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FOOTPRINT

Functional Tools for Pesticide Risk Assessment and Management

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Characteristics of European groundwater vulnerability scenarios

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Foreword

The present report was prepared within the context of the work package WP2 ('High resolution scenario-based spatial zonation') of the FOOTPRINT project (http://www.eu-footprint.org).

The preferred reference to the present document is as follows:
Højberg A.L., Kjær J. & Nolan B.T. (2006). Characteristics of European groundwater vulnerability scenarios. Report DL10 of the FP6 EU-funded FOOTPRINT project [www.eu-footprint.org], 38p.

Executive summary

The aim of the FOOTPRINT project is the development of three computerised tools to assess the risk of water resources being contaminated by pesticides and to help different communities identify alternative strategies to reduce the risk if identified. The strategy of Work Package 2 of the FOOTPRINT project was to develop high resolution spatial zonation based on the development of representative scenarios. However, subsurface systems are usually very complex and several surface and subsurface properties and their mutual effects typically determine the risk of groundwater contamination. Combined with the limited data available on subsurface systems at the EU-scale, it would only be possible to define some limiting properties for which a scenario approach would be appropriate, e.g. presence or absence of groundwater aquifers. Such information would not be very valuable and would not aid the end-users formulate alternative strategies. The FOOTPRINT approach to groundwater aquifer vulnerability therefore deviates from the scenario approach. Instead a basic and an extended approach are proposed.

The basic approach aims at providing the user with information on aspects that makes an aquifer more or less vulnerable. The descriptions are accompanied with data available at the EU-level, from which the user can get a very broad impression of the groundwater vulnerability at their location. In addition, contact details of national institutes providing relevant data supporting the vulnerability assessments are given. The basic approach focuses on educational aspects and the primary objective of the approach is awareness building.

In the extended approach, the main objective is to support water managers in identifying areas that are most likely to contribute to contamination of the aquifer by pesticides. For this purpose the approach should, as a minimum, allow a spatial differentiation between areas with respect to their vulnerability. From a practical viewpoint the method developed in the extended approach must be relatively easy to understand and use (assuming the required data are present) if water managers are to use it. An overlay/index method has been selected as a suitable balance between the required detail and ease of use. The basic principle in the overlay/index approach is that the vulnerability is assessed quantitatively by assigning an index or score to all relevant properties expressing the protective ability of the property. A final vulnerability map is reached by multiplication or addition (or some combination hereof) of the indexes/scores.

The method developed in FOOTPRINT is based on the origin-pathway-target concept, where the origin is the place of the contaminant release, the target is the water to protect, and the pathway includes all properties between the origin and the target. The FOOTPRINT method builds upon the MACRO meta-model which will be developed within FOOTPRINT and the origin is therefore the leaching from the root zone as predicted by MACRO and not the land surface. Pathways considered are concurrently the pathways from the root zone. The target is

the groundwater resource, i.e. the groundwater table, where only the uppermost aquifer is considered, as all groundwater resources must be protected according to the Water Framework Directive (WFD).

A comprehensive study on groundwater vulnerability has been undertaken in the COST Action 620 project. Although the framework proposed in COST 620 focuses on karst aquifers it is not completely centred towards karst aquifers, and the conceptual framework as well as several of the components of the approach is applicable for non-karstic aquifers as well. The framework proposed in the European approach has largely been followed in the method developed here. As such, the method considers the groundwater protection provided by the overlaying layers (O-factor), the effect of the precipitation regime (P-factor) and the importance of flow concentration (C-factor). The specific method proposed here is inspired by the PI method (Protective cover and Infiltration conditions). A challenging task in the index/overlay method is the definition of indexes/scores. Where possible, the weights assigned in the present study have been adopted from the PI method, while suggestions for weights are proposed for properties which are new to the FOOTPRINT method. The method has not yet been tested and these weights should thus be considered preliminary weights that are subject to modification based on future tests of the method within the context of the project.

The most significant deviation between the method developed here and many other overlay/index methods is the way the protective ability of the overlaying layers is included. Commonly this is defined as inversely proportional to the permeability or hydraulic conductivity of the layers, as this affects the transport travel time. While this is an important aspect when accidental spill is considered, it may be of less relevance for pesticides as they are applied repeatedly for crop protection and resemble an almost continuous input. The travel time is therefore less important, as the aquifer needs protection regardless whether the travel time is 3 or 30 years. The main protective ability of the overlaying layers is thus expected to be their ability to smear the concentration profile, whereby the maximum concentration is reduced.

1 INTRODUCTION

Assessment of the groundwater vulnerability is of outmost importance for water management. Not only does the groundwater constitute an important drinking water resource in many EU countries, but the EU countries are also obliged to fulfil the requirements set up by the Water Framework Directive (EC, 2000) on the protection of all waters with respect to the qualitative and quantitative status. Groundwater contamination by pesticides has become an EU-wide problem, and all EU member states, except Sweden, reporting on the pesticide situation in their states to the EUROWATERNET, reports that pesticides are considered a problem for the groundwater quality (EEA, 2004). Groundwater contamination is thus a major problem and actions are needed at different levels (farmers, water managers and politicians) if the extent of the problem is not to increase dramatically in the near future.

Within the FOOTPRINT project a suite of three tools will be developed to assist in a pesticide risk assessment at different scales relevant for different end-users communities: field/farm scale relevant to farmers and extension advisors, regional/catchment scale where water managers are the primary end-users and national/EU-scale relevant to policy makers and registration authorities.

The present report describes the FOOTPRINT approach to groundwater risk assessment, where two approaches are suggested with different objectives. A basic approach is proposed focusing on educational aspects to raise awareness of groundwater contamination by pesticides. In an extended approach a specific method is developed aiming at supporting planners at, in principle, any scale. The scientific basis for the approaches is discussed herein, with emphasis on the development of the specific method, while the technical aspects regarding the implementation of the approaches in the FOOTPRINT tools are only addressed to a limited extent. As part of the FOOTPRINT project a test phase of the tools is planned (WP6) and details of the presented method are thus subject to future modifications based on the results from the testing phase.

2 ASSESSING GROUNDWATER CONTAMINATION

The risk of groundwater contamination by any substance, e.g. pesticides, is dependent on numerous factors, ranging from the physical/chemical properties of the compound and the subsoil to the settings and dynamics of the hydrological system. While satellite images may provide high resolution spatial continuous maps of almost all surface properties, and the chemical/physical properties of pesticides may be acquired from manufactures specifications or laboratory experiments, observations on the subsurface system are difficult and mostly expensive to achieve. Furthermore, most observations are indirect measures, which have to be interpreted before use and in most instances they represent only a point measure in a generally very heterogeneous system. Predicting groundwater contaminations such as the migration and concentration levels are therefore inherently associated by uncertainties and the detail and precision of the assessments are directly linked to the available data with respect to both the resolution and data quality. As data can never be sampled to provide a complete temporal and spatial continuous insight of the subsurface geometry and physical/chemical behaviour, an assessment of the groundwater vulnerability will always have to rely on some simplification of the real system. Assessment of groundwater vulnerability is therefore no straightforward task that may be carried by any person by the accomplishment of a few simple tasks in a tool. In contrary, groundwater vulnerability assessments should only be carried out by persons who hold the hydrological/hydrogeological knowledge necessary to interpret the results and evaluate the effects of the assumptions and simplifications of the utilised method.

2.1 Common approaches

Several approaches to groundwater vulnerability may be found in the literature, the most common praxis is, however, the use of either physical distributed models, the application of overlay/index methods or the construction of empirical/statistical models. The methods are fundamentally different. While the distributed models aim at describing the physical/chemical processes based on natural laws, the overlay/index methods focuses on the mean effective properties of the subsurface from a protective point of view. Empirical/statistical models differ from overlay methods in that they are based on observed relations between the predictor variables and the contaminant of interest. Both methods rely on properties that significantly influence contaminant behaviour; but in the case of statistical models, the importance of the properties is quantified statistically.

2.1.1 Physical distributed modelling

Distributed modelling in the groundwater domain has had a rapid evolution in the last 20 years. The most widely used model systems in Europe are the MIKE-SHE model system (Abbott et al., 1986a,b) and MODFLOW (McDonald and Harbaugh, 1988). While MIKE-SHE was focused on an integrated description of the groundwater-surface water system, MODFLOW was originally developed as a groundwater model for saturated conditions only, but by the development of numerous packages an integrated modelling of the groundwater-surface water system can be accomplished. Both models can thus be applied to assess not only the groundwater vulnerability, but also the entire freshwater cycle, as required in the WFD. In many countries physical distributed models are now used routinely in the water management and may be expected to be use even more frequently to assist in the implementation of the WFD (Højberg et al., 2007).

Advantages

The physical based distributed models have several advantages in use. The models are based on physical/chemical laws describing both the physical processes, such as the water movement, as well as the chemical reactions of the compounds of interested and their (geo-) chemical interaction with the soil substrate. As such, the results from the physical based models integrate the physical/chemical properties of both the medium and the substance at interest. The models are furthermore able to predict an absolute concentration and its temporal development, e.g. a breakthrough in an abstraction well. Due to the generally lack of the knowledge of the subsurface system, the model predictions are, however, uncertain. But the uncertainty may be quantified by firstly a validation of the model by comparing observed and simulated quantities, and secondly by use of the models in an uncertainty assessment (Refsgaard et al., 2007). A very important ability of the distributed models is their ability to evaluate the effect of different management scenarios, whereby the effect of programmes of measure can be evaluated prior to its implementation.

Disadvantages

The distributed models do, however, have some disadvantages. The major disadvantages of these models in the concept of FOOTPRINT are that they are very time consuming to construct and run. Additionally, distributed models are commonly difficult to understand and use for non-experts. In terms of participation in the water management plans, which is endorsed in the WFD, the distributed models holds a great potential when the models results are interpreted and present correctly, but this similarly most often requires the support from model experts. The need for experts in the modelling process and interpretation hereof, combined with the extended time needed to use the models, makes the distributed models unfit for use in the FOOTPRINT approach, focus is therefore given to the index/overlay models.

2.1.2 Overlay/index methods

The basic concept of the overlay/index methods is "that some land areas are more vulnerable to groundwater contamination than others" (Vrba and Zaporozec, 1994). The methods do thus not attempt to estimate absolute concentration levels, but focuses on aquifer characteristics that influence its vulnerability towards contamination. Several methods have been developed and reported in the literature, examples are DRASTIC (Aller et al., 1987), GOD (Foster (1987), AVI rating system (Van Stempvoort et al., 1993), SINTACS (Civita, 1994), EPIK (Doerfliger et al., 1999) and the PI method (Goldscheider, 2000), a recent overview of some of the methods are provided by Gogu and Dassargues (2000). Common to most of the methods are that a differentiation is made between *intrinsic vulnerability* and *specific vulnerability*. Intrinsic vulnerability represents the inherent hydrogeological and geological characteristics which determine the sensitivity of groundwater to contamination by human activities. Specific vulnerability is defined for a given contaminant and is characterised through particular properties, which can be different from one contaminant to another. The European specialists of the COST Action 620 "vulnerability and risk mapping for the protection of carbonate (karst) aquifers" propose a formal definition of intrinsic and specific vulnerability (COST 620):

- The intrinsic vulnerability of groundwater to contaminants takes into account the geological, hydrological and hydrogeological characteristics of an area, but is independent of the nature of the contaminants and the contamination scenario.
- The specific vulnerability takes into account the properties of a particular contaminant or group of contaminants in addition to the intrinsic vulnerability of the area.

The different methods can be distinguished according to the target of the vulnerability mapping, where two targets can be identified (1) the *resource,* which is the groundwater aquifer in general, and (2) the *source* that comprises all groundwater abstraction points, such as abstraction wells and springs. For resource vulnerability mapping the groundwater surface is the target, in case of a confined aquifer the target is the top of the aquifer and not the potentiometric head. The pathways under consideration in resource protection are thus the flow from the land surface to the groundwater table, which is predominantly the vertical passage through the layers above the aquifer. These overlaying layers are mostly unsaturated but may be locally and temporally saturated. If source protection is under consideration the migration in the aquifer itself has to be considered additionally, which is the mostly horizontal migration within the aquifer to an abstraction point. Thus, methods concerning the resource focus only on the characteristics for the overlaying layers and their ability to protect the aquifer, while methods aiming at source vulnerability mapping include a description of the characteristics of the aquifer as well.

In addition to the intrinsic and specific vulnerability, some methods include hazard mapping displaying the potential sources of groundwater contamination resulting from human activities mainly at the land surface. Combining the hazard mapping with the intrinsic and/or specific vulnerability map a final risk mapped can be constructed pinpointing the areas at most risk, i.e. the combination of a high potential for contaminant release and a low protection of the aquifer.

To discriminate between different levels of vulnerability, e.g. low/moderate/high, it is necessary to combine all quantities expected to provide a protection of the aquifer into a single measure. This may be achieved in different ways, but the method used most frequently is a weighting system, where the effect of a specific parameter is expressed by a weight, e.g. clay materials provide better protection than gravel and are given a weight that expresses so. Such internal weights are assigned for all parameter groups included in the method, e.g. unsaturated zone properties, subsoils and precipitation. The parameter groups may additionally be assigned a parameter group weight, to stress the influence of one parameter type over the other(s) before the combined vulnerability is achieved by summation or multiplication of the different parameter groups. Commonly, the final vulnerability is divided into vulnerability classes, like proposed by Vrba and Zaporozec (1994) who distinguish between five classes (Very high, High, Moderate, Low, Very low).

Advantages

One of the main advantages of the overlay/index methods are that the methods are based on a logical framework in their characterisation of the subsurface properties with respect to their protective potentials. As such the methods are easier to understand than the more complex physical based models and therefore more suitable to use for none-modellers and also more suitable to enhance the participatory process. However, the methods should, as previously stated, only be used by people with sufficient knowledge on hydrological and hydrogeological knowledge to evaluate the limitations of the method. While the distributed models most often require detailed data in both time and space, the overlay/index methods generally consider vulnerability based on average long-term conditions and thus do not include the temporal variations. Furthermore, water managers are, by the WFD directive, obliged to collect most of the data required by the overlay/index methods, section 3.2. A vulnerability assessment by the overlay/index method may thus be linked to data requirements set by the WFD.

Disadvantages

One of the major disadvantages of the overlay/index methods are that they provide a relative measure rather than an absolute measure. While a relative measure may be sufficient to prioritise areas in a management strategy, the relative measures, such as “low vulnerability” is not a quantity that can be measured in nature and the methods are thus very difficult to validate.

A major challenge in developing the overlay/index methods is the assignment of weights, both relative within one specific parameter group and certainly between the different parameters included in the assessment. Weights may to some extend be based on literature reviews and field/laboratory experiments, but it is often difficult/impossible to convert experimental data acquired from a study designed for specific purposes to a large scale, where several parameters affect the final vulnerability. Another aspect in designing the weights are that a weighting scheme developed for one specific condition or scale not necessarily may be an adequate weighting for other conditions/scales. An example could be the weighting of the precipitation regime. In areas where precipitation only varies moderately this parameter may be assigned a low weight or be omitted completely, while this parameter can have significant importance in areas with extreme variation, or if the method is applied at very large scales (national and/or EU-scale) where variations in the climatic conditions is pronounced. The assigned weights must therefore to a large extend be based expert knowledge, designed to reflect the relative importance of the parameters in the way they are expected to influence the final vulnerability under the conditions for which the method is applied. As such, a great deal of subjectivity is associated with the definition of the weights. The rating or weighting system of most methods does typically result in a range of vulnerability values or indexes, which must be grouped into the number of vulnerability classes that is desired. Similarly to the weighting of the parameters, this final step is mainly based on subjective criteria.

The use of relative vulnerability categories and the subjectivity involved in the methods has the drawback that different methods applied to the same study area are likely to produce different results, which has also been documented in the literature (Corniello et al., 1997; Goldscheider, 2000; COST 620, Gogu et al., 2003). The discrepancies in the vulnerability maps produced by the different methods are likely to be explained by differences in which parameters the different methods take into account and how they are weighted. Thus, none of the methods may be discarded as useless, but they may have different conditions for which they are applicable. The non-consistency that may be expected in the use of different methods has two significant impacts:

1. Vulnerability maps produced for two different areas are not straightforward comparable, unless
    a. the same method is used in both cases,
    b. a rigid guidance and weighting system is applied to ensure that all parameters are evaluated identical,
    c. the areas are similar with respect to the characteristics influencing the groundwater vulnerability.
2. The reliability of the vulnerability maps is strongly linked to the inclusion of all significant parameter that influence the groundwater vulnerability

The first aspect has the practical implication that great care must be taken if a vulnerability assessment is carried out stepwise, which may be the case in very large catchments where areas suspected to most vulnerable is first studied. The second point stresses that vulnerability mapping should be carried out only by persons with sufficient knowledge on the specifc hydrological/hydrogeological system to evaluate which parameters that are dominant and must be included. Also, for very large catchments the hydrologic and/or hydrogeological setting may change and different methods may be applicable for different parts of the catchment.

2.1.3 Empirical and statistical models

Statistical approaches to groundwater vulnerability complement more physically based approaches and have been used in a number of studies conducted at regional and national scales (Ayotte et al., 2006; Eckhardt and Stackelberg, 1995; Nolan, 2001; Nolan and Hitt, 2006; Nolan et al., 2002; Rupert, 2003; Stackelberg et al., 2006; Tesoriero and Voss, 1997). Logistic regression is commonly used when contaminant concentrations are low and there are a large number of nondetects. Logistic regression assumes a binary response for the dependent variable (e.g., low, high) and predicts the probability that a contaminant exceeds a threshold value, such as a reporting level or health standard. More recently, nonlinear regression has been used to simulate nitrate concentration in groundwaters of the U.S. The Ground Water Vulnerability Assessment (GWAVA) model has an additive linear submodel for N sources and multiplicative exponential terms representing factors that either increase or decrease transfer and accumulation of nitrate in groundwater (Nolan and Hitt, 2006). Thus, the model is more physically based than other statistical approaches.

Advantages

Statistical models have potential advantages over physically based models and overlay approaches. Statistical models are appropriate for regional and national scales, for which it is difficult to parameterize more complex, physically based models. Compared with overlay approaches, weights are automatically obtained from the parameter coefficients of statistical models. Also, statistical models have built-in uncertainty analysis, in that the standard errors of parameter estimates can be used to construct confidence intervals. Finally, statistical models are based on measured values, so on average a well-calibrated model can simulate actual conditions.

Disadvantages

Statistical models are data hungry because they are based on measured data. A sufficient number of observations of both the predictor and dependent variables must be obtained for proper model calibration. When extrapolating into unsampled areas, statistical models have the same pitfalls as other approaches. Processes not accounted for in the model but that occur locally can cause inaccurate predictions. For example, a statistical model may account for contaminant load, precipitation input, soil type, and Hortonian overland flow, but the presence of focused recharge in topographically low-lying areas might cause actual contaminant concentrations to be greater than predicted by the model.

3 DATA AVAILABILITY

Regardless of the method applied for groundwater vulnerability the reliability of the assessment is inherently affected by the data available with respect to both the quantity and quality. In general, the more complex and detailed the applied method is, the more detailed (and hopefully precise) is the result, but also the more data hungry is the method. If the data availability is not balanced with the complexity of the method, i.e. a detailed method is based on a too simplistic or low quality dataset, there is a high risk of misclassification of the aquifer vulnerability. This will provide the user with a detailed, but false, vulnerability map, which is worse than no map at all.

3.1 Data at the EU scale

Public available data on subsurface geology at the EU-level is generally very limited. The available data are generally aggregated numbers that are of little use at the catchment/regional and smaller scales. Furthermore, data on subsurface geology are generally limited to data on aquifer characteristics, while data describing the overlying/protective cover, which are the key aspects in groundwater vulnerability assessments, are absent. More detailed and relevant datasets are often stored nationally and/or regionally within the EU-countries, but most of these data are difficult to access and/or not free to the public. Table 1 provides an overview of the data available at the EU level, a brief description of the data is provided below.

Project name, description and availability	Scale	Spatial extent	Format
A Digital Dataset of European Groundwater Resources 1:500.000 A digital dataset of EU groundwater comprising information on: - Type of aquifer - Groundwater hydrology - Groundwater abstraction Available at http://eusoils.jrc.it/ESDB_Archive/groundwater/gw.html	1:500.000	9 EU Countries	Digital as ArcView themes
IHME International Hydrogeological Map of Europe providing information on the dominating type of main aquifers and their productivity Available at: http://www.bgr.bund.de/EN/Themen/Wasser/Projekte/Berat__Info/Ihme1500/ihme1500__projektbeschr__en.html	1:1.500.000	EU25+	On-screen , graphic map is downloadable
Brigde A map of shallow aquifer typology with focus on groundwater bodies, which may be in direct contact with dependent ecosystems. Will be available at www.wfd-bridge.net (Wendland et al. in prep)	No information available	10 EU countries + Bulgaria	No information available
WISE Water Information System for Europe will provide graphical/statistical display of WFD -data, reported from member states, on the environmental assessment of national groundwater bodies and information on registered protected areas data Will be available at: http://wise2.jrc.it/home/php/index.php	Aggregated numbers	EU25	No information available
Waterbase EEA's database providing characteristics of the quantity and quality of European groundwater bodies: - type of aquifer (karstic, fractured or porous media) - thickness of and depth to groundwater body - percentage of area being arable land - mean long term average annual precipitation over the groundwater body - water quality data on nutrients, organic matter and 2 pesticides Available at http://dataservice.eea.europa.eu/dataservice/metadetails.asp?id=832	Aggregated numbers	EU25+	Digital as excel and access databases

Table 1. Available data on subsurface properties at the EU scale.

Spatial data on hydrological characteristic of groundwater aquifers in Europe are available from three different sources:

1. The **"Digital Dataset of European Groundwater Resources 1:500.0000"** provides various maps of various hydrogeological caracteristik of the primary aquifers in nine EU countries (Germany, Belgium, Denmark, France, Ireland, Luxembourg, Netherlands, and United Kingdom). On behalf of European Commission and European Crop Protection Agency published paper maps and reports were digitised and compiled (Hollis et al. 2002) and resulting maps are now available online (Table 1). The maps contains information on the type of aquifers (confined, unconfined or complex), the nature of water movement (intergranual, fissure mixed or karstic) complexity of the vertical sequence of aquifers (single or multiple aquifers), groundwater hydrology (directions of groundwater flow and water transfers, contours of the water table or the potentiometric surface, areas of seawater intrusion or saline groundwater, position of springs) and groundwater abstraction.
2. "**IHME**" (International Hydrogeological Map of Europe) is a series of general hydrogeological maps comprising 27 map sheets with explanatory notes, covering the whole European continent and parts of the Near East (Gilbrich, 2000). This map series were compiled by national experts under the auspices of the International Association of Hydrogeologists (IAH) and Commission on Hydrogeological Maps (COHYM). The maps have been joined to a single map that is available online at Bundesanstalt für Geowissenschaften und Rohstoffe (BRD). The map provides information on the dominating type of primary aquifers (porous, fissured incl. karst or insignificant aquifers) and on their productivity (highly productive, moderately productive, local and limited groundwater, essentially no groundwater).
3. **The "Brigde" project** (Background Criteria for Identification of Groundwater Thresholds, EU project within the sixth framework programme) provides a map of shallow aquifer typology with focus on groundwater bodies, which may be in direct contact with dependent ecosystems. The shallows aquifers classified as Carbonate rocks, Chalk, Volcanic Rocks, Crystalline Rocks, Schists, Sand and gravel, sandstone, Marls and clays and other aquifers are mapped for Bulgaria and 10 European countries. These maps are however under preparation and are therefore not yet available.

Temporal and spatial aggregated data stored in public databases are available from two different sources:

1. **Waterbase** is the generic name given to the European Environment Agency's (EEA's) databases on the status on quality and quantity of Europe's water resources.

Waterbase combines validated monitoring data from national databases with additional information on both the physical characteristics of the water bodies being monitored and on the pressures potentially affecting water quality (see Table 1 for details). Data are collected from various countries through the Eionet-water being a partnership network of the EEA and its member and participating countries (as of now comprising 31 contries).

2. **WISE** (Water information system for Europe) is an online reporting application within the Water Framework Directive. With time data reported from member states will public accessible within WISE. As of now member states have already reported data dealing with the location and environmental assessment of fresh and groundwater bodies and information on registered protected areas (article 3, 5 and 6). Compilation and standardisation of these reported data area however still in process and data are therefore not yet public available.

The digital dataset of European groundwater resources provides the most detailed information, but have some hindrance for a direct application to assess groundwater vulnerability. Like the other datasets it provides information only on aquifer properties and not on the protective covers, furthermore, some of the definitions are ambiguous, e.g. the term ‘complex aquifer’ as opposed to confined/unconfined, as has also been noted by Hollis et al. (2002).

3.2 Data at national and regional scales

In addition to the data available at the EU-level, much data has been collected at the national and regional scales in recent years and more will be collected in the near future to fulfil the obligations in the WFD. According to Annex II part 2 (on groundwaters) in the WFD, the member states are obliged to carry out an initial characterisation of all groundwater bodies. This characterisation may be based on existing hydrological, geological, pedological, land use, discharge, abstraction and other data, but must (among other aspects) identify “the general character of the overlying strata in the catchment area from which the groundwater body receives its recharge”. For groundwater bodies identified as being at risk of not achieving a good status, a further characterisation is required, which must include the following information:

- geological characteristics of the groundwater body including the extent and type of geological units,
- hydrogeological characteristics of the groundwater body including hydraulic conductivity, porosity and confinement,

- characteristics of the superficial deposits and soils in the catchment from which the groundwater body receives its recharge, including the thickness, porosity, hydraulic conductivity, and absorptive properties of the deposits and soils,
- stratification characteristics of the groundwater within the groundwater body,
- an inventory of associated surface systems, including terrestrial ecosystems and bodies of surface water, with which the groundwater body is dynamically linked,
- estimates of the directions and rates of exchange of water between the groundwater body and associated surface systems,
- sufficient data to calculate the long term annual average rate of overall recharge,
- characterisation of the chemical composition of the groundwater, including specification of the contributions from human activity. Member States may use typologies for groundwater characterisation when establishing natural background levels for these bodies of groundwater.

4 FOOTPRINT APPROACH TO GROUNDWATER VULNERABILITY

Given the complex nature of the subsurface system, the limited data available on aquifer properties on the EU-scale and the complete absence of data on the characteristics controlling the aquifer vulnerability, such as protective covers, it is not scientifically sound to pursue the FOOTPRINT scenario approach used to define the soil, crop and climatic variations within Europe. To establish a meaningful assessment of the aquifer vulnerability the assessment must be based on site specific information. The FOOTPRINT approach to groundwater vulnerability therefore differentiates from the scenario concept.

A basic principle in the FOOTPRINT project is that the suite of tools developed should be valuable to different end-users operating at different scales (field/farm scale, regional/catchment scale and national/EU-scale). Assessing groundwater vulnerability at the farm scale is impractical and would, at the best, be worthless. Two approaches are hence followed, where the first approach (basic approach) is targeted to end-users operating at the local scale, with educational focus, i.e. describing the properties that make an aquifer vulnerable, but no method is developed. The intended user of the second approach (extended approach) is water managers, the method developed here should assist the water managers to target their activities towards areas that are most vulnerable towards contamination by pesticides. This means that the method, as a minimum, should provide a spatial differentiation between areas of different vulnerability towards pesticide contamination. No distinction is made between the regional/catchment and national/EU-scale, as the method will, in principle, be scale independent. While the basic approach does not require data input from the user, the extended approach relies solely on data supplied by the user.

4.1 FOOTPRINT basic approach

No specific method will be developed for the basic approach. The focus is to raise the users awareness of problems associated to the use of pesticides. This is achieved by providing some general and simple information on aspects that makes an aquifer more or less vulnerable. Combined with a general description on groundwater vulnerability, the IHME and Bridge maps will comprise the basic information. From the IHME map, the user can identify the dominant characteristics of aquifers in the area, while the Bridge map displays the major composition of the shallow aquifers. The user may then, on a broad scale, identify whether they, for example, are situated above a karst aquifer where the shallow aquifer similarly are karst, which comprise the least protection of the aquifer.

Although the user is not requested to provide data in the basic approach the IHME map is not freely available at a digitised form and can therefore not be included in the FOOTPRINT tools. A link too the relevant homepage will thus be provided instead. Negotiation is ongoing with DG Environment whether it is possible to have the digitised groundwater maps included and distributed with the FOOTPRINT tools, which will provide the user with more detailed information for the nine countries that is covered by the maps. In addition to the data at the EU-level, the tool will include links to national institutes providing relevant data accessible to the public.

4.2 FOOTPRINT extended approach

From a practical viewpoint the method developed must be relatively easy to understand and use (assuming the required data is present) if water managers are to use the method. Due to the complexity of sophisticated models that require modelling expert to construct, run and interpret, these tools is not considered an option. Overlay/index methods are well suited for use in GIS environments, which is an advantage as the FOOTPRINT tools are developed in GIS, and many water managers are already familiar with GIS. Although more simplifications and assumptions are needed for these methods compared to the physical distributed models, they have been used widely as an acceptable balance between reliability and cost.

Index/overlay methods may be developed at very different degree of complexity. If the method is too complex it may not be used by many, on the other hand, if it is too simple the reliability will be questionable. Furthermore, recognising that the hydrological and hydrogeological settings are very complex and different aspects may be of different importance in different regions, it is not possible to develop one single method that includes all relevant aspects. A too simple approach combined with a rigid method not allowing modification by the user, will make the method unattractive where data coverage and knowledge is high. As a solution to this dilemma a method is developed that is easy to use once the required GIS maps have been constructed. A high degree of flexibility is accomplished by including an additional user defined method in the FOOTPRINT tool, allowing the user to introduce data not considered in the FOOTPRINT method. Albeit easy to use the FOOTPRINT method should not be considered a “push the button” method, as it is stressed that any method for vulnerability assessment require some basic hydrological and hydrogeological knowledge to understand the underlying philosophy of the method and its limitations, as well as an interpretation of the results.

In the development of the method it has been prioritised that the method should be generic in the sense that it should be applicable for both porous media and karst aquifers and that the data required for the method, to the widest extent, is based on data that the water manager can be expected to have collected for the WFD reporting, or can be relatively easily estimated.

The most recent comprehensive work on aquifer vulnerability in karst aquifers at the European level was undertaken in the COST action 620 project (COST 620). Experts from 15 countries joined efforts to develop a European Approach to aquifer vulnerability, while the COST 620 focused on karst aquifers the approach is not completely centred towards karst aquifers, and the conceptual framework as well as several of the components of the approach is applicable for none-karst aquifers as well. The FOOTPRINT method will, by large, follow the European approach and use identical definitions and nomenclature. A brief overview of the European approach is therefore provided below.

4.2.1 Outline of the approach (The European approach)

The European approach is based the origin-pathway-target concept, where origin is the term used to describe the location of a potential contaminant release. The target is the water, which has to be protected, and the pathway includes everything between the origin and the target. The vulnerability assessment is based on intrinsic vulnerability, specific vulnerability as well as hazard and risk mapping. The European Approach does not specify how the component factors should be measured or categorised or how vulnerability ratings should be established and is thus not a methodology, but provides a framework on how to assess aquifer vulnerability in complex karst environments. The overall framework of the European approach is illustrated in Figure 1.

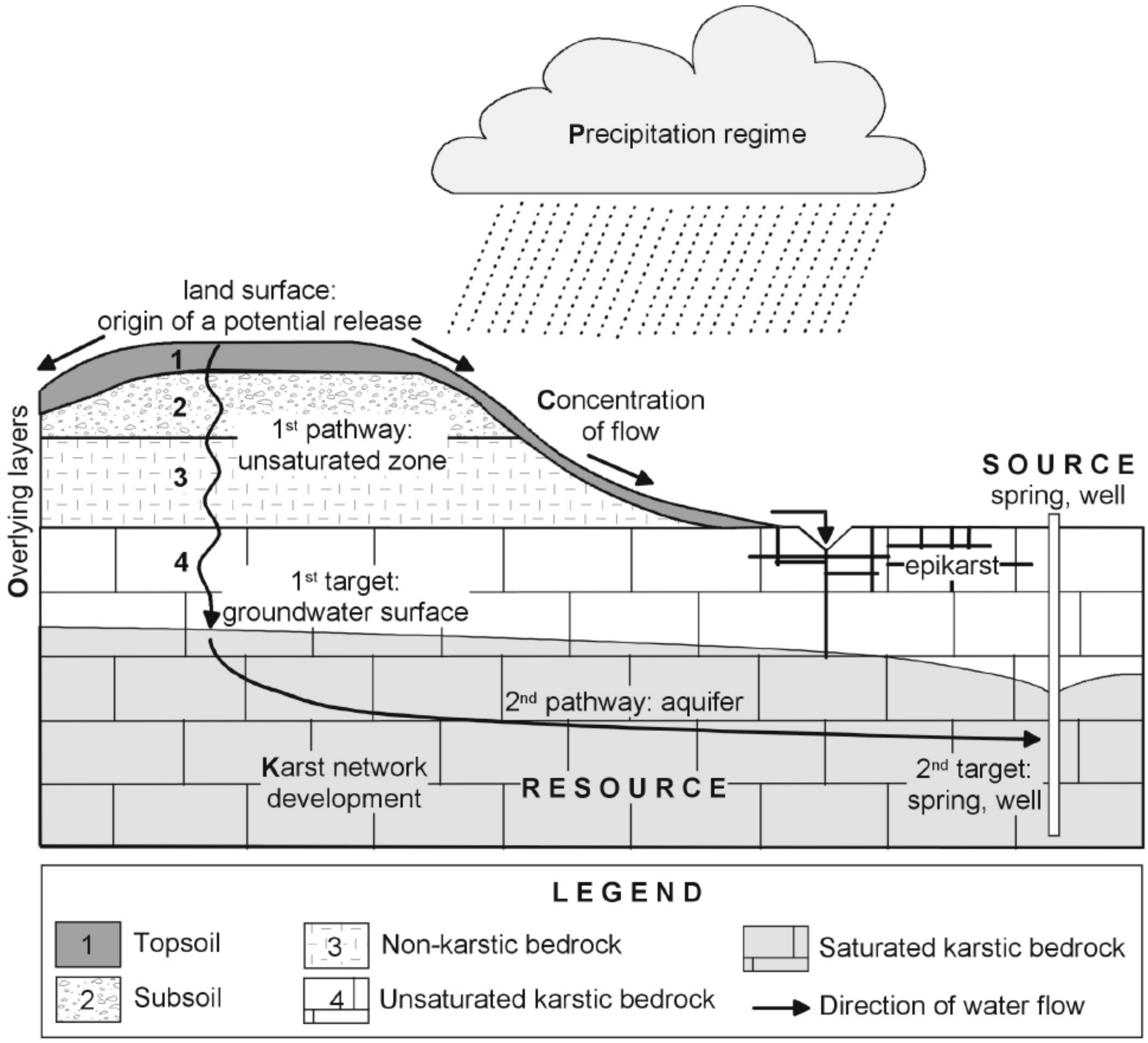


Figure 1. The European Approach to groundwater vulnerability mapping. The main factors for intrinsic vulnerability assessment are the Precipitation regime, the Overlying layers, the lateral Concentration of flow and the Karst network development (from COST 620).

Intrinsic vulnerability

Four factors are considered in the approach to assess intrinsic vulnerability: Protection by the overlaying layers (O), the precipitation regime (P), concentration of flows (C), and the karst network development (K).

Overlaying layers (O)

This factor characterises the protective capacity of the geological layers from the land surface to the uppermost aquifer, and is divided into four types:

1. **Topsoils**, which is the biological active zone of weathering of the earth crust and is the most reactive zone and thus the most important with respect to transformation of xenobiotics. Macropores, such as fissures, cracks due to periodically drying of the soils, worm holes etc. are abundant in the topsoil where preferential flow is an important flow process. The topsoil represents only granular (sand/gravel) aquifers. Note that topsoils are considered in a separate FOOTPRINT deliverable (FOOTPRINT deliverable 8).
2. **Subsoils**, is the granular non-lithified material below the topsoil. The preferential flow in this zone is generally much less than in the topsoil, similarly, the biological activity is much lower in this zone.
3. **Non karst rocks**, defined as lithified, non karstified rocks, such as sandstone, schist, shale and basalt. The major features of these type of rocks with respect to protection is the development of fissures, which may create preferential flow, depending on the in-filling materials.
4. **Unsaturated karst rocks**, which is the unsaturated part of karst aquifers. For aquifer protection the most important feature of this zone is the possible delopment of epikarst, whereby water flow from the surface may completely bypass the unsaturated zone, and its protective properties, and enter directly into the aquifer.

Each of the four types may consist of one or more geological layers, e.g. the subsoil may be composed of alternating sand and clay layers.

Precipitation regime (P)

This factor accounts for the effect of both the quantity of the annual precipitation and the dynamics of the precipitation, i.e. the frequency, duration, intensity and extreme events, which can have a major influence on the vulnerability. This factor may not be an issue at local/regional catchment scale, but may be important to include at e.g. national and EU-scales.

Concentration of flow (C)

The O factor implicitly assumes that all water infiltrates horizontal downwards to the aquifer. Where conditions are in favour (low permeability of the topsoil, significant slopes and intensive precipitation) a significant part of the water may be transported as runoff and infiltrate elsewhere. This is especially problematic if water is transported to an area where the protective ability of the overlaying layers is much smaller.

Karst network development (K)

Flow within an aquifer is controlled by the aquifer properties. In most granular aquifers flow is laminar, planar and relatively homogenous. In karst aquifer the flow may be much more complicated depending on the development of karst, where flow in conduits may play a significant role. The K-factor accounts for the degree of the karst development and should be considered when flow inside the aquifer is of concern, i.e. in source protection.

Of the four factors included in the European approach the overlay factor (O) and the precipitation factor (P) is generic, as it is not restricted to the evaluation of karst aquifer. The second two factors (C and K) are primarily relevant to karst aquifers.

Specific vulnerability

In the European approach, the intrinsic vulnerability is suggested to be combined with a specific vulnerability, when specific contaminants are of interest, such as pesticides. The specific vulnerability takes into account the physical/chemical properties of the contaminants and their possible interaction with the soil. Numerous reactions may be dominant depending on the properties of the contaminant. The most important reactions for pesticides are degradation and sorption. The basic idea for specific vulnerability mapping is the definition of a specific weighting factor, which corrects the intrinsic vulnerability maps in accordance to the processes expected to be relevant for the contaminant examined. The S factor is composed of: 1) a layer factor describing the geological layers effectiveness as protection based on the physical/chemical and hydraulic properties, and 2) a contaminant factor describing the contaminants potential to react in/with the soils. The construction of the layer and contaminant factor is a complicated 10 step approach, for a thorough description the reader is referred to COST 620. The overall framework of the European approach is illustrated in Figure 2.

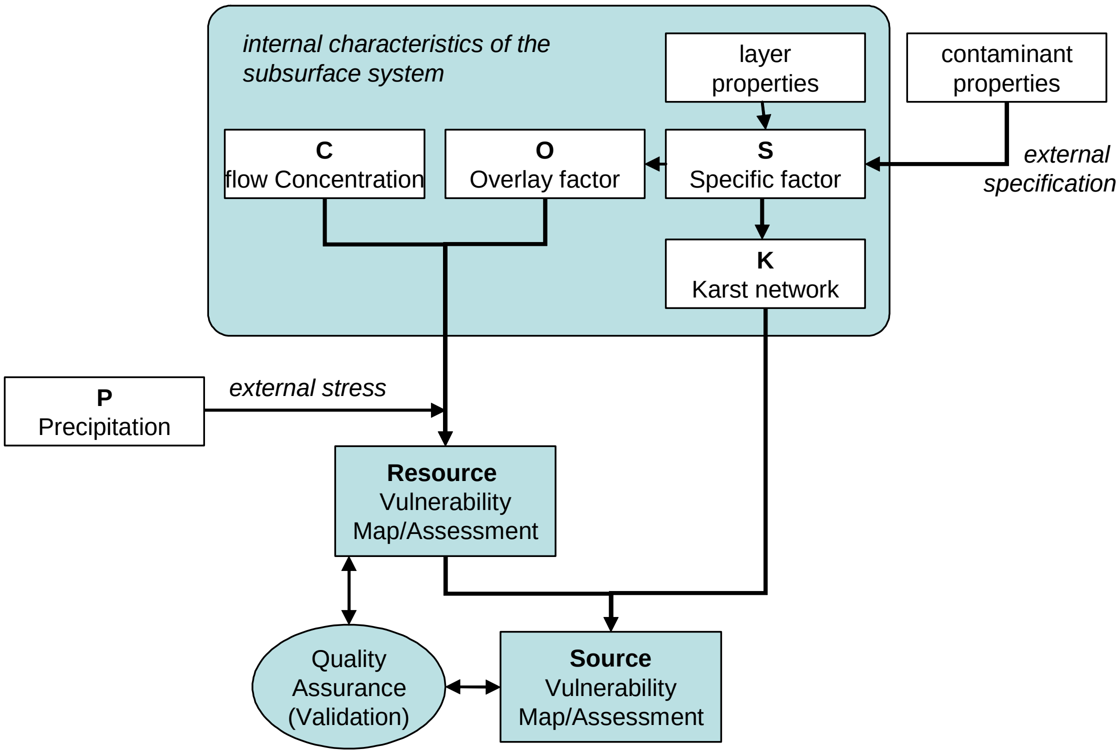


Figure 2. Illustration of the European approach to groundwater vulnerability, adapted from COST 620.

4.2.2 The FOOTPRINT method

Different aspects may important depending on the focus of a vulnerability map. The factors determining aquifer vulnerability is in the European approach defined as (COST 620):
If two points A and B in the catchment are compared in terms of vulnerability, it can be said that A is less vulnerable than B

- *if the transfer time from A to the target is longer than the transfer time from B;*
- *if the maximum concentration of a contamination coming from A is lower than the maximum concentration of the same contamination coming from B;*
- *if the duration of a contamination coming from A is shorter than the duration of the same contamination coming from B.*

In the FOOTPRINT approach to groundwater vulnerability the target is the resource defined as the uppermost aquifer, as this is the target in the WFD. Furthermore, only potential contamination by pesticides used for crop protection is considered.

Defining the entire aquifer as the target has a very important implication. If part of an aquifer is overlaid by a low permeable layer this part of the aquifer is often assumed well protected and the area on the land surface, above this part of the aquifer, is marked as less vulnerable.

However, assuming that all unsaturated flow within a watershed/catchment infiltrates a lower laying aquifer, the water above the low permeable layer may not infiltrate directly but result in a small local perched aquifer, which allows the water to flow horizontal to an area where infiltration is more favourable. The area on the land surface will thus still contribute to the contamination of the aquifer, although it may not happen directly below that specific area. A similar argument can be used for the protective importance of the aquifer type, i.e. unconfined or confined. Although a confined aquifer may be well protected from water directly above the confined conditions, the infiltrating water will either 1) form a perched aquifer creating in a downward gradient and infiltration 2) if the pressure in the confined aquifer is to high a new upper aquifer will develop, which needs protection, or 3) flow laterally and infiltrate the aquifer elsewhere.

Focusing on pesticide contamination from treated fields, the input is a diffusive source that is repeatedly released, as opposed to an accidental spill where the release is an instantaneous point source at very high concentrations. The definition of vulnerability proposed in the European approach may therefore not be adopted completely for FOOTPRINT. Discriminating intrinsic vulnerability based on the transfer time or travel time may be relevant in the case of accidental spill, because longer travel times provides more time for the water manager to take action. For a continuously source, such as pesticide treatment of crops every year, the travel time is in principle not important. If a pesticide leaches to the aquifer it poses a risk regardless whether the travel time is 30 years or only 3 years, as the aquifer must be protected in both cases. The only beneficial effect a longer travel time may have is if the pesticide is removed in the unsaturated zone by some reaction that is time dependent. If no removal occurs the travel time itself should not be used as vulnerability criterion.

The duration in which the contaminant is observed is similarly very important in the case of short-term inputs, especially at a source, as this may influence which action to take, e.g. temporarily shut down of an abstraction well. However, when the release is repeated the duration is not a suitable criterion in itself, as the input to the aquifer may be nearly continuously and the concentration levels must therefore be at an acceptable level at any time.

The criterion for pesticide application must therefore be that the pesticide concentration of the water entering the aquifer does not exceed an acceptable level. Specification of an acceptable absolute concentration level is not possible. This will depend not only on the transport pathway and reactions of a pesticide sprayed on a single field, but also the summed effect of all pesticides entering the same aquifer and their relative mutual timing. However, with respect to vulnerability assessment the focus should be on processes that lowers the maximum pesticide concentration.

The FOOTPRINT approach to groundwater vulnerability builds on the MACRO meta-model developed within FOOTPRINT, where pesticide transport in the root-zone is simulated by MACRO using the scenario approach for agro-environmental scenarios (deliverable 8) and climatic conditions (deliverable 9). The groundwater vulnerability assessment thus considers the transport of pesticides from the root zone to the groundwater aquifer and the contaminant origin is the root zone and not the land surface. This also implies that the pesticide leaching, as predicted by MACRO, can be utilised as the hazard mapping, displaying where pesticide contamination of the groundwater is likely to originate from.

Intrinsic vulnerability

Intrinsic vulnerability includes only the protective ability of the hydrologic and hydrogeological system, but does not include the properties of the contaminant. Combined with the focus of the FOOTPRINT approach on a reduction of the maximum concentration, the intrinsic vulnerability should describe the processes by which the maximum concentration of a conservative substance is reduced. Having the resource as the target, aquifer properties, i.e. the K factor in the European approach, is not considered. A schematic illustration of the factors included in the method is shown in Figure 3.

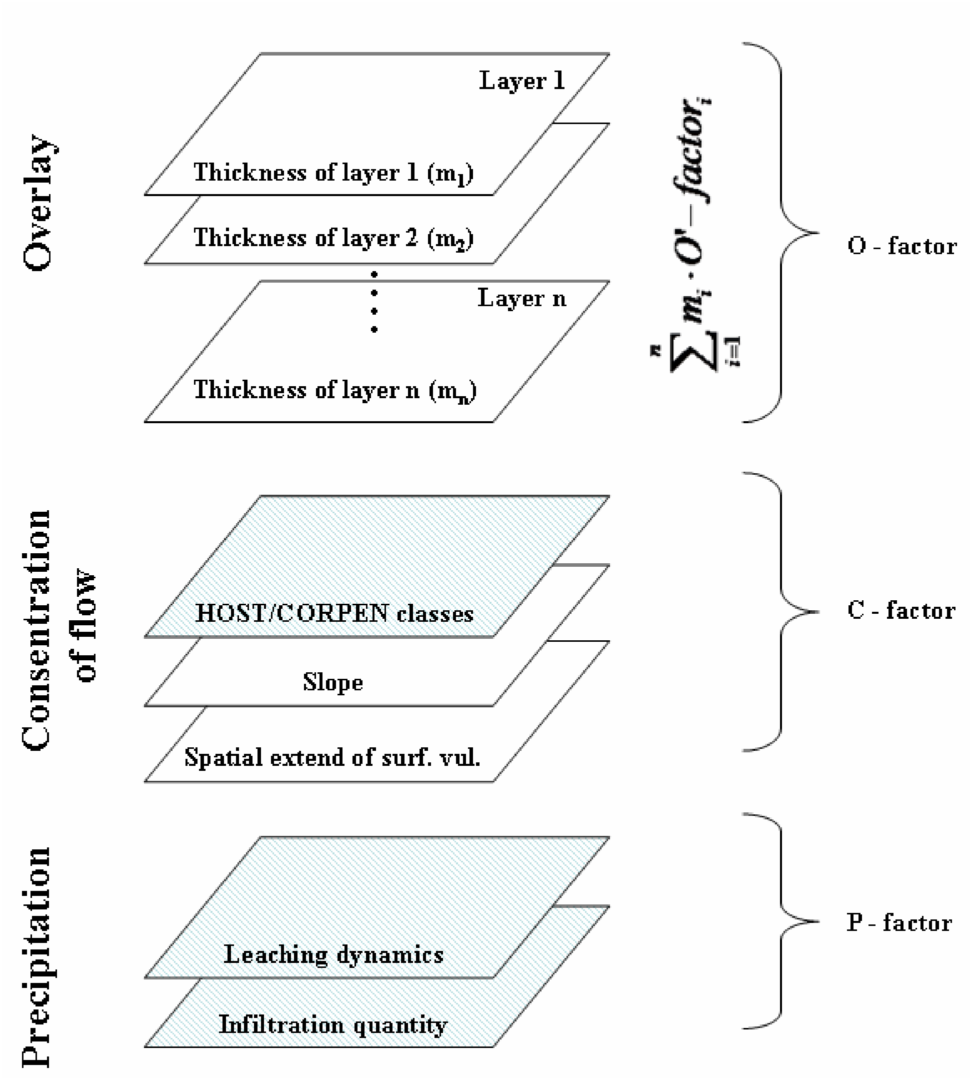


Figure 3. Illustration of the factors considered for intrinsic vulnerability. Shaded boxes displayes properties that is provided as default in the FOOTPRINT tool based on the FOOPTRINT scenario approach and the MACRO meta-model, values may, however, be modified by the user.

To achieve a final vulnerability map weighting schemes has to be applied to express the importance of the properties. The method proposed within FOOTPRINT is inspired by the PI method (Goldscheider et al., 2000) which has been applied to several areas within EU. The weighting schemes applied in the present method is therefore, where possible, adapted from the PI method. As the present method has not been tested at any site presently, the proposed weighting schemes, Table 2, 3 and Figure 4, should be considered very preliminary and subject to modification based on tests of the method.

Overlay factor (O)

The main intrinsic processes in an aquifer system are:

1. **Advective transport**, whereby pollutants are displaced by the mean effective groundwater velocity. If a solute moves by advection only, there is no lessening in concentration, i.e. the concentration is constant along the flow path.
2. **Hydrodynamic dispersion and diffusion** that cause a spread of the contaminant around the mean advective position. These processes result in an earlier breakthrough than by pure advection, but the maximum concentration is lower and the duration longer. For most conditions, the hydrodynamic dispersion is by far the most dominant process, molecular diffusion will only be important when the flow velocity is very low.
3. **Physical attenuation** occurs in media where the flow domain can be divided into mobile and immobile (or very slow flowing) zones, e.g. dual porosity effects. Physical attenuation is a kinetic process. For very slow transfer rates (the reaction is much slower than the flow velocity) the process may cause much earlier breakthrough and significant tailing, but also a much lower maximum concnetration. For higher reaction rates the process behaves identical to that of solute sorption to soil, with a slightly earlier breakthrough, a lower maximum concentration and longer duration.
4. **Dilution** is the mixing of different water fluxes, which may cause a lowering of the concentration (given that the mixing water is unpolluted).

Only advective transport has no positive effect on the concentration levels, while the last three processes may lower the concentration but with highly variable effect. Hydrodynamic dispersion occurs in all media and is mainly due to variations in the porewater velocity at different scales. Dispersion generally increases with the degree of heterogeneity and is commonly expected to be linear proportional to the porewater flow velocity. Physical attenuation occurs where large variations in flow velocities are observed, e.g. heavy clay lenses embedded in a sand/gravel layer. Hydrodynamic dispersion and physical attenuation have the same effect, i.e. a smearing of the breakthrough where the concentration has been lowered, and for both processes the effect will increase for increasing travel lengths, for very long transport paths, a dirac input function at the land surface may thus be converted to a continuous input function, with lower concentration, at the top of the aquifer. In the unsaturated zone the dominant flowpath is vertical and dilution is only expected to be important in the presence of small perched aquifers that may exist temporally, but is not likely to play a significant role for most conditions.

Quantification of the importance of the processes is not straightforward. Taking a stochastic approach, Gelhar and Axness (1983) developed a relation between the geostatistical parameter of an aquifer and the macrodispersivity. But the method has limitations and requires much data to characterise the aquifer adequately. Expressions have also been developed to describe the physical attenuation process (e.g. Haggerty and Gorelick, 1995) but a quantification of the process in terms of reducing the concentration levels is not straightforward in a complex system. Similarly, quantification of the effect of dilution can not be related to observable physical parameters.

A simple approach is therefore followed here. As default, the effectiveness of all subsoil layers (zone 2 in Figure 1) is assumed identical with respect to their ability to reduce the concentration level (identical O'-factors, Table 2). If the necessary information is available modification may be made by the user, by changing the O'-factor associated to the individual layers, this may for example be relevant in multilayered systems including both well sorted sand and highly heterogeneous moraine deposits. The non-karst rocks (zone 3 in Figure 1) may be divided into porous rocks and dense rocks. Most dispersion will occur in the porous rocks, whereas the matrix in dense rocks may be expected to contribute little to dispersion. However, double porosity is common in non-karst rocks, where the fine grained materials of the matrix and fissures/fractures comprise different porosities. This may enhance the smearing effect significantly, but for large fractures most of the water will not be in contact with the matrix and flow velocity may be too high for the rate-limited transfer to be important, resulting in a reduced effect of mass-transfer processes. The effectiveness of non-karst rocks is divided into porous and dense rocks, where the effectiveness is based on the degree to which large fractures are expected to occur. A similar approach is followed for the unsaturated karst, Table 2.

Subsoil

Type of subsoil	O'
All	0.10

Bedrocks

Lithology	L
Porous rocks	0.10
Dense rocks	0.05

Fracturing	F
no fissures/ non-jointed fractures	1.0
Fissures/ moderately karst	2.0
Large fractures/ well developed karst	0.5

Bedrocks: O'-factor = $L_i \cdot F_i$

Table 2. Preliminary weights for the effect of overlaying layers (O'-factor)

Precipitation factor (P)

While precipitation (amount, frequency, intensity etc.) may be expressed by simple statistics it is difficult to translate these numbers into a protection value or index. One of the major problems, when pesticide application is considered, is that a mean statistical value may have little relevance if it is not combined with the application timing. In the FOOTPRINT project detailed studies have been carried out to determine the important aspects for pesticide transport in the rootzone, i.e. the combined effect of soil types, climatic conditions, pesticide properties and application timing (Blenkinsop et al., 2006). These studies have been utilised to define the representative climatic scenarios and the FOOTPRINT scenario approach thus provides a very comprehensive evaluation of the effects of not only the precipitation dynamics, but also the combined effect of precipitation dynamics and application timing. Precipitation characteristics are therefore include through the MACRO meta-model and the recharge, infiltration below the rootzone, is divided in classes and weighted as specified in Table 3.

Recharge (mm/year)	P
0-100	1.75
>100-200	1.50
>200-300	1.25
>300-400	1.00
>400	0.75

Table 3. Preliminary weights for the effect of different infiltration rates.

Concentration of flow (C)

This factor is especially important for karst aquifers, where water may bypass the overlaying layers, and thereby their ability to lower the concentration level, but enter the aquifer directly in swallow holes or sinking streams. The factor may, however, also be relevant in other geological settings wherever water bypasses the protective covers from an area with high protection to an area with no or little protection. The MACRO meta-model does not account for the concentration of flows, instead an approach similar the one used in the PI method (Goldscheider et al., 2000) has been adopted. The first step is discrimination between the predominant flow processes, where the possible flow processes are identified and grouped into six different classes (class A to F):

- Infiltration is the dominant process (Type A).
- Fast subsurface storm-water flow is the dominant process (Type B)
- Very fast subsurface flow; macropores favour this process (Type C).
- Saturated overland flow is the dominant process (Type D).

- Hortonian flow occurs rarely (Type E).
- Hortonian flow occurs frequently (Type F).

A classification of the dominant flow processes can be assisted by the HOST/CORPEN method developed within the FOOTPRINT project (deliverable 8). The method is based on existing data and simple flow charts that guide the user to identify the dominant flow process. Classification by HOST/CORPEN is much similar to the one proposed in the PI method, but differs slightly in the way effects of slope and vegetation is included. For soil types favouring surface runoff, this process is expected to be important in HOST/CORPEN when the slope is >1% and erosive runoff occurs for slopes > 3%. In the PI method the effect of slope is divided into three intervals: < 3.5%, 3.5-27%, > 27%. The last interval is, though, not expected to be relevant in FOOTPRINT, as intensive farming is unlikely to be present at such slopes. Only two intervals for slope are thus considered here, namely < 3% and > 3%.

A default HOST/CORPEN classification will be provided in the FOOTPRINT tools from which default flow classes can be identified according to Table 4. Assigning the dominant flow processes to the HOST/CORPEN classes will, however, not be a fully automated step, as the user will have to answer some basic question to differentiate between the flow process A, E and F.

Sorption-degradation kinetics class	Topsoil texture	HOST class	Dominant flow process
d, k, m, h, t,	Any	1 to 8, 10, 11, 16, 17	A
		18, 20, 24, 25	B
		19,22, 27	C
		21, 23, 24, 25, 26, 29	D
Others	2, 4, 5	1 to 8, 10, 11, 16, 17	A
		18, 20, 24, 25	B
		19,22, 27	C
		21, 23, 24, 25, 26, 29	If capped & sealed, F
	1, 3	1 to 8, 10, 11, 16, 17	If topsoil capped & sealed, F. If topsoil compacted or slaked, E else A
		18, 20, 24, 25	B
		19,22, 27	C
		21, 23, 24, 25, 26, 29	D

Table 4. Definition of predominant flow processes based on the HOST/CORPEN classification system. Explanation of the different parameters are provided in the FOOTPRINT deliverable DL8.

Fast surface flow is problematic if the water flows from an area that provides a high degree of protection to an area where infiltration occurs rapidly, possibly bypassing all overlaying layers. The information of the predominant flow processes must thus be combined with a map displaying vulnerable areas, such as swallow holes and sinking streams. A combination of type F (frequent and much runoff) and a short distance to areas of rapid infiltration poses the greatest risk. The protective ability of areas producing horizontal flow on the surface are bypassed and the protective measure for this area should be reduced, depending on the distance to vulnerable zones.

Construction of the C-factor is a three step approach: 1) determining the predominant flow paths types (type A – F) from the HOST/CORPEN classification, 2) Assigning C'-factors to each flow type, 3) construct a surface vulnerability maps displaying vulnerable surface properties in the area, e.g. swallow holes and sinking streams and 4) combine 2 and 3 to correct the protective abilities for areas close to vulnerable surface properties to reach the final C-factor map. The HOST/CORPEN method provides default data at the EU-scale and step 1 and 2 is therefore automatically performed within the FOOTPRINT tool, but again, the user is allowed to modify these default values by providing other data. The approach and weighting schemes are given in Figure 4.

Intrinsic vulnerability classes

The final vulnerability score is computed as

$$\text{Intrinsic vulnerability score} = \left(\sum_{i=1}^{n} \mathrm{m_i} \cdot O' - factor_i \right) \cdot P \cdot C$$

where m_i is the thickness of layer *i*, *O'-factor* is specific overlay factor (Table 2) and *P* and *C* are the precipitation factor (Table 3) and flow concentration factor (Figure 4), respectively. The final intrinsic vulnerability score should be displayed by grouping the scores into appropriate classes, where the lowest class reflects very low protection and the highest class is where the risk of contamination by pesticides is very unlikely to be a problem. As the overlay factor is proportional with the layer thickness the intrinsic vulnerability is theoretically unbounded upwards, however, at some level an increase in layer thickness will not improve the intrinsic vulnerability, as the maximum concentration is already well below the criterion of 1 µg/l. The required reduction of the pesticide concentration will be analysed based on the MACRO meta-model and the vulnerability classes have therefore not been defined yet.

Step 1: Identification of HOST/CORPEN classes

Table 4

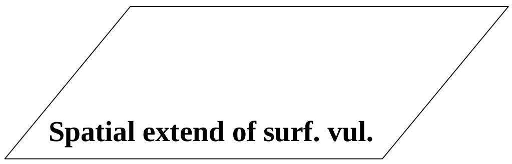
Types of predominant flow	HOST/CORPEN classes
A	
B	
C	
D	
E	
F	

Step 2: Dominant flow process C'-factor

Flow process	Slope < 3.5%	Slope > 3.5%
A	1.0	1.0
B	1.0	0.6
C	1.0	0.4
D	0.6	0.4
E	0.8	0.4
F	0.6	0.2

Step 1 and 2 can be generated semi-automatically based on default data, or user can modify the data

Step 3: GIS map with vulnerable surface areas



Supplied by user

Step 4: Correction for proximity to vulnerable areas; final C-factor

Vulnerability	Examples of surface vulnerability zones	C'-factor 0.2	0.4	0.6	0.8	1.0
high	swallow hole, sinking stream and 10 m buffer	0.0	0.0	0.0	0.0	0.0
	100 m buffer from sinking streams	0.2	0.4	0.6	0.8	1.0
	catchment of sinking streams	0.4	0.6	0.8	1.0	1.0
	area dischargin inside karst area	0.6	0.8	1.0	1.0	1.0
low	area discharging out of the karst area	1.0	1.0	1.0	1.0	1.0

Figure 4. Illustration of the construction of the C-factor and associated weights. Weights have been adopted from the PI method (COST 620).

Specific vulnerability

The term pesticide covers a wide range of substances, which physical/chemical properties vary tremendously. A general specific vulnerability map can therefore not be constructed, but has to be based on the actual pesticide. The only generalisation that may be made is that the protection offered by the subsoil layers are considered to be low for most pesticides, due to the very low microbial activity, sorption and degradation generally found in these layers (Aamund et al 2004). Protective capacity of the subsoil may, however, be significant for a few pesticides such as glyphosate (being strongly sorbed to the soil), and the phenoxyacids 2,4-D, mechlorprop and MCPA (being degradable in subsoil).

With the limited knowledge on pesticide reactions in the unsaturated zone below the topsoil it may be difficult to employ the sophisticated approach proposed in the European approach. A much simple approach is consequently suggested in the FOOTPRINT method.

Although the degradation rates are generally slow in the subsurface it may be important if the retention time is sufficiently long. The approach invoked for the present method is therefore to consider the retention time, where the protective ability increases with increasing retention time. For subsoil layers the retention time is assumed proportional to the layer thickness and inversely proportional to the permeability of the layer, as flow is expected to be dominantly matrix flow (absence of macropores). For karstic and non-karstic rocks an approach identical to that used for dispersion properties are employed, where porous rocks have a shorter retention time per length unit compared to the dense rocks. In case of fissures/fractures/karst development the retention time is reduced. Ideally, the retention time should be weighted by the degradation rate reflecting the actual degradation of the pesticide, but for slow degradation rates (DT50 > 2 years) no reliable methods exist to determine the actual rate.

The simple use of a retention map may possibly overestimate the protective ability because reactive processes are implicitly assumed to occur at same rates in all environments. While it may not be possible to differentiate between different rates of removal (degradation and irreversible sorption) it may be possible to differentiate between layers in which degradation is assumed to occur and layers in which no degradation is expected. This may, as an example, be based on observations of the redox potential of an aquifer and the knowledge that a pesticide is only degraded under aerobic conditions. To correct for this, the retention times for the individually layers are multiplied by a factor expressing the degree to which pesticides are removed, this correction could be binary (removal on, removal off) or, if knowledge allows so, be any decimal point.

The specific vulnerability assessment thus only focuses on the overlay factor, where the weights should be replaced by a scheme reflecting the retention time. Similarly to the overlay factor a S´-factor is defined for each overlaying layer, which is multiplied by the layer thickness to express the travel time in the specific layers based on its permeability. For this purpose the weighting scheme proposed in the PI method (Godlscheider et al., 2000) to compute the effect of the protective cover in the intrinsic vulnerability has been employed, Table 4. The S’-factor’s for the specific vulnerability map should be corrected if pesticides, e.g., is known not to degrade in specific subsurface layers/environments. The specific vulnerability score is thus computed as

$$\text{Specific vulnerability score} = \sum_{i=1}^{n} m_i \cdot S' - factor_i \cdot Reac_i$$

where $Reac_i$ is the removal correction factor for layer i.

Subsoil

Type of subsoils (grain size distribution)	S'
clay	500
loamy clay, sligthly silty clay	400
slightly sandy clay	350
silty clay, clayey silty loam	320
clayey loam	300
very silty clay, sandy clay	270
very loamy silt	250
sligthly clayey loam, clayey silty loam	240
very clayey silt, silty loam	220
very sandy clay, sandy silty loam, slightly sandy loam, loamy silt, clayey silt	200
sandy loam, slightly loamy silt	180
slightly clayey silt, sandy loamy silt, silt, very sandy loam	160

Type of subsoils (grain size distribution)	S'
very clayey sand, clayey sand loamy silty sand	140
sandy silt, very loamy sand	120
loamy sand, very silty sand	90
slightly clayey sand, silty sand, sandy clayey gravel	75
slightly loamy sand, sandy silty gravel	60
slightly silty sand, slightly silty sand with gravel	50
sand	25
sand with gravel, sandy gravel	10
gravel, gravel with breccia	5
non-lithified volcanic material (pyroklastica)	200
peat	400
sapropel	300

Bedrocks

Lithology	L
claystone, slate, marl, silstone	20
sandstone, quarzite, volcanic rock plutonite, metamorphite	15
porous sandstone, porous volcanic rock (e.g. tuff)	10
conglomerate, breccia, limestone dolomite rock, gypsum rock	5

Bedrocks: S'-factor = $L_i \cdot F_i$

Fracturing	F
non-jointed	25.0
sligthly jointed	4.0
moderately jointed, slightly karstified or karst feature completely sealed	1.0
moderately karstic or karst features mostly sealed	0.5
strongly fractured or karstified and not sealed	0.3
Epikarst strongly developed, not sealed	0.0
not known	1.0

Table 5. Weighting scheme for specific vulnerability,

A final vulnerability is achieved by the combinations of the intrinsic and the specific vulnerability maps, as the definition of the intrinsic vulnerability classes has not yet been defined, the definition of the final vulnerability classes is not possible.

5 CONCLUSIONS AND PERSPECTIVES

Two approaches have been proposed for implementation in the FOOTPRINT tools: 1) a basic approach that primarily has an educational and awareness raising purpose, which does not require input data from the user and 2) an extended approach that aims at discriminating vulnerable and less vulnerable areas within a focus area, which relies solely on user input data. The extended approach, by large, follows the framework proposed by European approach (COST 620) and a specific overlay method is developed which is strongly inspired by the existing PI method (Goldscheider et al., 2000). The main difference in the present method and most other methods is that travel time in the subsurface is not considered in the formulation of the intrinsic vulnerability because the aquifer must be protected regardless whether the travel time is 3 or 30 years. The intrinsic vulnerability includes the overlaying layers by considering their ability to smear the concentration profile and thereby reduce the maximum concentration. When specific vulnerability is addressed the potential removal of pesticides by irreversible sorption and degradation should be considered in addition to the intrinsic vulnerability. Most pesticides are, however, degraded very slowly in the subsurface and reliable estimates of the degradation rate are very difficult to obtain by present methodologies. A simple approach has therefore been chosen, where the specific vulnerability is defined by the travel time (or retention time) as even small degradation rates may be important if the travel time in the system is sufficiently long. A simple correction scheme is proposed to correct the pesticide removal in different subsoil layers. It is suggested that this correction scheme is used in binary way to express whether removal is expected to occur or not.

In the development of the method presented herein, it has been prioritised that the method should, to its widest extent, be generic, i.e. applicable for all conditions. However, the hydrological and hydrogeological settings are very complex and vary greatly within Europe, and the importance of different aspects similarly varies significantly. It is therefore not possible to develop one single method that includes all relevant aspects at the EU-scale. in addition to the outlined method a user defined method will be supported by the FOOTPRINT tool that allows the user to modify the proposed method.

A challenging task in the overlay/index method is the assignment of meaningful weights which should reflect their protective importance. In the present study the weights are, where possible, adopted from the PI method. Preliminary weights are assigned for the overlaying layers ability to smear the concentration front due to hydrodynamic dispersion, physical retardation (mass transfer between mobile immobile zones) and possibly dilution. It is essential for any method that its reliability is verified best possible. The proposed method will therefore be tested in a later stage in the FOOTPRINT project (WP 6), where it will be applied to selected field sites. In this test the weights may be subject to modification.

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