Mapping the vulnerability of ground water reservoirs with regard to surface pollution

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Data for geology, hydrogeology, and ground water chemistry have been used to evolve a preliminary ground water vulnerability map. By this type of map the possibility of ground water pollution can be predicted. The map may be of use in the land use planning and water planning.

As a test area in the ground water vulnerability project the 1120 km² large peninsula Djursland, in Jutland, Denmark, has been selected because of its geological, hydrogeological and chemical conditions which are representative for large areas in Denmark as well as in other countries.

By use of the geological basic data maps of Djursland a determination of the aquifer distribution, the piezometric head of each aquifer, and the inter-aquifer-flow relationships has been made.

EDP has been used to calculate and present the basic parameters necessary for the estimate of the vulnerability. The basic parameters include the following:

- total thickness of the geological deposits above the aquifers
- permeability of the deposits above the aquifers
- piezometric head
- hydraulic percolation time through the geological deposits above the aquifers
- reduction capacity and sorption capacity of layers above the aquifers.

The above-mentioned factors are combined and depicted in a ground water vulnerability map, which is preliminary verified by comparison with ground water chemistry maps, indicating the actual ground water quality.
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The major part of the Danish population relies on ground water for drinking water supplies. Less than 5% of the total water consumption is supplied from surface waters.

Compared to surface water supplies, the ground water supply is naturally protected against microbiological and chemical contamination. This has long been considered a persistent phenomenon. However, during the last decades there have been several major incidents of ground water contamination from sources such as chemical disposals, landfills, agricultural land use, and use of fertilizers.

As a result of a systematic hydrogeological mapping in accordance with the Danish Water Supply Act (1973; Amended by the Act 1978), the knowledge of the possibility of contaminating ground water has increased. At present, maps showing geology, hydrogeology, and ground water chemistry (the so-called hydrogeological map series, Miljøstyrelsen 1979) have been produced for most parts of Denmark. The maps – and the corresponding data files – are used a.o. in the water supply planning and the land use planning.

The situation at present is, that shallow aquifers, often, and deeper situated ground water, occasionally, contain nitrate, which may indicate pollution. Regional as well as local differences in e.g. geology, and pollution intensity are decisive for the particular situation.

In order to predict the possibility of ground water contamination it is necessary to use the basic information of the geological and hydrogeological conditions in different areas.

The objective of the research is to develop a method (tool) by which it is possible to predict the risk of ground water pollution caused by substances induced to the surface.

The ground water vulnerability concept

The ground water vulnerability is defined as the risk of chemical substances – used or disposed on or near the ground surface – to influence ground water quality.

Ground water vulnerability depends on a series of parameters, dynamic as well as static.

Some of the important parameters are:

- the thickness, the lithology, the permeability, and the water content of geological deposits above the aquifer
- the type of polluting compounds
- the ability of the deposits above the aquifer to neutralize, retain, or delay the actual polluting compounds
- the hydraulic conditions
- the pollution intensity in the aquifer
- the exploitation of the aquifers

The present project concerns only the *static* parameters disregarding the *dynamic* and historical events in the studied area. The static parameters include informations about geology, hydrogeology, and hydrochemistry.

The chemical composition of the ground water may be used as an indicator of the vulnerability, which can be estimated based on geological and hydrogeological data.

Chemical elements and compounds which may indicate a hydraulic contact with the surface are a.o.: nitrate (NO_3), sulphate (SO_4),and in many cases excessive carbon dioxide. Besides, water-rock interactions in the unsaturated zone and in the aquifers can be judged by the hydrochemical data.

In the vulnerability project the hydrogeological map series and the corresponding data files are used as much as possible to secure that the vulnerability maps at a later stage can be produced with a minimum of resources.

In the research programme preliminary vulnerability maps have been produced. In addition, the work has given valuable information of the basic lack of knowledge in the understanding of the transport and conversion of contaminants from the introduction at the ground surface to the appearance in the aquifer. This evaluation of the state of art in ground water protection is of great importance for reinforced research in this particular interdisciplinary science.

Previous investigations

Two main types of ground water vulnerability concepts have earlier been treated in the literature. The first type of concept bases the vulnerability statements on geological (lithological) information only, while the second type of concept bases the vulnerability statements on a combination of geological, hydrogeological and hydrochemical information. Examples of geological vulnerability are expressed in the maps produced by BRGM (e.g. BRGM, 1975) and maps described by Becker-Platen et al. (1979). LeGrand (1964) described the different factors influencing the vulnerability and called attention to the importance of geology, hydrogeology, and hydrochemistry in the estimate of vulnerability. LeGrand's approach is close to the proposal in the present project concerning vulnerability mapping. However, LeGrand did not use his idea for map preparation.

Test area

The peninsula, Djursland, fig. 1, has been selected as test area for the inves-

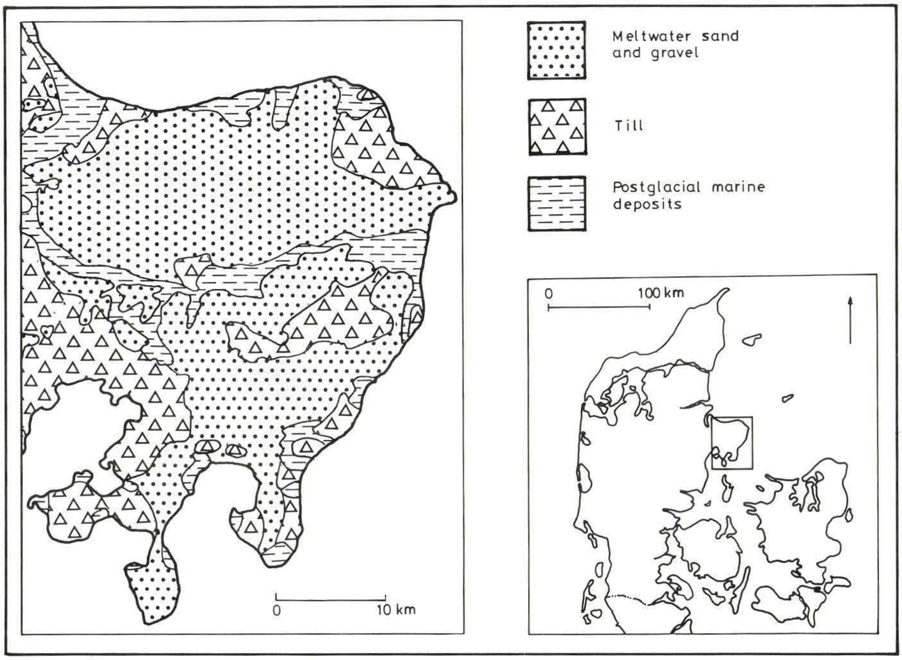

Fig. 1. Location and Quaternary geology of the test area, Djursland (simplified after Bornebusch and Milthers (1935) and Milthers (1948)).

tigations, partly due to the significant variety in the geological conditions and the related hydrogeological properties in the area, partly because indications of nitrate pollution in the area have been demonstrated through a recent ground water quality mapping (Villumsen and Kristiansen, 1979).

Finally it should be mentioned that Århus amtskommune has expressed an interest in getting an estimate of the vulnerability of the aquifers in areas, for which waste water infiltration is under consideration.

Geology of the test area

The geological conditions in the test area have been described by a.o.: Harder (1908), Grönwall and Harder (1907), Jessen (1920), Milthers (1919) and (1932), Ødum (1926), Gry (1935) and Rasmussen (1977).

The *pre-Quaternary* rocks in Djursland consist in the northern part of the area of Danian limestone. In the southern part of Djursland the Danian limestone is overlaid by Paleocene and Eocene clay and marl deposits.

Quaternary deposits are present almost everywhere in the test area, (Fig. 1). These deposits are mostly till, meltwater sand and gravel. Pre-Quaternary deposits are, moreover, present as floes in the till, especially in the southern part of Djursland. The thickness of the Quaternary deposits exceeds 100 m in several areas. In the north-eastern part of the test area the Quaternary deposits are very thin and in places only consisting of a thin layer of soil.

Postglacial marine deposits are present in a central narrow zone stretching from east to west, and in several but often small areas near to the coast. Fresh water deposits (peat and gyttja) are scattered all over Djursland.

In Djursland four categories of aquifers are identified. The main aquifer is the Danian limestone. Additionally a lower glacial and an upper glacial (Quaternary) aquifer consisting of sandy meltwater deposits are present. Of minor importance is the Postglacial sand aquifer of marine origin, Fig. 1 and 2.

Data available from the area

The basic data for this research consists mainly of ground water well records, which contain information of the lithology and the technical installation of the wells. Besides, chemical analyses of ground water in the area have been used.

The data was available in computer files at the Survey and at Århus amtskommune. Århus amtskommune has kindly placed its geological database (Thomsen, 1980) to the disposal of the Survey for the vulnerability project.

The test area contained a total of 1360 well records, at the start of the project. After an inspection in order to confirm data reliability and after an updating this number was reduced to about 1000. These well records were filed in two versions, one in an IBM 3033 at the NEUCC-center and another in an UNIVAC 1100/82 at the RECKU-center.

The files stored in the UNIVAC-version have been used for the production of the geological basic data maps (cyclogram-well-record-map, as described by Andersen (1973)).

These maps contain information of the interpretation of the geological profiles, represented by different colours, well dimensions, position of water level, position of screened intervals, specific yield etc.

Method of vulnerability mapping

During the research a number of thematic maps have been produced in order to visualize the different steps of the production process of the vulnerability maps. The thematic maps are described in the following chapters.

According to themes as

- aquifer distribution
- piezometric head
- inter-aquifer flow

the interpretation from point information to a 3-D geometric model has been carried out *manually*. Border lines for the aquifer distribution, iso-lines for piezometric head and limitation of the inter-aquifer flow areas have been drawn manually on pre-drawn computer maps. All other thematic maps have been calculated on a *computer*, using the same basic matrix programme and the same graphics (Appendix 1).

The following parameters were mapped by the computer:

- piezometric head
- layer-thickness of sediments above the aquifers (isopach maps)
- permeability index
- interflow index
- hydraulic percolation time
- reduction capacity } chemical reaction index
- sorption capacity }
- vulnerability index

Information density

Only 528 well records from the test area contained information usable for the computer calculations of the thematic maps. These well records were extracted for information of aquifer category (categories), vertical aquifer limitations, piezometric head, and of any vertical continuities between different aquifers.

The interpreted material was filed in a special software at the NEUCC computer center and combined with files of topography, lithology, geographical location, and different auxilliary table functions.

Table 1 shows the information density of the four aquifer categories in the area.

One of the main thresholds, which would prevent a total use of computer manipulation of geological informations is the interpretation of one-dimensional information to three-dimensional models. The general problem is that the density of the geological information often is very low compared to the presumed discontinuities in the lithological elements, vertical as well as horizontal. This was the situation in the test area.

However, in order to evolve the computer drawn maps it was necessary to assume continuity between neighbouring data points. The lack of data may result in a diminished disintegration due to the density of information, which

Aquifer category	Number of wells	Total size of aquifers km²	Number of separate aquifers	Wells pr. km²
Postglacial	40	90	4	0.44
Upper glacial	314	680	3	0.46
Lower glacial	90	390	5	0.23
Danian	249	890	1	0.28
Total	528	1120	–	0.47

Table 1.

varies between 0.2 and 0.5 km^{-2} for the four different categories of aquifers (Table 1).

Aquifer distribution map

Using the geological basic data maps of Djursland, and a newly constructed map of the Danian surface, an aquifer distribution map, Fig. 2, was produced manually.

The map has been constructed by a geological interpretation of the presence and spatial extension of actually observed aquifers. In this way the well records have been correlated and four different aquifers in the horizontal as well as the vertical direction could be distinguished. The four different aquifers can be categorized as follows:

a) Postglacial aquifer
b) Upper glacial aquifer
c) Lower glacial aquifer
d) Danian aquifer

In some areas it has not been possible to define an aquifer. Either because of the geological conditions being too complicated, and/or the density of information being too poor.

Piezometric head map

Because of lack of data it has not been possible to produce a map of the piezometric head for each category of aquifer (mentioned above).

However, based on information from the geological basic data maps and the aquifer distribution map, two maps showing the piezometric head have been produced (manually). One map represents the piezometric head of the

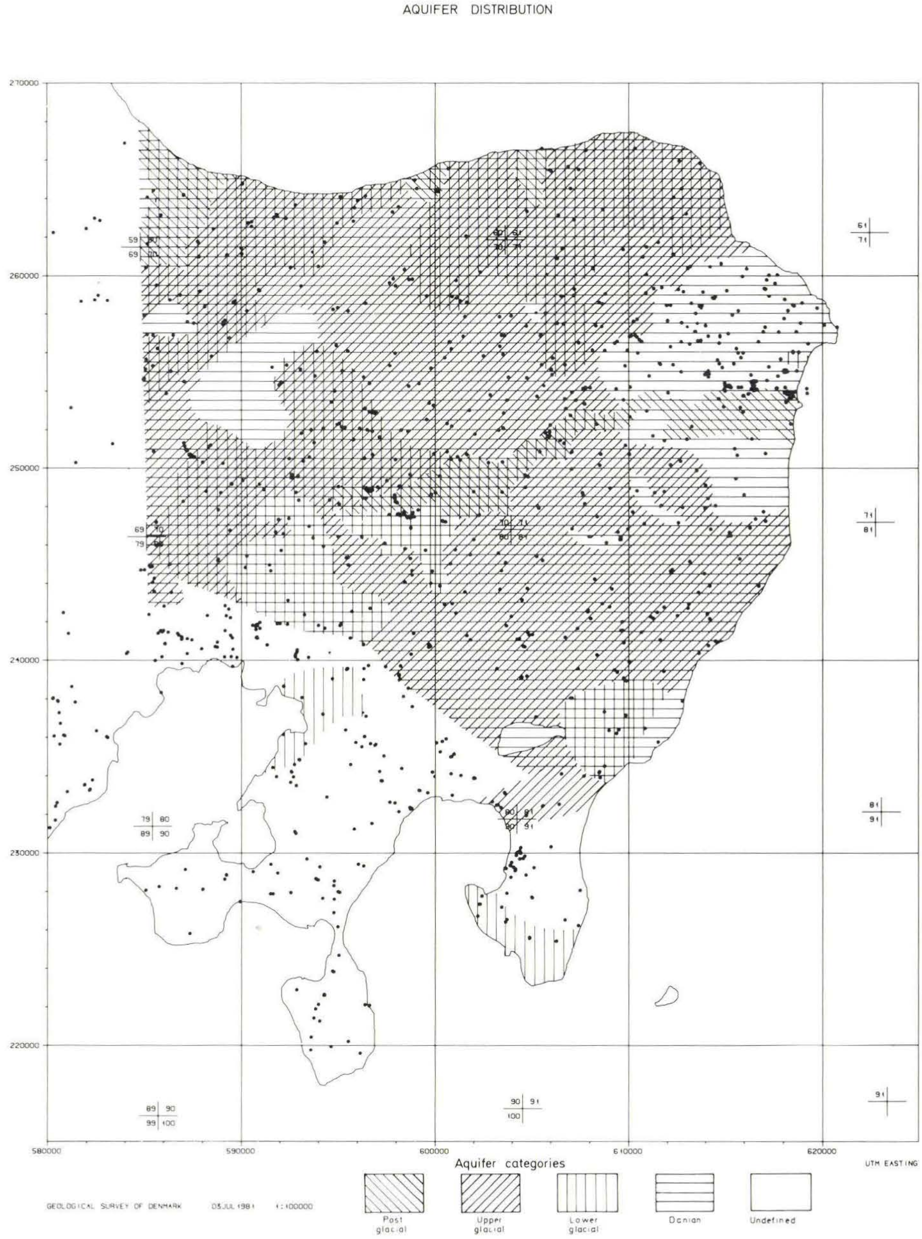

Fig. 2. Aquifer distribution showing the horizontal distribution of the different aquifer categories observed in the area. Black dots indicate location of wells.

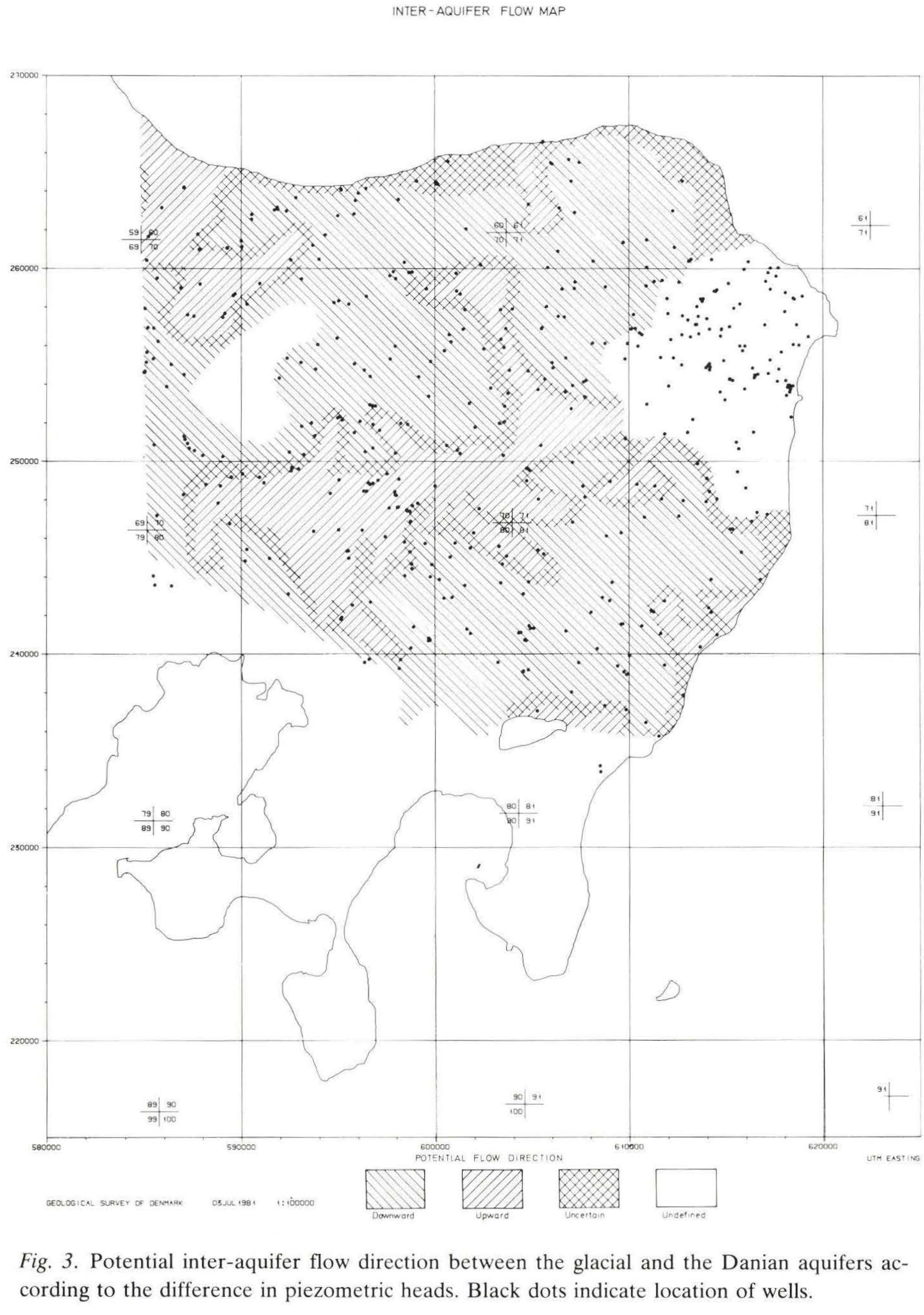

Fig. 3. Potential inter-aquifer flow direction between the glacial and the Danian aquifers according to the difference in piezometric heads. Black dots indicate location of wells.

Danian aquifer, and the other map represents the piezometric head of the main glacial (Quaternary) aquifer.

The main glacial aquifer consists predominantly of the upper glacial aquifer.

Inter-aquifer-flow map

An inter-aquifer-flow map has been constructed for the two main aquifers in the Djursland area. The two main aquifers consist of the Danian aquifer and the main glacial aquifer (either the lower glacial aquifer or the upper glacial aquifer).

By use of the above-mentioned piezometric head maps and the geological basic data map it has been possible to construct a map which shows the potential flow direction between the two main aquifers.

The map depicts four different types of areas

a) Areas with a potential downward flow direction
b) Areas with a potential upward flow direction
c) Areas with an uncertain flow direction
d) Areas with an undefined flow direction

The information of this map is valuable as a supplement to the vulnerability map because it may be possible by means of this to predict whether a contaminant in one aquifer may be transferred to another aquifer, Fig. 3.

Estimating subsurface water transfer ability (ART)

Infiltration to the uppermost aquifer depends on the hydraulic condition in the unsaturated zone and the piezometric head of the aquifer. Infiltration to an aquifer, which is not the uppermost, depends on the piezometric head difference between which the water transfer takes place.

In case of potential negative difference no transfer of water will take place. If the gradient is possitive e.g. higher piezometric head in the upper aquifer than in the lower, a transfer is possible.

As mentioned above information on the different aquifers may not be suitable in any case to calculate the transfer possibility. Consequently an approximate calculation has been made in order to estimate the possibility of entrance in an aquifer as the difference (ART) between aquifer top and piezometric level.

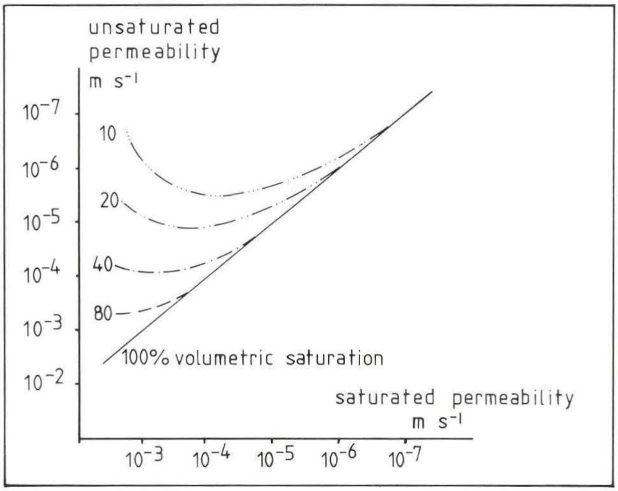

Fig. 4. The relationship between saturated and unsaturated permeability in homogeneous sediments.

Isopach maps

The total thickness of geological deposits above the aquifer is of great importance to the prevention of contamination of the aquifer.

Consequently, maps showing the total thickness of the covering layers above the aquifers have been constructed. As this thickness may vary in accordance with the surface contours a correction according to this has been calculated, by use of the surface contour matrix, see Appendix 1.

Permeability index maps

In order to evaluate the overall resistance against recharge of the different aquifers, calculations of a permeability index have been carried out.

Each lithological type, e.g. meltwater sand, till, limestone, etc. has been given a specific permeability (kp). Approximate average of measured values given in the literature, e.g. Todd (1959) is used. As reliable values of unsaturated permeability coefficients are not available a consequent use of saturated values has been decided although this may induce a general higher level of permeability coefficients, Fig. 4. The permeability index is a relative value indicating the total hydraulic resistance from soil surface to the aquifers given by

$$Pi = \sum_{j=1}^{n} Z_j / kp_j,$$

where n is the number of layers between aquifer and soil surface, Z_j is the thickness in metres of layer j, and kp_j is the permeability coefficient (m/sec.) of layer j.

Interflow index map

As an estimate of the possibility of a non-vertical water movement during infiltration an interflow index has been calculated. The assumption is that the ability of horizontal water movement in the layers above the aquifer depends on changes in permeability. Water flow through a porous medium with high permeability reaching a medium with low permeability tends to change flow velocity and direction.

On the other hand, the opposite situation may not induce a radical change in flow direction, assuming that the layers have field capacity of water saturation.

This implies that a decrease (negative change) in permeability will increase the possibility of interflow and discharge. Therefore an interflow index has been calculated for each well and aquifer given by

$$I = \sum_{j=1}^{n} | \log_{10} kp_j - \log_{10} kp_{j+1} | , \text{ if } kp_j \geq kp_{j+1},$$

where kp_j is the permeability coefficient of layer No. j.

Hydraulic percolation-time map

In order to estimate the travel time of water recharging an aquifer from the ground surface, a hydraulic percolation-time map has been constructed, plate 1.

The calculations are carried out assuming that the flow occurs under unsaturated conditions, no interflow is present, and that the recharge is 0.2 m y^{-1}. The flow is thus assumed to be a piston flow. Consequently, the calculated travel time will be estimated as the lowest obtainable one. Each lithological element has been given a specific retention capacity (SRC) % as the difference between the porosity and the specific yields, Fig. 5. Hence, the hydraulic retention time (RT), which is shown on plate 1, is then calculated by integration over the layers above the aquifers, writing

$$RT = \sum_{j=1}^{n} \int_{o}^{zj} (SRC_j / 0.2) \, dz,$$

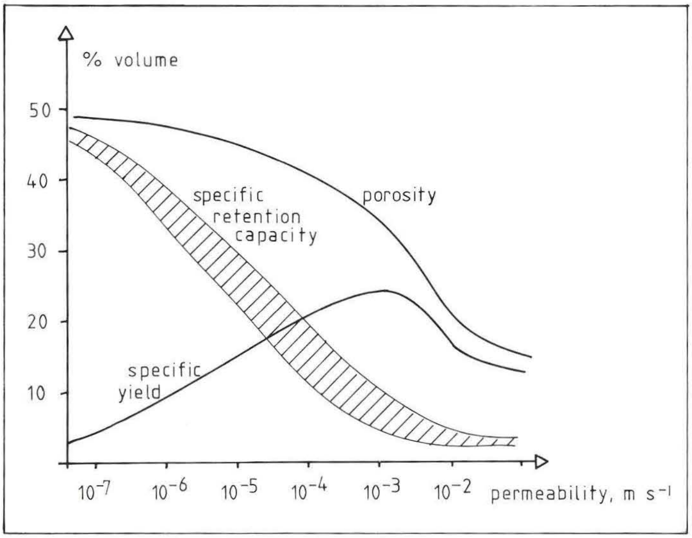

Fig. 5. Approximate volumetric porosity, specific retention and specific yield at 1 bar as a function of permeability in homogeneous sediments. (After Todd, 1959).

where zj is the thickness of layer j (m) and
n is the number of layers.

The dimension is thus years, and the hydraulic percolation-time map illustrates how fast a conservative contaminant will reach the aquifer after introduction at the ground surface.

Chemical reaction map

The ability of the layers above an aquifer to retain reactive chemical contaminants may in many cases be one of the most dominating mechanisms to avoid pollution of the aquifer. In accordance with this two types of chemical reaction maps have been developed, showing the chemical and hydraulic resistance against percolating solutions.

As the number of chemical reactions which can take place in the subsoils is so large, some main processes must be chosen to give a rough estimate of the chemical resistance. In the present study only two main processes have been taken into consideration, namely processes depending on the reduction capacity and processes depending on the sorption capacity.

Each lithological element has been given relative values of reduction capacity and sorption capacity. It is assumed that the ability of reactions is proportional to the hydraulic retention time in each lithological element. The chemical reaction index is then given by

$$SA = \sum_{j=1}^{n} RT_j * CEC_j$$

and

$$RA = \sum_{j=1}^{n} RT_j * ROX_j,$$

where SA is the relative sorption ability,
RA is the relative reduction ability
RT_j is the hydraulic retention time in layer j,
CEC_j is the relative sorption capacity in layer j, and
ROX_j is the relative reduction capacity in layer j.

Vulnerability maps

The possibility of contaminating an aquifer with chemical compounds used or deposited on the ground surface depends on several physico-chemical conditions of the layers above the aquifers.

In addition to these more static properties, many more dynamic factors have to be taken into account in the prediction of the risk of contamination.

During the calculation several static parameters have been included:

- the thickness of layers above the aquifers
- permeability and specific retention capacity
- reduction capacity
- sorption capacity
- infiltration flow velocity
- aquifer category and piezometric head
- interflow

Although many parameters have been combined during calculation of the thematic maps, only four themes were used for calculation of the vulnerability index, namely

1) the water transfer ability, ART.
2) the interflow index, I.
3) the reduction ability, RA.
4) the sorption ability, SA.

The interflow index, the sorption ability, and the reduction ability are converted to values from 0 to 4 by proportional reduction.

The piezometric head parameter (ART) has been converted as follows:

0–5 metres difference corresponds to ART′=3.5
5–15 metres difference corresponds to ART′=2.5
15–30 metres difference corresponds to ART′=1.5
>30 metres difference corresponds to ART′=0.5

Values of the four thematic parameters were equally weighted according to their significance to the vulnerability.

The vulnerability index is then calculated as a mean value of the four parameters,

$$VUL = MEAN\ (ART', SA', RA', I').$$

where the apostrophe denotes the converted parameters.

The vulnerability index has subsequently been corrected to surface contours, and the three vulnerability maps have been produced by use of an element size of the matrix of $(0.5 \times 0.5)\ km^2$, plate 2. A vulnerability map of the Postglacial aquifer has not been calculated as the data of thematic parameters were too scattered.

Appendix 2 contains an example of the calculation of the vulnerability for a ground water well in the test area.

Verification of the vulnerability maps

Chemical analyses of the ground water can be used for a preliminary verification of the vulnerability estimate (page 19). In the hydrochemical basic data map, which is included in the hydrogeological map series (Miljøstyrelsen, 1979), the water analyses are not related to the different aquifers found in the mapped area. Therefore these maps are not directly suitable for the verification as the vulnerability estimate is aquifer-related.

Aquifer-related hydrochemical basis-data maps

A total of 250 chemical analyses of ground water were available from the four aquifers in the Djursland area. New aquifer-relevant hydrochemical basic-data maps were drawn on these analyses and compared with the vulnerability maps. Due to inadequate data only about 1/3 of the total analyses could be used for this preliminary verification.

Comparison of the predicted vulnerability and the ground water chemistry

As already pointed out, the occurrence of some chemical components in the ground water may be an indication of a geologically vulnerable area. Thus, by using single chemical parameters as indicators attention has been drawn to more time-depending and dynamic factors, as for example groundwater movement, point sources and historical contaminant load.

As a preliminary test (verification) of the predicted vulnerability a comparison between the vulnerability maps and the ground water chemistry maps depicting the nitrate content has been performed. The test showed for each of the aquifers that high nitrate concentrations were only present close to predicted vulnerable areas.

On the contrary, in some areas of high vulnerability only low concentrations of nitrate were present. However, as the historical element has not been considered, this may imply that the vulnerability cannot be detected by the water quality itself.

Accordingly, a more comprehensive verification of the vulnerability maps is necessary and a detailed plan for this has been composed.

Use of the vulnerability maps

The purpose of the present research project was to develop a method of producing ground water vulnerability maps, based on existing records and general principles.

During this research a number of different problems occurred because of the lack of knowledge of many physico-chemical and hydraulic processes which made it necessary to include several assumptions. Subsequently, some of these processes had to be estimated by relative values. Other processes were known under saturated, but not under unsaturated conditions, and hence the estimate of the processes has been given, assuming saturated conditions, and this may lead to an overestimate of the final vulnerability prediction.

As a consequence of these assumptions it is evident that the vulnerability map will depict only the general tendency of the possibility of contamination in the aquifers.

As already mentioned the information density is lower than 0.5 km^{-2}, implying that only diffuse permanent pollution sources can be related to the vulnerability prediction of the maps. Therefore it is recommended that these maps are used for regional planning only and with a supplement of some other information about the historical development in the contamination of the areas, information about point sources, and about the horizontal groundwater movement.

The preliminary vulnerability maps produced by the method described above may be a new and promising tool for future groundwater protection management.

The degree of details in the maps is attuned to the density of the available background information; and it serves as a general limitation that specific, detailed questions of groundwater protection cannot be solved by means of the vulnerability maps alone. The maps, however, may be a valuable tool for planning by means of which a.o. the need for further investigations in site-specific cases can be estimated.

Further investigations

With the termination of this stage of the vulnerability project an important result has been achieved. The planning of the ground water protection is one of the main questions in Denmark at the moment. Therefore, the results of the vulnerability project have to be evaluated, critically, and the basis of the vulnerability maps has to be improved.

In phase 2 of the vulnerability project, which is financially supported by a.o. the EEC, the Survey has planned investigations for this purpose. The main elements in this study are *a verification* of the preliminary vulnerability maps and detailed hydraulic and chemical investigations of *the unsaturated zone,* i.e. the zone between the terrain and the ground water aquifer. Finally *microbiological vulnerability* studies are included together with *geological mapping.*

The verification phase is necessary to evaluate the applicability of the maps, which are produced entirely on existing data.

One of the most uncertain factors in the estimate of the vulnerability is attached to the unsaturated zone. In order to increase the reliability of the preliminary vulnerability maps it is necessary to gain access to data for bulk process kinetics and for the quantitative nitrate and sulphate reduction in the unsaturated zone in various geological deposits.

The above mentioned investigations were started in the autumn of 1982 as a co-work with the following participants:

The Geological Survey of Denmark, State Laboratory for Soil and Crop

Research, Århus amtskommune, and Institute of Hygiene, University of Århus.

Concluding remarks

The risk of polluting compounds, used or disposed on or near the ground surface, to influence ground water quality is in the present study illustrated in preliminary ground water vulnerability maps, which have been produced for the test area, Djursland, Denmark.

By the estimate of the ground water vulnerability geological, hydrogeological, and chemical conditions have been taken into account. Verification of the vulnerability maps has been performed by use of data for the chemical compositions of ground water.

The preliminary vulnerability maps, now available, have been produced under assumptions not totally valid for water movement and chemical reactions in the unsaturated zone. This has been necessary, however, as the exact values for factors influencing the ground water vulnerability, especially in this zone, are not known at present. It should be stated, that despite this weakness, the vulnerability maps in the present version may be used for practical purposes e.g. the planning of ground water protection. Research work on a.o. chemical reactions in the unsaturated zone has recently been started at the Survey as a second phase of the ground water vulnerability project. It is expected that this work will contribute to an improvement of the basis on which the future vulnerability maps can be produced.

Acknowledgements. Århus amtskommune is thanked for placing its geological database to the disposal of the Survey. Per Jacobi, Lyngby, has evolved the software and performed the technical preparation of the thematic maps, produced by computer. For the permission to publish the technical description (Annex 1) and for valuable discussions we express our gratitude to Per Jacobi. The study has been supported by grants from the EEC.

Dansk sammendrag

DGU har i efteråret 1981 afsluttet første etape af det såkaldte sårbarhedsprojekt, hvor der for et forsøgsområde (Djursland) er fremstillet sårbarhedskort, der viser risikoen for at forurenende stoffer fra jordoverfladen kan påvirke grundvandets kvalitet.

Grundvandets sårbarhed afhænger af en række faktorer, geologiske, hydrogeologiske, fysiske og kemiske – alle egenskaber ved de lagserier, der ligger over grundvandsreservoirerne.

I princippet udarbejdes der ét sårbarhedskort for hver reservoirtype. På Djursland, hvor der findes 3 reservoirtyper, der har praktisk betydning (Danienkalk og to glaciale smeltevandssandreservoirer) bliver der således tale om 3 sårbarhedskort.

De faktorer, der er medtaget i den nu afsluttede fase af sårbarhedsprojektet er følgende:

- den umættede zone/dæklagets tykkelse, permeabilitet og specifikke vandindhold
- bjergarternes reduktionskapacitet
- bjergarternes adsorptionskapacitet
- infiltrationshastigheden
- reservoirets type og trykforhold
- lagfølgens permeabilitetsændring
- geografisk placering og topografi.

Disse faktorer danner grundlag for en beregning af et sårbarhedsindex, der ved hjælp af EDB udtegnes som et skraveret kort, hvor de mørkeste skraveringer viser de mest sårbare områder (plate 2). Datagrundlaget tillader ikke en detaljeret sårbarhedsvurdering inden for mindre områder. Kortene vil derfor i første omgang være et redskab i den regionale planlægning, ligesom det ved hjælp af sårbarhedskortene kan afgøres, hvor behovet er størst for supplerende undersøgelser forud for etablering af lossepladser m.v., som kunne tænkes at true grundvandet.

Ved hjælp af foreliggende kemiske analyser af grundvandet er der foretaget en foreløbig verifikation af sårbarhedskortene.

Amtskommunerne foretager i overensstemmelse med vandforsyningsloven (1978) en hydrogeologisk kortlægning af geologiske, hydrogeologiske og grundvandskemiske forhold.

Det har vist sig at være hensigtsmæssigt at udnytte disse kort og de tilhørende databaser ved udarbejdelse af sårbarhedskort. Sårbarhedskort kan derfor opfattes som en naturlig overbygning på den hydrogeologiske kortserie.

I den næste fase af sårbarhedsprojektet, der ligesom fase 1 støttes økonomisk af EF, er det planlagt at forbedre videngrundlaget for sårbarhedskortene, specielt hvad angår vandbevægelse og kemiske omsætninger i den umættede zone. Herudover indgår i fase 2 en mere omfattende verifikation af sårbarhedskortene, opbygning af en geologisk model over Djursland for at få et bedre grundlag for beregning af lagmægtigheder og permeabilitetsforhold samt undersøgelser af mikrobiologiske forhold i relation til grundvandsbeskyttelse. I disse undersøgelser deltager DGU sammen med Statens Planteavlslaboratorium under landbrugsministeriet, Århus amtskommune og Hygiejnisk Institut ved Århus Universitet.

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Appendix 1

Description of lay-out and technical preparation of maps

Surface contour map

In order to make most of the thematic maps by computer it was necessary to produce a simplified surface contour map.

From a geodetic map (1:50.000) about 2000 points were digitized by use of the UTM-net coordinates. The points were chosen by a subjective evaluation of the general morphological trends of the surface, i.e. points were mainly placed where marked changes in slopes were present, whereas only few points were placed in plain areas.

In addition, the values of altitude and UTM coordinates of all wells were used giving a total number of morphometric points of more than 3000.

The surface morphometric matrix was then calculated by 3-D lineary interpolation and consists of 150 × 204 elements covering an area of approx. 1910 km^2 including coastal areas.

Thematic Maps based on Well-data

The basic assumption during the calculation procedure was that information deriving from a specific point are representative to the area between the neighbouring points.

This implies, that the information depicted on the maps cannot be disintegrated more than the basic information density.

The present procedure for map construction uses a matrix system with an element size of (0.25×0.25) km^2, which corresponds to the order of magnitude of the basic information density. In the final calculation of the vulnerability index an element size of (0.5×0.5) km^2 has been used as a consequence of a lower accuracy of this parameter.

The production of the different thematic maps is based on the following principles:

a) Each theme is depicted on a separate map for each aquifer category.

b) Only well records containing information of a particular aquifer are used for calculations of that aquifer.

c) Each element in the map matrix has been calculated by lineary 3-D interpolation of the five nearest parameter values weighted by the 2. power of the distance to the element.

d) The protomatrix for Djursland consisting of 150×204 (30.600) elements has been divided into four submatrices in accordance with the distribution of the four different aquifer categories.

e) The themes which directly depend on the surface contours have been corrected with respect to the surface contours.

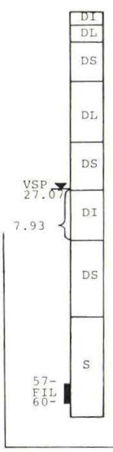
f) Many of the thematic parameters have been calculated using relative values of physico-chemical properties. As exact information is still undiscovered, the corresponding thematic parameters are given as relative index.

Appendix 2

Calculation of the vulnerability

Well DGU file No. 81.76 used as an example of the calculation-procedure for vulnerability of the sandlayer (DS + S) 35 m below ground surface. The single steps in the procedure as well as some of the pre-defined values of kp, SRC, CEC and ROX for the given geological layers are illustrated:

Well no 81.76



Geology	Depth in m	kp	log kp	I	SRC	RT	CEC	SA	ROX	RA
DI	0–2	0.00005	-4.3	2.7	0.2	2	1	2	1	2
DL	2–4.3	0.0000001	-7		0.45	5.175	4	20.7	1	5.175
DS	4.3–10.8	0.0001	-4		0.16	5.2	2	10.4	1	5.2
DL	10.8–20	0.0000001	-7	3	0.45	20.7	4	82.8	1	20.7
DS	20–27.3	0.0001	-4		0.16	5.84	2	11.68	1	5.84
DI	27.3–35	0.00005	-4.3	0.3	0.2	7.7	1	7.7	1	7.7
DS	35–46.7	0.0001	-4		0.16		2		1	
S	46.7–62	0.0001	-4		0.16		3		2	
		ART= 7.93		I = 6		RT = 46.615		SA = 135.28		RA = 46.615

ART' :

ART = 0-5 m ART' = 3.5

ART = 5-15 m ART' = 2.5

ART = 15-30 m ART' = 1.5

ART = > 30 m ART' = 0.5

I' :

I' = 4 -(I/4.3)

SA' :

SA' = 4 -(SA/300)

RA' :

RA' = 4 -(RA/250)

ART = 7.93 m ART' = 2.5 I = 6 I' = 2.60 SA = 135.28 SA' = 3.55 RA = 46.615 RA' = 3.81

$$\text{VULNERABILITY} = \left(\frac{ART' + I' + SA' + RA'}{4}\right) = 3.12$$

Symbols :

DS	Meltwater sand
DI	Meltwater silt
DL	Meltwater clay
S	Sand
FIL	Filter
VSP	Piezometric surface
kp	Permeability coefficient
I	Interflow index
SRC	Specific retention
RT	Hydraulic retention time
CEC	Relative sorption capacity
SA	Relative sorption ability
ROX	Relative reduction capacity
RA	Relative reduction ability

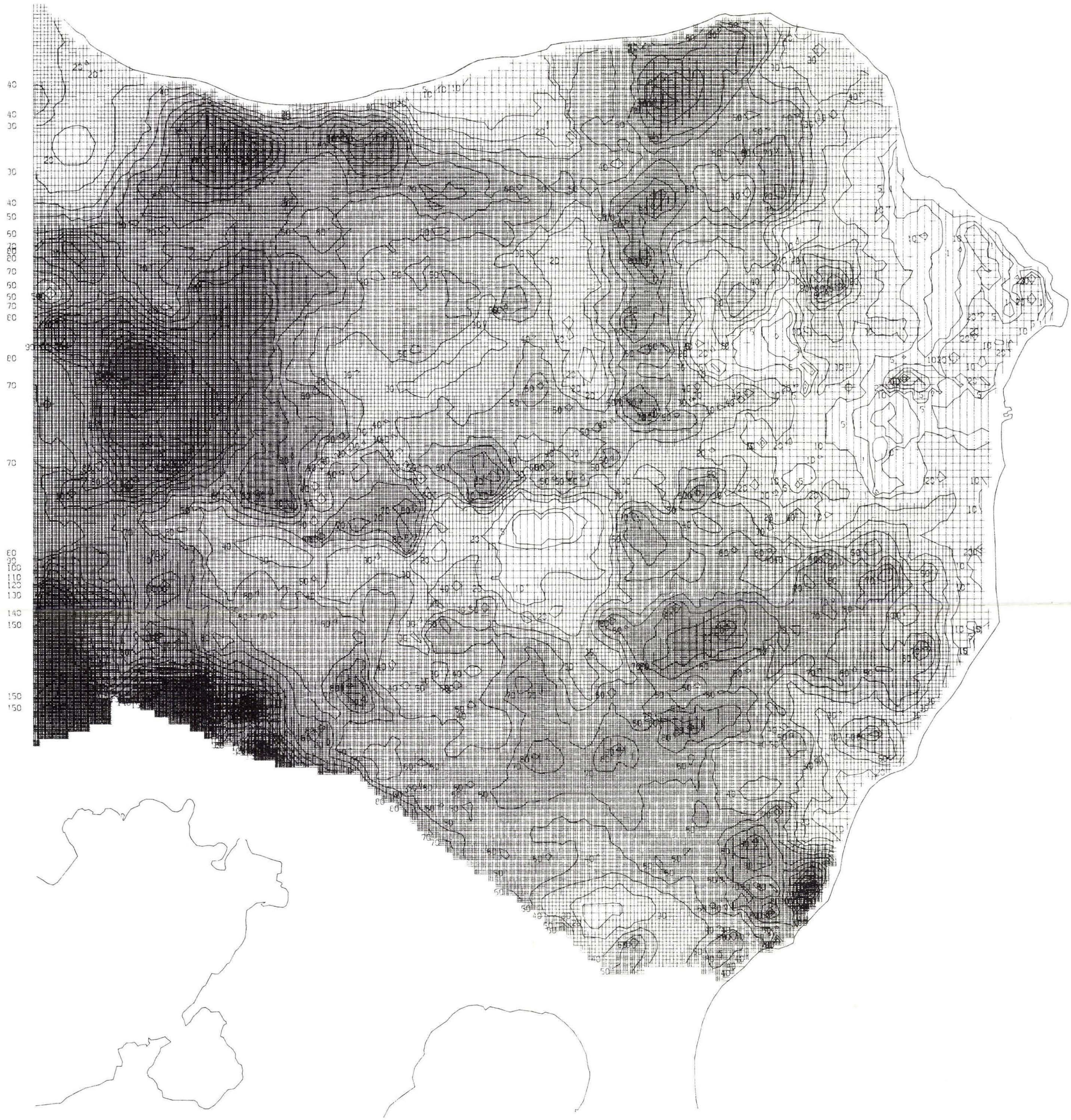


Plate 1. Hydraulic percolation time to the Danian aquifer, given in approximate years.

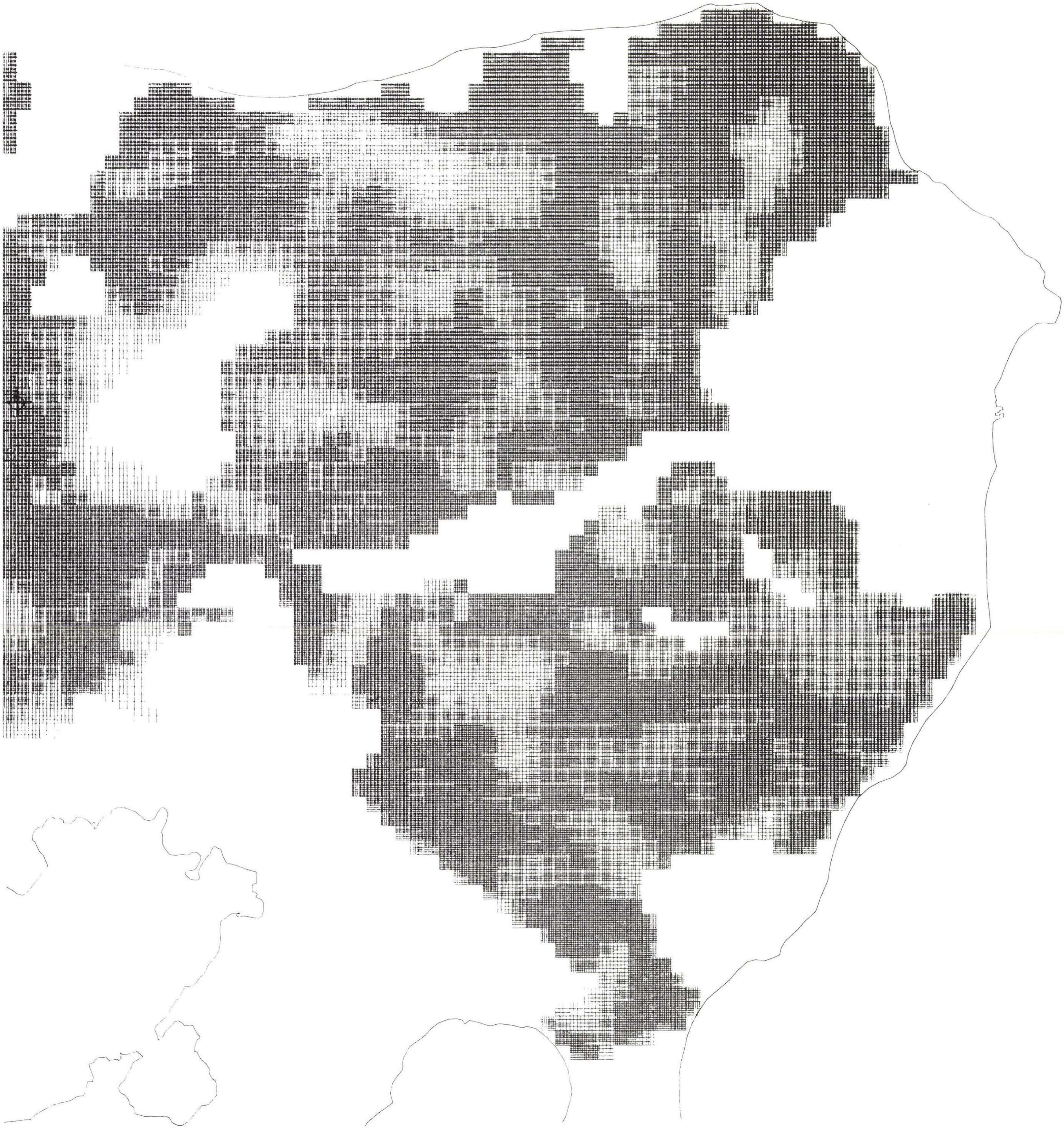


Plate 2. Vulnerability of upper glacial aquifers in the test area. Increasing shading corresponds to increased vulnerability. White areas are undefined.