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# Modelling groundwater discharge areas using only digital elevation models as input data

Lars Brydsten, Umeå University

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**Svensk Kärnbränslehantering AB**
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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*Keywords:* Groundwater, Discharge areas, Digital elevation model, Geomorphometry, Biosphere, Surface ecosystem.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

# Abstract

Advanced geohydrological models require data on topography, soil distribution in three dimensions, vegetation, land use, bedrock fracture zones. To model present geohydrological conditions, these factors can be gathered with different techniques. If a future geohydrological condition is modelled in an area with positive shore displacement (say 5,000 or 10,000 years), some of these factors can be difficult to measure. This could include the development of wetlands and the filling of lakes. If the goal of the model is to predict distribution of groundwater recharge and discharge areas in the landscape, the most important factor is topography. The question is how much can topography alone explain the distribution of geohydrological objects in the landscape.

A simplified description of the distribution of geohydrological objects in the landscape is that groundwater recharge areas occur at local elevation curvatures and discharge occurs in lakes, brooks, and low situated slopes. Areas in-between these make up discharge areas during wet periods and recharge areas during dry periods. A model that could predict this pattern only using topography data needs to be able to predict high ridges and future lakes and brooks. This study uses GIS software with four different functions using digital elevation models as input data, geomorphometrical parameters to predict landscape ridges, basin fill for predicting lakes, flow accumulations for predicting future waterways, and topographical wetness indexes for dividing in-between areas based on degree of wetness.

An area between the village of and Forsmarks' Nuclear Power Plant has been used to calibrate the model. The area is within the SKB 10-metre Elevation Model (DEM) /Brydsten and Strömgren 2004/ and has a high-resolution orienteering map for wetlands. Wetlands are assumed to be groundwater discharge areas. Five hundred points were randomly distributed across the wetlands. These are potential discharge points. Model parameters were chosen with the geomorphometric model so that elevation ridges or peaks were given a maximum distribution without overlapping discharge points, the areas classified as "probably recharge areas". The hydrological model (ArcGis Hydrological modelling extension) predicted lakes and waterways; these areas were classified as "probably discharge areas". The topographic wetness index (TWI) was calculated for the entire calibration area. Statistics for the distribution of TWI areas for "most likely recharge areas" and "most likely discharge areas" were calculated. Hitherto unclassified areas with TWI values lower than the 3$^{rd}$ quartile for "most likely recharge area" (4.2) were classified as "probably recharge areas" and areas with higher TWI values than the 1$^{st}$ quartile for "most likely discharge areas" (7.9) were classified as "probably discharge areas". The remaining areas were classified as "undefined".

The model was validated with the same DEM, the localities map's wetlands and lakes (discharge areas), and soil map's exposed bedrock exposures (recharge areas) for the area immediately to the east of the calibration area. The models were run with the parameters the calibration gave and a map with five classifications was generated of the validation area. Another 500 randomly distributed points were assigned as discharge areas (lakes and wetlands) and the points were linked to the model map. The results showed that only 1.2% of the points were incorrectly classified, 3.4% were undefined, and 95.4% were correctly classified. Validation with exposed bedrock (recharge areas) gave lower results. 1.0% of the points were incorrectly classified, 13.8% were undefined, and 85.2% were correctly classified. The conclusion is that topography has a significant influence on the distribution of recharge and discharge areas in the landscape.

# Sammanfattning


Avancerade geohydrologiska modeller kräver data rörande topografi, jordarter i tre dimensioner, vegetation, bergets sprickighet mm. Vid modellering av dagens situation kan dessa data inhämtas med olika tekniker. Däremot vid modellering av en framtida situation i områden med possitiv strandförskjutning, säg om 5 000 eller 10 000 år, kan däremot flera faktorer vara svåra att förutse, t ex utvecklingen av våtmarker och igenväxning av sjöar. Om syftet med modellen är att prediktera fördelningen av inströmningsområden respektive utströmningsområden i landskapet är den viktigaste faktorn topografin, så frågan är i vilken grad topografin ensamt kan förklara fördelningen av de geohydrologiska objekten i landskapet.

En förenklad beskrivning av de geohydrologiska objektens fördelning i landskapet är att inströmningsområden förekommer i lokala höjdpartier och utsrömningsområden i sjöar, bäckar och lågt liggande sluttningar. Områdena emellan dessa utgör utströmningsområden under våta perioder och inströmningsområden under torra perioder. En modell som ska kunna prediktera detta mönster enbart med topografin som indata, ska ha förmågan att prediktera höjdryggar, blivande sjöar och bäckar. Den här studien har unyttjat GIS-program med fyra olika funktioner som använder digitala höjdmodeller som indata, geomorfometrisk parametrisering för att förutsäga höjdryggar, bassängfyllning (basin fill) för att förutsäga sjöar, flödesackumulering (flowacc) för att prediktera blivande vattendrag och topografiskt våthetsindex för att dela in mellanliggande områden efter blöthetsgrad.

Ett område mellan Forsmarks by och Forsmarks kärnkraftverk har använts för att kalibrera modellen. Området ligger inom SKB 10-meters höjdmodell (DEM) /Brydsten och Strömgren 2004/ och har en orienteringskarta med mycket hög upplösning för våtmarker. Våtmarker antas vara utsrömningsområden. Över våtmarksytorna slumpades 500 punkter, vilket får utgöra potentiella utströmningspunkter. Med geomorfometriska modellen valdes modellparametrar så att det som klassas som ryggar eller topppar fick en maximal utbredning utan att överlappa utströmningspunkterna, dessa ytor klassas som ”mycket troliga inströmningsområden”. Med den hydrologiska modellen (ArcGis Hydrological modeling extension) predikterades sjöar och vattendrag och dessa ytor klassas som ”mycket troliga utströmningsområden”. För hela kalibreringsområdet beräknades det topografiska våthetsindexet (TWI). Statistik för fördelningarna av TWI för ”mycket troliga inströmningsområden” och ”mycket troliga utströmningsområden” beräknades. Hittills oklassade områden med TWI-värden lägre än 75 %-kvartilen för ”mycket troliga inströmningsområden” (4,2) klassas som ”möjliga inströmningsområden” och områden med högre TWI-värden än 25 %-kvartilen för ”mycket troliga utströmningsområden” (7,9) klassas som ”möjliga utströmningsområden”. Kvarvarande områden klassas som ”odefinierade”.

Modellen validerades med samma DEM och fastighetskartans våtmarker och sjöar (utströmningsområden) och jordartskartans bergblottningar (inströmningsområden) för ett område omedelbart öster om kalibreringsområdet. Modellen kördes med de parametrar som kalibreringen givit och en karta med fem klasser genererades över valideringsområdet. Även här slumpades 500 punkter ut över de antagna utströmningsområdena (sjöar och våtmarker) och punkterna länkades till modellkartan. Resultatet blev att endast 1,2 % av punkterna var felaktigt klassificerade, 3,4 % odefinierade och 95,4 % korrekt klassificerade. Valideringen mot bergblottningar (inströmningsområden) gav något sämre resultat, 1.0 % av punkterna felaktigt klassificerade, 13,8 % odefinierade och 85,2 % korrekt klassificerade. Slutsatsen blir att topografin har mycket stor betydelse för fördelningen av in- och utströmningsområden i landskapet.

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# 1 Introduction and objective

The distribution of groundwater recharge and discharge areas in the landscape can be described simply as recharge areas at local heights and discharge areas at local depressions. The area in between the two can be a discharge area during wet periods and recharge area during dry periods. This simplified description depends on topography; however, advanced geohydrological models use many more factors such as soil distribution in three dimensions, vegetation, land use, and bedrock fracture zones. To model geohydrological conditions, these factors can be examined using different techniques. If a future geohydrological condition is modelled in an area with positive shore displacement (say 5,000 or 10,000 years), the data from some of these factors can be difficult to collect. Even if factors such as topography and fracture zones are more or less constant over time, factors like soil and vegetation distributions varying rapidly over time. If only the distribution of groundwater recharge and discharge areas are of interest, not flow pattern or flow velocities, can topography alone explain the distribution pattern?

Groundwater discharge points occur in existing surface waters (such as lakes and brooks) and in low angle slopes. These discharge areas often have special geomorphometrical characteristics. Looking down a slope, a person should see a concave curve. The curvature is perpendicular to the concave slope and this "channel" is narrower downstream /Grip and Rodhe 1985/. In addition, the catchments are large.

This study aims to develop a model that accurately predicts future groundwater recharge and discharge areas. The model needs methods for finding future lakes and brooks and methods for describing landscape curvatures. These methods have been developed in GIS-programs. For example, finding future lakes and brooks can be done using ArcGis 9 within the extension Hydrological modelling, and landscape curvatures can be calculated using the program LandSerf 2.1 /Wood 1996/.

This is a potential method for estimating future recharge – discharge patterns in areas where no other data than topography are available such as outside the present shoreline.

# 2 Data sets used for model evaluation, calibration and validation

## 2.1 Data sets used for evaluation and calibration

In this model, only a DEM will be used as input data, so it is important to choose a model area that has a DEM with the best possible accuracy. The SKB 10-metre DEMs in Forsmark /Brydsten and Strömgren 2004/ and in Oskarshamn are the most accurate DEMs in the SKB GIS-archive.

In Forsmark and Oskarshamn's 10-metre grids, there are no existing geohydrological maps so it was necessary to use indirect measurements from other maps of groundwater discharge areas such as wetlands, lakes, and brooks.

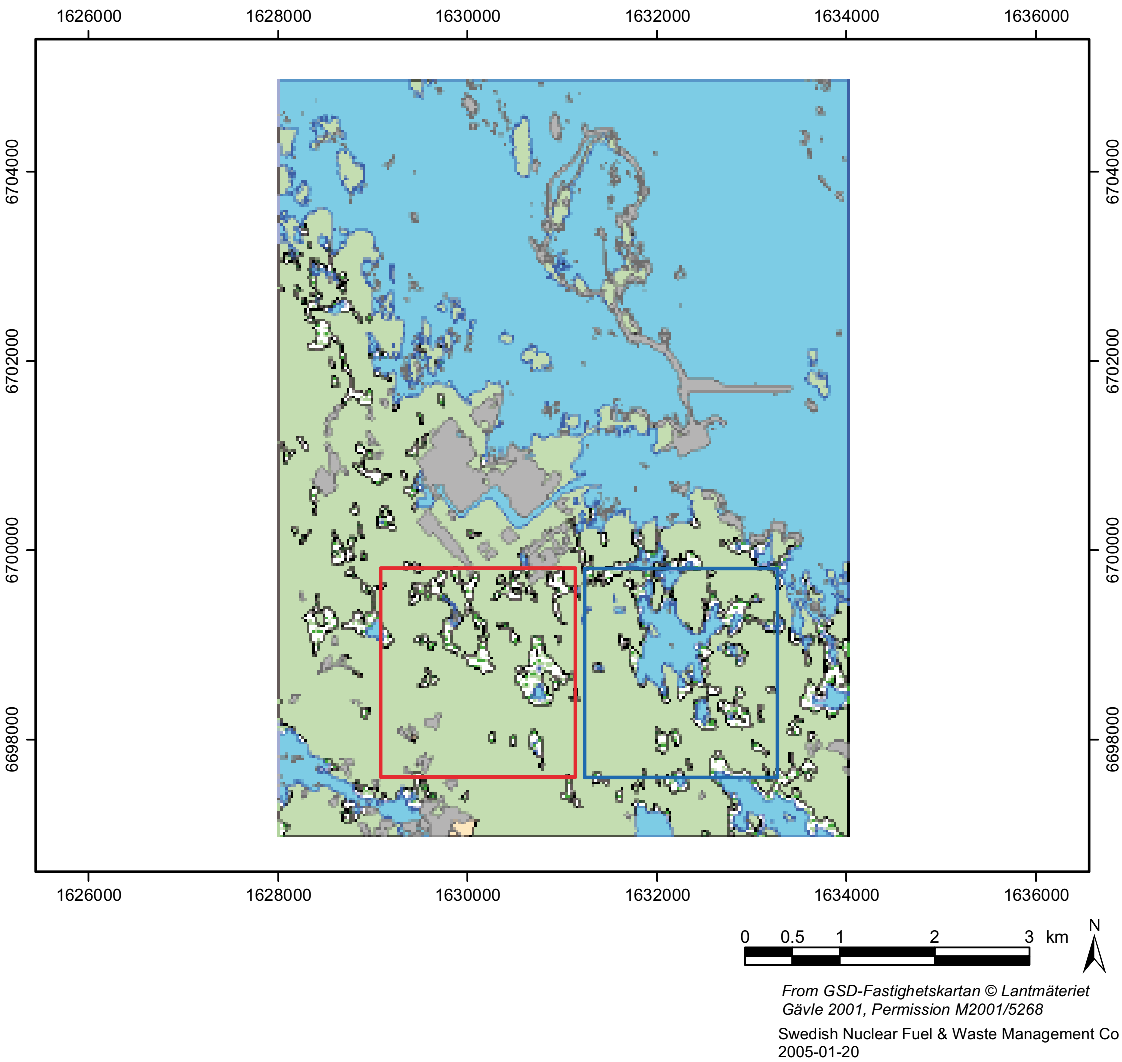


***Figure 2-1.** Extension of the calibration area (red frame) and validation area (blue frame).*

Within the 10-metre grid in Forsmark, two maps can be used: the digital localities map with lakes, brooks, and wetlands in four classes; and an orienteering paper map. Because the orienteering maps show more details about the wetlands, these maps were chosen for model evaluation and calibration. In addition, all objects marked on the orienteering map were checked in the field. It was impossible to check the objects marked on the localities map because these maps often use aerial photos.

The orienteering map was scanned, and the digital map was rectified to the Swedish national coordinate system RT 90 using orthophotos and the GIS-program ArcGis 8.

The orienteering map shows wetlands in three classes /IOF 2000/:

(i) uncrossable marsh – a marsh that is uncrossable or dangerous for a runner,

(ii) marsh – a crossable marsh that usually has a distinct edge,

(iii) indistinct marsh – an indistinct or seasonal marsh or area of gradual transition from marsh to firm ground.

All three wetland classes are treated as potential groundwater discharge areas. The wetlands, lakes, and brooks were digitised on screen with the rectified orienteering map as background. The brooks where digitised as lines and converted to polygons using a buffer distance of 5 metres. The final map polygon map has two classes:

(i) possible groundwater discharge areas,

(ii) possible groundwater recharge areas.

## 2.2 Data set for validation

The area chosen for model validation is situated east of the calibration area and has exactly the same proportion and area. The wetlands, lakes, and brooks were selected from the digital localities map and made up the possible groundwater discharge areas; the rest of the area was treated as possible groundwater recharge areas.

# 3 Model evaluation

## 3.1 General

The model were evaluated using four GIS-functions:

(i) Geomorphometrical classification – Using the 1st and 2nd order differentials of the DEM, the landscape are classified into six geomorphological features: peak, ridge, pass, plane, channel, and pit where peaks and ridges should be indicators for recharge areas and pits for discharge areas.

(ii) Basin fill function – This fills the sinks in a DEM, creating a new DEM. The difference between the filled DEM and the original DEM shows where future lakes will be formed.

(iii) Flow accumulation function – This calculates the accumulated flow or number of up-slope cells based on a flow direction grid. A high flow accumulation value indicates flowing surface water (brook).

(iv) Topographical wetness index (TWI) – This calculation is based on flow accumulation values and slopes where a high TWI-value indicates a discharge area.

The geomorphological classification was used to find recharge areas. The basin fill function was used to find discharge areas in lakes and surrounding wetlands. The flow accumulation function was used to find discharge areas associated to brooks. Finely TWI was used to calculate the probability of discharge areas associated with wetlands.

## 3.2 Modelling extensions of groundwater recharge areas

We used geomorphological classification to map ridges and peaks and to change parameters in the calculation so that the extensions of the ridges and peaks are as large as possible without intersecting with the discharge areas in the calibration data set.

For the geomorphological classification, we used the GIS-program LandSerf /Wood 1996/ (http://www.soi.city.ac.uk/~jwo/landserf). The program uses a DEM as input data and calculates five curvature values for each cell in the DEM. Based on these five values, the DEM is classified into six geomorphological features. The curvature calculations are as follows:

(i) slope – the rate of maximum change for locations on grid (degrees),

(ii) cross-sectional curvature (Cross) – intersecting with the plane of slope, normal and perpendicular aspect direction,

(iii) maximum curvature (Maxi) – in any plane,

(iv) minimum curvature (Mini) – in any plane.

The curvature values are calculated for a rectangular window where the user chooses the size of the window. The smallest window is 3×3 cell, and the size must be an odd value (5, 7, 9, etc). The program uses a bivariate quadratic function for calculation of the curvature values:

$$Z = ax^2 + by^2 + cxy + dx + ey + f$$

The DEM is classified into six geometrical features using the classification scheme presented in Table 3-1. For example, to be classified as a peak, the maxi and mini values are positive and the slope is zero.

**Table 3-1. Geometrical features classification scheme, where the plus sign is a positive value, minus sign a negative value and the zero sign a value within zero +/– the tolerance value.**

| Feature | Slope | Cross | Maxi | Mini |
|---|---|---|---|---|
| Peak | 0 | # | + | + |
| Ridge | 0 | # | + | 0 |
| | + | + | # | # |
| Pass | 0 | # | + | – |
| Plane | 0 | # | 0 | 0 |
| | + | 0 | # | # |
| Channel | 0 | # | 0 | – |
| | + | – | # | # |
| Pit | 0 | # | – | – |

The user sets the slope tolerance value. The tolerance value is the highest slope value allowed while still being classified as a plane.

The user can change two parameters: the size of the local window (the scale) and the slope tolerance value. A great number of calculations were done with the LandSerf program with different settings of the two parameters. The groundwater discharge polygon in the calibration data set was transformed to a point data set by randomly spreading 500 points over the area. After each calculation in LandSerf, the resulting geomorfological classifications were converted to ESRI grid format and then into ESRI shape format (polygons). The point data was then joined to the polygon shape file, and each groundwater discharge point was associated with a geomorphological feature. The goal was to receive a maximum area of peaks and ridges with few or no discharge points placed on peaks or ridges.

The optimal combination of window size and slope and curvature tolerance value was found to be an 11×11 window and 4 degrees. The total area of peaks and ridges are 26% of the model area, and only 3.3% of the discharge points are situated on a peak or a ridge (Table 3-2).

The results show that groundwater discharge points in pits, channels, and passes is more common than in planes (Nb/Area quota), but the differences are too low to be used for modelling groundwater discharge areas.

**Table 3-2. Results from the calibration running LandSerf with an 11×11 window and a slope tolerance of 4 degrees.**

| | Number of points (%) | Area (%) | Nb/Area |
|---|---|---|---|
| Pit | 4.2 | 0.7 | 5.6 |
| Channel | 47.4 | 28.4 | 1.7 |
| Pass | 9.8 | 6.4 | 1.5 |
| Ridge | 2.9 | 22.7 | 0.1 |
| Peak | 0.4 | 3.0 | 0.1 |
| Plane | 35.3 | 38.8 | 0.9 |

## 3.3 Modelling groundwater discharge areas associated with lakes

The SKB 10-metre DEM for the Forsmark area has elevation values for the land surface, the lake bottoms, and the sea bottom; that is, the water is removed from the landscape. Characteristics of future lakes (due to positive shore displacement) such as extension, area, volume, and maximum water depth, can be calculated using the basin fill function in the GIS-programme ArcGis 8. The basin fill function fills the sinks in a DEM, creating a new DEM. The difference between the filled DEM and the original DEM shows where future lakes will form.

A comparison between an existing lake and the same lake modelled with the basin fill function often shows that the modelled lake is larger and deeper. The reason for this is that the DEM seldom has the correct information of the lake threshold elevation due to the regularly spaced values in a DEM, and the distance between the true location of the threshold and the nearest DEM point can be up to 5 metres in a 10-metre DEM.

## 3.4 Modelling groundwater discharge areas associated with brooks

Future brooks (due to positive shore displacement) are modelled with the flow accumulation function in ArcGis hydrologic modelling extension. The calculation are made in three steps:

(i) the original DEM is filled with the Basin fill function,

(ii) the filled DEM is used to calculate a flow direction grid, where each cell in the grid is linked to one of eight neighbours with the highest downstream gradient,

(iii) the flow direction grid is then used to calculate the accumulated flow or the number of up-slope cells.

The digitised brooks from the orienteering map were placed on top of the flow accumulation grid. Brooks on the orienteering map are shown with three symbols:

(i) uncrossable watercourse – minimum 2-metres wide,

(ii) crossable small watercourse – including a major drainage ditch less than 2-metres wide,

(iii) minor water channel – a natural or man-made minor water channel that may only intermittently contain water.

With the information tool in ArcGis, the flow accumulation values were determined at the transition from crossable small watercourse to minor water channel at a great number of places. These flow accumulation values varied between 150 and 400 with an average value of approximately 200. A flow accumulation value of 200 corresponds to an area of 20,000 $m^2$, and with a specific runoff of approximately 7 $l\ s^{-1}\ km^{-2}$ the calculated mean runoff is 0.14 $l\ s^{-1}$. This is a very low flow, so some of these brooks with flow accumulation values lower than approximately 1,000 are probably dry during part of the year.

The flow accumulation grid was reclassified into two classes, no data value for values lower than 200 and 1 for values higher than 200. The reclassified grid was then converted to shape-format using ArcToolbox. Only approximately 4% of the model area is classified as potential groundwater discharge area associated with brooks.

## 3.5 Modelling groundwater discharge areas associated with wetlands

In the model evaluation, approximately 25% of the model area is classified as most likely recharge areas and 25% as most likely discharge areas. This means that approximately 50% of the model is not yet classified. The goal is to divide this area into three classes: probably a recharge area, undefined area, and probably a discharge area. This will be performed using a topographical wetness index. The TWI is used to calculate the likelihood for soil saturation /Beven and Kirkby 1979/. The wetness index is defined as follows:

$$TWI = \ln\left(\frac{Flowacc}{\tan\beta}\right)$$

where

*TWI* is topographical wetness index

*Flowacc* is specific catchments area

$\beta$ local slope in degrees

High wetness index occurs in places with high flow accumulation values and flat slopes. The flow accumulation grid often shows great differences in values in adjacent cells, and small changes in elevation values can denote great changes in the flow accumulation grid. Therefore, the resulting TWI-DEM is often very patchy. In order to reduce this phenomenon, both the slope grid and the flow accumulation grid were smoothed using a low pass filter with a 3×3 kernel before the calculation of wetness index.

The overall pattern in the summary statistics is logical: the ridges and peaks are dryer than the areas “in between”, and the areas “in between” are dryer than lakes and brooks for all statistical results. Unfortunately, the distribution of TWI-values for different objects are overlapping (Figure 3-1), so it is impossible to use the TWI, with high accuracy, to determine which part of the “area in between” should be classified as groundwater discharge areas or recharge areas. Instead it must be a probability calculation based on Table 3-3 and Figure 3-1.

As a first attempt, the 1st quartile for the lakes and brooks distribution will be used. “In between” TWI-values higher than the 1st quartile in the distribution for the lakes and brooks (7.2) will be classified as “probably groundwater discharge areas”, while “in between” TWI-values lower than the 3rd quartile for ridges and peaks (4.9) will be classified as “probably recharge areas”. All TWI-values between 4.9 and 7.2 will be classified as “undefined”. With these class boarders, the TWI-values for the class “in between” is as follows: “probably recharge areas” = 8%; “probably discharge areas” = 20%; and “undefined” = 22% of the total model area.

**Table 3-3. Summary statistics of topographical wetness index (TWI) for modelled ridges and peaks, lakes, and brooks, and the areas between these objects. Q_25 and Q_75 are the 1st and 3rd quartile.**

| | TWI_ridge_peak | TWI_in-between | TWI_lake_brook |
|---|---|---|---|
| Max= | 14.8 | 15.1 | 18.8 |
| Min= | 1.2 | 2.0 | 2.1 |
| Mean= | 4.3 | 7.3 | 9.1 |
| Median= | 4.0 | 7.1 | 8.8 |
| Q_75= | 4.9 | 8.7 | 10.7 |
| Q_25= | 3.3 | 5.7 | 7.2 |

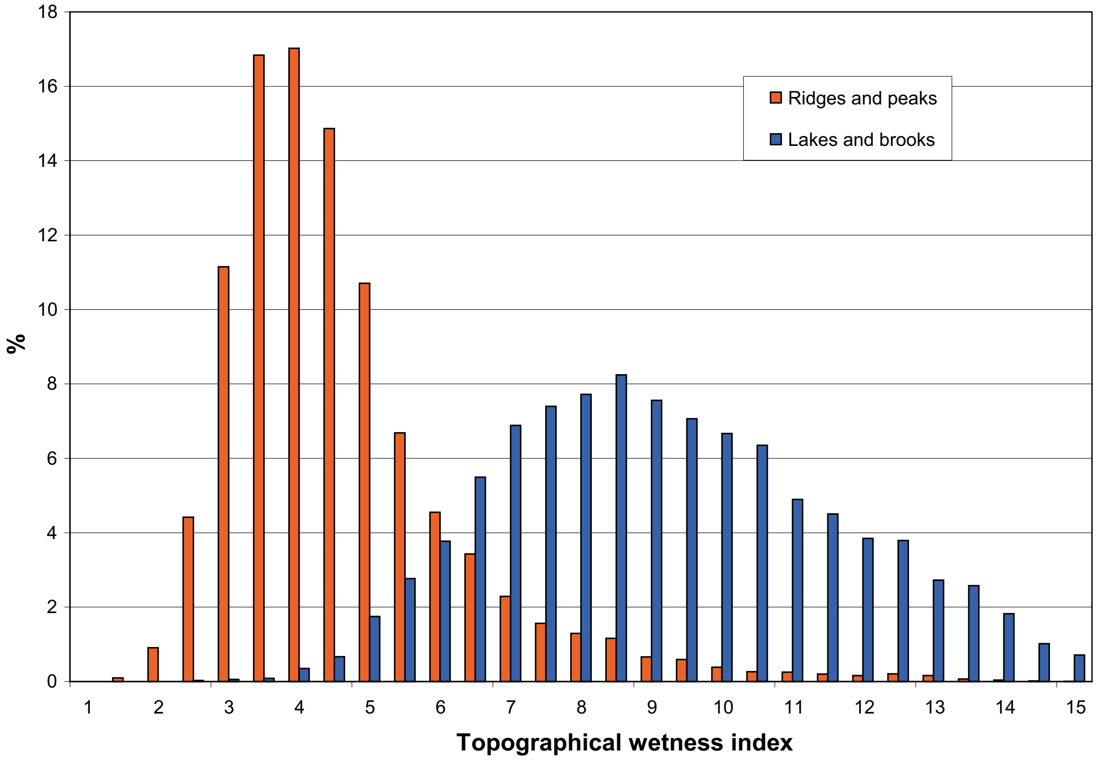


***Figure 3-1.*** *The distribution of TWI-values for modelled ridges and peaks (red), and lakes and brooks (blue).*

# 4 Validation of the model

The validation of the model is also made in the Forsmark area as the calibration, but it is not intersected with the calibration area. The dataset used for validation is presented in Section 2.2, and the extension is shown in Figure 2-1.

In the validation area, the only indirect measurement of groundwater discharge areas is lakes, brooks, and wetlands from the localities maps. These objects were merged to one single GIS-layer as “potential ground water discharge areas”.

On this layer, 500 points were randomly spread as “potential groundwater discharge points” and will be used as a validation data set.

The DEM (the 10-metre SKB DEM) was treated exactly as the calibration scheme in Chapter 3:

(i) using the LandSerf program with a window of 11×11 cells and a slope tolerance of 4 degrees for detecting ridges and pits in the landscape and build up the areas that will later be classified as “Most likely groundwater recharge areas”,

(ii) using the basin fill function in ArcGis to determine the potential discharge areas associated with lakes that will later be classified as “Most likely groundwater discharged areas”,

(iii) using the flow accumulation function in ArcGis to calculates the accumulated flow in order to detect existing or future brooks that will be classified as “Most likely groundwater areas”,

(iv) using topographical wetness index (TWI) for dividing areas not distinguish by (i), (ii), or (iii) by statistical methods into “Probably discharge area” (TWI > 7.2), “Probably recharge area” (TWI < 4.9), or “Undefined” (4.9 < TWI <7.2).

The 500 points that were randomly placed over lakes or wetlands from the localities map were joined to a modelled grid and each point was linked to a modelled geohydrological feature (Table 4-1).

Another way to validate the model is to check against possible recharge areas. Rock outcrop areas from the soil map were chosen as possible groundwater recharge areas. The bedrock is often exposed due to wave washing and due to the positive shore displacement in the area; at some time, all parts of the model validation area have been situated at the seashore. The wave washing is strongest at steep shores and at crests, places with possible groundwater recharge areas. Table 4-2 shows the results from the test. Only 1% of the points were incorrectly classified.

**Table 4-1. Results from validation of the model when 500 random points were placed on lakes and all types of wetlands from the localities map.**

| | Number of points | % |
|---|---|---|
| Most likely discharge area | 458 | 91.6 |
| Probably discharge area | 19 | 3.8 |
| Undefined | 17 | 3.4 |
| Probably recharge area | 2 | 0.4 |
| Most likely recharge area | 4 | 0.8 |

**Table 4-2. Results from validation of the model when 500 random points were placed on rock outcrop areas from the soil map.**

| | Number of points | % |
|---|---|---|
| Most likely discharge area | 3 | 0.6 |
| Probably discharge area | 2 | 0.4 |
| Undefined | 69 | 13.8 |
| Probably recharge area | 100 | 20.0 |
| Most likely recharge area | 326 | 65.2 |

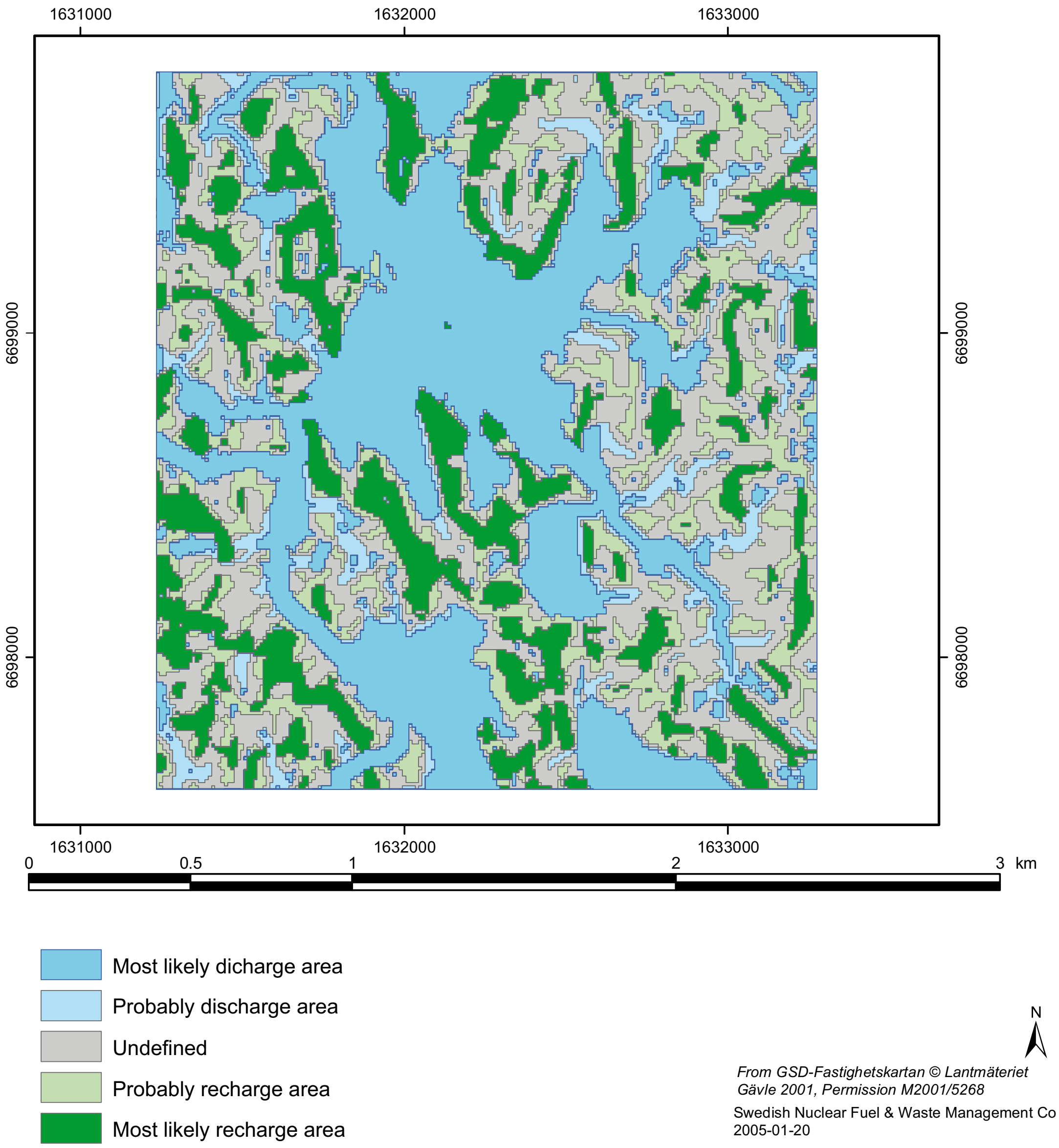


***Figure 4-1.** The distribution of different geohydrological object types over the validation area.*

# 5 Discussions

Wet areas in the orienteering map are not always ground water discharge areas. Small wet areas in the map are often pools of rainwater collected in small pits directly on bare rock, which is not a discharge area. Furthermore, these phenomena are often situated on ridges, typical geometry for recharge areas. If these areas were deleted from the calibration data set, the total area of the "Probably ground water recharge areas" should be larger.

The calibration area is dominated by Lake Bolundsfjärden. The DEM used in this study has elevation values for land surfaces and lake sediment surfaces. The basin fill function re-creates the lake surfaces, surfaces that often have higher elevation than the true lake surface elevation. This is due to the fact that the lake threshold value is not always represented in the DEM because the lake threshold is not situated close to a DEM node. The result is a zone around the lake that will be classified as "Probably a ground water discharge area". This is not necessarily an error because flat areas close to lakes in the Forsmark area are often wetlands.

The distribution of TWI-values for modelled ridges and peaks, and lakes and brooks are partial overlapping (Figure 3-1). /Hjert et al. 2004/ proposed an alternative way to calculate slope (Tan$\beta$) in the TWI that to a less degree was affected by changes in the DEM resolution. This alternative method will be incorporated in the next version of the model.

In the model are, the total area of lakes was with the basin fill function calculated to 22% of the model area. To set this area as a potential groundwater discharge area requires that the lake bottom sediments are permeable for groundwater flows. If not, only the parts of the lakes close to the shore are treated as discharge areas. This can be solved in the model by only selecting lake bottom areas situated shallower than a specified water depth. In this case, the deeper part of the lake bottoms are not classified as a recharge area or discharge area but as a geohydrological inert area.

Finally, we conclude that topography significantly influences the distribution of groundwater recharge and discharge areas. By using DEM and GIS-programs, the distribution of ground water recharge and discharge areas in the landscape can be predicted.

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