

Selection of suitable surface geological structures for permanent disposal of hazardous waste and other solid low- to medium-active wastes

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Abstract: One of the ways to dispose hazardous wastes is to deposit them in natural rock structures. The principal aim of this task was to distinguish surface geological structures with the highest potential for the disposal of hazardous waste on regional level. To solve these problems in an optimum way, it was necessary to formulate a complex methodology for the selection of the localities and to define and classify criteria important for the selection process. Absolute priority was given to geological and hydrogeological criteria. The use of the method of gradual elimination of "negative" areas was the basic feature of regional assessment of Slovakia. The result of this assessment is presented in two maps: the map of evaluation of geological and hydrogeological factors and the map of important legislative, hydrological and socio-economic factors of hazardous waste disposal.

Key words: waste, hazardous waste, disposal of hazardous waste, site selection criteria, regional assessment, geological and hydrogeological factors

Introduction

Much attention is currently given to hazardous wastes. The total quantity of wastes is increasing with alarming speed, thus increasing every day the danger of environmental contamination and long-range negative effects on human health. The principal task in the process of site location and selection is to assure that the depositories shall be situated at such sites which, due to their natural characteristics and present land use, will provide a high level of protection of human health and the environment. To fulfil this task, it is necessary to define the suitable geological environment and to analyse all factors entering the process of site location and selection.

To ensure long-range security of the depository, the multi-barrier principle is applied. It is based on creating several independent barriers above each other, which will be able to prevent hazardous substances from escaping from the depository. In the

case of failure of one of the barriers, its function is taken over by the next one. Since rocks forming the immediate underlier of the depository are the last barrier, it is necessary for them to possess the following functions:

- stability of basic depository conditions and its construction elements,
- insulation in case of failure of technical barriers,
- retention to capture products of leachate and dangerous substances.

Basic requirements for the quality of the immediate geological barrier may be expressed as follows:

- sufficient dimensions and thickness:
 - minimum area 1 km²
 - minimum thickness 5 m
- stability of foundation environment:
 - low compressibility
 - high plasticity
 - low solubility
- low permeability:
 - filtration coefficient
 - $< 1 \times 10^{-9} \text{ m.s}^{-1}$
- high retention capacity:
 - contents of clay minerals with adsorptive properties
 - $> 10 \text{ mass. \%}$
- tectonic and seismic stability:
 - outside active fault lines
 - and intensely tectonically failed areas

The geological barrier must provide long-range protection of human health and of the environment. Therefore, the quality of the geological environment should be given absolute priority in the process of the selection of sites for hazardous waste disposal.

Methodology of finding and selection of sites suitable for the disposal of hazardous waste

Several alternative methods of input data synthesis and analysis may be used for the selection of hazardous waste depositories (WOODSIDE, 1993). They are for example:

- intuitive method - the specialist evaluates all input data as a whole and on the basis of experience he decides, which locality is suitable. The main argument in favour of this method is the fact that there is close functional dependence between the characteristics of a locality and therefore they must be evaluated as a whole.
- gradual elimination method - each factor is evaluated individually. Limiting values of acceptability of the factor (i.e. criteria) are determined and they are applied in elimination, i.e. exclusion of certain territories from further evaluation. Evaluated are environmental, technical, social, economic and political factors. In the evaluation process, all components of input factors are analysed in succession and "unacceptable" territories are gradually identified and eliminated.
- method of significance (weight) analysis - the importance of individual factors entering the process of site selection is expressed by a numerical value. For instance permeability in the underlier of the locality is one of the most important factors in the site selection process. The presence of clays is an indicator of low permeability, and so places with a 3 m thick clay layer in the underlier may be classified with the highest grade, say 10. Another locality, with sandy schlieren, may have a value of 3. Similar values may be assigned also to other factors. Relative significance of the factors is determined by calculating the total of the values and the most suitable locality is considered to be the one with the best score.
- method of criteria combination - is based on the selection and various combinations of input criteria. In its application we may use the method of gradual elimination or the method of significance analysis. A combination of certain criteria is used for the identification of suitable, or unsuitable territories. Later on, the process is repeated and the combination of criteria is always different. For instance, one combination gives priority to the thickness of underlying clays and population density is less stressed. Another combination may emphasize the situation of the locality in relation to the distance from producers of waste and regards seismicity as a less important factor. The result of the application of this method is the selection of several localities representing different aspects.

Each of the above methods has its good points, but also its shortcomings. The intuitive method is the only one which makes allowances for mutual interconnections between the factors, however, it includes the subjective opinion of the specialist. It is hardly applicable in regional evaluation. The method

of gradual elimination is best applied on regional scale, but due to the application of initial (e.g. legislative) criteria, territories with high potential for disposal of dangerous waste are often excluded. The method of significance analysis may be best used at low number of localities with significantly different characteristics. However, its application can lead to great variations in the evaluation, since it does not take into account the mutual relationship between factors under consideration. The method of criteria combination takes into consideration interrelationships between the factors and it is useful in public relations. However, when using this method, we do not get localities ordered according to suitability and its application is very complicated with greater number of localities.

Criteria for site location and selection and input factor analysis

An important task in the process of location and selection of sites for hazardous waste disposal is to determine unambiguous criteria. These criteria, used to evaluate the whole territory such as Slovakia, can best be defended in discussions with the public.

Working criteria are usually derived from factors which must be considered in the process of site location and selection. When assessing a territory from the viewpoint of hazardous waste disposal, the factors can be divided into two groups:

1. primary factors
2. secondary factors.

Primary factors represent qualitative characteristics of a natural geological barrier and factors of groundwater vulnerability. They include geological, hydrogeological, hydrological and geomorphologic factors.

Secondary factors represent conflicting interests from the environmental viewpoint. Among the most significant are legislative factors, mining activities, present land use, infrastructure of the country and other socio-economic factors.

Functional criteria for site location and selection

In the majority of methods used for location and selection of localities for hazardous waste depositories involve criteria of site selection. The determination of the criteria is a multi-stage process, beginning with the determination of general criteria, i.e. determination of basic requirements on the evaluated system. They are only descriptive and they are not associated with a concrete locality. General cri-

teria must be gradually made more specific, taking into account the required host environment and the factors affecting this environment. The result are so-called functional criteria, which may be of semi-quantitative character. The process continues with a detailed analysis of input factors and operational or executive criteria are quantified subsequently. They are defined as the limit (boundary) value of a factor.

The most important criteria for the selection of sites for the disposal of hazardous waste involve: geological, hydrogeological and geomorphologic criteria.

Other criteria, i.e. legislative, hydrologic and socio-economic ones are not subjected to special evaluation. In the process of location and selection of sites for hazardous waste disposal, the criterion is basically their presence or absence on the territory under consideration (national parks, deposits, protected hydroeconomic areas etc.). Sometimes, the distance from a potential depository is evaluated as well, e.g. the distance from surface flows and water reservoirs > 300 m, distance from the nearest drinking water source > 500 m etc.

Hierarchy and degree to which the criteria are obligatory

After the analysis of factors entering the process of location and selection of sites for hazardous waste disposal and after the determination of the functional criteria, it is necessary to determine the hierarchy of the criteria and degree to which they are obligatory.

The degree, to which the criteria are obligatory, depends on the stage of the process of location and selection of a site. For example, in the stage of regional assessment of the territory the criterion of hydraulic conductivity is regarded as obligatory. Other hydrogeological parameters may be considered to be important, or necessary. They will be regarded as obligatory at the evaluation of potential areas or specific localities. However, in each stage of the process of location and selection of localities, absolute priority is given to the criteria of geological barrier quality and groundwater vulnerability.

According to the degree of restriction, we propose to divide the criteria into three groups in the following way:

1. Exclusive criteria
2. Limiting (evaluating) criteria
3. Additional (accessory) criteria.

Exclusive criteria

Exclusive criteria are used to eliminate territories which do not fulfil the pre-condition of required

geological barrier quality and groundwater vulnerability. Excluded are also the areas the protection of which is decreed by law, residential areas, and areas of major infrastructures. Excluded territories are not any more the object of survey and selection and their elimination, especially in the stage of regional assessment, saves considerably time and costs.

1. Hydrology and groundwater protection

- protection zones of natural curative water resources, degrees I, II and III.
- temporary protection zones of curative water resources
- hygienic protection zones of degrees I, II and III of ground- and surface drinking water resources
- protected area of natural groundwater accumulation
- protected water management area
- drainage area of an exploited water flow
- exploited water reservoir and flooding area of a water reservoir under construction
- territory with important groundwater resources
- important recharge areas
- floodlands (flooded by centennial waters)
- moist areas

2. Areas of protected nature

- national parks and their protection zones
- protected land areas and their protection zones
- state natural reserves
- local natural reserves
- natural monuments

3. Mineral deposits

- mining area of strategic deposits (surface and underground)
- protected deposit area
- proven reserves of strategic deposits
- mined deposits of non-strategic minerals
- mined out mineral deposits
- potential deposits of strategic importance (sensu SLAVKAY - PETRO, 1995)

4. Residential areas and infrastructure

- municipalities and their surroundings
- industrial areas
- large construction works (airports etc.)
- holiday resorts and others.

5. Geological and hydrogeological parameters

- presence of rocks with filtration coefficient $k_f > 1 \times 10^{-6} \text{ m.s}^{-1}$ to the depth of 90-100 m
- presence of gravel and sand formations to a great depth
- presence of lithologically inhomogeneous rock complexes

6. Limiting factor values

- filtration coefficient of immediate geological barrier $k_f > 1 \times 10^{-9} \text{ m.s}^{-1}$

- groundwater table depth < 3 m
- highest 100-year groundwater level reaching higher than 1.5 m from the bottom of depository
- immediate barrier thickness < 5 m
- specific yield > 7 l.s⁻¹. km⁻²
- slope inclination > 6°
- areas prone to landslides
- areas sensitive to erosion
- areas near active faults and significant fault zones
- collapsible materials
- clay mineral contents < 30%
- adsorption clay contents < 10%
- organic matter contents > 5 %
- low plasticity - plasticity index < 15%
- high compressibility
- presence of soluble minerals
- pH < 5.5
- cation exchange capacity < 5 mg/100 g
- salt and alkali contents > 0.65 %

Limiting (evaluating) criteria

Factors regarded as limiting ones entering the process of location and selection of sites, determine (limit) the utilisation of a territory for the storage of hazardous waste with graded importance. It may be possible to establish and operate a depository in such area only under the pre-condition of technical measures eliminating the effects of the unfavourable factors. When these factors reach certain limiting values, they become exclusive and this leads to the elimination of these territories from further consideration.

1. Geomorphological

- slope inclination
- intensity of geomorphologic processes

2. Geological

- landslide
- erosion
- weathering
- tectonic and seismic stability
- thickness and composition of natural geological barrier
- homogeneity of rock environment
- properties of rock environment

3. Hydrogeological

- hydraulic parameters
- groundwater quality
- distance from surface water flows and drinking water reservoirs and resources

Additional (accessory) criteria

Additional criteria are considered at the final decision-making regarding a site. When finally order-

ing the localities according to their potential, a situation may occur when two or more sites will have very similar characteristics, the most important consideration then becomes:

- distance from waste producers
- accessibility of construction material
- density of road and railway network
- climate
- land-use plans etc.

The procedure of location and selection of sites for hazardous waste disposal in Slovakia

After the evaluation of merits and shortcomings of the above mentioned methods, we propose to use for the location and selection of sites with high potential for the disposal of hazardous wastes in Slovak conditions the method of gradual elimination. The process of site location and selection should be carried out in three stages, according to clearly defined criteria. In final decision-making it is possible to use also the method of significance analysis, or use accessory criteria and the method of gradual elimination.

The stages of finding and selection of potential dangerous waste depositories may be characterised as follows:

- regional assessment - evaluation of the Slovak territory using exclusive criteria. The result of this evaluation is define potential areas.
- assessment of potential areas - consists of three stages:
 1. distinguishing of prospective sites using exclusive and limiting criteria. The result of this phase is the selection of 3-5 prospective sites.
 2. ordering of the prospective sites according to their suitability. At localities with very similar characteristics, additional criteria will be used in final decision-making.
- preliminary survey of sites with the highest potential for the construction of hazardous waste depositories. The result of this stage is the evaluation of basic requirements for the siting of a hazardous waste depository and proposal of geological surveys for the further stage of the investigation. In some cases this stage may exclude the site from being considered further.

Regional assessment

Basic feature of this proposal is the use of the method of gradual elimination of "negative" areas. The elimination is done using basic geological and

hydrogeological, hydrologic and legislative criteria regarded as exclusive. It allows to site a depository in areas with the greatest probability of success. The obtained data serve for:

- outlining areas where the depository will have minimal potential of surface and groundwater resource contamination.
- preliminary determination of the characteristics of spatial variability of geological environment in the outlined areas.
- characterisation of basic hydrogeological parameters.
- locating areas with occurrences of non-renewable mineral resources, protected areas of nature, protected water management areas and densely populated areas.

Geological, hydrogeological, legislative and socio-economic factors are evaluated simultaneously. The result of regional assessment of the Slovak territory will be presented in two maps:

- map of evaluation of geological and hydrogeological factors from the viewpoint of hazardous waste disposal
- map of important legislative, hydrological and socio-economic factors of hazardous waste disposal.

At the end of this stage of the selection process, the transparency maps outlining the "negative" areas can be overlaid to show the areas where storage of waste will have minimum environmental impact.

Geological and hydrogeological factors evaluation map

The map of evaluation of geological and hydrogeological factors is a special analytical map (Fig.1). It is based on an analysis of existing geological and hydrogeological maps of much larger scale than usually used in regional assessment (1 : 25 000, 1 : 50 000 and 1 : 200 000). The obtained information on geological and hydrogeological conditions was evaluated on the basis of:

- transmissivity coefficient
- the presence of gravel and sand formations
- spatial variability of the geological environment.

Values of hydraulic parameters are determinative for the definition of hydrogeological aquifers and aquicludes. Their identification on the map allowed the exclusion of all areas with transmissivity coefficient exceeding $1 \times 10^{-4} \text{ m.s}^{-1}$. In the following phase, the attention was aimed at formations classified on the map by low transmissivity, but with the presence of gravel and sand layers at various depths. In view of the generally high permeability of sands and gravels, and thus the enormous potential

for the dissemination of contaminating substances, the areas with significant layers of these sediments were excluded from further survey and selection process. The criterion of spatial variability of the geological environment was used in rock complexes with low transmissivity, where very marked lithologic inhomogeneity of rocks complexes had been proved. Usually they are formations of rhythmic flysch, flysch complexes with predominant sandstones and other formations of flyschoid character. These were eliminated and they are not the object of further selection.

Areas remaining as suitable have the highest potential for the deposition of hazardous waste. They should be given greatest attention in further phases of the process of location and selection of sites.

Map of significant legislative, hydrologic and socio-economic factors

The map of significant legislative, hydrologic and socio-economic factors is a special synthetic map (Fig. 2a, 2b, 2c). Using a set of exclusive criteria, which can be applied on the scale 1 : 500 000, areas protected by legislation, areas with important socio-economic activities and some areas unsuitable from the hydrologic viewpoint were eliminated. Protected nature areas :

The following protected nature areas were eliminated in the regional assessment:

- national parks and their protection zones
- protected land areas and their protection zones
- state nature reserves.

It was not possible to distinguish other small-scale protected nature areas on the scale 1 : 500 000. They will be the object of evaluation in next phases. On the map they are marked by a green contour and green hatching (except state nature reserves).

This category of factors is subject to Law No. 278/1994 Dig. on the protection of nature and environment.

Water-management protected areas:

Water-management protected areas may be regarded as the most important category of protected areas. The following areas were eliminated in the regional assessment:

- protection zones of natural curative water resources, degrees I, II and III.
- temporary protection zones of curative water resources
- hygienic protection zones of degrees I, II and III of ground- and surface drinking water resources
- protected area of natural groundwater accumulation
- protected water management area

- drainage area of an exploited water flow
 - exploited water reservoir and flooding area of a water reservoir under construction
 - territory with important groundwater resources.
- These areas are marked in the map by a blue contour and blue hatching.

The following laws apply to water management protected areas:

Law No. 138/1973 Dig. on water (Water Act)

Law No. 238/1993 Dig. - amendment and complementation of the law No. 138/1973 Dig. on water

Governmental Regulation No. 13/1987 Dig. on some protected areas of natural water accumulation

Notice of the Ministry of Health No. 15/1972 Dig. and No. 17/1983 Dig. on the protection and development of natural curative resources.

Protected forests:

The category of protected forests includes protective forests and special purpose forests. Since they are usually small areas, their inclusion into this map is more or less informative only. They must be given greater attention in a more detailed evaluation of the territories. They are marked in the map by a green contour.

The applicable law to forests is Law No. 61/1977 Dig. on forests and Note 14/1978 on the categorisation, exploitation and economic adjustment of forest.

Mineral resources and mining activities:

The presence of mineral deposits and areas with mining activities is marked in the maps by black colour. On the map there are marked:

- mining areas of strategic surface and underground deposits
- protected deposit areas of surface and underground deposits
- proved reserve of strategic deposit
- mined deposits of non-strategic minerals
- mined out mineral deposits
- potential deposits of the strategic minerals.

Data on mineral deposits and mining activities were processed on the basis of data from the data base of Geofond. Data on potential solid mineral resources in Slovakia were taken from the Map of Prognostic Resources, prepared by SLAVKAY and PETRO (1995) for the purposes of radioactive waste disposal.

Hydrologic criteria:

From hydrologic data, only the presence of floodlands and more extensive wetlands was evaluated in this phase. Their inclusion in the maps is for the information of specialists involved in the next stages of survey. On the map they are marked by a blue contour.

Other criteria:

The only other exclusive criteria we used in the regional assessment was the criterion of population density. Population density was obtained according to the Atlas of SSR (1980). Areas with a density exceeding 150 inhabitants per km² were selected. We consider this factor to be only informative. It was not possible to apply other factors due to the scale of the map. It will be however necessary to consider them in next stages of location and selection of sites.

The maps of the evaluation of geological and hydrogeological factors and the maps of significant legislative, hydrologic and socio-economic factors are constructed to allow them to be overlaid to allow extraction of maximum quantity of data. This facilitates the identity of "positive" areas, i.e. areas with the highest potential for hazardous waste deposition. Areas so determined as suitable are the object of the next phase of the survey process.

Evaluation of potential areas

The evaluation of potential areas includes collecting data on geological, hydrogeological and geomorphologic conditions of territorial units outlined in the previous phase. The following elements are stressed:

- slope and topography of the area
- geological structure of the area on the scale 1 : 50 000, to the depth of 100 m. It is necessary to identify the depth, extent and thickness of all significant aquifers, or highly-permeable materials.
- well survey (determination of basic hydrogeological parameters)
- tectonic features
- slope stability
- sensitivity to erosion
- presence of strongly weathered materials
- local karst forms
- engineering-geological properties of rocks
- mineral deposits
- mining activities, identification of mined out ground.

The analysis of obtained data using exclusive and limiting criteria allows the identity of such geological, hydrogeological and geomorphologic elements, which, due to their dimensions, could not be evaluated on regional scale. Their presence may seriously limit the suitability of a site, or even exclude the site from further evaluation.

* As significant are regarded gravel and sand formations with a thickness exceeding 1.5 m, sandstones exceeding 3 m and faulted limestones and dolomites of a thickness of at least 4.5 m, with a surface exceeding 1 km²

Scale 1 : 1 500 000

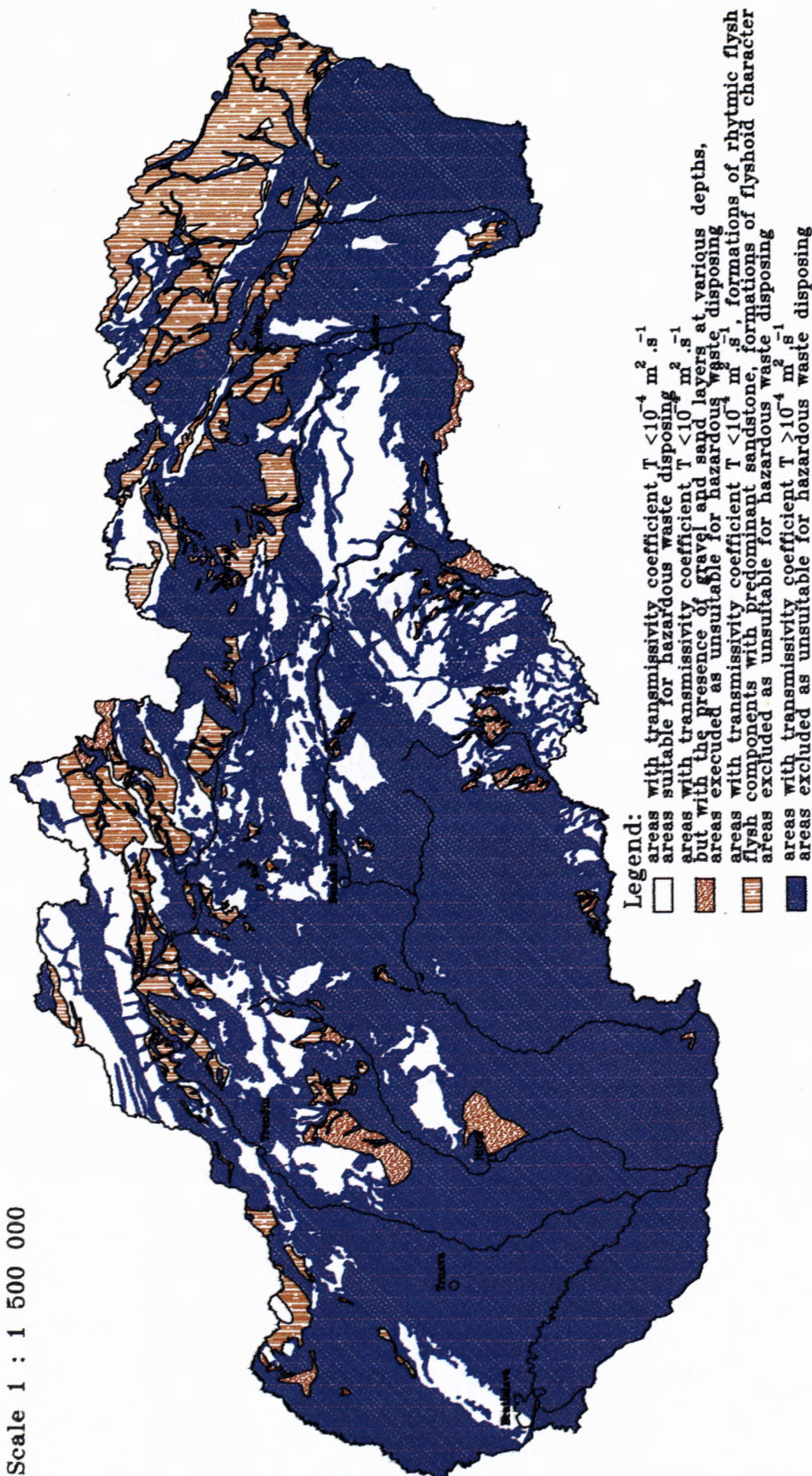
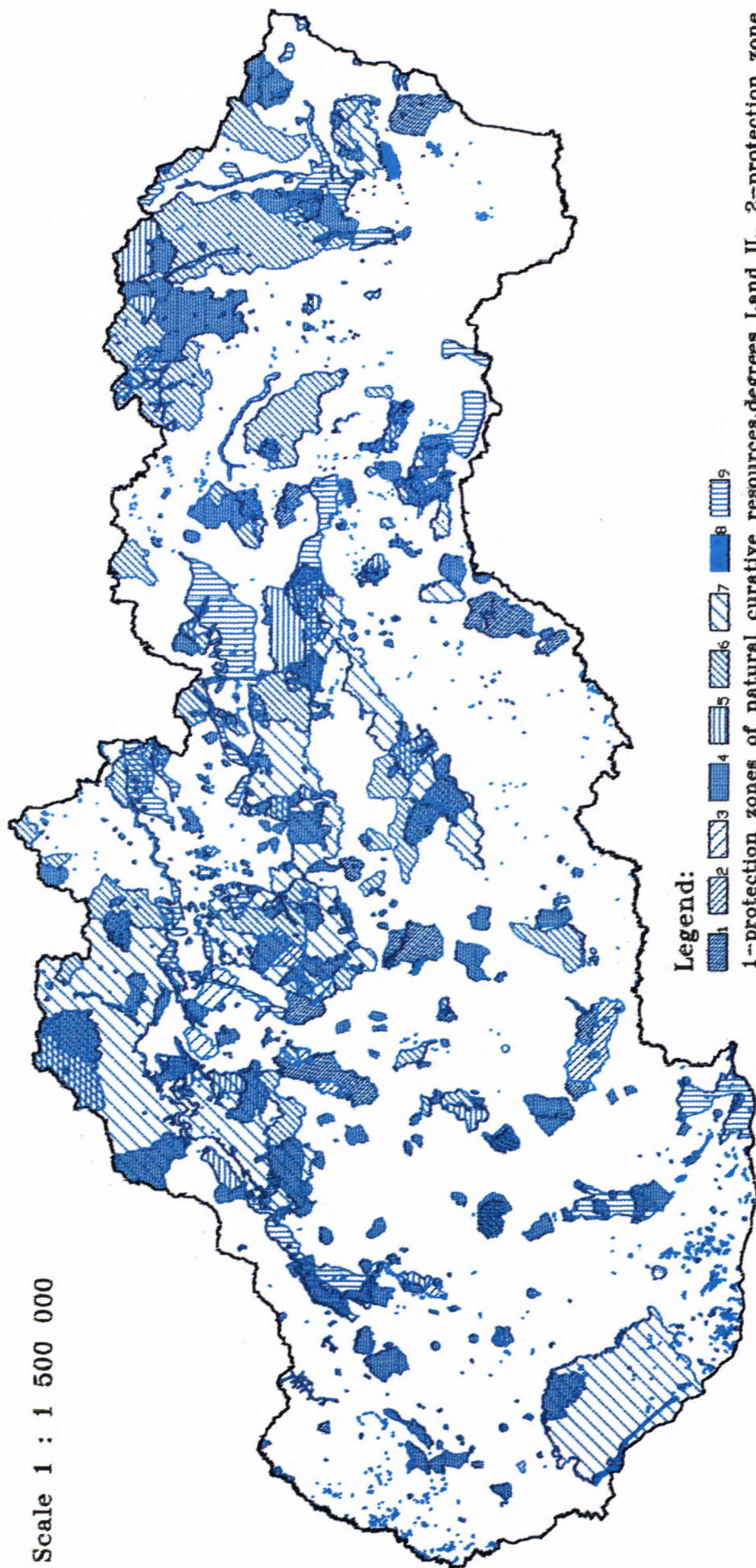


Fig. 1 Map of evaluation of geological and hydrogeological factors from the viewpoint of hazardous waste disposal

Scale 1 : 1 500 000



Legend:



1--protection zones of natural curative resources,degrees I.and II., 2--protection zone of natural curative resources, degree III., 3--temporary protection zones of curative resources, 4--hygienic protection zones of degrees I. and II. of grouned and surface drinking water resources, 5-- hygienic protection zone of degree III. of grouned and surface drinking water resources, 6--drainage area of an exploited water flow, 7--protected area of natural ground water accumulation and protected water management area, 8-- exploitedwater reservoir and floating area of a water reservoir under construction, 9--territorywith important ground water resources

Fig. 2a Map of important legislative, hydrological and socio-economic factors of hazardous waste disposal - part I

Scale 1 : 1 500 000

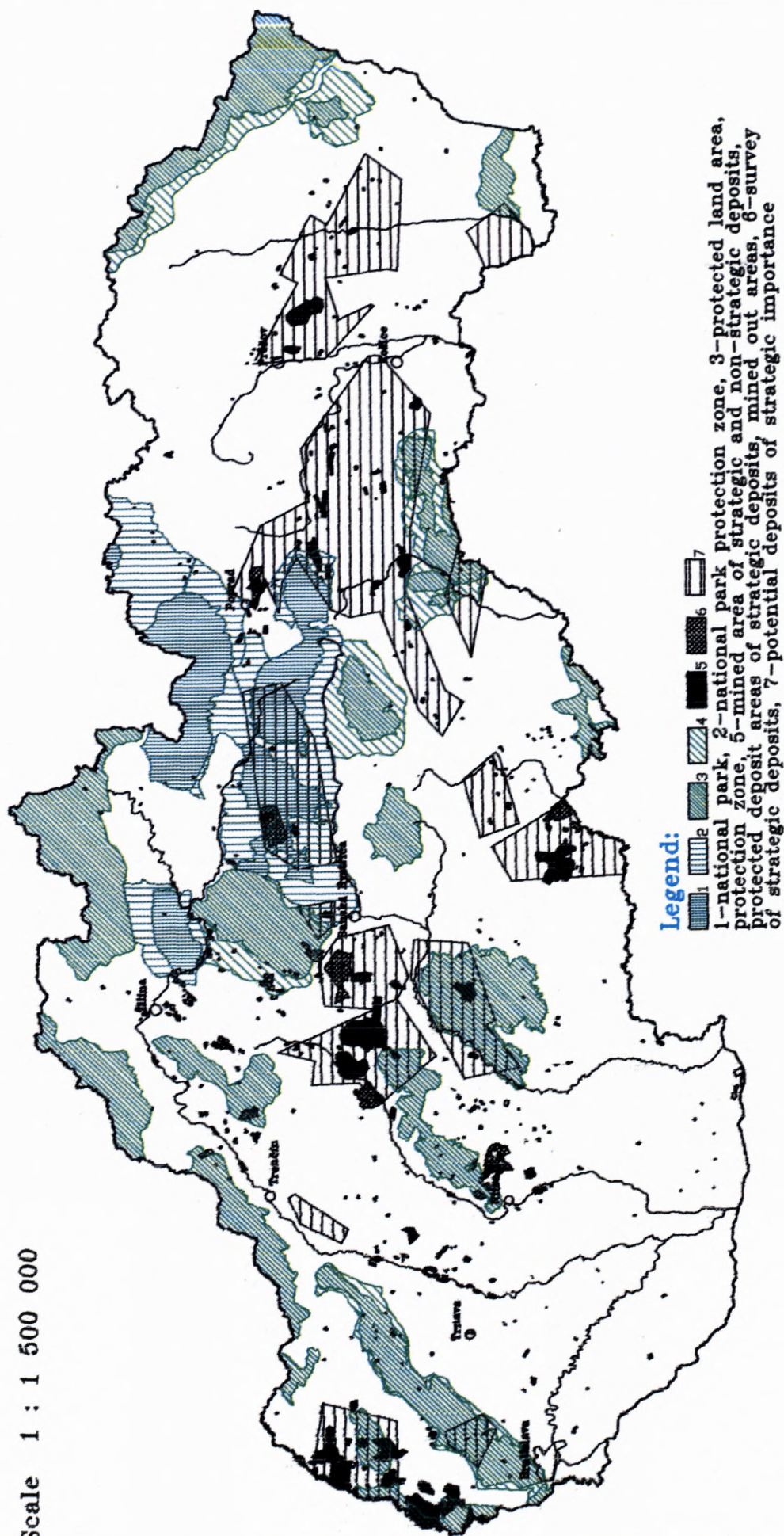


Fig. 2b Map of important legislative, hydrological and socio-economic factors of hazardous waste disposal - part II

Scale 1 : 1 500 000

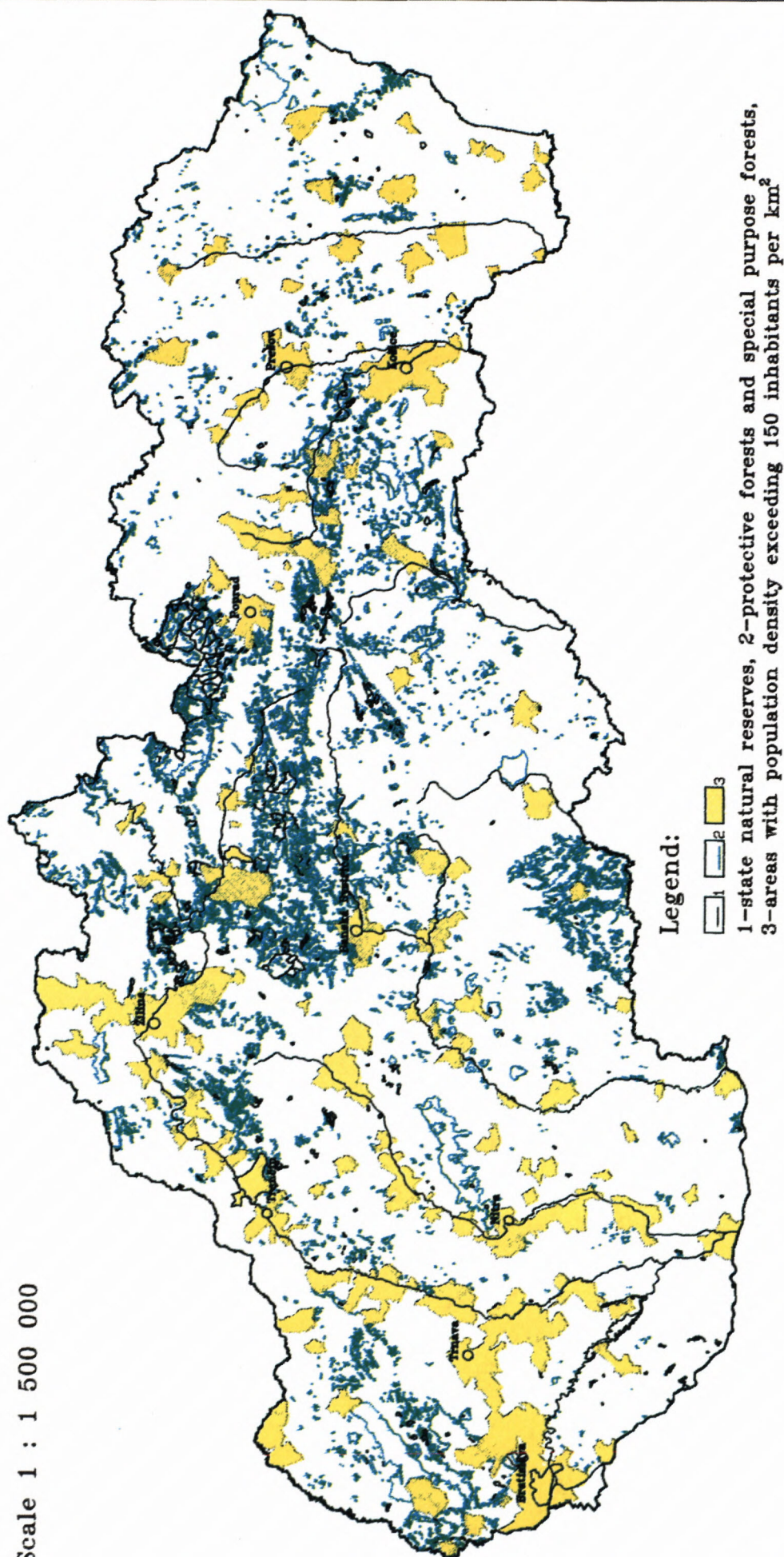


Fig. 2c Map of important legislative, hydrological and socio-economic factors of hazardous waste disposal – part III

It is also necessary to identify areas protected by legislation, which, due to their small extent, could not be eliminated in the stage of regional evaluation (e.g. protected parks, gardens etc.).

The result of the second stage of the process of location and selection of sites is the determination of sites (3-5) with the highest potential for the storage of hazardous waste. It is possible to order the sites according to their suitability using comparative analysis or accessory criteria.

Preliminary survey of the sites

Preliminary survey of the sites is carried out with the aim to define such geological, hydrogeological, geomorphologic, engineering-geological and geotechnical characteristics, which could affect negatively the long-term stability of the depository.

The object of the survey is the site (or two sites), which was identified as the most suitable in the previous evaluation. A territory of approx. 1 km² is investigated to a depth of 100 to 150 m.

In view of the specific character of the problem of hazardous waste, the principal task of the survey will be the determination of the following parameters:

- a) geomorphologic stability and speed of geomorphologic processes
- b) lithologic composition of rocks, stratigraphy, degree of deformation, spatial variability
- c) structural-tectonic conditions on the site and in the wider surroundings
- d) mineralogical-petrologic composition of rocks
- e) geochemistry of the rocks
- f) contents, type and micro-structural analysis of clay minerals
- g) hydrogeological characteristics - local hydrogeology, hydraulic parameters (filtration coefficient, transmissivity, specific yield etc.)
- h) physical-mechanical properties
- i) geomechanic properties.

The stage ends by recommendation of the site for further survey or its refusal.

Conclusion

The problems of regional geological evaluation of surface geological structures for hazardous waste deposition have not been solved so far in Slovakia. The result of the proposed study will be two maps, the cartographic interconnection of which will clearly identify areas with the highest potential for the storage of hazardous wastes. The proposed methods and functional criteria may be used also in the selection of sites for a depository of low- and medium-radioactive waste, or for the siting of depositories of solid municipal or other waste.

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