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Spatial quick-clay predictions using multi-criteria evaluation in SW Sweden

Abstract The transformation of marine and glaciomarine clay deposits into high sensitive and quick clays is largely dependent on the influence of local and regional geologic history and the resulting stratigraphy. The general conditions that facilitate quick-clay development are well known from numerous laboratory investigations during the last century, but their local and regional in-field variation is less understood. In this study, the geographic distribution of quick clay in SW Sweden is predicted using a multicriteria evaluation model that incorporates both qualitative information (established theory and expert judgment concerning the influences on both quick-clay development and the stratigraphic and geomorphologic distribution of sediment types) and observational data (maps of surficial deposits, geotechnical records and digital elevation data). This information duality cannot be avoided if knowledge from different disciplines is utilized. Considering this, model transparency is important for improvements and for characterizing its reliability for risk analysis. The model was constructed stepwise by an initial parameterization with subsequent hierarchical structuring, weighting and standardization of criteria, before running the full analysis. Comparisons between regional model results and geotechnically documented localities have yielded promising results concerning the model's ability to predict general trends. However, the large natural and site-specific variability of clay sensitivities is not always captured by the model. These deviations are examined and suggestions are given for minimizing their effect. Applications of model methodology and results are briefly discussed.

Keywords Quick-clay development · Leaching · Stratigraphic modeling · Multi-criteria · Evaluation · Southwestern Sweden

Introduction

Quick clay loses over 98 % of its shear strength when disturbed (remolded) and is therefore a major threat in areas where initial slope failures can become extremely dangerous both in their areal extent and liquefaction (Rosenqvist 1953; Torrance 1983). Although a general theory for quick-clay formation is well known and many factors affecting the quick-clay forming potential have been identified (reviewed e.g. by Rankka et al. 2004 and briefly presented below), predictive modeling of quick-clay distribution has not been previously been done. A major reason for this is that quick clay forms at depth, involving processes that are only in part related to the readily available observations of surface features, such as slope and surface soil types. On the other hand, there is considerable conceptual knowledge about the stratigraphic architecture, derived from geological understanding of the Quaternary glacial environments. The thicknesses and relative positions of marine clay and permeable sandy deposits and bedrock fractures are considered decisively important for groundwater leaching, probably the most important process in quick-clay formation.

Although precipitation and relief are certainly driving factors, models describing the interplay with the geologic architecture

remain largely qualitative due to limited documentation and the site specificity of the leaching effects. In contrast, empirical data and quantitative calculations characterize slope stability evaluations, reflecting the need for practical applications of safety factors, reinforcement recommendations and land-use zoning. Unfortunately in this case, the exclusion of theoretical stratigraphic information creates a greater uncertainty regarding the overall ground stability than is necessary if methods for the combination of qualitative and quantitative knowledge are used.

Multi-criteria evaluation methods (MCE, Voogd 1983) have since the early 1990s been increasingly popular, not least in GIS applications. Common for many multi-criteria models is the weighting and criteria standardization procedures. Analytical Hierarchical Process methods (AHP; Saaty 1980) have yielded satisfying results, for instance in landslide hazard zonation, compared to other available methods (Ayalew et al. 2005; Komac 2006; Yoshimatsu and Abe 2006; Yalcin et al. 2011). MCE and AHP procedures have been criticized mainly because of rank reversal problems (e.g. Belton and Gear 1983), difficulties that arise from the comparison scale (Lootsma 1993), the compensatory nature of the method and the degree of subjectivity in the weight derivation. The MCE and AHP methodological benefits, which we consider outweigh the drawbacks, are often summarized as the transparent structure, the opportunities to use most any kind of data or information (including quantitative observations and qualitative expert judgment and belief), possibilities for communicating the model structure and its components to others and the user's ability to adapt the model to different purposes and improve input information (e.g. when new datasets are made available). Especially the ability to include conceptual information is valuable since many criteria (e.g. those dealing with stratigraphic criteria) are hard to sample in sufficient quantity in the field or by other means.

The main objective of this study is to predict quick-clay formation by preparing and running a spatial model that considers paleogeographic, hydrogeological and stratigraphic variation. This is achieved by an initial criterion weighting procedure and the generation of single criterion maps (using measured or conceptually derived data that have been standardized). These model components are then combined and the model performance and applicability is tested. The strengths and limitations of the initial GIS application of our MCE model also provide perspective for model improvement needs, as well as for its practical possibilities. We describe first the conceptual and geological basis of quick-clay development.

Quick-clay developments in SW Swedish geological settings

Retreat of the Scandinavian ice sheet at the end of the last glaciation resulted in relatively rapid environmental changes (Lundqvist and Wohlfarth 2001) that are frequently reflected in observed stratigraphic sequences (cf. Olausson 1982; Stevens et al. 1991). The deposits from environments with glacial, glaciomarine, open marine and near-shore conditions have varied characteristics that are decisive

for the relationships and processes in the ground today, especially the groundwater pressures and movement that can develop clay sensitivity and influence slope stability. The very coarse-grained till and glaciofluvial deposits formed beneath the ice or in close proximity to a retreating ice front are frequently in strong contrast to the fine-grained, clayey sediments deposited only a short distance from the ice front in glaciomarine settings.

A clay deposit is, by definition, quick if the unitless sensitivity (i.e. the undrained undisturbed to remolded shear strength ratio, Eq. 1) is over 50 while the undrained remolded shear strength is below 0.4 kPa. Clays with lower sensitivities are divided into low ($St < 8$), medium ($St 8-30$) and high sensitive clay ($St 30-50$) classes (Karlsson and Hansbo 1989). In general, there is a good correspondence between sensitivity and the remolded shear strength. High and quick sensitivities are most often dependent on a low remolded shear strength rather than a high undisturbed shear strength since the undisturbed shear strength is less variable than the remolded (Bjerrum 1954).

$$S_t = \frac{\tau_u}{\tau_r} = \frac{\text{undrained undisturbed shear strength}}{\text{remolded shear strength}} \quad (1)$$

Rosenqvist (1946, 1955) first suggested that quick-clay development is dependent upon the destabilization of the flocculated clay structure that is characteristic of deposits from certain depositional environments, such as the marine settings following deglaciation of SW Sweden (Fig. 1). A flocculated structure is most common when water salinity has suppressed electrostatic repulsive forces sufficiently so that the combination of attractive van der Waals and electrostatic forces will allow edge-to-face and edge-to-edge bonding of clay-sized particles to occur. Negatively charged particles attract hydrated ions from surrounding water to create a diffuse double layer that satisfies the net charge balance and that varies in thickness in connection with the charge and concentration of ions in solution (van Olphen 1977). In other words, the distance from the surface at which the net negative charge of the particles is balanced, by an excess of cations relative to anions in solution, decreases as the charge on the cations increases and as the concentration of the bulk solution outside the double layer increases (Torrance personal communication 2011).

Low total porewater cation content is associated with quick-clay formation in SW Sweden (Talme et al. 1966; Quigley 1980; Andersson-Sköld et al. 2005). A slightly higher cation concentration may occur if the ratio of Na^+ to other base cations is high. The normal development of glaciomarine and marine deposits into quick clay, by successively lowering the total porewater cation concentration and the relative amounts of specific cations (Fig. 2), is a relatively fast geological process. In most cases, it still involves thousands of years, considerable groundwater exposure and appropriate geochemical leaching. In laboratory conditions, clay leaching of marine sedimented clay using approximately 3 times the pore volume of freshwater increased the sensitivity approximately 20 times during 18 months (Bjerrum and Rosenqvist 1956). These processes have presumably advanced farthest in nature where the stratigraphy inherited from the glacial and post-glacial environments best meets hydrogeological prerequisites for groundwater movement within and adjacent to the clay deposits. The amount of precipitation that is able to infiltrate and further impact on deeper clay deposits is

mainly determined by stratigraphical and surficial distribution of sediments, as well as the hydraulic gradient.

Post-depositional processes related to high groundwater fluxes may, however, affect the undisturbed and remolded shear strength of clay deposits in either direction. The introduction of bivalent cations, especially Mg^{2+} , may induce the sediment to regain or maintain a higher shear strength. Such cations might be a result of soil weathering or supplied by percolation from bedrock sources and could alter the clay shear-strength properties if diffused or carried by groundwater flow to the leached sediment (Moum et al. 1971, 1972; Andersson-Sköld et al. 2005; Solberg personal communication 2012). The addition of dispersants sometimes facilitates a lowering of the remolded shear strength and consequently causes a net increase in sensitivity (Söderblom 1969). These two processes are, nevertheless, considered to be subordinate to leaching in most cases.

Modeling methodology

MCE methods were used to predict where post-depositional processes have likely advanced sufficiently for the formation of quick clay. Our model attempts to predict likelihood of leaching, which we believe to correlate strongly with elevated sensitivity, and hence quickness. For simplicity, we consider sensitivity only as defining quick clay (cf. Fig. 3). To reduce ambiguity, the model objective is formulated as: Which areas best fulfill the requirements for freshwater leaching of marine clays and are thus susceptible to quick-clay formation?

The suggested model was developed, tested and run on a desktop computer using the ArcGIS environments running the Spatial analyst (® ESRI 2006, 2011) to capture, analyse and present data, although the model structure can be used in most any GIS or advanced modeling software. The Hawth's tools (Beyer 2006), GME extension (Beyer 2012) and Patch analyst (Rempel et al. 1999) were complementarily used where the standard ArcGIS functionality was limited (i.e. area wise criteria calculations and handling of coordinates in data set tables). All criteria-map data sets were held at or resampled to a 50-m raster pixel size. The SWEREF 99TM reference coordinate system, which is the current standard for applications covering large areas in Sweden, was consistently used throughout the work. Further information on MCE methods are given by Malczewski (1999).

The modeling steps are (as illustrated in Fig. 4 and further explained in coming sections):

1. Formulating the model objective,
2. Identifying conditioning criteria from literature and structuring them hierarchically,
3. Assigning criteria weights,
4. Using utility functions to standardize the observed criteria ranges and to generate single criterion utility maps,
5. Identifying and applying constraints
6. Aggregating criteria maps (including constraints) into one resulting map corresponding to the model objective, and
7. Presenting and testing of model results.

Once all criteria weights and site-specific utilities were calculated and defined, they were combined using weighted linear combination (Voogd 1983) to obtain the overall utility, U_i , expressed in a unit-less likelihood ranging from 0 (lowest) to 1

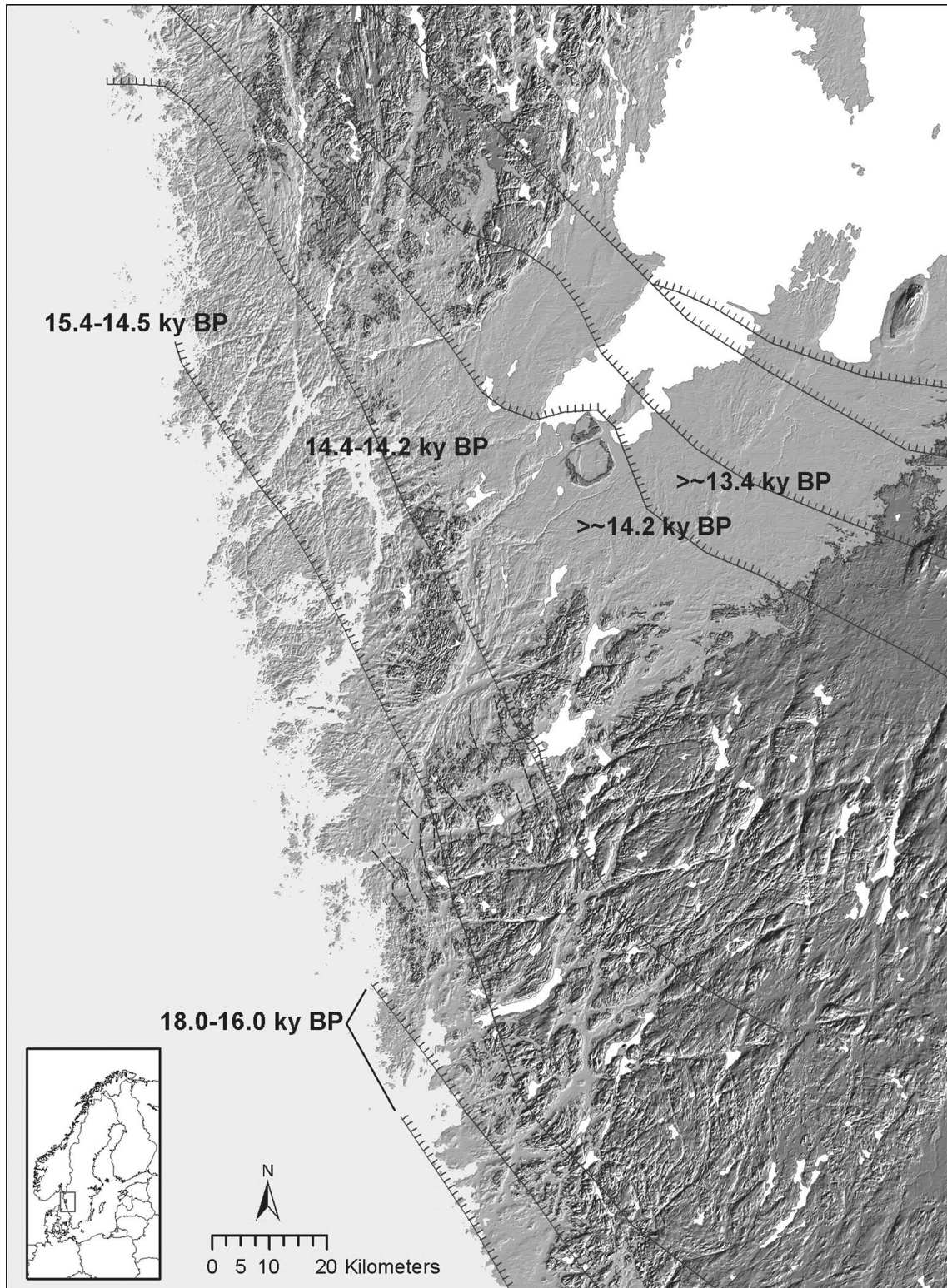
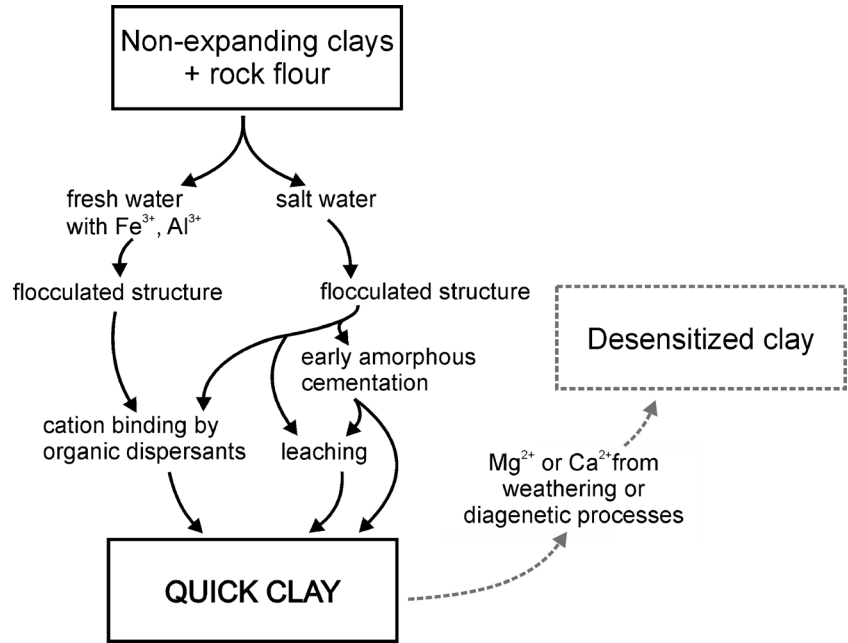


Fig. 1 Paleogeographic setting in SW Sweden. *Light to medium gray areas* were isostatically suppressed and flooded subsequent to ice retreat (i.e. are under the marine limit) and *black lines* indicate positions where ice remained stagnant during retreat for considerable time which resulted in abundant coarse-grained deposits (modified after Lundqvist and Wohlfarth 2001; Pässe and Andersson 2005)

(highest; Eq. 2). Here, each weight (from the AHP) and utility product for all criteria were summed. The product of all Boolean constraints used, c_b , was incorporated by multiplication to exclude

areas with no quick-clay susceptibility. The total score, U_i , was calculated for every pixel in the resulting raster map and is hereafter referred to as quick-clay susceptibility index (QCSI). Since all

Fig. 2 Sequential quick-clay formation (Modified after Brand and Brenner 1981)



weight sets were normalized to 1 and the different sets multiplied, the highest possible QCSI is 1.

$$U_i = QCSI = \sum (w_j u_{ij}) \cdot c_b \quad (2)$$

Where w_j is the weight constant for the j th criterion (relative to the problem formulation and illustrating the single criterion's relative importance) and u_{ij} is the standardized criterion score, utility, for the same criterion on the j th dimension (e.g. the degree to which the criterion is fulfilled at a specific site represented by a raster grid cell). The model structure was incorporated in the GIS (i.e. ArcMap model builder), easily accessible for later modification or revision.

Criteria structuring

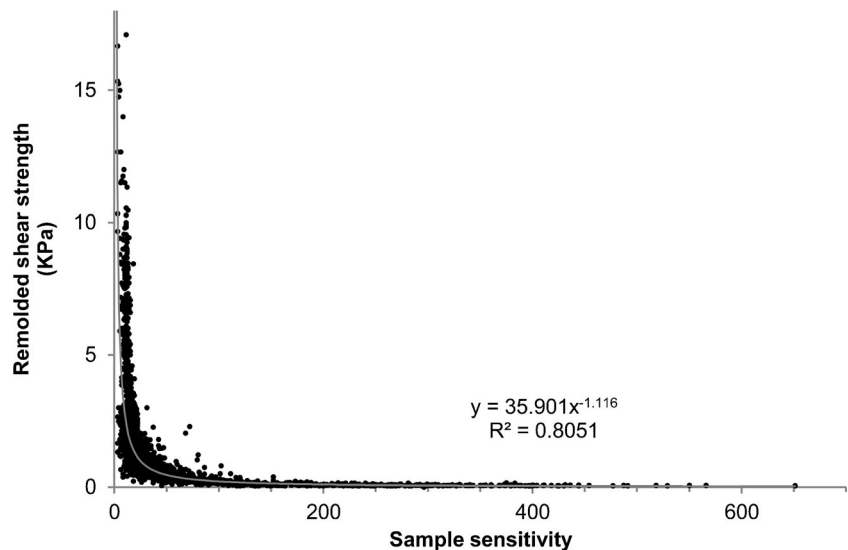
A large number of criteria, known from the literature to be involved in leaching and thus quick-clay formation (Rankka et al.

2004), were considered before the final set of criteria was formalized. Criteria with limited occurrence, variability or effect on leaching in southwestern Sweden (e.g. clay mineralogy, precipitation, presence of organic or inorganic dispersants and chemical composition of groundwater) were excluded from further modeling, although they might be locally important for quick-clay formation. The selected criteria were hierarchically structured into groups of thematically similar criteria (Fig. 5). Proxy information sources were considered in some instances where hard data are absent.

Criteria weighting

The AHP methodology (Saaty 1980) was used to sequentially assess weights for the multiple preconditions that affect advective clay leaching and, consequently, diffusion and quick-clay formation by lowering of cation concentrations. Relative criteria weights,

Fig. 3 Distribution of undrained remolded shear strength and sensitivity of 2,847 samples, including multiple levels from the sediment cores used for comparisons in this study (STA 2006–2011; SRA 2008; STA 2005–2009; SGI 2011b; SRA 2002; Gatubolaget 2008)



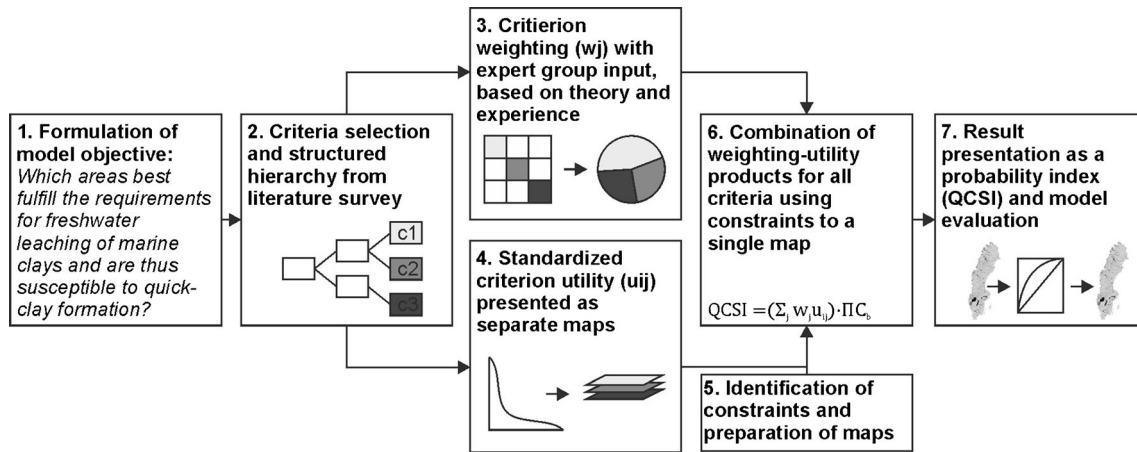


Fig. 4 Flow chart showing model components and their combination

with respect to the model objective, were derived for each hierarchical level using an ordinal scale (Table 1) and pairwise comparison matrices (Table 2). A group of nine experts consisting of geologists, civil engineers and geotechnical practitioners (consultants and governmental planners) participated in an initial weighting of criteria. These and additional experts were later given the chance to review the final set of weights which were confirmed and adopted without change (Fig. 6). The actual weights entered into

the model were derived from the pairwise comparisons by first normalizing the row sums then squaring the matrix repeatedly to obtain an acceptable accuracy of eigenvalues to get the principal eigenvectors. Further mathematical details are given by Saaty (1980). AHP calculations have been done using Logical Decisions® v 6.1 for Windows.

To assure acceptable consistency in the pairwise comparison process, consistency ratios (C.R.) have been calculated using Eq. 3

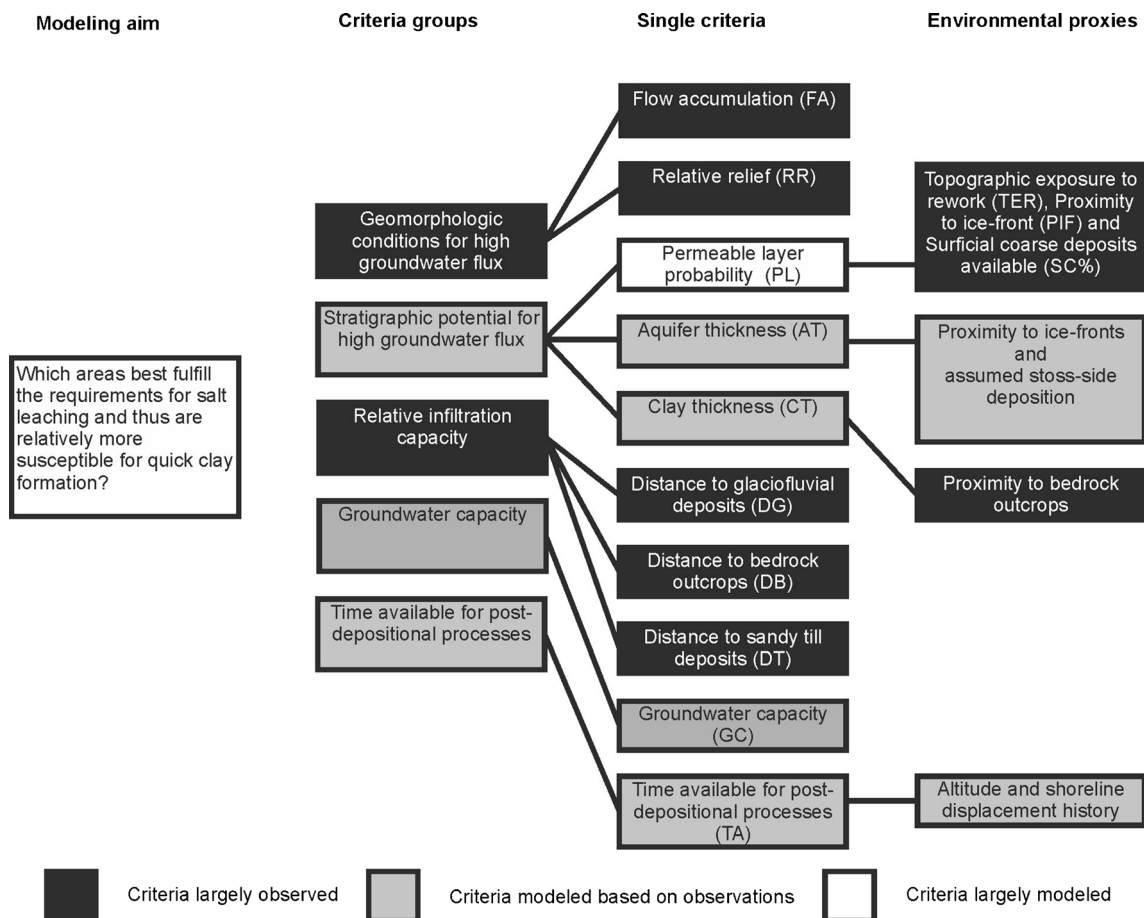


Fig. 5 Hierarchy of model objective, criteria and criteria proxy data

Table 1 The rating scale used in AHP weighting (modified after Saaty 1980)

Relative importance	Definition	Explanation
1	Equally important	Two criteria contribute equally to the objective
3	Moderate more important	Experience and judgment slightly favour one criterion over another
5	Strongly more important	Experience and judgment strongly favour one criterion over another
7	Very strongly more important	One criterion is favoured very strongly over another; its dominance demonstrated in practice
9	Extremely more important	The evidence favouring one criterion is overwhelming
Reciprocals of above	The members of each pairwise comparisons have reciprocal values	By definition
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

(and included in Table 2). To do so, consistency indices (C.I.) were first calculated for the weighting matrix and a random matrix (Eq. 4).

$$\text{C.R.} = \frac{\text{C.I. of matrix}}{\text{C.I. of "random matrix"}}$$
 (3)

where

$$\text{C.I.} = \frac{\lambda_{\max} - n}{n - 1}$$
 (4)

in which λ_{\max} =principal Eigenvalues (i.e. the product of the matrix and the unadjusted weight vectors) and n =number of criteria being compared in the weighting matrix.

Criteria standardization and map generation

The first step to account for the effect of each criterion is to construct maps of single criteria. Hard data, when existing, are preferred; however, when data on crucial, high-weight criteria are sparse or missing, proxy data and conceptual information were also considered in the quantification of criteria. The Swedish data used in this study to quantify the different criteria are available without cost for research purposes. Subsequent to the criteria map generation, the variable effect of each criterion was specified. To be directly comparable regardless of any differences in quantities or units, all criteria were standardized using single criteria utility functions (Fig. 7) into a common 0–1 range, where 0 is no effect and 1 is optimal fulfillment of quick-clay prerequisites. The utility functions were fitted, in collaboration with the expert group, to what is assumed to be the true criteria variation in quantity and utility. These functions can have any mathematically expressible shape. Two functions were applied in some cases to account for naturally occurring trends in criteria where each function was used for a specific interval of observed values. Finally, utility functions were reviewed and confirmed by the expert group. The assignment and use of utility functions have been reviewed by Keeney and Raiffa (1993). The treatment of individual criteria is further explained below.

Geomorphologic conditions beneficial for high groundwater flux

Relative relief is defined as the maximum elevation difference between the highest and lowest lying point of a predefined area. Here, a migratory, circular search window ($r=300$ m) was used to

calculate the relative relief within each ca. 0.28 km² circle from the DEM (NLSS 2010a). It is assumed that the relief reflects the likelihood for high (even artesian) groundwater pressure gradients.

Flow accumulation (i.e. the accumulated number of DEM raster cells, upstream from a point of interest) was calculated using standard hydrologic tools within the GIS. The result reported is each raster cell's available catchment. The utility function has been designed to represent primarily the flow oriented transverse to surface waterways by relatively decreasing the utility of flow in rivers and streams. The available groundwater flow is assumed to follow the topography, and the flow-accumulation tool was used to quantify this.

Stratigraphic potential for high groundwater flux

Clay thickness was derived by ordinary kriging interpolation of stratigraphic values from documented localities (SGU 2012c). Since the data density varies and data are often absent, cokriging interpolation methods were used to take advantage of more easily sampled, covariate proxy data of proximity to bedrock outcrops. More details on cokriging procedures are available in Goovaerts (1998). The asymmetric shape of the utility function (Fig. 7) was used as a constraint to exclude areas where near-surface dry crust formation and vadose processes have strengthened the clay deposits in the upper subsurface interval.

Aquifer thickness was extracted from the Swedish Geological Survey stratigraphic database (SGU 2012c). Glaciofluvial deposits have not been possible to distinguish from till deposits. These records, from nearly 2,000 localities, were interpolated using ordinary cokriging and the proxies assumed stoss-sides and proximity to ice-front positions as covariates. First, stoss-side deposits were assigned to areas where the slope aspect deviation is less than 15° from the optimum orientation parallel with the prevailing glacial striae directions and the bedrock slope is more than 7°. The prevailing ice direction was interpreted from more than 6,000 glacial striae observations (SGU 2012e), which were interpolated using ordinary kriging methods. Second, proximal and distal distances to ice-front positions were separately calculated as a second covariate.

The *permeable layer probability* was assigned to areas based on available coarse-grained surface deposits (SC%) and there topographic exposure to reworking during shoreline regression especially where the mid-Holocene (ca. 7 kyBP) stagnation in relative land uplift was significant (TER, cf. Pässe and Andersson

Table 2 Matrices including weights for criteria groups and individual criteria

Consistency ratio of criteria groups: 0.042												
	Geomorphologic conditions for high groundwater flux			Stratigraphic potential for high groundwater flux			Relative infiltration capacity		Time available for post-depositional processes			
	1	1/3	1	1	1/3	1	1	1	3	3		
	Stratigraphic potential for high groundwater flux			Relative infiltration capacity			Time available for post-depositional processes		Weight			
	1	1/3	1	1	1/3	1	1	1	3	0.17		
	Relative infiltration capacity			Distance to glaciofluvial deposits			Distance to sandy till		Weight (total weight)			
	1	1/3	1	1	1/3	1	1	1	3	0.52		
	Groundwater capacity			Distance to bedrock			Distance to sandy till		Weight (total weight)			
	1	1/3	1	1	1/3	1	1	1	3	0.18		
Time available for post-depositional processes												
	Geomorphologic conditions for high groundwater flux			Stratigraphic potential for high groundwater flux			Relative infiltration capacity		Weight			
	1	1/3	1	1	1/3	1	1	1	3	0.062		
	Flow accumulation			Distance to glaciofluvial deposits			Distance to sandy till		Weight (total weight)			
	1	1/3	1	1	1/3	1	1	1	3	0.061		
	Relative Relief			Distance to glaciofluvial deposits			Distance to sandy till		Weight (total weight)			
	1	1/3	1	1	1/3	1	1	1	3	0.64 (0.12)		
	Flow accumulation			Distance to bedrock			Distance to sandy till		Weight (total weight)			
	1	1/3	1	1	1/3	1	1	1	3	0.11 (0.019)		
	Permeable layer probability ^a			Distance to sandy till			Distance to sandy till		Weight (total weight)			
	1	1/3	1	1	1/3	1	1	1	3	0.26 (0.047)		
Geomorphologic conditions for high groundwater flux	1	1/3	1	1	1/3	1	1	1	3	0.17		
Stratigraphic potential for high groundwater flux	3	1	5	5	1	5	5	5	7	0.52		
Relative infiltration capacity	1	1/5	1	1	1/5	1	1	1	3	0.18		
Groundwater capacity	1/3	1/5	1/5	1/5	1	1/5	1	1	1	0.062		
Time available for post-depositional processes	1/3	1/7	1/3	1/3	1	1/3	1	1	1	0.061		
Geomorphologic conditions for high hydraulic pressures. C.R: 0.000	Weight (total weight)	Permeable layer probability ^a	Clay thickness	Aquifer thickness	Stratigraphic potential for high groundwater flux. C.R: 0.062	Aquifer thickness	Weight (total weight)	Relative infiltration capacity. C.R: 0.037	Distance to glaciofluvial deposits	Distance to bedrock	Distance to sandy till	Weight (total weight)
Relative Relief	0.75 (0.13)	1/7	1/3	1	0.081 (0.042)	Distance to glaciofluvial deposits	0.081 (0.042)	Distance to glaciofluvial deposits	1	5	3	0.64 (0.12)
Flow accumulation	0.25 (0.043)	1/5	1	3	0.19 (0.098)	Distance to bedrock	0.19 (0.098)	Distance to bedrock	1/5	1	1/3	0.11 (0.019)
Permeable layer probability ^a	0.73 (0.38)	1	5	7	0.73 (0.38)	Distance to sandy till	0.73 (0.38)	Distance to sandy till	1/3	3	1	0.26 (0.047)

Figures given in parentheses are weights relative to the full model objective. A measure of the weighting consistency (C.R.) is given for each matrix

^a Permeable layer probability is in turn defined by the subcriteria topographic exposure to rework (TER), 0.70 (0.24); proximity to ice-front (PIF), 0.25 (0.095); and surficial coarse deposits available (SC%), 0.05 (0.019)

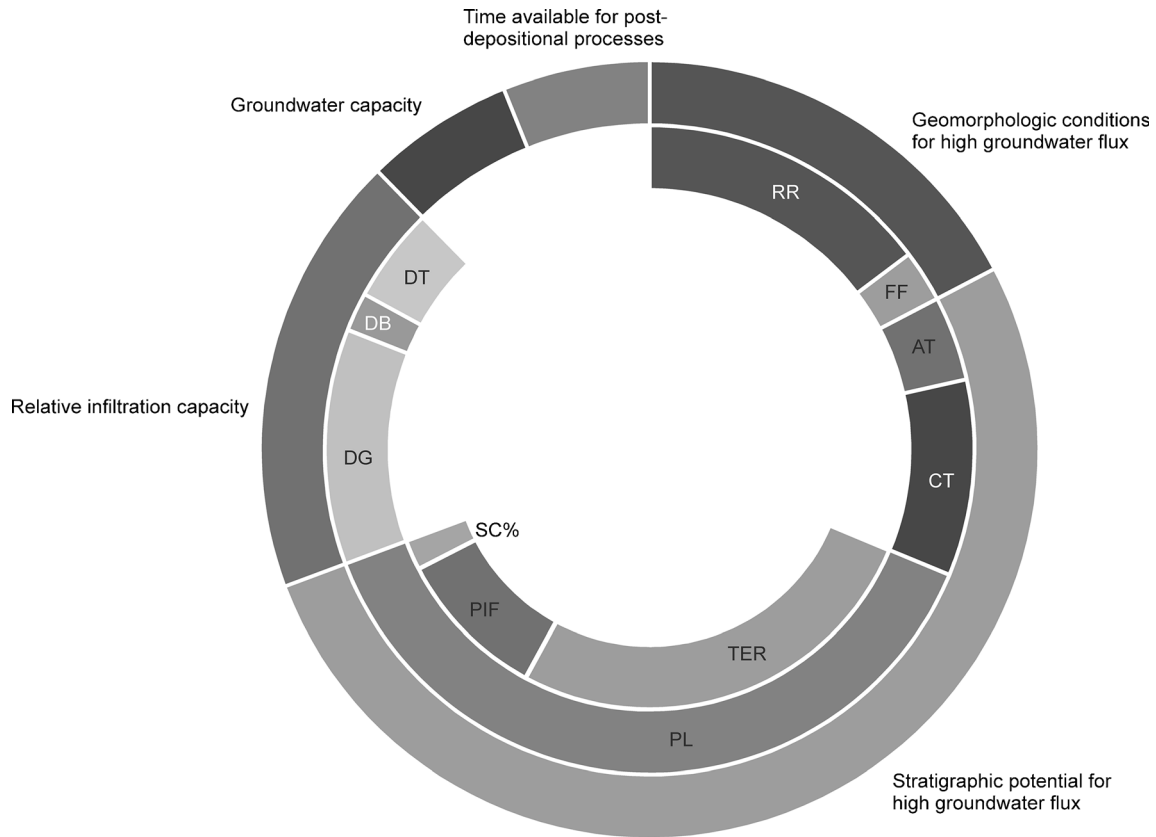


Fig. 6 Relative criteria weights represented by the angular extent of each field

2005). No difference was made between different classes of glacial sands, glaciofluvium and sandy till recorded on surficial geology maps (SGU 2012a, b). Further, areas close to ice-front positions (PIF) were considered highly likely to have sand-layer formations and were given higher weight. A non-symmetrical utility function for this factor was chosen to account for differences in the sedimentological environments on the ice-proximal and the ice-distal sides of these ice-front positions (Fig. 7). The three sub-criteria (Fig. 5) were incorporated in the model using weights and utility functions.

Relative infiltration capacity

Surface run-off from up-slope, low-permeable bedrock areas can infiltrate in outcropping, coarse, glacial deposits. The leaching effectiveness of groundwater pathways was assumed to decrease with distance from the surficial permeable deposits as the presumed thickness and layer continuity declines. This was considered by calculating the Euclidian (straight line) distance from surficial sandy till and glaciofluvium. The spatial extent of these deposits at the surface is often small enough to be excluded even from the 1:50,000 maps of surficial deposits (SGU 2012a), but they are still believed to provide important *infiltration capacity*. Hence, the distance to bedrock, where glacial deposits often outcrop, was used as a proxy for unmapped glacial drift deposits, although it is recognized that coarse deposits may be absent in some areas.

Groundwater capacity of sediments and bedrock

The groundwater production capacities of rock and sediment were interpolated from well log records (SGU 2012d) using ordinary

kriging. No distinction was possible to make between bedrock and glacial deposit aquifer capacity.

Time available for post-depositional processes

The time that a land area has been located above the present sea level was used as a proxy for the time available for post-depositional, quick-clay forming processes. The number of years was calculated using empirical equations simulating shoreline fluctuations caused by eustacy and isostacy in the late Pleistocene and Holocene (Pässe and Andersson 2005). Ordinary kriging interpolation of each necessary term preceded the full calculations covering the whole area, and resulted in time-above-sea-level maps.

Boolean constraints

Some areas have very poor preconditions for developing quick clay and were thus given a utility of zero. Areas above the marine limit are not usually considered since leaching in glaciomarine and marine fine sediments is the primary cause for quick-clay formation in the area. The marine limit was interpolated from the literature records (references listed in Pässe 1996). Marine or glaciomarine conditions have not existed during sediment deposition above this level. Areas covered by coarse glacial sediments were also excluded. Clay deposits only rarely occurs beneath coarse glacial sediments, for instance in connection with ice readvances during glacial stadials, but these occurrences are of minor spatial extent. Note that sandy layers within the Holocene clay deposits develop much later and are not part of this constraint.

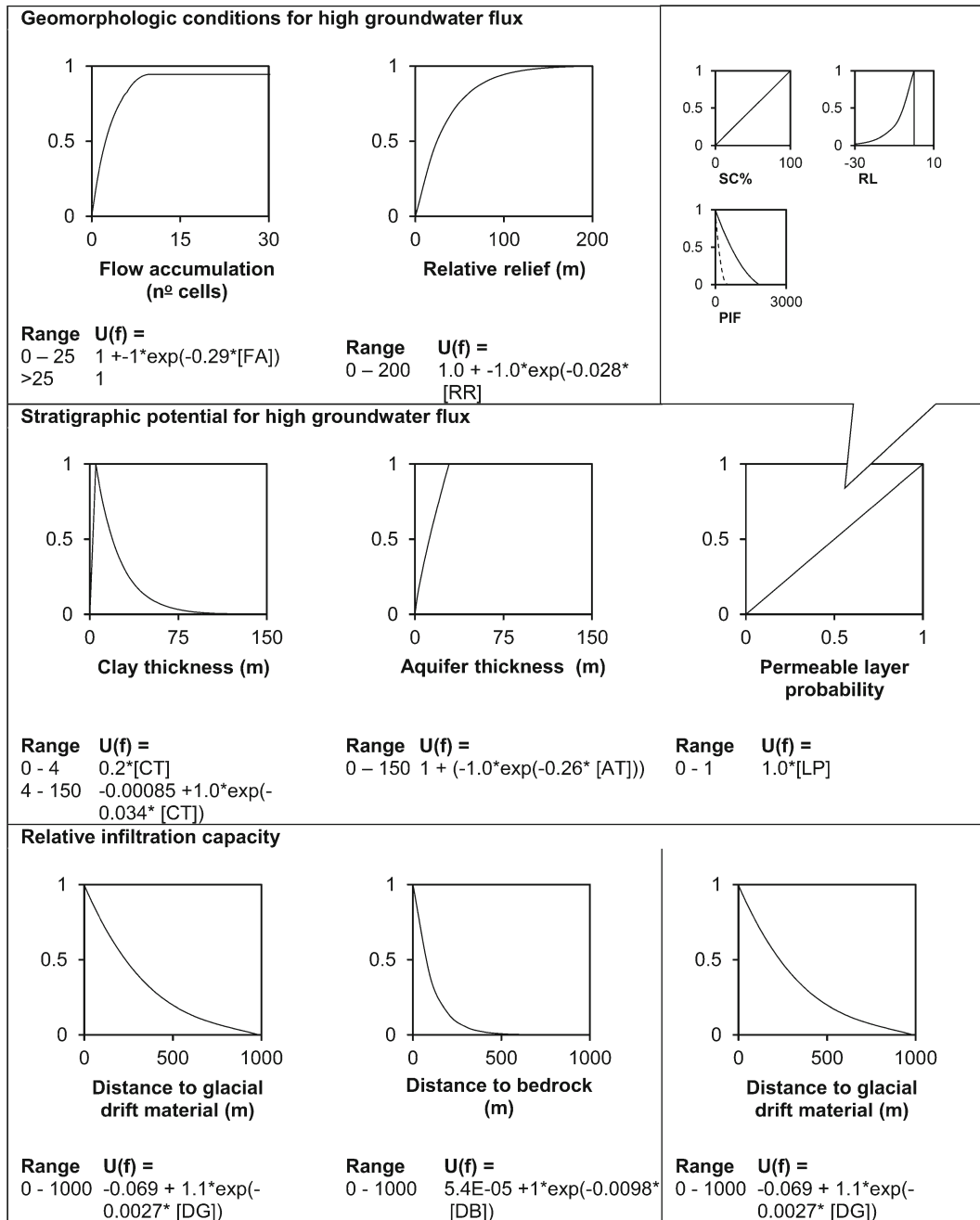


Fig. 7 Criteria utility functions by which actual values were standardized relative to the relative impact (0–1) of the criteria across the range of all values. The *hatched line in the upper right PIF panel* indicates ice-proximal distance, while the *solid line* is the ice-distal distance

Model testing

The model results (Fig. 8) were validated using fall cone sensitivity records from 392 sites where ST II type sampling equipment was used in the field. Only the maximum sensitivity recorded (St 13 to 707) in each sediment core were used for model validation. The majority of the sampling and fall cone testing has been commissioned by the Swedish Transport Administration, including its predecessors, and later completed by consultant companies, mainly preceding construction and reconstruction of roads E45 and the adjacent Norge-Vänerbanan railroads (STA 2006–2011; SRA 2008) and E6 (STA 2005–2009). Additional data from a recent stability

survey within the Göta älv River valley (SGI 2011b) and from the western Sävån stream valley (SRA 2002; Gatubolaget 2008) have also been used. The archival information was used in three separate ways, described below.

First, a regression plot (Fig. 9) was used to visualize the distribution of observed sensitivity samples over the QCSI range. This was done to see how well the model performs at a local level. The arithmetic sensitivity means were calculated for each 0.05 QCSI class allowing interpretation of overall sensitivity trends. The equation of the resulting regression line was then used to transform QCSI into an estimate of sensitivity. The distribution of

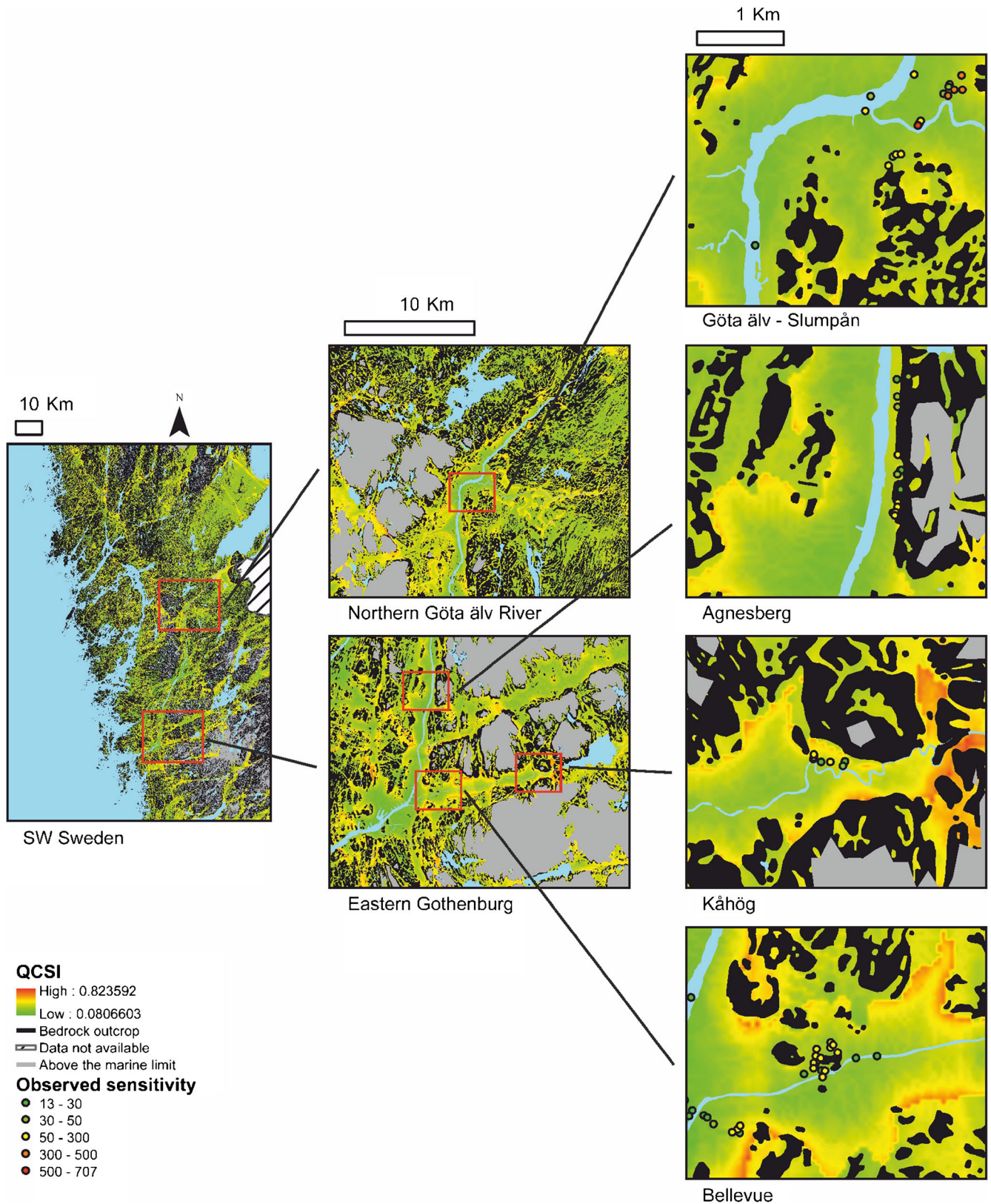


Fig. 8 Model results with increasing detail (larger scale). The four maps to the right have been resampled (using bilinear resampling) at 5-m resolution for visualization purposes. These areas coincide with those studied in greater detail by Persson and Stevens (2012). Sensitivity observations (STA 2005–2009 and 2006–2011; Gatubolaget 2008; SGI 2011b) are shown for comparison. The hatched area to the right in the left figure has been excluded because of the shortage of geological data

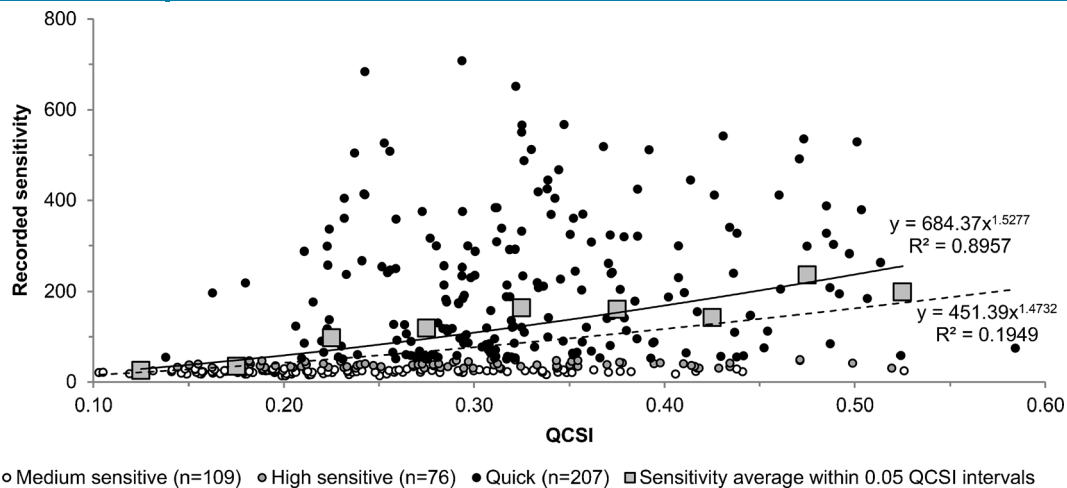


Fig. 9 Distribution of core-maximum sensitivity values ($n=392$) from laboratory fall-cone tests plotted against QCSI. The correlation coefficients using both individual sensitivity observations (*hatched line*) and average sensitivity values within 0.05 QCSI intervals (*solid line*) are indicated. The few samples in the 0.55–0.60 range have not been averaged

sensitivity classes against QCSI was also cumulatively plotted (Fig. 10).

Second, Relative Operating Characteristics curves (ROC) describe the relation between the two key characteristics: ROC sensitivity (a statistical term not related to the “clay sensitivity” defined by its shear strength ratio) and specificity for every possible cutoff value (cf. Fawcett 2006). Sensitivity in a ROC context is sometimes referred to as true positive rate or hit percent, while specificity is also known as true negative rate. In ROC curve construction, specificity is commonly represented as false positive rate (i.e. $1 - \text{specificity}$). Here, ROC analysis was used to test the QCSI model’s ability to discriminate between quick (sensitivity > 50) and non-quick (sensitivity < 50) samples given varying QCSI cutoffs (cf. Fig. 11). The geotechnical data (specified above) were used for these comparisons. Specificity corresponds to correctly classified, non-quick clays, while ROC sensitivity relates to correctly classified quick clays. The SPSS Statistics 20 software (IBM 2011) was used for calculating the ROC sensitivity, specificity and related statistics. The area under the ROC curve is often used to indicate model success rate and to compare between competing models. The SPSS standard settings were used for all calculations concerning ROC.

Finally, QCSI was compared to previously mapped quick-clay areas (SOU 1962; Söderblom 1969, 1974; Cato 1981; Andersson-Sköld et al. 2005; SGI 2011a, 2012). This evaluation is more focused on general trends of QCSI relative to deposits containing both sensitivities over 50 and very low remolded shear strength (<0.4 kPa) thus satisfying both quick-clay defining characteristics.

Model results and comparison with empirical documentation

Approximately 81 % of the analysed land surface (Fig. 8) is elevated above the marine limit at its maximum immediately after the local deglaciation or is composed of bedrock or soil unlikely to cover clay and thus lacks quick-clay forming potential. The regression line equation for the 0.05 QCSI classes (Fig. 9) is used to transform QCSI values into a sensitivity estimate. Given the spatial extent of QCSI values (Fig. 8) and the sensitivity distribution (Table 3) within each class, the model suggests that ca. 3,000 km² of southwestern Sweden contain quick-clay deposits at some stratigraphic levels. Very high likelihood (QCSI > 0.40) for quick-clay properties occurs in ca. 5 % of the total land area. Such high QCSI values are explained largely by the elevated utility of several high-weight criteria (e.g. probability of permeable layering, aquifer thickness and distance to surficial drift deposits) near valley margins. Even higher values are expected when

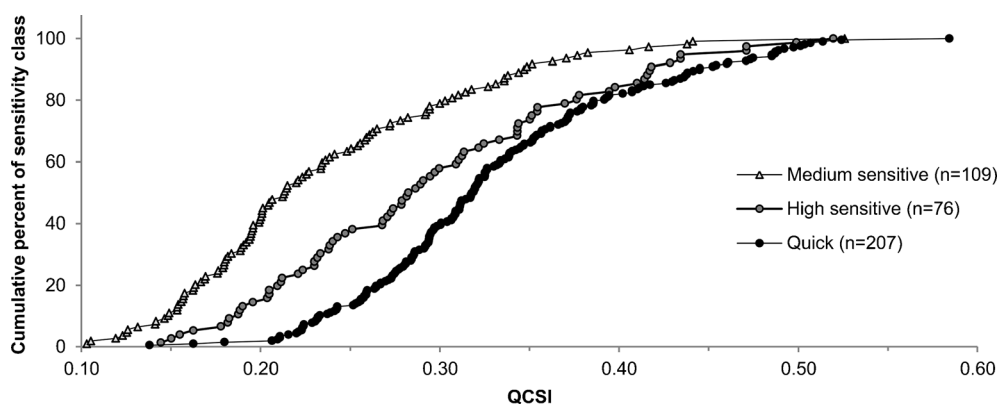
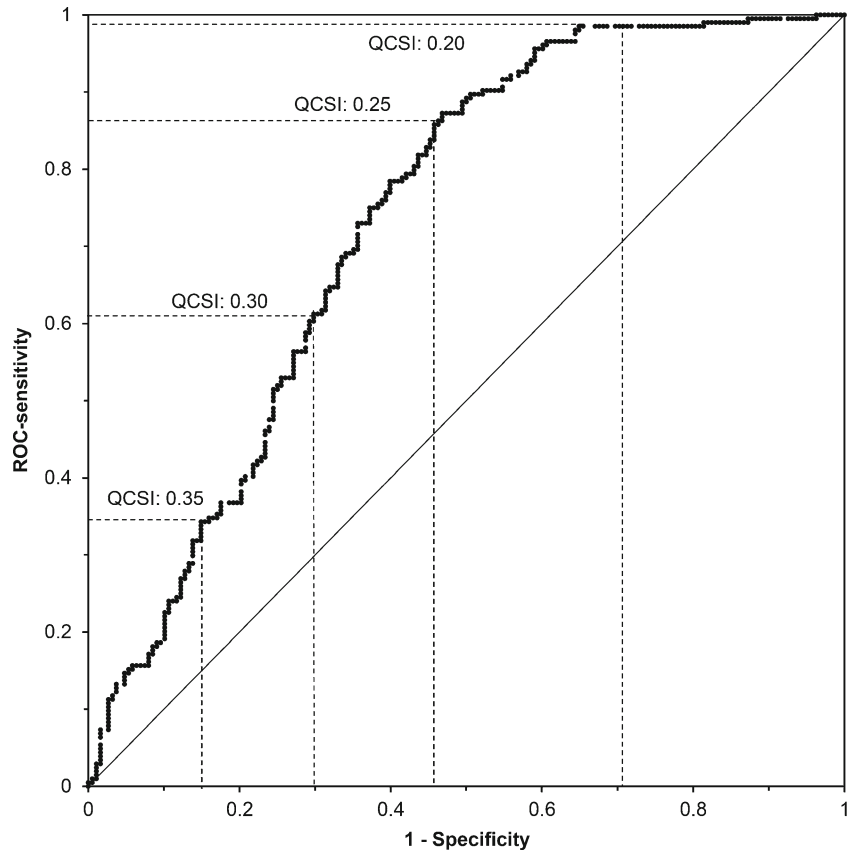


Fig. 10 Cumulative frequency of observed clay sensitivities over the QCSI range. The total number of samples within each class is given in *parenthesis*

Fig. 11 Binomial ROC curve. Empirical data points are shown in black. Dashed lines correspond to QCSI values. The diagonal line represents a random model with no predictive capacity. Diagonal segments are produced by ties



this setting coincides with ice-front positions. These patterns are consistent with the overall trends in the measured sensitivity values. In many, perhaps most, of the highly probable quick-clay areas (high

QCSI) the very high to quick sensitivities are located at great depths, far from erosive processes and anthropogenic influence, and are consequently unlikely to be mobilized during landslide events.

Table 3 Typical characteristics of model QCSI classes where St is the geometric mean of the highest sensitivity reported from each sediment core, MS is medium sensitivity, HS is high sensitivity and QC is quick clay, τ_r is the geometric mean of the lowest remolded shear strength in each core, TP rate is true positive rate and FP rate is false positive rate if the upper end of the QCSI class is used as ROC cutoff

QCSI range	Description	Areal extent (%)	St	Distribution of St classes	τ_r (kPa)	TP rate	FP rate
<0.20	No to very low potential for effective leaching and quick clay formation. Porewater salinity is still often marine or near-marine. Areas with QCSI values of 0 consist of bare bedrock, sandy till or other unsusceptible soil or are located over the marine limit.	82	27	MS, 75 % HS, 19 % QC, 6 %	0.79	0.99	0.70
0.20–0.30	Low potential for effective leaching and quick clay formation in the lower half of the interval. Some quick deposits may occur especially where QCSI is over 0.25.	8	61	MS, 30 % HS, 21 % QC, 49 %	0.44	0.61	0.30
0.30–0.40	Intermediate to very high degree of leaching expected.	6	100	MS, 14 % HS, 16 % QC, 70 %	0.25	0.19	0.90
>0.40	Very high probability for leaching clay to quickness. Other post-depositional processes related to groundwater flow are also effective, possibly leading to desensitization.	6	111	MS, 9 % HS, 23 % QC, 68 %	0.19	–	–

The maximum archive values of sensitivity from 392 sediment cores (Fig. 9) demonstrate a high variability. In these cores, low sensitive samples ($St < 8$) are largely lacking and have never been found to be the dominant or highest sensitivity class. Such cores are rarely chosen for documentation in geotechnical investigations. Approximately half of the samples are quick clay, while the medium and high sensitive samples amounts to 28 and 19 %, respectively. Of the full QCSI range (i.e. 0–1), sites with predicted 0.1–0.8 values are common in the study area. Since actual tested samples of quick clays are only found in the 0.10–0.58 interval; it is also evident that quick-clay formation occurs at sites with relatively low QCSI values (> 0.20). Sensitivity generally increases with higher QCSI values (Table 3 and Fig. 10). Quick and medium sensitive samples, at opposite ends of the QCSI scale, are satisfyingly predicted. However, the model's predictive capacity with respect to individual stratigraphic criteria varies, and its testing is limited by the scarcity of actual observations, especially in rural areas. Medium sensitive samples are concentrated within the lower QCSI range, with approximately 68 % of samples ($\pm 1\sigma$ from the class mean) between 0.15 and 0.32 (Fig. 10). The corresponding range for the quick-clay samples is 0.25–0.41. However, the high sensitive samples between these (St 30–50) are somewhat more widely dispersed over the QCSI range, with a defined peak near QCSI 0.26 (68 % of samples between 0.21 and 0.39). It could be argued, based on the wider distribution of high sensitive samples, that these sensitivity values are the “normal” conditions for SW Swedish clay, and this is maintained in many settings despite several favourable criteria (STA 2005–2009 and 2006–2011). The wider spread here may in part be because the model assumes that clay sensitivity will always increase with leaching, whereas divalent cations supplied by groundwater are also capable of reversing the decreasing sensitivity trend (Fig. 2). The distribution of deviations is given in Fig. 12.

High QCSI conditions occur predominantly in the south and central Bohuslän province (e.g. parts of the Ljungskile–Stenungsund area) and in the Göta älv River valley and its tributary valleys, especially at lower elevations (specifically Slumpån and Grönån and to some degree also in the streams Lärjeån and Sæveån downstream from Lake Aspen). Quick-clay formation is inferred from QCSIs and limited geotechnical records to be less common in the eastern and northern parts of the study area (e.g. in the Dalbo and Vara flatlands), where leaching has presumably been limited by the lower relief and hydraulic gradients that accelerates post-depositional processes. However, some local quick-clay deposits are known from site geotechnical surveys in this area. Even further to the east, north and south, the geomorphology has precluded marine conditions following deglaciation. Only patchy occurrences of high probability occur south of Gothenburg. The results of several separate site investigations in the literature are generally consistent with our model predictions although there are exceptions (see below). Investigations done after the 1977 Tuve landslide (Cato 1981) indicate leaching and quick clay in some parts of this site, as the model results also suggest (QCSI consistently > 0.40 and > 0.50 values in adjacent areas). Significant leaching has been observed by Andersson-Sköld et al. (2005) in clay pore waters from Surte and Hogstorp, corresponding to areas of high QCSI from the model results. The extent of the Ellesbo, Utby, Strandbacken and Fuxerna quick-clay deposits, as reported by Söderblom (1969), is fairly well predicted. His observations from Lödöse are less in agreement with QCSI results possibly due to the close proximity to the drainage outlet of the Gårdaån stream or high upward gradients near the stream bank toe (cf. Lefebvre 1996).

Further, two Göta älv River valley surveys (SOU 1962; SGI 2012) have both documented quick deposits between Vesten and Intagan on the western side of the northern reach of the Göta älv River (where QCSI is consistently > 0.35 , reaching > 0.50 in places), in parts of the Lilla Edet–Göta area (QCSI 0.30–0.35) and along the river between Surte and Agnesberg (where QCSI varies abruptly over short distances but is mainly > 0.30). All of these sites have comparably high QCSI values and are located relatively close to bedrock outcrops where infiltration and effective groundwater pathways are expected. Quick-clay areas documented in conjunction with landslide events (SGI 2011a) are focused to areas of high QCSI. Additionally, a series of spatially related quick-clay areas have been mapped by the Swedish Transport Administration (STA 2006–2011) in the comparably narrow Vallbyån stream valley corresponds to model areas of high QCSI.

One example of poor local correlation between QCSI and measured sensitivity is at the Slumpån–Göta älv River confluence area (Fig. 8), where unpredicted high sensitivity values are most probably explained by effective groundwater pathways apparently not realistically captured by the model. The effectiveness of leaching is probably also favoured by thinner local clay thicknesses than modeled by the cokriging interpolation which is suggested by significantly less negative magnetic anomalies (ca. 20 nT) here than in surrounding clay areas (SGU 2012f). Thick and continuous drift deposits in the area are not well constrained by the model (i.e. largely theoretically characterized). In general, most geotechnical surveys focus on depth to bedrock or to glacial drift, and the drift thickness, its continuity and its hydraulic conductivity are not usually specified. Due to the scarcity of empirical data, the degree to which permeable layers have been correctly predicted has not been satisfactorily verified, whereas the distance to glacial drift is entirely observational and has only minor errors related to the mapping practice and later digitalization. When bedrock proximity is used as a proxy for unmapped drift deposits, some areas will be identified falsely as having such deposits present. Clay thickness records are relatively frequent but are, similarly to other geotechnical records, skewed towards built up areas. The clay-thickness interpolations may also suffer from highly undulating bedrock surfaces not explained or spatially unresolved in the model. However, the QCSI effect of thickness deviations of stratigraphic units is commonly small since the impact is also dependent on their individual weights and utility functions. For instance, thin permeable materials underlying the clay may be as effective in creating an upward water flux and cation leaching as is thick layers, but thicker layers have a greater chance of being continuous and therefore more important over a larger area.

The area under the ROC curve (Fig. 11) for the entire area is close to 0.73, suggesting a reasonably good prediction model. A perfect prediction model would have a very low rate of false positives or negatives and thus an area under the curve of near 1 (i.e. cover the whole area). The presented ROC has an asymptotic significance lower than 0.05, suggesting a model that performs consistently better than guessing. Approximately 75 % correctly classified quick samples are reached at 0.28 QCSI. At the same QCSI threshold level 63 % of the non-quick samples are correctly classified.

While there is a good agreement between model results and broad sensitivity trends the correlation for individual sensitivity measurements is lower (Figs. 9 and 12). This can be attributed to two main groups of causes related to the model ability to quantify quick-clay development and to original documentation of clay sensitivity.

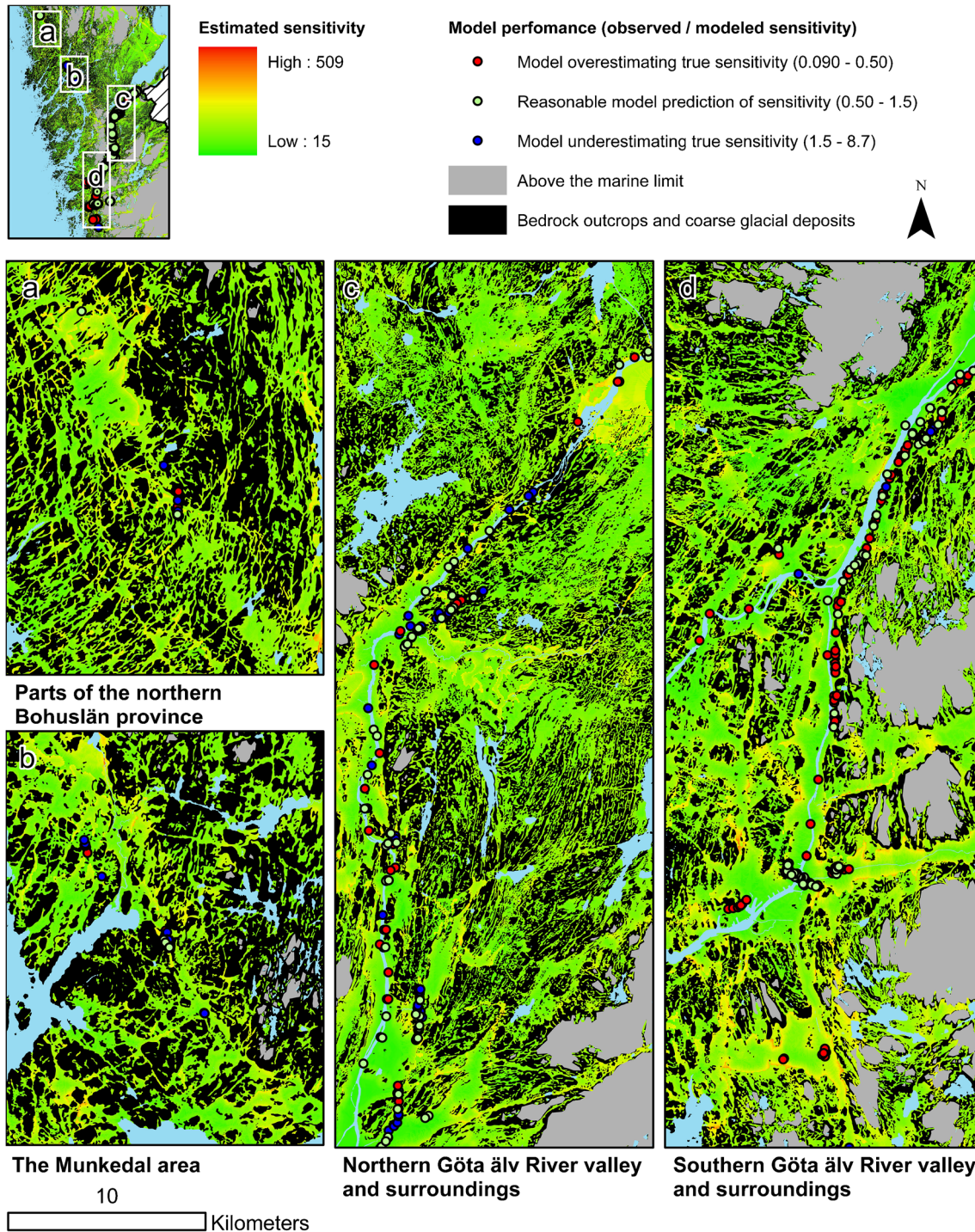


Fig. 12 Model deviations at the sites for geotechnical investigations expressed as a ratio between recorded and estimated sensitivity (*filled circles*) achieved by applying the regression line equation for the averaged QCSI classes on the QCSI result map (Fig. 8). A model prediction deviating at most 50 % from the recorded value will be reported as reasonably good. Everything beyond this is reported to be either over or underestimated. The map *colours* show the estimated QCSI distribution (model results) in each of the areas considered

First, the large natural variability of clay sensitivities is known to vary by at least one order of magnitude in the same stratigraphic unit in samples separated spatially by less than 100 m (cf. Talme et al. 1966). This is consistent with what is observed in the geotechnical comparison data used in this study. In contrast, with a model resolution of 50 m, it is evident that

important stratigraphic details (such as a lenticular permeable layer) might be neglected or misrepresented in modeling results which makes stratigraphic and certain geographic trends more systematic but less consistent with actual values. The most severe problem related to the AHP, for our purposes, occurs when a high weight criterion (cf. Fig. 8) has a low utility which cannot be

easily compensated by other criteria with lower weights (e.g. aquifer thickness). Rank reversal problems (cf. Belton and Gear 1983) are minimized when using the eigenvector derivation of weights. All weighting matrices within this study have C.R. of less than 0.1 which indicates a consistent analysis (Malczewski 1999). Subjectivity in the assigning criteria weights and characterizing utility, use of theoretically derived data or low-density spatial datasets, the omission of certain criteria that might be locally important also affects the ability to predict clay sensitivities. No significant impact has so far been possible to attribute to any of the disregarded criteria. To illustrate this, precipitation (which could be used as a covariate for groundwater flux modeling) has been found subordinate to criteria responsible for the collection and transport of water and has thus been excluded from modeling in favour of single use of groundwater capacity which has been assumed to give a more accurate representation of the effect that groundwater has on leaching.

Second, geotechnical observations used for comparisons might suffer from unknown clay disturbance during unrecognized landslide activity (which seems to be the case at the Småröd landslide site and in some parts of the Northern Göta älv River valley) as well as later influence from sample transport, storage and laboratory procedures (Bjerrum and Lo 1963; Söderblom 1969; Lessard and Mitchell 1985). Further, standard testing procedures result in sensitivity values at only selected depths and the highest sensitivity levels may have been missed. At the same time, suspected quick-clay areas are more extensively sampled than low or high sensitive clay areas that are less problematic for construction. This is believed to be compensated, to some extent, by frequent investigations preceding bridge construction in central valley settings where the leaching potential is often low.

Settings where the model underestimates true sensitivities (cf. Fig. 12) are consistently characterized by active groundwater pathways and effective leaching environments, such as near bedrock outcrops, narrow valley sections, tributary and side valleys, or close to permeable deposits (cf. Talme 1968; Lefebvre 1996). A

large natural stratigraphic variation over short distances makes prediction less site specific. In areas with a historically high landslide frequency, extensive sensitive clay deposits may likely have existed, but these have been partly reworked, consolidated and dewatered so that they today have a lower average sensitivity. Since the supply and selective adsorption of Mg^{2+} and Ca^{2+} is believed to limit or reverse sensitivity development, this might explain some low and medium sensitive clays at comparably high QCSI values.

Advancement in both the empirical and theoretical basis for sensitivity modeling as well as economic considerations (i.e. cost of landslides and preventive measures) will motivate future model revisions (summarized in Table 4), for instance, the use of new datasets and 3-D GIS procedures. Additional geotechnical data exist that have not been considered in the model (e.g. in archives at municipality offices and consultant companies), but were too time demanding to digitalize for modeling purposes alone. A national geotechnical database that would rationalize such work in Sweden has been suggested by Rydell (2002). Recent results from the SGI Göta älv River valley investigations (SGI 2011c) could be used for further model refinements and possibly for general model development (e.g. using an Artificial Neural Network framework). Existing high-resolution Light Detection and Ranging elevation data sets covering parts of the study area (Vattenfall power consultant AB 2007; NLSS 2010b) have not yet been utilized because of limited spatial coverage and purchase costs.

The inclusion of additional empirical data may, in its simplest form, be done by the incorporation of new datasets in the model structure as they become available by repeating the criteria utility map construction procedures for specific criteria. The use of the current, regionally developed model is sufficient for some purposes, although an expected increase in model performance might motivate further consideration of local conditions to evaluate the ground-system relationships and their influence on quick-clay development. It is possible to fit the sensitivity

Table 4 Possible future advancements of model stages

Model stage	Current state	Possible improvement actions
Data mining	Manual digitalization of geotechnical survey results	Considerable data from diverse, governmental and private archives are available if the work input can be justified or combined with other goals, regionally or locally. Incorporation of in situ estimations of sensitivities from cone penetration tests (cf. Löfroth 2011) could further increase the data set. These developments could be aided by a national geotechnical database (Rydell 2002).
Use of elevation data	50 m DEM used (NLSS 2010a)	Incorporation of the 2 m DEM (NLSS 2010b) for increased accuracy and precision of geomorphological criteria.
Stratigraphic criteria quantification	Kriging and Cokriging interpolation	Further geomorphometric work to account for bedrock shape and undulation and extension of the paleogeographic work (Stevens et al. 1984; Pässe and Andersson 2005) to better quantify important levels for the formation of permeable layer deposits. Force interpolation through new data points as they become available.
	Criteria subjectively standardized	Further geophysical and geological work aiming to classify areas and criteria variability more specifically to allow use of local utility function sets.
	AHP weighting process	Using artificial neural networks on large data sets (e.g. SGI 2011c) to minimize subjectivity in weighting.
	2–2.5D model perspective	Introducing 3D modeling to improve stratigraphical interpretations of sensitivity trends.
Model evaluation	Statistical assessment	Compare to additional data to improve model validation and to increase model specificity. A sensitivity analysis of model inputs (criteria considered, weights and utility functions).

assessment to local and better known sensitivity patterns, leading to new criteria weights or utility functions that would presumably improve the correlation with the locally documented sensitivity values. These developments would benefit from extra data mining of geotechnical archives to increase spatial coverage. New geophysical measurements (e.g. resistivity profiling, Persson and Stevens 2012) and expansion of previous paleogeographic work (Stevens et al. 1984; Pässe and Andersson 2005) would help substantiate parameter values that are largely based on conceptual modeling in the current QCSI model.

Quick-clay delineation from the QCSI maps alone is not considered appropriate (nor intended). The limitations of the methodology applied for QCSI modeling imply that predictions are appropriately combined with knowledge of the uncertainties (as suggested in Table 4). In selecting a suitable QCSI threshold for practical use in landslide hazard zoning, it is important to recognize that this cutoff value is a trade-off between the share of correctly classified quick clays and areas wrongfully classified as such (cf. Table 3). A more conservative transformation function for QCSI to sensitivity, perhaps exponentially shaped, could be applied and Boolean constraints excluded (given the accuracy and precision of input data sets) as safety precautions when the model is applied in high-risk areas.

The most obvious practical application of the QCSI model is for slope stability zoning by improving hazard and risk assessments for expansive slide development. The first step in current Swedish method for zoning is to evaluate large areas cost-efficiently (Skredkommisionen 1995), which is a main strength of the QCSI model. The model has been constructed for and tested on southwest Swedish settings, but its structure could be applicable in other similar areas.

Conclusions

The suggested modeling framework takes advantage of both qualitative information (established theory and expert judgment concerning quick-clay development and the regional distribution of sediment types) and observational data (geological observations and geotechnical records). The use of stratigraphic knowledge in a semi-quantitative way to specify leaching vulnerability is the most novel aspect of this modeling. The model transparency is important in that new information will naturally allow improvement in the criteria selection and weighting aspects that are central to the used methodology. In fact, the model provides, when compared with empirical data, new perspectives of geological assumptions, as well as those dealing with the development of quick clay itself. This feedback to the modeling procedure will be especially important since it is the first prediction model for quick-clay occurrences.

The model is successful in predicting the average clay sensitivity trends within the regional study area. Although the results for site-specific predictions are encouraging, the high variability that characterizes sensitivity observations requires additional model improvements and new data. In particular, site testing including geophysical profiles would provide useful 2D perspectives, helping to link the borehole-based sensitivity samples to the geographic and 3D stratigraphic considerations used in the QCSI model.

Southwest Swedish quick and non-quick clay deposits are environmentally more similar than they are different, both during and after deposition. This is illustrated by the comparably narrow QCSI interval represented and correlated with known sensitivity values.

However, small environmental differences account for large differences in shear strength characteristics and clay sensitivity, creating a modeling challenge. Permeable units (within or beneath the clay), especially if well connected to groundwater infiltration areas, decisively impact on quick-clay distribution in southwestern Sweden. Further work constraining this impact should increase the accuracy of the QCSI predictions and increase the usability in landslide hazard work.

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