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RESEARCH ARTICLE

Groundwater vulnerability assessment and protection measures - an example from Sweden

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Abstract: The purpose of this study is to highlight the importance of groundwater vulnerability assessment and the need for groundwater protection measures. An example is taken from the Tanum Municipal area in Sweden and a case study was conducted with the available data on boreholes, water levels and chemical analysis. The case study included fieldwork on the site, observation of lineaments and aerial photographs, land use maps, drainage patterns and bedrock characteristics. The private owners in general do not site boreholes according to the scientific investigations resulting in low yield for the boreholes on average. The indiscriminate drilling of wells close to the coast induces seawater intrusion. Groundwater quality of the boreholes for the parameters such as pH, Chloride, Magnesium, Potassium, total hardness, Nitrate and Fluoride were analysed. The results showed that the poor groundwater quality in most of the boreholes is due to poor well construction and indiscriminate construction of wells close to contaminant sources without knowing the hydro geological background of the study area. A classification system was used based on the characteristics of lineaments and the other aquifer parameters. Then aquifer vulnerability classes and the protection zones were derived based on the results. It was revealed that the area was vulnerable and therefore, protection and legislative measures are important to control further deterioration of the groundwater resources. This study would be useful in developing of the vulnerability zones and protection zones for groundwater.

Key words: Groundwater chemistry, lineaments, protection, vulnerability.

INTRODUCTION

The vulnerability of an aquifer to groundwater contamination is in large part a function of the susceptibility of its recharge area to infiltration. Areas that are replenished at a high rate are generally more vulnerable to pollution than those replenished at a slower rate. Unconfined aquifers that do not have a cover material are susceptible to contamination. Bedrock areas with large fractures are also susceptible by providing pathways for the contaminants. Confined, deep aquifers tend to be better protected with a dense layer of clay material. Wells that connect two aquifers increase the chance of cross contamination between the aquifers.

In addition to serving as a source of drinking water, a well can act as a direct pathway for pollutants from the land surface into the water supply. Thus a major consideration in ground water contamination is the position and condition of the well. Most of the contaminants that commonly cause concern originate above ground, often as the result of human activities.

Soil overlying the water table provides the primary protection against groundwater pollution. Bacteria, sediment and other insoluble forms of contamination become trapped within the soil pores. Some chemicals are absorbed or react chemically with various soil constituents, thereby preventing or slowing the migration of these pollutants into the groundwater. In addition, plants and soil microorganisms use some potential pollutants, such as nitrogen, as nutrients for growth, thereby depleting the amount that reaches the groundwater. Large amounts of potential pollutants concentrated in a small area can cause localized ground water contamination, depending on the depth and type of soil above the water table.[1]

To protect water wells against contamination, it is important to use the natural protection provided by soil maintaining adequate separation distances between wells and potential sources of contamination.[2] After an aquifer has been contaminated it is difficult to entirely define or isolate a contaminant plume. It is also difficult and extremely costly to remove it. Even after the source of contamination has been removed, an aquifer may remain contaminated for a period from a few years to a few centuries. Thus, it is often unrealistic to talk about a 'cure' for groundwater contamination. Prevention is the key, and prevention includes finding major potential sources of contamination.[3]

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Therefore, studies that develop groundwater vulnerability and protection zones based on the available quantity and quality data for different groundwater potential areas is needed to formulate guidelines and policy aspects to avoid environmental hazards to groundwater resources. The overall objective was to study the vulnerability of the aquifer and to recommend protection measures for the study area (Figure 1). To achieve this objective the following steps were carried out:

1) Study on the chemical properties of the groundwater of the project area
2) Explain the possible sources of pollution
3) Identify the aquifer vulnerability zones of the project area
4) Delineate the different groundwater protection zones of the project area
5) Recommend the protective and remedial measures

METHODOLOGY

Background information of the project area

Location: This study was conducted in Tanum Stand, Sweden (Figure 1). Tanum Strand is located 490 km away from Stockholm (west ward) and is a tourist resort. It is a small world in itself and is situated directly by the sea, 2 kilometres south of Grebbestad and is surrounded by archipelago. It resorts under the Tanum Hede Municipality, which is populated with 12,000 inhabitants.

The main occupation of the people is fishing followed by the wood industry. It is also important to note that rock carvings of the Bronze Age are in the Tanum municipality area and was declared a UNESCO world heritage site. These carvings are in danger of being totally dissolved by acid rain and measures are being taken to slow down the dissolution of the rock around the carvings by covering the carvings with roofs. The acid rain problem is also of interest to this study as it may have impacts on groundwater pollution via widely open fractures in the aquifer. The environment is of great concern to the Tanum Municipality and they actively work towards ecologically sustainable solutions. i.e. ecological sanitation (urine separation toilets), pollution control from industries, bio fuel for cooking and heating, the use of solar energy and heat energy from boreholes to protect the environment and the groundwater.

Land use: Land use in the Tanum municipal area is mainly for forestry and agriculture (on small scale) on open land (Figure 2). Small areas are used for town development. The towns are mainly confined to the coastal areas. The eastern side of the study area is covered with forest and the western side has mostly open land. A small extent of wetland runs across the study area.

Geology: When the bedrock in Sweden started to be formed, the earth was already more than one and a half thousand million years old and had a crust that was largely similar to the one that is known today. The bedrock seen in the geological map is a two-dimensional surface mosaic of rocks (Figure 3). Most rocks have formed under completely different conditions than those prevailing today in Sweden.[4] The bedrock would have formed at great depths in the earth crust or in the sea long days before. Mountain-building processes may have placed the originally horizontal layers in a vertical direction and magmas might have intruded the older rock types. Weathering and erosion have subsequently exposed structures that have been hidden for million of years.[5] Another complication arises when attempting to interpret the bedrock geology because for long periods Sweden was located at latitudes with completely different climatic conditions than the current conditions.

The clay occurs on top in the sequence and the granite at the deepest lithological level. In most places close to the coast the basement rock, the Bohus granite, is encountered at a relatively shallow depth. Fracturing occurs extensively over the area and is due to several tectonic events. Preferential extensive fracturing resulted in large fracture zones oriented in a west-east direction and also a set of fractures oriented in a north-south direction. The west-east oriented fractures formed due to the Alpine orogenic push (from a southerly direction) and the north-south fractures occurred due to the North Atlantic Ridge push (from a NW direction).

Thrust or strike-slip faulting occurred in the areas that experienced the most stress, which mostly covers the Tanum municipality area. The least stressed zones (where extension occurred) are situated more to the south of Sweden, with larger intrusions of dolerite in these areas.

The intrusion of dolerite dykes that did occur in the Bohus granite is mainly along the coastline. The development of the dykes was due to stress release along the coast and the dykes occur where the largest fractures also formed.

A last set of fractures also found in the granite, which is not vertical but horizontal, are the most important fractures to consider for large yielding wells. These fractures occurred due to stress release when uplifting occurred at the end of the last glaciations.

Geohydrology: As shown in Table 1 the porphyritic granite has the highest hydraulic conductivity value, because it contains porphyroblasts or openings in the rock, which if they are connected can result in a high

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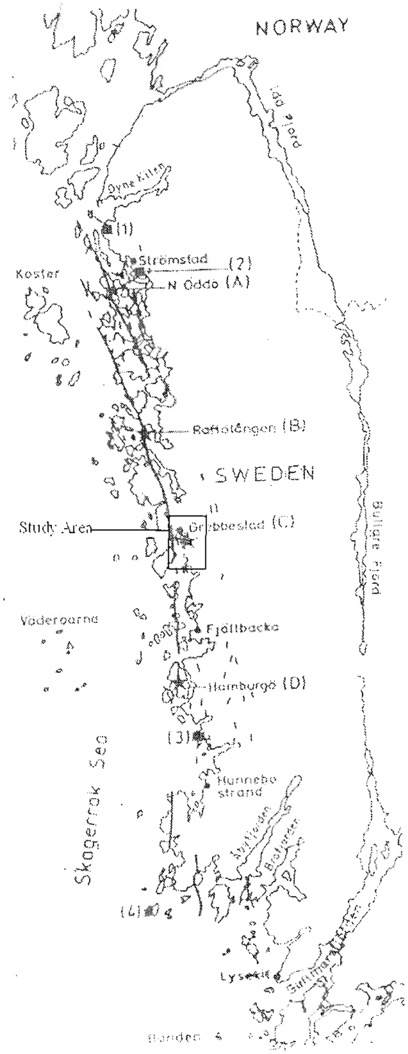

Figure 1: Study area in Sweden

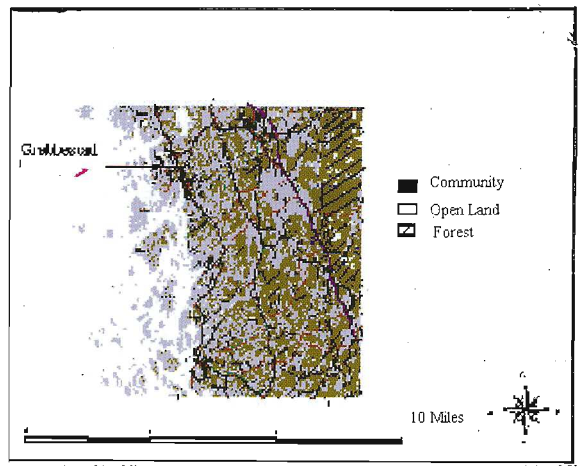

Figure 2: Land use map of the study area

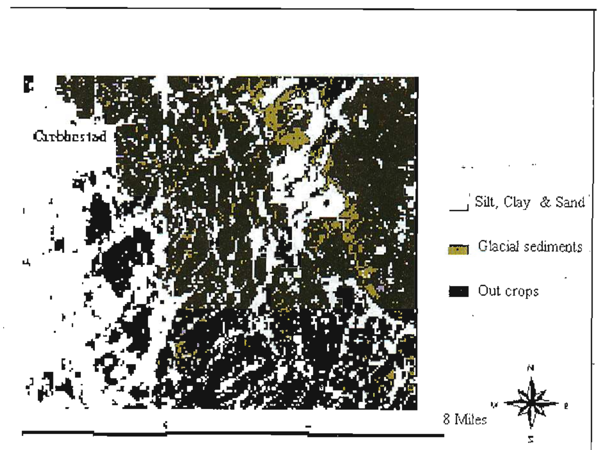

Figure 3: Geology of the study area

The Tanum municipality area consists the following lithologies:

Clay	–	covers a very small percentage of the area
Silt	–	covering 40 percent of the area mostly in low-lying valleys
Sand	–	covering 10 percent of the area, confined to areas close to the coast, in fracture zones
Gravel and rocks	–	to a less extent
Glacial sediments	–	small amounts of glacial sediment cover the area
Till and clay	–	small amounts cover the area
Basement granite	–	covering 45 percent of the area.

yielding aquifer. Grey and red granite has the second highest value because it contains no voids, as in the porphyritic granite, but is still higher than the metabasites because it is more coarse-crystalline than the metabasites. The coarseness of the crystals depends on the cooling time and chemical composition of the rock.

The aquifers encountered in the Tanum area are the following:

i The aquifers in hard rock – Granitic basement rock consisting of a lot of fractures.

ii The aquifers in glaciofluvial deposits – some of the most important groundwater resources in Sweden.

On average, wells drilled into the crystalline rock yield 600 – 2000 L/h.[6] Yields up to 730,000 L/h have been noted in the glaciofluvial deposits.

Field Work: This study was mainly based on the available data of the study area and fieldwork for a period of 3 months from April to June, 2002 analysing the lineaments, aerial photos and remote sensing maps which contained 42 bore holes (Figure 1). During the field work the aerial photographs were analysed with actual field observations on lineaments. Pumping tests were conducted in 5 selected bore holes and compared with the available data. Geophysical studies were conducted to compare the locations of wells. The following data were used for analysis.

1) Geophysical and hydrogeological maps
2) Data on boreholes
3) Assessment of the chemical analysis of the boreholes on pH, Chloride, Magnesium, Potassium, Total Hardness, Nitrate and Fluoride.
4) Land use maps

Chemical analysis was done in the Swedish Geological Survey Laboratory. Samples were collected using depth samplers at three depths after well construction. pH and total hardness were measured by the pH meter and the portable water quality kit. Chloride, Magnesium, Potassium, Nitrate and Fluoride were analyzed by colorimetric methods using the UV/ Visible Spectrophotometer.

All the available data on the study area and the data collected during the field work were analysed and interpreted. Based on the results the study area was delineated into vulnerability and protection zones.

RESULTS AND DISCUSSION

Borehole Yield

A statistical representation has been made of the borehole data of the Tanum Municipality Area. The median yield of 42 bore holes in this area is 200 L/h, which is much lower than the estimates done by the Swedish Geological Survey (SGS). It could be possible that wells were in general not sited using scientific methods, resulting in a statistically low yield for the boreholes on average. Some high yielding boreholes occur but are very limited, such as 8 000 and 10,000 L/h. It cannot be concluded that the high yielding boreholes are situated in glacio-fluvial deposits, since data on geological logs are not available.

Chemistry of the groundwater

Chemical analysis of groundwater was done on 10 randomly selected wells. However, the data was not adequate to conduct statistical analysis. Chemical constituents and parameters taken into consideration were pH, Chloride, Magnesium, Potassium, Total Hardness, Nitrate and Fluoride.

pH: In the study area the lower range of pH (5.2-5.6) was observed close to Tanum Hede and a high pH value of 7.7 to 8.1 was observed in wells west of Grebbestad. The low pH may be due to a variety of factors, such as acidic granite or due to industries or acid rain. Land use in this area is open land and there could be some industrial pollution. The high pH in one well west of Grebbestad showed the trends of typical salt-water intrusion. To confirm this interpretation it is necessary to analyze the composition of this water and check whether it has the typical chemical composition of saltwater, such as a high value for chlorides.

Chlorides: A normal distribution for chloride values was observed over most of the study area (values that range from 10 – 32 mg/L) except the anomalous values (Figure 4).

Table 1: Variations in exploitation potential of groundwater in different rock types

Rock type	Median capacity (L/h)	Regional hydraulic conductivity (m/h)
Bohus granite	400	2.4×10^{-8}
Porphyritic granite	500	3.4×10^{-8}
Metabasites	320	1.5×10^{-8}
Grey and red granite	400	2.7×10^{-8}

Source: Swedish Geological Survey, 2002

1) In a well situated west of Grebbestad the chloride value was as high as 1700 mg/L. In the same well, a high pH was observed.

2) In the south-eastern corner of the study area (340 mg/L).

In the case of Grebbestad the high chloride value correlates well with the high pH value, and if all other typical saltwater constituents were included in the analysis, it can be deduced that the high chloride values in this well may be due to salt-water intrusion.

The cause of the high Chloride value for the second case is uncertain. Geological information of this area is insufficient, thus the origin of this water may be geologically induced. It may be connate (old fossilised) water from a very deep origin or may be attributed to industrial activities. The borehole is too far from the sea (11-12km) for salt-water intrusion. The depth of the borehole is 82 m, which is deeper than the average borehole of 40-60 m drilled in the area, thus it may be fossilised water that has been encountered.

Magnesium: High values of Mg were observed in two boreholes in the study area, one borehole in the north and the other in the southwest (Figure 5). High magnesium values for the northern borehole may be due to geological factors but cannot be determined from the existing data. High magnesium values for the southern borehole can be linked with a high value for potassium in the same borehole. This may mean that the borehole penetrated rocks consisting mostly of (acid) granite with a high occurrence of the mineral orthoclase. Orthoclase is a mineral that weathers easily and may contribute to the high values of magnesium and potassium in the borehole.

Potassium: High potassium values were found in the same southern borehole where high values of magnesium have been encountered. A normal distribution of potassium values was observed in the rest of the study area.

Total hardness: The total hardness was high in most of the boreholes where seawater intrusion has been experienced. Total hardness relates to ions in solution, especially to calcium and magnesium and it can be seen that the well, which has experienced seawater intrusions, has the highest total hardness.

Nitrate: High values of nitrate (12 mg/L) were encountered in a well almost in the centre of the study area (Figure 6). This shows an oxidising environment in the well and it is also a sign of microbial contamination. Maximum allowable limit of nitrate concentration for drinking water is 10 mg/L[7]. Nitrate concentration of more than 10 mg/L may cause blue baby syndrome in pregnant mothers. However the majority of the wells are with NO_3^- concentration lower than 1mg/L. Nitrate contamination could result from agricultural practices. However, the cause of the high nitrate concentration is possibly not due to agricultural practices as this borehole occurs in an afforested area and phosphate does not occur in conjunction with the nitrate as a typical indication of agricultural contamination. It must, however, be stressed that analysis for phosphate has not been carried out extensively over the whole area for a definite conclusion.

Another option is that the contamination of the well may be due to the placement of the well close to a septic tank or pit latrine. It is recommended that this well not be included in the groundwater background-monitoring network, as this well has been contaminated. A clean well in proximity can be analysed instead to get background information of the groundwater regime that governs the specific area.

Fluoride: Fluoride is encountered extensively all over Sweden and especially in the granitic outcrop areas. Fluoride is a key element of many minerals occurring in granite, such as apatite and fluorite. Of the wells that have been tested in the area, some have fluoride concentrations as high as 3.4 mg/L in the groundwater (Figure 7). The well in the northern part of the study area contains 3.4 mg/L and the well to the south contains 2.1 mg/L; both are above the acceptable standard for fluoride in drinking water limit of 1 mg/L.[9] However the fluoride distribution indicates that about 83% of the samples were below 1 mg/L.

Referring back to the potassium and magnesium contour maps, it can be seen that the same boreholes that have high concentrations of potassium and magnesium also have high fluoride concentrations, which is a definite sign for granite being the host dissolution rock. Very high levels of fluoride may cause osteoporosis or induce severe skeletal damage such as brittle bone disease.

Aquifer vulnerability

Aquifer vulnerability is the probability of groundwater pollution in the event of a pollutant release at the ground surface. Susceptibility is a qualitative measure of the relative ease with which a groundwater resource can potentially be contaminated by anthropogenic activities and includes both aquifer vulnerability and the relative importance of the aquifer in terms of its classification. There is a standardized system called DRASTIC model[9] where the aquifer vulnerability is determined within hydro geological settings based on depth to the groundwater, recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. However, there are several other methods such as classification of lineaments,[10] using GIS and Remote sensing techniques.[11,12] Groundwater vulnerability can also be assessed using logistic regression.[13] In this study classification of lineaments based on geo-hydrological factors are considered.

The aquifer in the Tanum area is especially vulnerable as the thickness of overburden above the outcrop in some areas is not very significant. The overburden serves as a protective layer (the unsaturated zone) above the water table. Where the unsaturated zone is small (due to too little overburden or a shallow water table), the aquifer is much more susceptible to pollution than otherwise. In the Tanum area the water table is shallow and the overburden is relatively thin. The bedrock is exposed in 45% of the study area and fractures

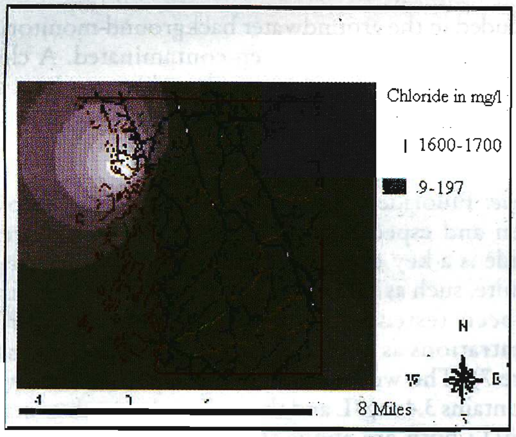

Figure 4: Chloride variation of the study area

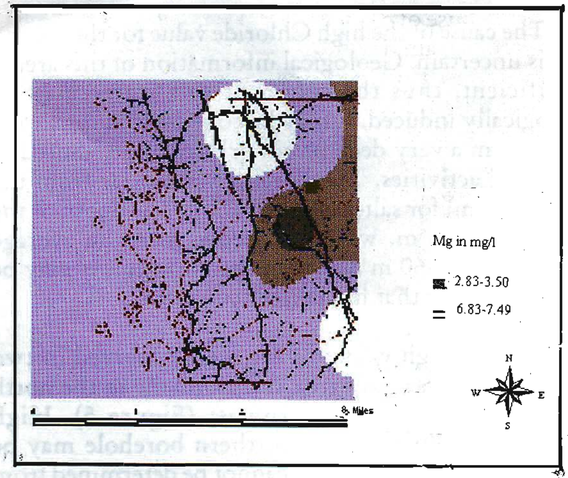

Figure 5: Magnesium content variations in the study area

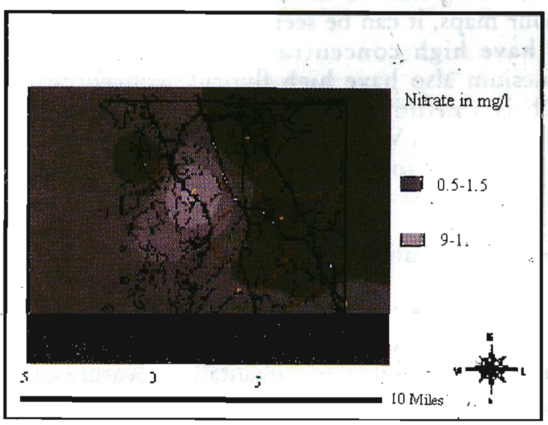

Figure 6: Nitrate content variation over the study area

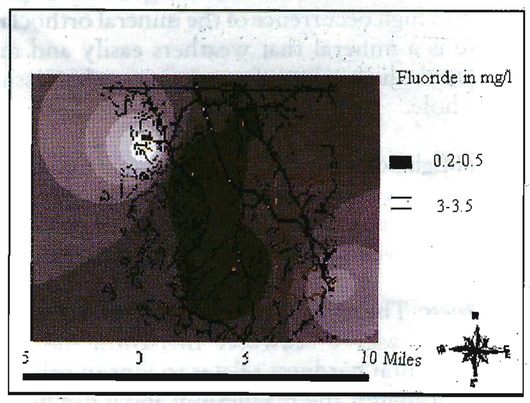

Figure 7: Fluoride content variations in the study area

are in direct contact with the surface. These fractures serve as direct pathways between the surface and the aquifer. In addition to the above, Tanum experiences high annual average rainfall of 700 mm during the whole year and with fractures in contact with the surface, recharge will be very high (which makes the aquifer more vulnerable at the same time more dilution of the pollution). All of the above in an aquifer that does not allow for long residence time has a low attenuation potential.

Classification of lineaments

Lineaments have been outlined and classified based on the length, thickness and the field observations and other yield data of the boreholes (Figure 8). The classes are as follows:

Class 1 Large lineament with a considerable length. It was however determined that these fractures are not as high yielding, these lineaments occur mostly in the valleys and coincide with the N-S and E-W fracturing that formed during orogenesis. Processes involved in the formation of the fractures have been explained in the sub heading of geology in this paper.

Class 2 Thinner lineaments, which are also shorter and may have formed during other stages of deformation that can be seen on the orthophoto as lines where tree growth covers the fractures.

Class 3 The shortest and thinnest lineaments, which can only be seen in outcrops. These lineaments have not been inferred to have a high yield potential since their fracture aperture is too small.

It was attempted to see whether there is any connection between the lineaments and the yields. It could only be concluded that none of the high yielding boreholes were situated on the Class 1 fractures (in the valleys). The reason for this may be that the main fracture zones have been extensively grounded to form mylonite and clay in the fracture zones. These large fracture zones formed due to orogenesis and resulted from strike-slip faults where mylonite will form extensively on the slip plains.

The one high yielding borehole (10 000 L/h) occurs on Class 2 lineaments, which may not be as extensively mylonised. No high yielding boreholes were observed in association with the Class 3 lineaments, as these fractures may have too small fracture apertures to be significant aquifers.

Delineation of aquifer vulnerability zones

The following factors were considered in mapping of the aquifer vulnerability (Figure 9).

1. Occurrence of lineaments (fractures)
2. Areas with basement rock outcrop
3. Location of surface water bodies
4. Areas of preferential recharge
5. Economically important aquifers (associated with glacio-fluvial sediments)
6. Closeness to the sea

Aquifer vulnerability area 1 (AVA1):

Areas where Class 2 and 3 lineaments occur and have basement rock outcrops have been classed as AVA 1. Such areas may serve as high recharge areas that will increase the risk of aquifer pollution significantly. Aquifers close to the coast that occur in association with fractures were also classed as 1 due to the high probability of seawater contamination in these areas. The well located west of Grebbestad has high chloride, total hardness, calcium and magnesium, showing seawater contamination. It shows that the well is located in the AVA1 which has a high probability of seawater contamination. In addition the well located in south of Grebbestad too is within the AVA1 which too has higher values of chloride, Nitrate and Magnesium. This shows that the well located in the Class 2 and 3 lineaments of high recharge areas has a high risk of aquifer pollution.

Aquifer vulnerability area 2 (AVA2):

Areas where Class 1 and 2 lineaments occur, the basement rock does not outcrop and recharge is thus lower than in vulnerability areas classed of as 1 were classified as AVA2. Also included as AVA2 are the till areas which serve as an aquifer of high economic value, but has a relatively large attenuation capacity due to a larger amount of overburden than areas where the Bohus granite outcrops occur.

Aquifer vulnerability area 3(AVA3):

AVA3 takes into account areas where Class 1 lineaments occur (that due to clay layers and overburden may have higher attenuation capacity than the rest of the areas) and also more inland areas where large clusters of lakes are found that may be connected to aquifers. Human activity is less pronounced (forests cover this area) and the possibility of pollution is thus greatly reduced in this area. The wells located in this area have not recorded higher values of the chemical parameters tested in this study.

Protection zones

Protection zones around boreholes should be much larger than what is normally recommended and should be determined by using, for example, a model such as DRASTIC. The rule for protection zones around a well is 30-50 m, but the zone of protection should depend on the local geological situation. Care should be taken not to install a septic tank / pit latrine which has the potential to pollute the groundwater in the immediate vicinity, if it is close to a major fracture. Although it is the common belief that fractures close with depth, weathering on the surface may make fractures appear smaller than they really are (by having weathered material inside the fractures), and these fractures may gain aperture with depth up to a certain level. In such an area it might be advisable to increase the protection zones around boreholes up to 100-200 m, where the zoning will also depend on the horizontal and vertical extent of the fractures encountered.

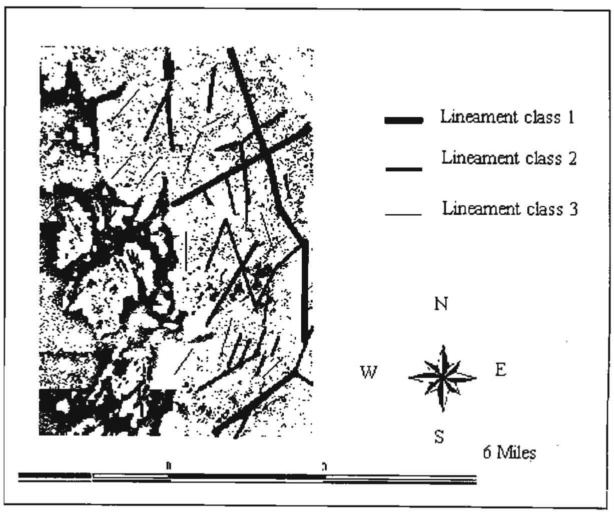

Figure 8: Lineaments on air photos

Protection zones around some of the boreholes have been assigned as follows:

Radial zones around the boreholes, with the first zone up to 100 m, the second up to 200 m.The radial distance for the zones has been chosen as 100 m because the high intensity of fracturing of the Bohus granite. It was thought that the normal 30-50 m protection zones would be insufficient.

Definite protection zones, classed as protection zone 1 and 2:

Protection Zone 1: Boreholes that intercept Class 3 lineaments (small fractures) and Class 2 lineaments that occur in the outcrop areas, which may serve as high recharge zones, are included as high-risk zones around boreholes. These areas are thus very vulnerable, more so than the lineaments, which are covered by vegetation or that has a protective clay layer (in the valleys where agriculture occur). Also areas are included where many small lakes occur, as these lakes coincide with the Class 3 lineaments.

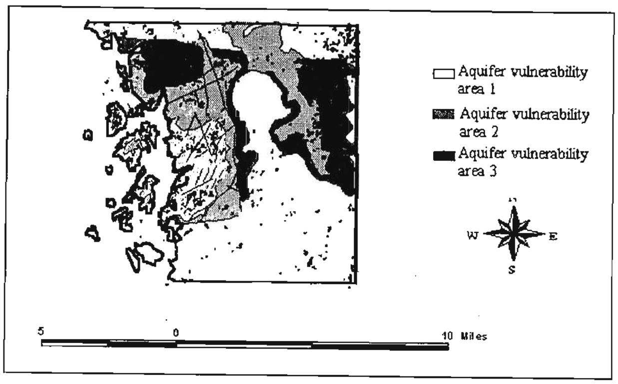

Figure 9: Delineation of aquifer vulnerability zones

Protection Zone 2: Zones where Class 2 or Class 1 lineaments occur near a borehole that is covered by vegetation and a protective layers is present above the bedrock.

CONCLUSION

Borehole yield data shows that the yield of the wells in the study area is much less than the estimated values by the Swedish Geological Survey. This concludes that most of the boreholes were not sited using scientific methods, resulting in low yield for the boreholes on an average. Private owners drill wells and abstract water without taking into consideration the possible pollution sources.

Contour maps based on the available data from boreholes on groundwater chemistry showed that vulnerability of aquifers was due to poor well construction and indiscriminate construction of wells close to contamination sources without knowing the hydrogeological background of the study area.

The lineaments (fractures) have been classed according to their inferred significance as potential aquifers. It has been observed that the Class 2 lineaments yield overall the largest amount of water and these areas should thus be protected. The Class 1 lineaments did not seem to yield much water and this may be due to mylonisation. If mylonisation is the cause, these areas may have a greater buffering capacity than the other classes of fractures in that they have an inherent clay layer above and in the fractured zone. The Class 3 fractures (small fractures that *outcrop*) may be small, but still may have a great impact on the aquifer as they serve as large *recharge zones* to the aquifer. Therefore, Class 2 and 3 lineaments have been classed as highly vulnerable areas and areas where Class 1 and 2 lineaments occur are classed as moderately vulnerable areas. The area that covers the Class 1 lineaments is classed as the low vulnerable area. Accordingly, the Protection zone 1 covers the area of Class 2 and 3 lineaments and Protection zone 2 covers the areas where Class 2 or Class 1 lineaments occur near a borehole.

Recommendations

The indiscriminate placement of wells close to contamination sources such as sea, latrine, industry etc. should be controlled. Proper well construction and maintenance is necessary according to the scientific investigations that were conducted.

This case study could be used as an example and the vulnerability and protection zones must be developed for Sri Lankan aquifers to introduce proper legislation which would control the following activities based on the vulnerability and protection zone demarcations:

i. Private boreholes should not be located in highly vulnerable areas.
ii. Keeping of proper inventories of boreholes in the area and improvement of the geological database
iii. Proper storage and use of chemicals e.g. pesticides, insecticides and fertilizers especially on farms
iv. Develop regional groundwater monitoring network

The success of the groundwater protection programme however will depend on the general awareness of the community regarding the risk that negligent actions can cause to the environment and the groundwater.

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