Estimating groundwater resources in hardrock areas – a water balance approach

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Among decisionmakers in counties and municipalities, there is a great need for simple but hydrogeologically correct estimations of the groundwater resources. Today's methods are often based on extensive field investigations and complicated mathematical flow modelling or too simplified annually based water balances. In this paper, a groundwater balance method is presented that is especially adapted to small and complex aquifers, such as in hardrock, in which the storage capacity of the aquifers gives the extraction limits. The balance is focused on the development over time of the storage, to which groundwater recharge and withdrawal from well users are added and drawn. A computerised system has been developed as an expert system for users, who are not professional hydrogeologists. The balance can be used for calculating the maximum acceptable number of consumers in an area or for the set of a maximum acceptable sanitary standard, based on available groundwater resources. The balance method has so far been used as a planning tool within several areas around Stockholm, Sweden. The results are reasonable, compared to experiences of the real groundwater situations in the areas, although a true validation has not yet been carried out.

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Introduction

Many densely populated areas in the Scandinavian countries are located in areas with limited groundwater sources. Some of the biggest cities, such as Stockholm, Gothenburg, Helsinki and Bergen are located in hardrock terrain with a large surface area of bare outcrop and in the lower parts soils, mainly consisting of till, clay and in places sand and gravel. The outer areas, which commonly have a mixture of summer housing and permanent housing, generally rely on a small-scale water supply based on private drilled wells. There is also a hard exploitation pressure on those areas, which are usually located in attractive surroundings. The areas are slowly converting from pure summer housing to permanent housing. In addition, the sanitary standards in the areas are steadily improving, which in turn increases the specific demand for fresh water and increases the amount of sewage water produced. A too high groundwater extraction sometimes leads to saltwater intrusion or other groundwater quality problems, such as increased nitrate content and bacteria. The municipal and county administrations often have to take decisions whether an increased exploitation can be accepted, based on the available water sources and the possibilities to handle the sewage water. There are acute quality problems in some areas in municipalities along the Swedish eastern coastline, such as in Värmdö, Nacka, Österåker and Norrtälje municipalities in the county of Stockholm.

Basis for municipal decisions

There is a large number of different qualitative and quantitative methods previously used for the estimation of groundwater quantities and vulnerability. The qualitative methods do not give absolute values of discharge possibilities but instead give a relative measure. Such methods include local experiences and some variable methods, the DRASTIC method (Aller et al. 1987) and the LeGrand method (LeGrand 1983), which are vulnerability methods developed in the USA for comparison between different areas. A specific variable method, adapted to Swedish conditions, the *Risk Variable* method (the RV-method), has been developed and tested for the occurrence of salt groundwater in Sweden using GIS in Norrtälje municipality, Stockholm county (Lindberg & Olofsson 1997). Although the qualitative variable methods can sometimes give valuable information, the results are not always easily understandable, which can lead to inconsistent decisions. Quantitative methods, on the other hand, give calculated values for the possibilities of extraction of groundwater. The methods are commonly based on direct measurements of physical properties, often hydraulic measurements in wells and more or less complex and sophisticated calculations using water balances or mathematical modelling. The latter has commonly been carried out during big construction projects in some areas, e g., within the nuclear waste repository programme in Sweden (for example, Follin 1995). However, mathematical modelling requires an extensive amount of data, especially in hydrogeologically heterogeneous areas, and can usually only be carried out by experts. Therefore, the costs of such investigations are quite high. The groundwater balances that have been carried out, on the other hand, have generally been too simple, and have usually not taken the artificial and time-dependent discharge as well as the heterogeneous rock characteristics into consideration.

Groundwater balances have been used as a decision tool in municipal planning in Sweden since the beginning of the 1980s (Sund & Bergman 1980). The balances were originally based on a simplified recharge-discharge approach in which the annual groundwater recharge (strictly formed from precipitation) in an area was compared to the annual withdrawal of groundwater by household consumption.

$$P \cdot C \cdot A = Q \cdot n \pm r \quad (1)$$

P=precipitation C=coefficient of infiltration A=area
Q=specific withdrawal n=number of persons r=rest term

The part played by precipitation, which could infiltrate into the ground, the *coefficient of infiltration (C)*, is assumed to vary between different geological terrains (usually a fraction of 0.05-0.2). If the artificial discharge from the area (by pumping) was equal or higher than the recharge, water supply problems could not be avoided. The method was frequently used during the 1980s (Sund & Bergman 1983, Eriksson & Tilly 1984, among others).

The limitations of recharge and extraction

The recharge and discharge of groundwater are highly varying functions of the spatially and time-dependent distribution of precipitation, geological conditions, topography, type of land use and vegetation, housing and sanitary standards. Methods for recharge estimations in the most common soils in Sweden (in till) are given by Johansson (1987). Very little research, however, has been carried out regarding the recharge to rock. Bergman (1972) measured the loss of water during artificial sprinkling of water on bare hardrock outcrops, which only can give an approximate measure under fully saturated conditions. The flow from soil to rock is an even more uncertain variable. It can only occur at specific hydrogeologically conditions where a conductor in the rock is hydraulically connected to a conductive reservoir in the soil (Olofsson 1994).

In vegetation-covered areas of southern and central Sweden and Finland, groundwater recharge is assumed as small or negligible during the summer period, because the potential evapotranspiration greatly exceeds the precipitation (Fig. 1). Therefore, groundwater recharge in those areas usually occurs during the spring and autumn.

During winter, a considerable part of the precipitation is sometimes stored in snow and added to the infiltration during the snow-melting period. Although the potential groundwater recharge in the county of Stockholm is as high as 270 mm per year, the amount of groundwater that can be stored in the hardrock is much lower in reality. In practice, maximum discharge from the hardrock is limited by the kinematic porosity of the geological material, since a heterogeneous fractured rock and a heterogeneous till comprise drainable as well as non-drainable pores (Fig. 2).

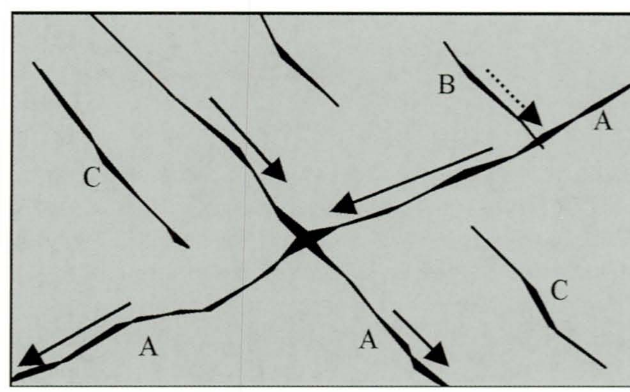

Fig. 2. Fractures in hardrock: A= drainable, flowing. B= drainable, no flow C= not drainable, no flow (Olofsson et al. 2000).

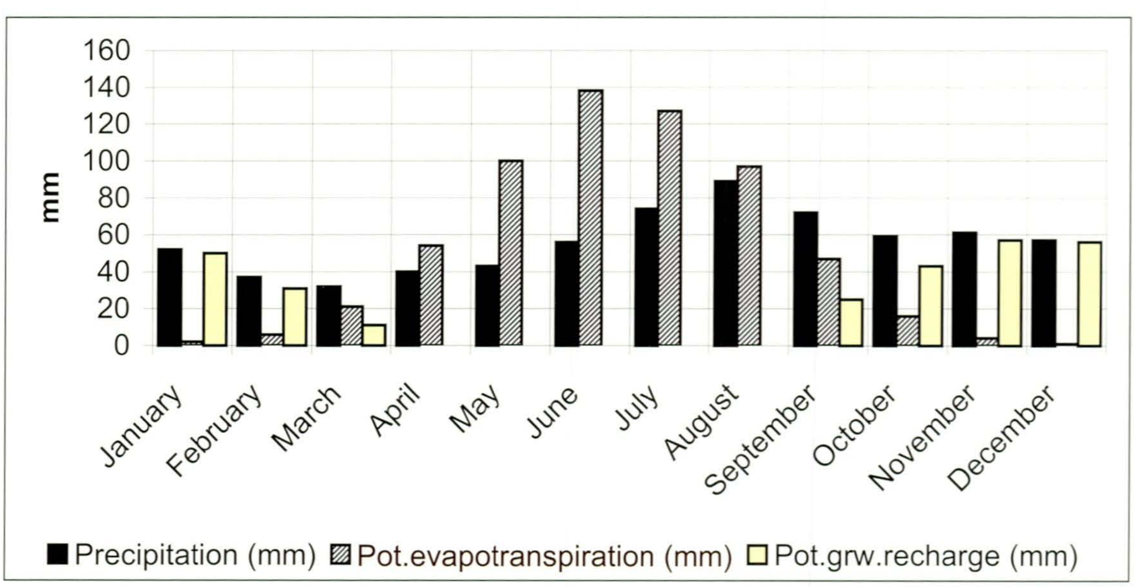

Fig. 1. Monthly available amount of water for infiltration in Stockholm county (based on data from Swedish Meteorological Hydrological Institute, SMHI).

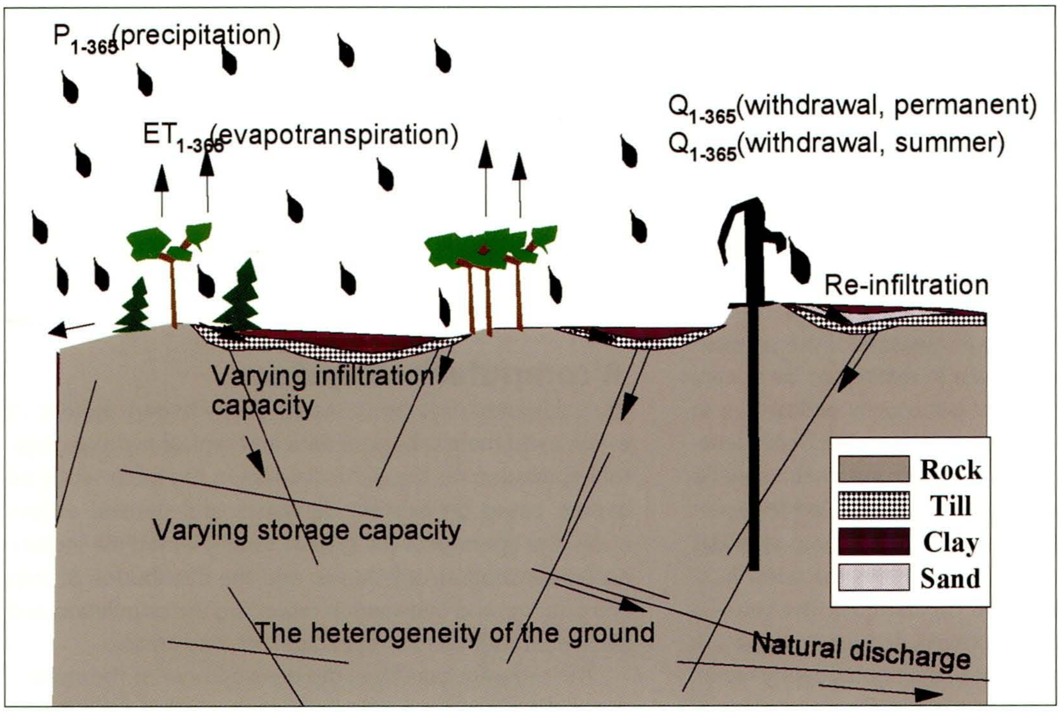

Fig. 3. A new groundwater balance approach; important factors.

The kinematic porosity in hardrock is very small, usually much less than 0.05% (Carlsson & Olsson 1981, Olofsson 1991); therefore, in practice, only a minor part of the potential recharge can be stored. In soil, however, the kinematic porosity (often similar to the effective porosity) is a hundred (in till) to a thousand (in sand) times higher, i.e. a 1 dm-thick layer of well-sorted saturated sand may contain as much drainable water as a one hundred metre thick sequence of hard crystalline rock. In areas of bare outcrops, such as along a great part of the Swedish coastline, this is a fundamental limitation for withdrawal of groundwater. Since much of the annual extraction within these particular areas is focused to the summer season, the groundwater resources are heavily stressed during this period.

An extended groundwater balance model

In order to take into consideration the limitations of recharge, withdrawal and storage capacities, a water balance model has been formulated and tested as part of the municipal planning of some areas in the archipelago of Stockholm. The requirements were that input data to the balance should be given from generalised literature values, from existing hydrometeorological data, from existing topographical and geological maps, and from official and unofficial information on sanitary standards, housing use, etc. The model should also take into consideration the actual storage capacities of the rock and soil. The extended groundwater balance is given in Fig. 3.

The balance can be mathematically formulated as:

$$\sum_{i=1}^{365} (\sum_{g=1}^{m} N_i \cdot \varphi_g \cdot A_g \cdot \tau_g = Q_i \cdot n_i \pm \sum_{g=1}^{m} \Delta S_{g,i} \quad (2)$$

$$N_i = P_i - ET_i + R_i (\text{if } N_i < 0 \text{ then } N_i = 0) \quad (3)$$

$$S_g = \sum_{j=1}^{h} \phi_j \cdot d_j \quad (4)$$

where:

P = Precipitation (mm)
ET = Evapotranspiration (mm)
N = Nett infiltration (mm)
R = Artificial recharge (mm)
φ = Infiltration factor (%)
A = Area (m^2)
τ = Homogeneity factor (%)
Q = Specific withdrawal (m^3)
n = Number of users
ΔS = change in storage (m^3)
ϕ = kinematic porosity (%)
d = thickness of the soil and rock layers (m)
j = 1,2 ...h are various soil and rock types at depth
g = 1,2...m are various soil and rock types at the ground surface

Withdrawal of groundwater is given as:

$$Q \cdot n = Q_p \cdot n_p + Q_s \cdot n_s \quad (5)$$

Q_p, n_p = permanent housing Q_s, n_s = summer housing

The groundwater levels may sometimes vary on a daily basis in very small aquifers. However, in practice, the groundwater situation as a whole is slowly changing due to seasonal variations and, hence, the groundwater balance is usually made on a monthly basis instead of daily, which makes the compilation of data easier.

Storage

The central part of the balance is the storage. For each surface soil (and rock), a stratigraphy is built up. If no information on the stratigraphy and soil thickness is given from borings, a typical *stratigraphy* is built up representing a stratigraphy which is common in the surrounding areas (a hydrogeological type setting). In eastern central Sweden, for example, clay usually covers a coarser soil, such as sandy-silty till, which in turn is resting on the fractured hard crystalline rock. Each stratigraphical unit is given typical values of *kinematic porosity* taken from the literature, a typical *thickness*, based on drillholes or general experiences and a typical *depth to the groundwater level*. However, all units beneath the uppermost unit are usually assumed as fully saturated. The *homogeneity* factor is a rough measure of the percentage of stored groundwater, which in reality can be re-captured. Some of the groundwater will usually be lost due to the natural groundwater discharge. Decreasing homogeneity means that it is much more uncertain whether a specific infiltrated amount of water really can be re-used for water supply. The factor depends on the geological material and is usually given values between 50 and 100%, the latter for a homogeneous sand and gravel. For hardrock the value is also affected by the fracture pattern, and several fracture sets in various orientations increase the homogeneity factor. When the storage is filled up, no further recharge occurs and when it is empty no discharge is possible.

Recharge to the storage

The *recharge* to the storage is given by the *precipitation* when it is exceeding the *potential evapotranspiration*. Therefore, in principal there is no recharge in areas with vegetation during the summer season. However, it is not impossible that some recharge may occur during the summer in hardrock outcrop areas, if the fractures are locally saturated during summer rains. Recharge occurs as long as the total storage is not filled up. When a state of full saturation is reach, recharge may continue but only with the speed of the natural and induced groundwater flow. In large parts of the Scandinavian countries, surface runoff is usually of minor importance except in hardrock outcrop areas, especially on steep slopes and on natural discharge areas, e.g. fens. However, after intensive rainfall and snow melting, the surface runoff may be considerable. Rodhe (1987) has shown that most of the water found in minor streams in Sweden emanates from groundwater. Hence, the *infiltration factor* given in the water balance (eq. 2), usually varies between 60% of the potential infiltration for a terrain with some parts consisting of clay, and 100% for areas consisting of sand and gravel. Different infiltration factors are usually set for various soils depending on the local conditions.

The values of precipitation and potential evapotranspiration are obtained from hydrometeorological databases as mean monthly values, but also values representing special dry conditions, e.g., 20 or 50 years return time, are used.

Furthermore, there is a possibility to include artificial recharge into the balance, such as collection of precipitation and percolation systems as well as re-infiltration of treated sewage water.

Withdrawal of groundwater

Many exploitational areas, especially summer housing areas, show a significant seasonal variation of groundwater extraction. Whereas our knowledge of water consumption in permanent housing areas with a high sanitary standard is quite good, there is a significant lack of information on consumption in summer cottages with varying sanitary standards. A distinction is made between the water consumption in summer cottages and in permanent houses, based on literature values and local experience (eq. 5).

A computerised system

The computer program consists of an 'expert system' in which hydrometeorological data and typical hydrogeological information for the particular region has been set by an 'expert', based on existing databases and general experiences. The operator of the system, usually within the municipal administration, only has to add the distribution of soils and outcrop, and information regarding the population and the sanitary standard of the actual housing areas.

The program calculates the development of the storage during the year. A specific balance modelling can also be carried out in order to calculate the maximum number of houses in a specific area, or the acceptable degree of permanent housing and sanitary standard with respect to the actual groundwater resources.

Examples from eastern Sweden

The groundwater balance model has so far been used within several areas in three municipalities in Stockholm county, Sweden (Fig. 4). Some basic information and results from the calculations are shown in Table 1, compared to the real experiences of the groundwater situation in the areas.

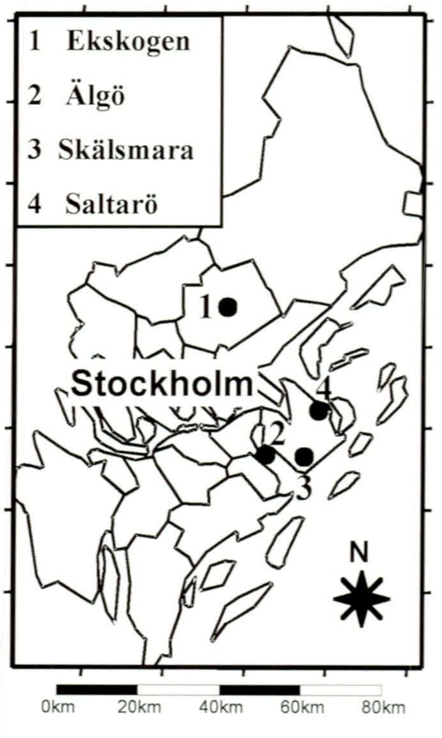

Fig. 4. The location of some examples of groundwater balances in the Stockholm area.

Table 1. Results from groundwater balance calculations within some areas in the vicinity of Stockholm.

Variable	Älgö	Ekskogen	Saltarö	Skälsmara
Reference	Olofsson (2000)	Jacks et al (2000)	VaiVa-projekt(2000)	(unpubl. 1997)
Municipality	Nacka	Vallentuna	Värmdö	Värmdö
Area (ha) total (netto)	200 (160) ha	160 (160) ha	510 (400)	350 (200)
No of houses	540	269	763	387
No of Persons per house	2.5	2.3	2.3	2.5
Degree of permanent housing (%)	35%	16%	28%	40%
Specific withdrawal (m^3)	Summer 100 L/p,d Perm. 180 L/p,d	Summer 100 L/p,d Perm. 150 L/p,d	Summer 150 L/p,d Perm. 200 L/p,d	Summer 150 L/p,d Perm. 200 L/p,d
Geology	Rock 80% Sandy silty till 10% Clay 10%	Rock 70% Sandy silty till 10% Clay 20%	Rock 57% Gravelly sandy till 9% Clay 32% Org.soils 2%	Rock 61% Sand 1% Clay 33% Org.soils 5%
Topography	0-50 m.a.s.l fairly rough	30-70 m.a.s.l. moderate	0-30 m.a.s.l. moderate	0-30 m.a.s.l. moderate
Minimum fill of storage Normal year (dry year)	39% (20%)	78% (73%)	78% (73%)	69% (60%)
Minimum fill of storage at 100% permanent housing Normal year (dry year)	0% (0%) model stops at 81% (51%) perm.houses	51% (31%)	60% (44%)	46% (25%)
Balance result (ann.) (Recharge/withdrawal)	1.17	1.51	1.52	1.31
Groundwater quality situation today	Moderate quality problems today (Cl^-, microbes)	No quality problems today (Cl^-, NO_3^-, PO_4^{3-})	Small and local quality problems (Cl^-)	Moderate quality problems today (Cl^-, microbes)

Although a true validation of the balance estimations has not, and probably cannot be carried out, the results from the balance calculations clearly correlate with the actual groundwater situation within the four presented areas. If the storage situation is not taken into consideration, an overestimation of the groundwater resources is the likely outcome. Such calculations using the simplified balance equation (eq. 1) at Älgö have given much higher recharge values and extraction possibilities (VIAK 1989). The HBV-model (Sanner 1995) at Ekskogen gave a theoretical groundwater recharge of 210 mm compared with the calculated available groundwater recharge of only 41 mm using the above balance approach (eq. 2-5). Still, the extraction of water from the area was less than 15% of the potential recharge (Jacks et al. 2000).

One area, Älgö, is already today very close to overexploitation. The balance modelling at Älgö indicates that the groundwater resources can also sustain specific dry years (with a recovery time of 20 years) with the current housing situation (65% summer houses). However, the proximity to Stockholm favours an increasing tendency towards permanent housing, which will definitely lead to stress on the water resources. Using a withdrawal value of 180 litres per person per day, the groundwater situation may collapse during specific dry years, and already when the permanent housing reaches 50% (Fig.5). The situation can then only be solved by artificially increasing the storage, decreasing the water consumption per person, desalination of seawater or connecting to the mainland district water supply. The two last-mentioned methods are very expensive since they

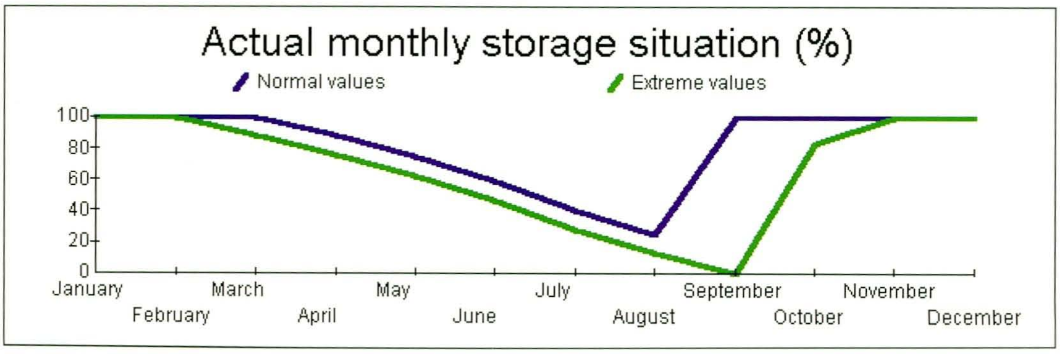

Fig. 5. Results from water balance calculations at Älgö. Development over time of the groundwater storage for normal years and specific dry years. The storage is empty when the permanent housing reaches 81% (normal years) and 51% (dry years).

require construction of a distribution network, mainly through rock blasting, instead of relying on today's private wells.

Re-infiltration of sewage water (grey water) was not considered here since withdrawal of groundwater was made in drilled wells and infiltration is usually carried out in the most superficial and unsaturated parts of the soil. Microbe analyses on groundwater from Ekskogen and Älgö indicate that there are no shortcuts between infiltrated sewage water and the wells (Jacks et al. 2000).

Discussion and conclusions

The groundwater balance approach presented above gives reasonable values of groundwater recharge and withdrawal possibilities in areas with limited groundwater resources, although a true validation is very difficult to carry out. The simplicity of the balance makes it easily understandable and it requires a limited amount of locally measured data, since much of the information needed can be collected from hydrometeorological databases, maps, general literature values and from local experience. Therefore, it can be used as a tool in municipal planning but only as an aid in decision making.

There are, however, several uncertainties, especially related to representative values of the homogeneity and infiltration factors. Further experiences from application of the water balance in various geological terrains will improve the selection of representative values.

Considerable emphasis should also be given to the typical geological sections for each type of soil. Stratigraphy will be the most important single factor, because the kinematic porosity varies with a factor of up to 10^4 between different geological materials. The stratigraphy must therefore be defined by an experienced hydrogeologist, and all available drillholes and previous experiences should be implemented. Another important factor, which requires detailed hydrogeological knowledge, is the delineation of the recharge area. The hydrologically defined drainage basins are generally dissimilar to the recharge areas of the specific wells, especially in hard rock areas with well-developed fracture zones. In many cases, the study area should also be further subdivided into sub-areas based on changes in the geological conditions. In all the examples presented above, no such subdivision was made since the terrain types were rather similar within the different areas.

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References

Aller, L., Bennet, T., Lehr, J.H. & Petty, R.J. 1987: DRASTIC – a standardised system for evaluation of groundwater pollution potential using hydrogeological settings. Report. *U.S.Environmental Protection Agency*.

Bergman, G. 1972: Bestämning av infiltrations-koefficienter för bergytor och perkolationsbanor i jordlager (Estimation of infiltration coefficients in the bedrock and percolation pathways in soil). *University of Stockholm, Dept.of Quaternary Geology*, Final report STU 69-519/U386. (In Swedish)

Carlsson, A. & Olsson, T. 1981: Hydraulic properties of a fractured granitic rock mass at Forsmark, Sweden. *Sveriges geologiska undersökning* Ser C 783, Uppsala.

Eriksson, U. & Tilly, L. 1984: Översiktlig bedömning av risken för saltvatteninträngning på Djurö, Värmdö kommun (Estimation of the risk for saltwater intrusion at Djurö, municipality of Värmdö). *Report, K-konsult*. (In Swedish)

Follin, S. 1995: Geohydrological simulation of a deep coastal repository. *Swedish Nuclear Fuel and Waste Management Co. Technical Report* 95-33.

LeGrand, H.E. 1983: A standardized system for evaluation waste-disposal sites. Report. *National Water Well Association*, second edition.

Jacks, G., Forsberg, J., Mahgoub, F. & Palmqvist, K. 2000: Sustainability of local water supply and sewage system – a case study in a vulnerable environment. *Ecological Engineering 15*, 147-153.

Johansson, P-O. 1987: Estimation of groundwater recharge in sandy till with two different methods using groundwater level fluctuations. *Journal of Hydrology 90*, 183-198.

Lindberg, J. & Olofsson, B. 1997: Risk för salt grundvatten – en studie med hjälp av GIS över delar av Norrtälje kommun (Risk for saline groundwater – a study using GIS in Norrtälje municipality). Research report. *Royal Institute of Technology (KTH), Norrtälje municipality and Swedish Geological Survey*. (In Swedish)

Olofsson, B. 1991: Groundwater conditions when tunnelling in hard crystalline rocks - a study of water flow and water chemistry at Staverhult, the Bolmen tunnel, S Sweden. *BeFo, Research report 160*: 4/91.

Olofsson, B. 1994: Flow of groundwater from soil to crystalline rock. *Applied Hydrogeology, vol. 2, no 3*, 71-83.

Olofsson, B. 2000: Om VA-frågan på Älgö (About water and sewage water on Älgö). Summary of presentation at Nacka municipality 2000-04-05. Report, *Division of Land and Water Resources, Royal Institute of Technology (KTH), Stockholm*. (In Swedish)

Olofsson, B., Jacks, G., Knutsson, G. & Thunvik, R. 2000: Groundwater in hard rock – a literature review. In Nuclear waste state-of-the-art reports 2001. *Swedish National Council for Nuclear Waste (KASAM). SOU 2001:35*, 115-191.

Rodhe, A. 1987: The origin of streamwater traced by oxygen-18. Doctoral dissertation, *University of Uppsala, Division of Hydrology, Report A 41*.

Sanner, 1995: Better decision basis with effective precipitation. *Grundvatten 2/95. Geological Sveriges geologiske undersökning, Uppsala*. (In Swedish)

Sund, B. & Bergman, G. 1980: Saltvatteninträngning i bergborrade brunnar. (Saltwater intrusion in drilled wells). *Swedish Environmental Research Institute (IVL), Report B 584*. (In Swedish)

Sund, B. & Bergman, G. 1983: Furusund – grundvattenprognos (Furusund – groundwater prognosis). *Swedish Environmental Research Institute (IVL)*, Report to the municipality of Norrtälje. (In Swedish)

VaiVa-projekt, 2000: Saltvattenutredning för Saltarö (Saltwater investigation at Saltarö). Report to *Värmdö municipality 2000-07-31*. (In Swedish)

VIAK, 1989: Balansberäkning av grundvattenbildning och uttag inom Älgö (Estimation of groundwater recharge and discharge at Älgö). *Report to Nacka municipality, 1989-04-10. VIAK AB*. (In Swedish)