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1.3 The VULK analytical transport model and mapping method

1.3.1 Introduction

VULK is an analytical computer programme, which was developed at the Hydrogeology Centre of Neuchâtel (CHYN) under the scope of COST 620 as a tool for intrinsic vulnerability assessment (Jeannin et al. 2001). The acronym VULK stands for **vul**nerability and **k**arst. The conceptual framework underlying VULK comprises a simple method for transfer time mapping, both for resource and source vulnerability. The computer programme allows for calculating contaminant transport at selected points. Further development aims at coupling VULK with a GIS, so that it will be possible to create attenuation maps showing the maximum concentration of a potential contamination event. It is also foreseen to implementing concentration of flow and specific transport processes into the model.

Jeannin et al. (2001) described the mathematical background of VULK in detail. This section aims at presenting the general idea of this computer programme, as well as its actual and potential future application for intrinsic and specific source and resource vulnerability assessment and mapping, or validation of vulnerability maps that were made using other methods (e.g. PI, COP, LEA, Time-Input; see the respective chapters in this report).

1.3.2 Basic idea of VULK

COST 620 states that vulnerability assessment has to answer three basic questions (see Brouyère, this report). If a pollution occurs somewhere in a catchment,

- How long does it take to reach the target?

- At which concentration will the target be polluted?
- For how long will the target be polluted?

The first two questions are generally more important that the last one. The target may be the groundwater surface (resource vulnerability) or a spring/well (source vulnerability). For intrinsic vulnerability, a conservative contaminant is taken as the reference. However, the same three questions also apply for reactive contaminants and so the concept can also be extended to specific vulnerability assessment.

The three basic questions directly lead to the definition of the criteria to be considered:

- *Transfer time* between the release of contaminants and the arrival at the target
- *Concentration* level at the target
- *Duration* of contamination at the target

The basic idea of VULK is consequently to model the breakthrough curve at a defined target resulting from an instantaneous release of conservative contaminants at a given point (origin) within the system, which is usually located on the land-surface. The calculated breakthrough curve allows determining the transfer time, duration and concentration level of a potential contamination event at the given point. It is thus possible to characterise the groundwater vulnerability at the given point or to validate an existing vulnerability map for this point. In many cases, a vulnerability assessment will only comprise transfer time and concentration, while the duration is a less important criterion.

1.3.3 Model concept

The VULK tool has been developed to simulate mass transport resulting from an instantaneous input of conservative contaminant at a given point (DIRAC-type input function). However, it is also possible to use other input functions, such as continuous contaminant release. The model is based on a 1-D single- or dual-porosity analytical advective-dispersive transport solution for non-reactive steady-flow transient transport. The simulated signal thus corresponds to the travel time distribution of a 1-D section.

All compartments on the pathway between the point of contaminant release (origin) and the discharge point (target) are considered as separate sub-systems (Fig. 49). Up to five sub-systems can be taken into account: The soil, subsoil, non karst rock and unsaturated karst rock are relevant for resource vulnerability assessment, and the saturated zone of the karst aquifer has to be considered additionally for source vulnerability assessment.

Thus, VULK uses the factors O (overlying layers) and K (karst network development) of the European Approach. The concentration of flow (C factor) in the catchment of sinking streams is not considered until present.

The sub-systems are coupled by means of successive convolutions, i.e. the output of one system is the input of the next one. Dilution processes can also be taken into account. Depending on the case to be solved, the user can select the number of sub-systems and chose between a single- and a dual-porosity approach.

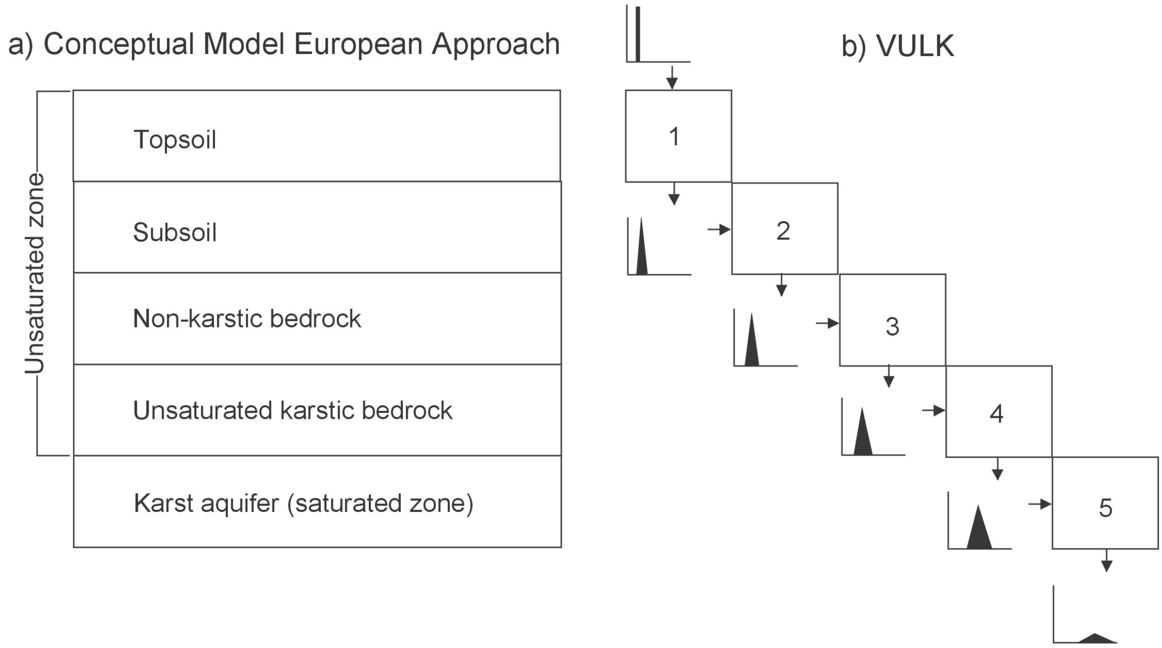

Fig. 49: Conceptual model of the European Approach and principle of the VULK model (Jeannin et al. 2001).

1.3.4 Input data

As a first step, the user has to decide, whether a single or dual porosity approach is to be used, and how many sub-systems are to be modelled (between 1 and 5).

For the single-porosity model, the parameters in each sub-system are: the *flow velocity*, the *flow distance* through the sub-system, the *coefficient of longitudinal dispersivity* of the media, and a *dilution factor*. For the dual-porosity model, the *porosities* of both media and the *exchange coefficient* have to be introduced additionally.

The *flow velocity* can either be measured directly by means of field experiments (tracer tests) or calculated on the basis of the hydraulic properties of the respective sub-system. In fact the hydraulic conductivity (saturated) of the medium is estimated and a hydraulic gradient of 1 is assumed in order to transform the hydraulic conductivity into a Darcy flux. This flux has to be divided by the medium porosity in order to provide an estimate of the flow velocity.

In the overlying layers (sub-systems 1–4), the layer thickness is taken as the *flow distance*; in the saturated part of the aquifer (sub-system 5), the horizontal distance to the spring or well is used (however, the *true flow path length* of a water molecule through the underground is impossible to determine). The layer thickness can be obtained using field methods (geophysical sounding, boreholes), geological maps and sections; the horizontal distance to the spring can simply be taken from a topographic map.

The *dilution* is simply the ratio between the output and the input discharge. For instance it is 0.1 if the input discharge is 10 % of the output one. The multiplications of the dilution factors of the respective sub-systems have to be equal to the ratio between the discharge rate at the pollution input point and the one at the outlet of the system (often a karstic spring).

The *coefficient of dispersivity* is difficult to assess. It is strongly depending on the flow distance and its influence on the breakthrough is not as large as flow velocity or dilution. Then, as a first approximation it is suggested to put it as 5 % of the flow distance.

For the dual-porosity model the *porosity* of the main flow system has to be distinguished from the one of the surrounding matrix where flow is supposed to be only of local significance, i.e.

completely controlled by flow conditions in the adjacent conduit. Porosity of the main system is similar to the one of the single porosity case. Porosity of the matrix has to be evaluated based on our knowledge of the medium (e.g. rock type). The mass transfer between the two porosities is simulated according to the first order exchange kinetic law, with an *exchange coefficient* acting as calibration parameter.

1.3.5 Output data

The output data of VULK are theoretical travel time distributions (unit pulse input) and breakthrough curves (relative concentration input), which allow determining the *transfer time*, the *concentration* and the *duration* of a contamination event. Jeannin et al. (2001) defined mathematical criteria how these values can be determined from the breakthrough curves in a comparable way. The *transfer time* is defined as the period between the times at the centre of gravity of the input function and the centre of gravity of the observed breakthrough curve. The observed maximum *concentration* of the breakthrough curve is normalised by the input concentration. The *duration* can be defined as the breakthrough curve standard deviation.

At present, it is only possible to calculate these criteria (transfer time, concentration and eventually duration) for selected points. Future development aims at coupling the transport model VULK with a GIS, which will allow for the creation of vulnerability maps based on the combination of these three criteria. However, a simple method of transfer time mapping has already been established and is described in the following section.

1.3.6 VULK as a mapping method

The VULK computer programme itself allows calculating the transport of a contaminant that is released at a given point on the land-surface, and, consequently, characterising the groundwater vulnerability at this point. However, the conceptual model underling VULK (Fig. 49) can also directly be used as a method of transfer time mapping, both for the resource and the source.

The methodology of transfer time mapping is shown in Fig. 50. For a resource map, only the four sub-systems of the unsaturated zone are considered (topsoil, subsoil, non karst rock, unsaturated karst). For a source map, the lateral transport in the saturated zone is additionally taken into account. For each sub-system, two layers of information are required: the mean flow velocity [m/s] and the thickness or distance respectively [m]. Multiplying these data for each layer gives the transfer time through this layer, and adding up all the transfer times gives the transfer time of the whole system.

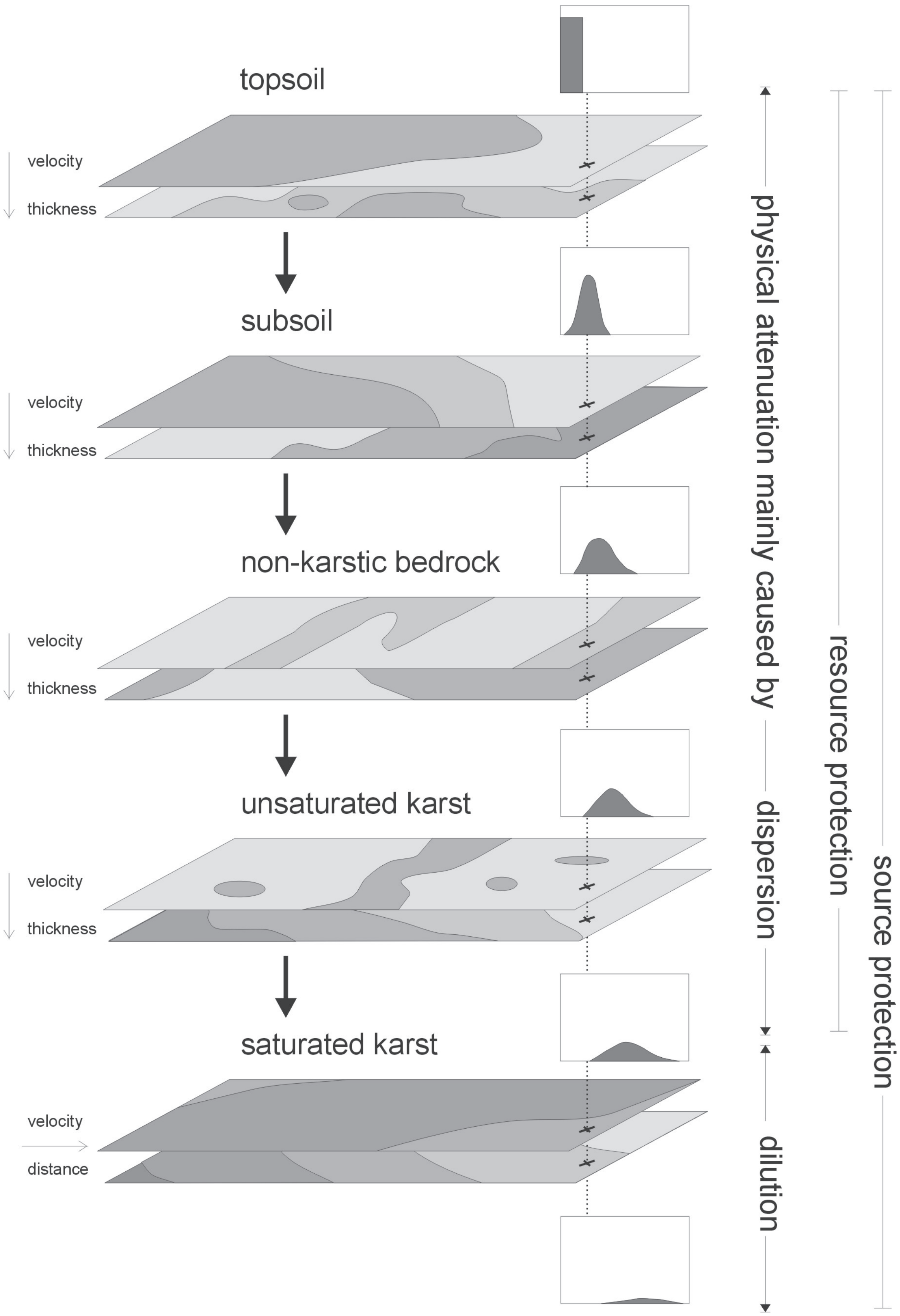

Fig. 50: Transit time mapping and calculation of theoretical contaminant breakthrough curves for selected points (graphic: Michael Sinreich, unpublished).

The mean flow velocity strongly depends on the respective hydrologic conditions, of course. It is suggested to use flow velocities that are likely to occur during average storm rainfall conditions. It has to be stated that the proposed mapping method is based on simplifications and uses data that are difficult to assess in a reliable way for large areas. However, the advantage of this approach is that the map can be validated by means of tracer tests.

In addition to the transfer time maps, it is possible to calculate the contaminant attenuation for selected points in the system using the VULK computer programme (Fig. 50). Plotting the transfer time and the attenuation (output divided by input concentration) in a diagram, allows characterising the groundwater vulnerability at these selected points.

1.3.7 Other possible applications and future developments

The VULK computer programme can also be used for the validation of an existing vulnerability map, which was prepared using another method of vulnerability assessment, e.g. PI, COP, LEA or the Time-Input Method described in this report. The results of the VULK simulation are to be compared with the evaluation of groundwater vulnerability on map. A good correlation between the simulation and the map indicates a high reliability of the vulnerability map – and of the mapping method applied. However, VULK uses strongly simplified assumptions and can thus not be used as the only validation method. The breakthrough curves calculated with VULK should be compared with breakthrough curves obtained from 'real' tracer tests with conservative tracers.

At present, VULK is further developed at the Hydrogeology Centre of Neuchâtel (CHYN) within the framework of two PhD theses, in order to allow for wider applications.

The PhD thesis of Alain Pochon aims at extending and modifying VULK so that it can be used for intrinsic vulnerability mapping in an effective way in all types of hydrogeological environments. Therefore, the VULK programme and mapping method is applied in various test sites and validated by means of tracer tests. VULK is to be coupled with a GIS, so that not only transfer time, but also contaminant attenuation can be determined on area. Another development aims at implementing the concentration of flow (the C factor of the European Approach) into the VULK model. This is indispensable for the application in karst systems that are not only recharged by diffuse vertical infiltration through the soil, but also by sinking streams and/or by concentrated infiltration of lateral flow components (surface or subsurface flow) at the base of slopes.

The PhD thesis of Michael Sinreich aims at taking into account reactive contaminant transport processes, particularly retardation and degradation, so that VULK can also be used for specific vulnerability assessment and mapping. It is also foreseen to use VULK within the framework of groundwater risk assessment. Risk assessment means to evaluate the potential consequences of a contamination event. Any type of contamination scenario can be used as input function for VULK, for example instantaneous or continuous. As the sub-systems are treated separately, it is possible to simulate a contaminant release at any point within the system, for example at the land surface, below the soil zone or within the groundwater body. And it is possible to simulate the consequences of the given contamination event at any point within the system, for example at the groundwater surface or at a spring or well. So VULK appears to be a very flexible tool for groundwater risk assessment.

1.3.8 Reference

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