that are calculated from measured or predicted environmental concentrations (PECs) divided by toxicological or administrative threshold values (Predicted No Effect Concentrations, PNECs; Maximum Tolerable Risk Limits, MTRs; Toxic Reference Values, TRVs; generic Reference Doses, RfDs, etc.) or other environmental quality standards. The Short-Term Pesticide Risk Index for Surface Water (PRISW-1, Verro et al., 2002) mentioned earlier is also an example of a TER approach. A variation on these concentration–toxicity ratios is the (simulated) unit area load (UAL) of pollutants in subcatchments of rivers divided by the maximum permitted unit area load (UAL_{max}) used to map risks by runoff of storm water pollutants by Mitchell (2005).

Human health and risk is often expressed as the Standardized Incidence or Morbidity Rate (SIR, SMR) for certain diseases and health phenomena (such as cancer or vascular diseases) or as the Standardized Mortality Rate (SMR), the ratio between the observed and the expected number of deaths in an area. Cancer rates in some risk maps are expressed as the probability of getting cancer in a certain area (number of cases) or the lifetime excess cancer risk (Bién et al., 2004; Hellweger et al., 2002; Ragas et al., 2006).

2.6. Cumulative risk maps

There are only few papers that explicitly deal with mapping cumulative risks, in our case approximately ten papers out of the 150 that were screened. In order to map cumulative risks, the risks of the single stressors must be combined in a single parameter. The most common way to do this is to model the joint action of the compounds. Often the concentration-addition model (CA) is used for this purpose. Moiseenko (1999), for example, calculated the ratios between environmental concentrations and Russian toxic threshold values (GCs) and summed these ratios for a number of metals to calculate the overall integrated toxicity index (I_{tox}) in surface waters conforming to the concentration–addition principle. This I_{tox} parameter was calculated for each grid cell of the Russian Kola region and a map was constructed that displayed the potential combined effects on aquatic life. A very similar approach was adopted by Rapant and Kordík (2003) and Rapant et al. (2009) who summed environmental risk indices, IERs, for various contaminants (mostly metals) in environmental compartments and mapped the outcome for the whole Slovak Republic. IER values are analyzed concentrations divided by risk limits such as PNECs or drinking water standards.

Another way to deal with cumulative stressors consists of a statistical approach. Clustering analyses such as Principal Component Analysis (PCA) can be used not only to reduce the dimensionality of a multivariate data set, but also to display and map the different dimensions of the data set. Korre (1999a,b) explored the use of PCA

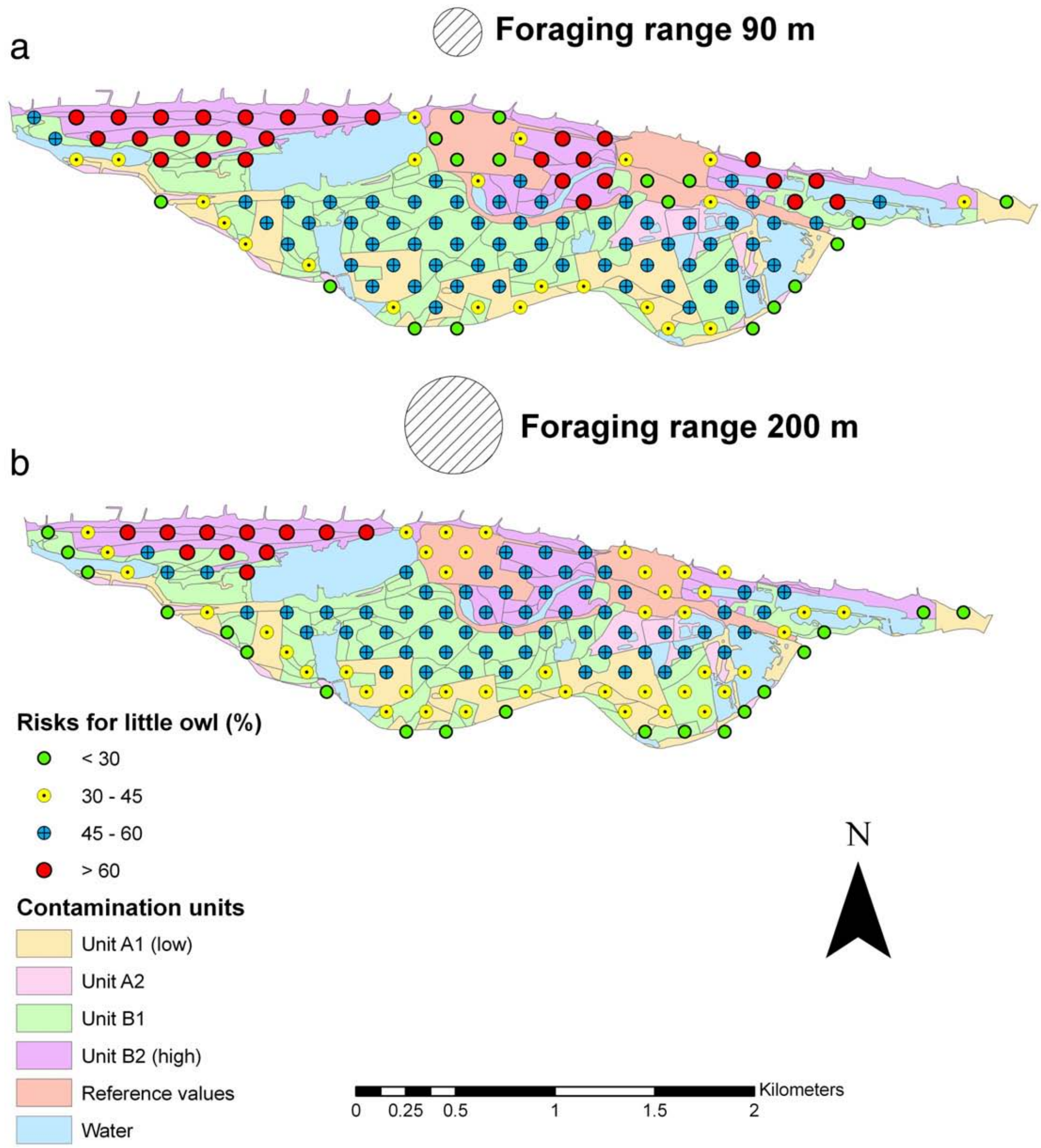

Fig. 1. Example of a 'true' risk map. Site specific Cd exposure risk for the little owl (*Athene noctua*) with an assumed foraging range of (a) 90 m and (b) 200 m. The hatched circles indicate the surface areas for the two foraging ranges. The exposure risk is indicated as the probability for the modelled Potential Exposure Concentration (PEC) to exceed the Potential No Effect Concentration (PNEC). Contamination units indicate areas with comparable sedimentation histories that have a similar metal distribution in the soil (Kooistra et al., 2001).

and Canonical Correlation Analysis in combination with GIS. Distinctive pollution sources could be separated quantitatively. However, they did not apply the methods to risk assessment, only to the assessment of contamination sources. Tran et al. (2003) combined self-organizing map neural networks and PCA to perform regional environmental assessment of ecosystems. Based on data on land cover, population, roads, streams, air pollution and topography the method indicated areas of poor environmental quality for a case study of the U.S. Mid-Atlantic region. It yields a single ranking for which the results may be mapped.

Mapping statistical parameters may be suitable for scientists. However, because it is rather technical, the approach is probably less effective for communication about risks with the general public, decision makers and other non-specialists.

In ecological risk assessment, one also needs to deal with the fact that many species are exposed simultaneously to pollutants. One of the concepts that can be used for this situation is that of species sensitivity distributions (SSDs; Posthuma et al., 2002). Traas et al. (2002), for example, used the multisubstance Potentially Affected Fraction of species (msPAF) for secondary poisoning of mammals and birds by toxic metals. The model for the calculation of the msPAF was applied to all grid cells of a map of the Netherlands. In this way, risk maps were made for cadmium, zinc and copper. A map of the combined risk was constructed using response addition (or 'no interaction'). Multisubstance PAFs, but this time for aquatic organisms, were also used by De Zwart (2005) to map the consequences of pesticide use in the Netherlands for aquatic ecosystems in field ditches.

2.7. Vulnerability maps

The term 'risk' is usually used when there is a known stress level that acts upon humans or ecological receptors. Vulnerability, on the other hand, means how well (or not) a receptor, an area or a (eco) system can cope with stress. Vulnerability or sensitivity maps, therefore, display the parts of a geographical area and certain features in it that are more or less vulnerable to a particular kind of stress that is often not (yet) being exercised. A good example of such maps are the oil sensitivity maps that have been developed in different parts of the world and that can be used by authorities to respond accurately to oil spills. These maps are made for coastal areas where spills may wash ashore. The oil sensitivity maps range from rather simple, for example habitat classifications plus symbols for sensitive objects such bird colonies (Tortell, 1992; Nelson, 2000), to more complex maps based on indices calculated from biological surveys of species and biotopes in coastal areas (Van Bernem et al., 1994; McMath et al., 2000; see Fig. 2 for an example). There also exist maps for other stressors such as ecological sensitivity maps for the ecological effects of fisheries (MacDonald et al., 1996).

The combination of vulnerability and land use may also be used to map the risks of cumulative stress. Giupponi et al. (1999) conducted a mapping exercise in which they overlaid map layers for land vulnerability and impact by diffuse agricultural pollution in the watershed of the Venice lagoon in Italy. Different parameters for impact and vulnerability were combined in a (weighted) multicriteria approach to simulate the risk for surface waters and ground water. Both human and ecological endpoints were used, i.e., pollution of drinking water, toxicity to mammals, toxicity to aquatic life and eutrophication. The methods were later also applied to make maps at the European scale (Giupponi and Vladimirova, 2006).

3. Risk maps for communication

At a European workshop (DCDEP, 2000) risk communication was defined as "an interactive process of exchange of information and opinions between individuals, groups and institutions, involving discussions of types and levels of risk and measures for dealing with risks". The goal of risk communication is to assist stakeholders in taking risk-based decisions based on a balanced judgment, that reflects the factual evidence about the matter at hand, in relation to their own interests and values (OECD, 2002). For the purpose of making risk maps several issues are very important: to acknowledge how risks are being perceived, to identify the target audience, and to use accurate cartography and visualisation techniques, notably with regard to scale and the use of colours and symbols. These issues are briefly discussed in the following paragraphs.

3.1. Risk perception

Risk communication is challenging, especially when dealing with consumers or with residents in a particular area. Scientists and non-scientists rank risks differently (Holtzhauer et al., 1998; DEFRA, 2000; Garvin, 2001) and the general public is often suspicious of invisible threats such as radiation, infectious diseases and environmental pollutants. Even when the actual risk is low, solutions to risk problems may be rejected when there is a high degree of public outrage.

There are many factors that influence risk perception like the type of risk (for example: voluntary versus involuntary imposed risks, familiar versus unfamiliar risks, dreaded versus undreaded) and social dimensions (group processes, inequitable distribution of risks). And for each individual there are also behavioural and personality factors involved in their attitude towards hazards (Bouyer et al., 2001). So, when communicating about risks, good communication skills are necessary and the sender must be perceived as a trustworthy and responsible player (Drottz-Sjöberg, 2003).

Risk communication is a two-way process. Stakeholder involvement and public participation is required to make better decisions because it leads to better awareness of risks and greater acceptance of risk management strategies that are jointly agreed upon. For risk mapping, this may even evoke participatory use of GIS or the use of GIS for conflict solving (Duncan, 2006). Most of all, good risk communication before specific policies on pollutants are developed and implemented may prevent unnecessary concern.

3.2. Target audience and stakeholders

It is crucial in risk communication that the target audience and stakeholders are identified at the start of the risk assessment process and that the means of communication are directed at this audience in order to improve the efficacy of the process. Some of the major players and stakeholders in risk communication and risk management of chemicals are (e.g., OECD, 2002; Drottz-Sjöberg, 2003):

- specialists/risk experts/scientists,
- local, regional and national authorities,
- emergency response services,
- other decision and policy makers (legislators, politicians, regulators, etc.),
- industry,
- workers and employees of companies,
- the media (press),
- the general public (including consumers and residents),
- nongovernmental organisations, and
- public interest groups.

Maps that are made for communication purposes should be tailored for the intended users and their particular level of understanding. In the words of Frye (2001): "Target your map to the person least prepared to understand your map's message". However, at present only a handful of published risk maps are specifically designed to meet the demands of defined end users. An example of a risk map that is explicitly aimed at the use by a defined target audience is provided by Dellinger (2004). He presents a map that indicates the safety of walleye (fish) consumption to members of native American people in the Great Lakes area that are harvesting this fish species which may contain increased mercury levels. Maps that combine spatial risk assessment and modelling of future scenarios allow spatial planners, authorities and policy makers to evaluate the environmental impact of different scenarios in advance, which facilitates taking decisions that will lead to less environmental stress. Giupponi et al. (1999), for instance, compared the effect of pollution risk from agricultural activities on water resources in the watershed of the lagoon of Venice with and without the introduction of low input techniques in current agricultural practice, and showed that this had a considerable impact on the risks of surface and ground water contamination. A second example of maps for spatial planners is provided by Bién et al. (2004) who mapped the concentrations and human health risks at a site contaminated with benzene until 50 years from now. They also combined these risk estimates with a change in land use from industrial to residential.

3.3. Scale and spatial aggregation

One could say that different pollution risks each have a specific spatial scale of relevance, depending on the spatial extent of the pollution and the spatial distribution of the risk receptors. Health risks that arise from the exhaust from traffic typically occur at the local level, a road or a network of roads in an area or town. Carbon dioxide emissions, as we know, act at a global scale. The spatial scale of the map may have implications for the users. Jensen (1998), for example, mapped benzene levels in air at the scale of individual houses for a town in Denmark. It is easy to imagine how such maps, when not communicated carefully, could cause public unrest, not to mention how such information may affect the value of properties. So depending on the type of risk, the message that needs to be conveyed and the target audience, one should determine the most appropriate and effective scale for the map.

Another important issue in risk mapping is the type and level of spatial aggregation. Areal units can be divided into grids and polygons and these may have considerably different sizes (also depending on the scale). Bartels and Van Beurden (1998), Van Beurden and Douven (1999) and Elliott and Wartenberg (2004) show examples of risk maps with different areal units but that are based on the same data

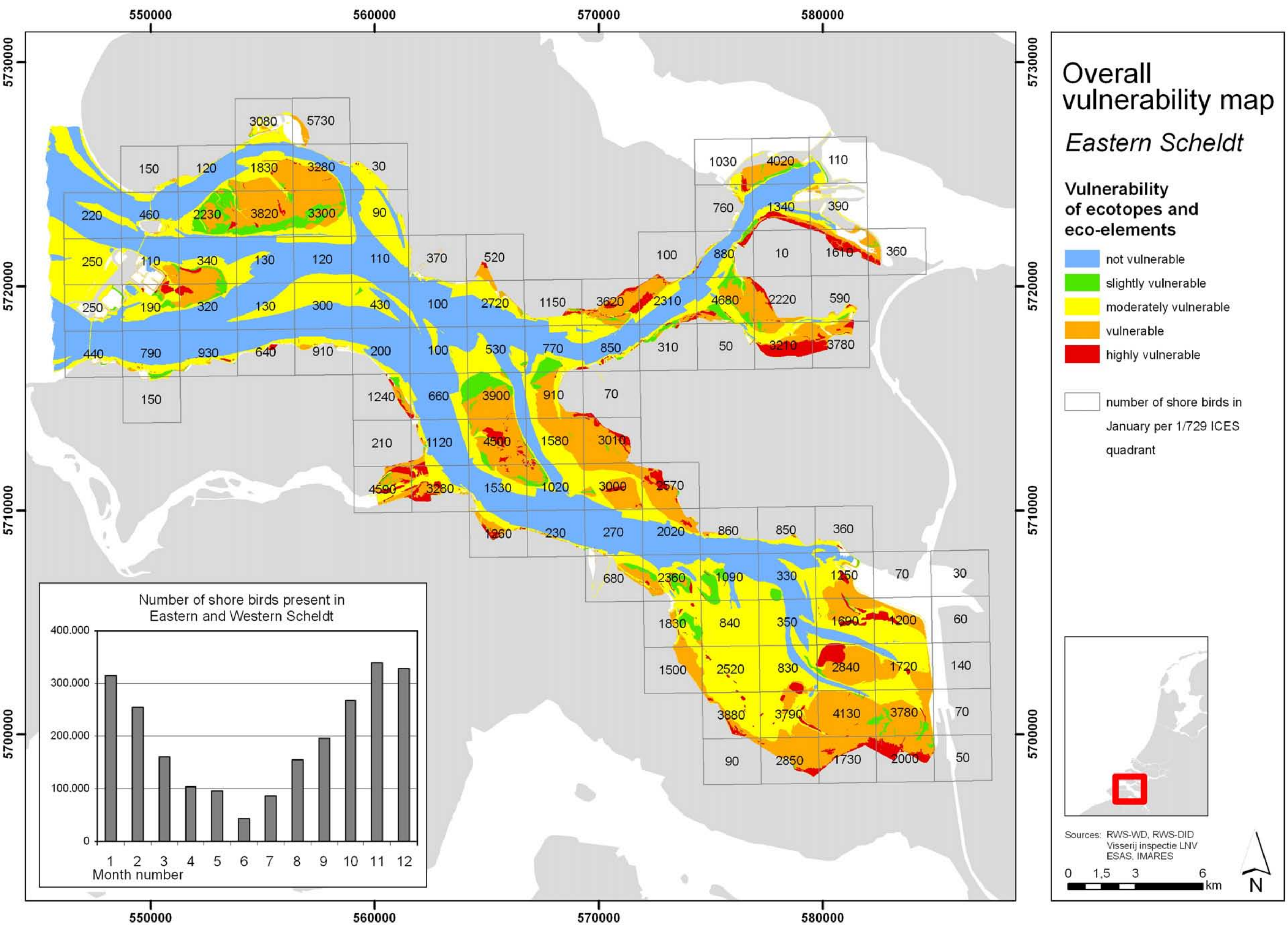

Fig. 2. Oil vulnerability map of the brackish Oosterschelde area in The Netherlands. The map is based on a ranking of estuarine habitats and elements of particular interest (i.e., sea grass fields, oyster and mussel banks) according to their ecological vulnerability to oil pollution (impact and potential recovery) following the method developed by Lahr et al. (2007). Reproduced with kind permission of the Directorate Rijkswaterstaat of the Netherlands Ministry of Transport and Public Works.

set. The visual differences between these maps are dramatic. When the areal unit is large and data are averaged, whole regions or provinces may seem at risk whereas a high risk may only occur at one or two localities when displayed in a finer grid. In this case the risk is 'smeared' (Moen and Ale, 1998). Such phenomena are referred to as the Modifiable Area Unit Problem or MAUP (e.g., Holt et al., 1996; Usery, 2001). A map user such as a policy maker may easily be tricked by maps with the wrong level of aggregation and take the wrong decisions. As for the choice of the scale, the aggregation level of an environmental risk map should match the level relevant for the user.

3.4. Colours and symbols

Colours and symbols are used to distinguish between areas and features in maps but also to convey information about their properties. Hence, the choice of the colours and symbols is pivotal to the information and the message that is passed to the reader of the map. An extensive discussion on how to choose the right colours and symbols is beyond the scope of this paper, but this information can be found in almost every important textbook on cartography (e.g., MacEachren, 1995; Brodersen, 2001, on the internet). One important issue to mention briefly is the misuse of colours.

In western civilisations the colour red is associated with danger and the colour green with safety (Bartels and Van Beurden, 1998; Moen and Ale, 1998) but one needs to be very aware that such interpretations are culturally determined (Frye, 2001). In graphic and map making software the user may choose from a large number of colour schemes to display quantitative differences in maps. Often these contain several bright colours (see Frye, 2001). This may seem appealing to the users at first but the use of different colours makes it difficult for users to grasp differences in intensity. Although these may come across as less spectacular, greytones and monochrome schemes are more suitable for this purpose. Bartels and Van Beurden (1998) convincingly show with examples that a greytone map allows users to identify the areas with high and low noise levels at a single glance. Monochrome maps are also more suitable for the colour blind. However, different colours can be used for mapping qualitative differences. When existing thresholds such as environmental quality standards are exceeded, it may be perfectly justified to use an alarm colour such as red or purple.

More or less the same as for colour use applies to the choice of map symbols. One should avoid symbols that incite alarm when there is no reason for it and one should avoid using symbols that can easily be misinterpreted. Summarising, colours and symbols should be chosen in such a way that they make the map intuitive and easily accessible. The lay-out should be self explanatory so that the reader will easily absorb the message of the risk map. Suggestive use of symbols and colours (red, purple) should be avoided when the actual risk is low.

Certain colour schemes may also facilitate the visualisation of cumulative stress. It is possible to display the risks of two or three risk factors at the same time in one map by using different types of colours simultaneously. One example can be found in the article by De Vivo et al. (1998). They made several maps for metals in Sardinian stream sediments. Each map displays the concentrations of three metals using a different colour, red, green or blue (the RGB light scheme), for each metal. Relative concentrations are shown with lighter and darker colours. Where the concentrations of all three metals are high the colours mix and turn white, according to the rules of RGB (also see Assmuth et al., 2007). Jackson et al. (2004) use such a 'matrix' colour scheme as well. Colour intensity is used to show the magnitude of a first factor, and colour brightness for a second.

4. Discussion

Maps are the best known way to visualize geospatial data, that is, data that refer to the location of objects or phenomena distributed on Earth. Map making has been revolutionised by the introduction of GIS. GIS functions as a medium for both storage and presentation of geospatial data and also enables spatial modelling and interactive processes. These days, map making technology is easily available and anyone could decide to make one. However, this should be done carefully and with sufficient knowledge of cartography, environmental risk assessment methods and risk communication processes.

This paper provided an overview of the most important categories of risk maps for environmental pollutants (Table 1). Risk maps can be used in many ways. Maps that display actual risks of existing stressors such as pollutants may be used to identify areas of concern and populations at risk or to pinpoint suitable locations for monitoring purposes. But it is even better to prevent risks by looking ahead at the spatial distribution of possible future stress factors. Contamination risk maps and vulnerability maps are very suitable for planning future activities in such a way that risks to the human population and to ecosystems can be prevented or at least reduced. Furthermore, simulation and modelling of the risks in time will help decision makers to look at different scenarios for future developments and to evaluate the effects of policy measures well in advance.

Risk maps can be communicated to the target audience in many ways. According to Frye (2001) each map medium has its own challenges. He distinguishes between handheld maps (such as road maps), tiny maps (on the internet, in newspapers) and large format maps (posters etc.). The larger the map and the closer the distance at which it is read, the more complex and detailed the symbology that it can contain. Smaller maps and maps viewed from a distance should only show the most necessary information but, on the other hand, support brighter colours than handheld maps. Atlases provide a good way to pass extra information with a map, in the form of figures, graphs and tables. This offers more room for exploration of the spatial information and facilitates interpretation. A nice example of such risk maps with supporting information for a larger audience is the global atlas of children's health produced by the World Health Organization (Gordon et al., 2004).

However, these days the internet is perhaps the most important medium for distribution of risk and vulnerability maps and it is expected that in the future the number of risk maps published on the internet will increase further. Current developments in online mapping tools allow web-based access to a large variety of risk maps and mapping applications. Besides the traditional presentation of a static map on the web, more advanced applications allow interactive mapping where the users themselves can select, view and generate specific maps of interest from online databases (e.g., EPA National-Scale Air Toxics Assessment, http://www.epa.gov/ttn/atw/nata/; the Dutch digital atlas for public health, http://www.rivm.nl/vtv/object_document/o4235n21143.html). These technologies create possibilities for simple map comparisons, zooming and printing that cannot be achieved with static printed maps. More advanced features include dynamic mapping by combining assessment models and scenario analysis tools to assist real-time decision making during emergency events (Gao et al., 2009). Further development of these applications is closely related to the current progress in the field of geo-informatics. The main challenge here is to improve interoperability between systems by using common standards for the management and exchange of geospatial data by which web-based services can be accessed without knowledge of the underlying platform and implementation (Kooistra et al., 2009).

Risk maps made for communication with the public obviously need to meet other requirements than risk maps intended for scientific analysis and for explorative purposes. The wrong use of risk maps and cartographic techniques can easily lead to misinterpretation and provoke unrest when there is no need. In the worst case maps may even be used for deliberate falsification or propaganda (Monmonier, 1996). 'Risk', defined before as the probability of an effect, is of course only the technical side of a risk problem as opposed to 'outrage', which relates to the non-technical aspects, i.e., to how the risk is being perceived (OECD, 2002; Persensky et al., 2004). Even when the actual risk is low, solutions to risk problems may be rejected when there is a high degree of public outrage. The reputation of companies and authorities is driven by this outrage factor, not by risk or hazard (www.psandman.com).

Once a map has been published it is often difficult for the user to determine how reliable it is. Therefore, it is the joint responsibility of the map makers and the people that communicate the risk assessment results to make risk maps in an appropriate way and to avoid misinterpretation. Clear descriptions of the applied methods, the location of observation points and the supporting data must always be made accessible to interested users in order to judge whether the presented values in a map are accurate and to facilitate their personal interpretation of the data. One only needs to surf the internet and look at some risk and vulnerability maps to find out that this prerequisite is massively violated. Even legends to the maps are often lacking.

5. Conclusion

Based on the issues that have been presented and discussed in the previous paragraphs some general rules of thumb can be formulated for making risk maps of environmental pollutants for communication purposes. The following steps are of importance:

- Clearly formulate the objective of the map (remember that every map has a purpose; Frye, 2001).
- Identify the target audience of the map and the stakeholders that should be involved in the risk communication process.
- Tailor the maps specifically to meet the requirements of the target audience (notably the level of simplicity).
- Use appropriate risk assessment methods and risk indicators. Make a transparent description of the methods accessible to interested users and also provide access to the underlying data of the map.
- Use appropriate cartography and spatial operations (level of spatial aggregation, interpolation techniques).
- Get the visualisation right (scale, colours, symbols, etc.). Always provide a legend, also when publishing the map on the internet.
- Provide context for the interpretation of the maps (for example quantitative information on familiar risk factors to compare with; e.g. Ragas et al., 2006).
- Use appropriate communication channels and techniques to reach the intended audience.
- Ideally, the producers and communicators of risk maps should provide expert knowledge to any (public) debate following publication of the maps in order to guard against incorrect interpretation and misuse of the maps.

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