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# Mapping suitability of controlled drainage using spatial information of topography, land use and soil type, and validation using detailed mapping, questionnaire and field survey

Abraham Joel, Ingrid Wesström and Ingmar Messing

## ABSTRACT

Controlled drainage has the potential to moderate the variability in temporal water runoff and to control N leaching. The objective of this study was, firstly, to present a feasibility study to identify land that is suitable for installation of controlled drainage in four counties in the coastal areas of southern Sweden and, secondly, to present a methodology to validate land that has been identified as suitable. In the feasibility study, digital data of land use, slope gradient and soil types were individually rated and combined into suitability classes. Of 726,000 ha cultivated land, 21% was classified as very highly or highly suitable, 13% moderately suitable and 6% marginally suitable. The validation study comprised analyses of the study areas from (i) digitized information on existing drainage network associations, provided by regional authorities, (ii) a questionnaire study directed to land users and (iii) physical investigation of soil properties of chosen fields on 82 farms. At least 67% of the land being appointed as being suitable for controlled drainage in the feasibility study was drained or had a drainage demand. There was a high correspondence between the results obtained in the validation study as compared to the feasibility study.

**Key words** | controlled drainage, digital mapping, drainage status, land suitability evaluation, southern Sweden, stake holders

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## INTRODUCTION

Drainage is a prerequisite for agriculture production in humid parts of the world. As a consequence of subsurface drainage, a larger proportion of the runoff percolates through the soil profile and the surface runoff decreases. The risk of outflow of easily transported solutes like nitrate may increase considerably. In southern Sweden the nutrient leakage from arable land is generally largest during winter and early spring, depending on excess of precipitation and reduced plant nutrient uptake. The nitrogen leakage is largest in areas with intensive agriculture, light textured soils, large density of animal husbandry and large amounts of precipitation. About 45% of the anthropogenic nitrogen loads to surrounding seas come from agriculture (SNV 1997*a*).

The drainage demand varies within year and between years, depending on climatic conditions and which crop is grown. The farmer has few options to manipulate a conventional drainage system. The outflow of water is governed by the boundary conditions set by the design of the system. A controlled drainage system, however, gives better possibilities to vary the drainage outflow to meet the demands of both crops and environment. By regulating the outlet level in control structures in manholes along the collector drains, it is possible to manipulate the ground-water level in the soil. By raising the level during periods of small drainage demand, and thereby keeping a higher groundwater level, water can be saved and utilized by

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crops for increased transpiration and growth. Furthermore, the amounts of subsurface water runoff and leakage of nutrients can be reduced.

Controlled drainage has been shown to have major effects on subsurface runoff water quantity and quality (e.g. Gilliam *et al.* 1979; Tan *et al.* 1993; Drury *et al.* 1996; Lalonde *et al.* 1996; Paasonen-Kivekäs *et al.* 1998). For example, results from 14 studies showed that the losses of nitrogen and phosphorus from arable land were, on average, reduced by 45% (10 kg $ha^{-1}$) and 35% (0.12 kg $ha^{-1}$), respectively, as compared with conventional drainage (Evans *et al.* 1989). The total outflow amounts were reduced by 30%. In field trials on a loamy sand in Sweden, nitrogen leakage was 20–30 kg N smaller per ha and year in controlled drainage than in conventional (Wesström *et al.* 2001; Wesström 2002). The main reason for the smaller nitrogen losses in controlled drainage was the smaller subsurface water runoff (Wesström *et al.* 2003). Furthermore, smaller losses of phosphorus and up to 18% larger yields were registered (Wesström & Messing 2007).

The extent to which Swedish agricultural land is suitable for controlled drainage is not yet reported. There are possibly large zones, for example in the coastal areas of the southern parts, which should be suitable for controlled drainage. It is supposed that the introduction of controlled drainage in these areas would bring about a considerable decrease in anthropological nitrogen loads from arable land to surrounding seas.

There are many onsite conditions that need to be fulfilled in order to achieve a cost-effective and good performance of a controlled drainage system at field level. Many of these conditions represent the sampled effect of several parameters. Ideal conditions for controlled drainage are soils with relatively large water permeability and a high natural groundwater table or a poorly permeable soil layer at a depth of 1–3 m (Evans & Skaggs 1985). This is necessary to get a quick reaction in the system and to keep water within the field. Another important aspect is the topography: with larger differences in the level within a field, the larger number of control structures have to be installed at a higher cost. The slope gradient should not exceed 1–2% (Evans & Skaggs 1985).

The main objective of this work is to develop and test a methodology for estimating potential land for controlled drainage using a few parameters that can be obtained from available map datasets, and validating the findings using information from authorities, land users and observations in field. Firstly, we present a feasibility study to determine land that would be suitable for installation of controlled drainage in the coastal areas of southern Sweden. The agricultural land is classified with regard to potential for controlled drainage considering the parameters slope gradient and soil type. Secondly, we present a methodology to validate land that has been identified as suitable in the feasibility study using data from (i) digitized information on drainage network associations derived from local authorities, (ii) a questionnaire study directed to the land users and (iii) physical investigation of soil properties of chosen fields.

## METHODS

Areas included in this study were the counties of Halland, Skåne, Blekinge and parts of Kalmar (Figure 1) (55°20′N–57°33′N and 11°52′E–17°09′E). These areas are the most prone to nitrogen leakage in southern Sweden (SNV 1997*b*) due to the large degree of land with light textured soils and intensive cropping and animal production. They are characterized by an average duration of vegetation period of approximately 200 d and a humidity

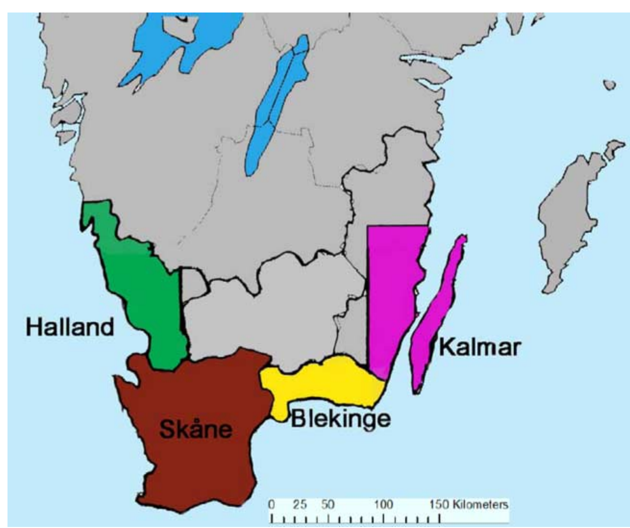


**Figure 1** | The studied areas Halland, Skåne, Blekinge and parts of Kalmar counties.

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(precipitation minus potential evapotranspiration) during the vegetation period of 0–150 mm. General crops grown are cereals, rapeseeds, sugar beets and potatoes.

## Feasibility study

We have used digitized data of elevation (a total of 84 datasets), land use type (50 datasets) and soil type (34 datasets). All data were processed with the software ArcInfo 8.2. In Figure 2, a schematic overview of the procedures in data handling is presented, resulting in (i) rating of slope gradient, land use and water permeability and (ii) suitability classification for controlled drainage.

### Elevation dataset and rating of slope gradient

The elevation dataset was produced by the Swedish Land Survey Authority (Lantmäteriet). It contains an elevation value with one decimal in each cross-point in a 50 m × 50 m grid. Each dataset comprises a mapping unit of

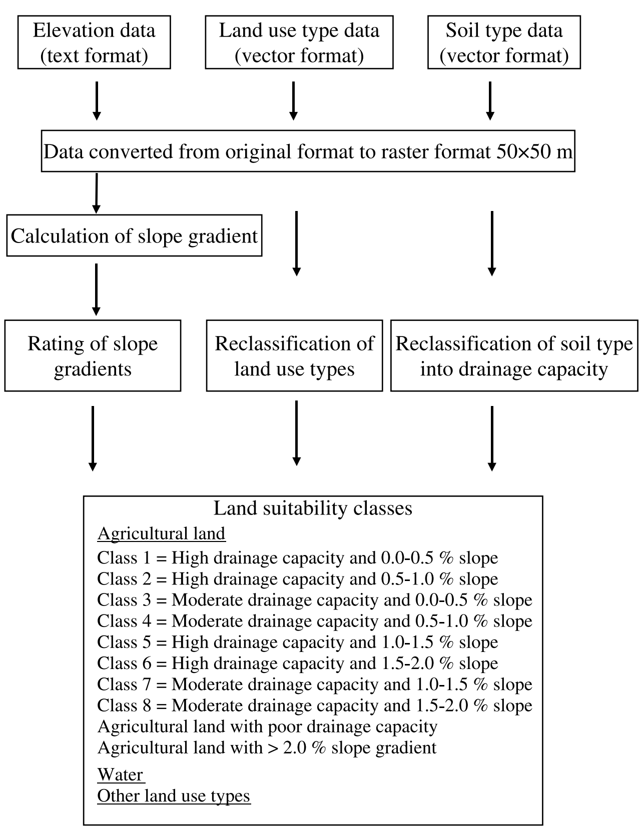


**Figure 2** | Schematic presentation of the data treatment in the feasibility study.

25 km × 25 km. Data were delivered in text format with point values, which was converted to grid format (raster) in ArcInfo. The final elevation data were presented in 50 m × 50 m pixels. Subsequently the slope gradient for each pixel was estimated in relation to the surrounding pixels in accordance with Burrough & McDonell (1998). The slope gradient data were rated into the following five classes: (1) less than 0.5%, (2) 0.5–1.0%, (3) 1.0–1.5%, (4) 1.5–2.0% and (5) more than 2%.

### Dataset and classification of land use type

Terrain maps produced by the Swedish Land Survey Authority in the scale 1:50,000, each representing a 25 km × 25 km area, were used to outline agricultural land in the study zones. The maps contain detailed classification of the landscape elements and are therefore convenient in physical planning. The dataset consists of several layers with information like land use, hydrography, settlements and road networks. In our study only the layer land use was used, consisting of: settlement areas of different types, industry land, recreation land, open water, coniferous and mixed forest, deciduous forest, high mountain forest, cutting areas, arable land, open land, peat exploitation area, rock outcrops and horticulture. Following reclassification, the land use was organized into: (i) waters, including all types of surface waters (sea, lake, rivers, etc.), (ii) agricultural land, including arable and grazing land, and (iii) other land use types including all other than those defined in (i) or (ii).

### Soil type datasets and rating of water permeability

All soil type data used in this study derive from the Geological Survey of Sweden (SGU). The access to digital map material with the convenient scale 1:50,000 was relatively limited. Therefore, local, regional and national datasets at different scales, between 1:50,000 (local) and 1:1,000,000 (national), were used.

*Local datasets from SGU (Serie Ae).* The maps show the extension of different soil types in the upper part of the ground and the occurrence of rocky outcrops. The soil types are classified according to the way of formation and particle size distribution. Shallow soils less than 0.5 m in thickness

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are generally not recorded. The mapping is originally compiled at a detailed scale but generalized to 1:50,000 to improve readability. To present the map information as complete as possible, each surface (polygon) is described with one of three attributes: J1 (surface layer above 0.5 m), J2 (normal mapping depth at 0.5 m below soil surface) and J3 (soil type below 0.5 m). The J2 attribute was used in this study since it corresponds to a depth where the drainage properties have a large significance.

*Regional datasets (SGU, Modell JC)*. This mapping treatment is made with a similar methodology as for the local datasets, but because of the need of generalization the recommended scale is 1:100,000 to 1:200,000.

*Dataset of soil types in Skåne county* is a compilation and rearrangement of the datasets of the modern soil type maps (SGU, serie Ae, scale 1:50,000), wherever they exist. The soil types are rearranged into 14 classes, and thereby some changes in the dataset have been made. The smallest areas have subsequently been removed or enlarged when the polygon size has been increased from 5 to 50 m. The dataset gives a comprehensive overview of the soil types and the degree of generalization is such that it is suited for application in the scale range 1:100,000 to 1:400,000. The soil type information displayed uniquely represents the J2 layer.

The area that lies within Kalmar was analyzed using information from local datasets. The mapping material covered 80% of the area studied. The remaining 20% was complemented by information from the national dataset. Of the area in Blekinge, approximately 50% was studied using information from local datasets, 25% from regional datasets and 25% from national datasets. The whole of Skåne was analyzed using information from the datasets of soil types in Skåne. Finally, in Halland, approximately 60% of the area was analyzed with information from the local dataset and 40% from the national dataset.

A general rating of soil types relative to their potential drainage capacity (including water permeability and soil water holding capacity) was made according to the following, based on the classification of particle sizes typical for the dataset utilized in this study:

(1) high drainage capacity in sandy textured and coarser soil types, having less than 5% clay content;
(2) moderate drainage capacity in mineral sedimentary and moraine soil types with clay contents from 5% to 15% maximum, and in organic soils (peat and gyttja), and in moraine with no reference to dominant particle size;
(3) poor drainage capacity in mineral sedimentary and moraine soil types with more than 15% clay, based on the assumption that controlled drainage keeps the soil profile in a more moist condition and thereby, to a certain degree, prevents crack formation, and in fine and medium silt.

## Data preprocessing

In order to achieve an exact combination of the parameters, all vector and tabular data were converted to raster data with a cell size of 50 m × 50 m pixels. The size of the pixels had been determined from the accuracy of the elevation data. Since four pixels are equivalent to 1 ha, we assumed that spatial variability at the field level will be represented with enough accuracy. Tanga *et al.* (2005), for example, represented landscape characteristics in 1 pixel per ha. After the rasterization each pixel got a numerical value: this value can represent many properties of a location such as soil texture, land use and elevation. From geographical points of view, each parameter is exactly represented by this in the defined mapping grid system. A series of mathematical operations can be used to combine the effect of various properties.

## Suitability classes for controlled drainage

Suitability classes were determined by overlay analysis of the three parameters (slope gradient, land use type and drainage capacity) (Figure 2). Two of the parameters had three classes and one of them five, resulting in 45 different subclasses. After recombining these subclasses into groups and removing the water areas (all types of surface waters) and land other than agricultural land, a resulting 8 suitability classes and 2 unsuitability classes were defined. Areas in classes 1–2 were considered very highly suitable, in classes 2–3 highly suitable, in classes 5–6 moderately suitable and in classes 7–8 marginally suitable. Agricultural land with low water permeability and agricultural land with

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more than 2.0% slope gradient were considered non-suitable for controlled drainage.

## Validation study

The validation study covers two levels in the study areas. One overview level, with the objective of testing if the land that was shown to have potential for controlled drainage in the feasibility study also had drainage demand, is presented in the section on information about drainage conditions. The second is at farm and field level, in which several requirements for the functionality of controlled drainage were evaluated for particular fields by questionnaire and field investigations.

### Information about drainage conditions

The authorities in each of the four studied counties (Halland, Skåne, Blekinge, parts of Kalmar) provided us with data concerning drainage conditions and drainage demands on agricultural land based on registered drainage network associations (associations of land users for construction and maintenance of drain ditch and tile systems for draining a specific area). A total of 6,413 drainage network associations were included in the study. The information about the drainage network associations were documented in digital and paper formats. Information in digital format did not describe the drainage systems in detail or the individual fields that were drained. Nevertheless, they provided very good indications on which areas were in demand of drainage or that were drained at the time of the study. Detailed drainage plans, etc, may, when necessary, be extracted from the dataset.

The drainage network associations in Skåne were sampled in digital format. In Halland, the information was provided in paper format. These maps were digitized within the framework of our project. In Blekinge, the information was provided in table format, one point with coordinates for each drainage network association. These point markings were digitized. In Kalmar, paper maps containing information concerning the size of the areas that are estimated to be influenced by the drainage network associations were digitized. Around each drainage network association a zone was estimated, which was assumed to be influenced by the drainage network association. This zone in Halland and Skåne was estimated to cover 500 m on both sides of the main drains and, in Blekinge, to cover a circular zone with a radius of 500 m around each point of a drainage network association (Figure 3). This makes it possible to estimate how much of the land found to be suitable for controlled drainage in the feasibility study may still be suitable, based on the implication that it is drained or has a drainage demand.

### Questionnaire

The objective of the questionnaire study was to gather information from the land users concerning (i) which type of soils were cultivated, especially the occurrence of light textured soils, (ii) which of these soils were in demand of drainage, (iii) occurrence of layers with poor water permeability and (iv) the normal range of groundwater levels.

The questionnaire consisted of 11 questions. Question nos. 1–4 concerned soil type, nos. 5–7 actual drainage conditions, no. 8 occurrence of layers with poor permeability, and no. 9 regular groundwater levels (Table 5). Question nos. 10 and 11 were included to get information on what the land users knew or believed concerning implementation of controlled drainage on their land. In addition to the questionnaire, maps of the land users' fields were attached on which they were supposed to point out which fields were presently drained and which non-drained fields were in demand of drainage implementation (Figure 4). Furthermore, two information folders about controlled drainage were attached.

The questionnaires were primarily sent to land users where physical field investigations were carried out (see the preceding subsection), in order to be able to compare the results from these two sub-studies. Additionally, a number of questionnaires were sent to land users where no physical investigations were performed. A total of 124 questionnaires were sent to land users in the four counties (Table 1). Of these, between 35–70% responded to the questionnaire study.

### Field investigations

Soils were sampled at a number of the farms used in the questionnaire study, to be analyzed and represent the

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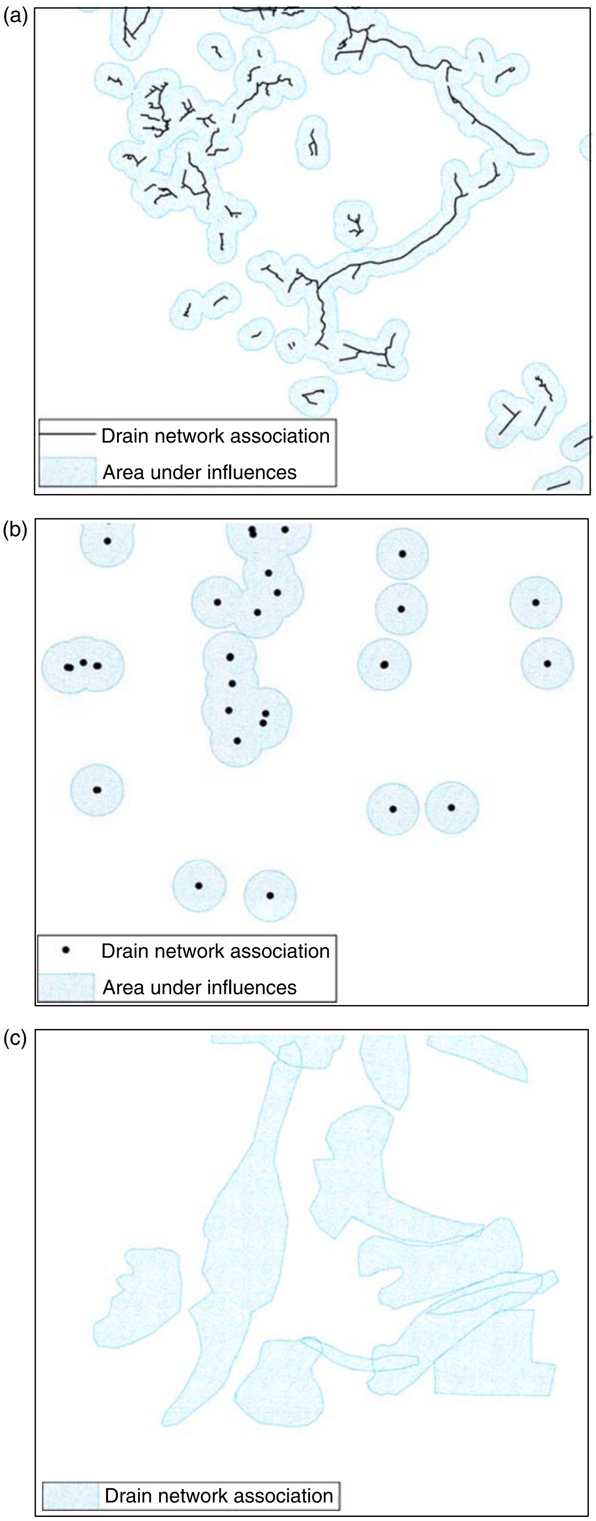


**Figure 3** | Examples of treatment of digitized drainage network associations and estimated zones that are drained or have drainage demands in (a) Halland and Skåne, (b) Blekinge and (c) Kalmar.

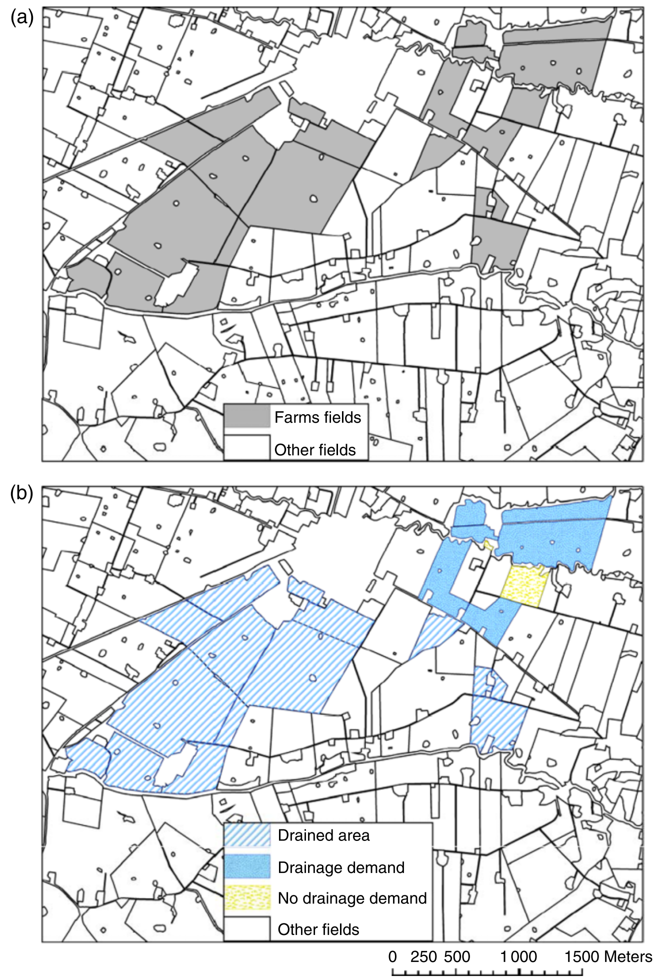


**Figure 4** | Example of information sampled from land users concerning their concepts of which fields are drained and which ones are in demand of drainage: (a) sent materials to land users, (b) replied information from land users.

in-field 'reality' as compared with the corresponding soils identified on the general maps compiled in the feasibility study. Twenty-four sub-areas, within the areas defined as suitable for controlled drainage in the feasibility study (primarily classes 1–4 and, to a certain extent, classes 5–8) were chosen for this purpose. Within each sub-area, a number of farms were chosen for detailed studies. The choice of suitable farms was made by consulting one of the regional datasets on land users/field units and selecting units positioned in the potential areas (as found in the feasibility study).

Altogether 148 fields at 82 farms (Table 1) were investigated regarding the factors (i) texture, (ii) groundwater level, (iii) occurrence of poorly permeable layers and

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**Table 1** | Compilation of the number of sent and responded questionnaires

| County | Sent (no.) | Farms where field investigations were carried out (no.) | Responded (no.) | Total area (ha) |
|---|---|---|---|---|
| Halland | 25 | 13 | 17 | 2,551 |
| Skåne | 25 | 23 | 17 | 4,412 |
| Blekinge | 20 | 13 | 11 | 1,144 |
| Kalmar | 54 | 33 | 19 | 2,170 |
| Total | 124 | 82 | 64 | 10,277 |

(iv) slope gradient. The soils were sampled with auger down to 1.7 m depth, depending on the properties of the soil profiles. On Öland, in particular, the sampling depth was seldom more than 80 cm due to the predominant occurrence of stones or rock outcrops. If groundwater and/or poorly permeable layers of clay were found, the depth of these factors were noted. The position of the sampling sites were stored with GPS, both to ensure that the sampling was made at the proper position and to store the position for treatment in Arcmap. Furthermore, the land users at these farms were interviewed (non-formalized) to gather complementary information to the questionnaire study outlined in the preceding section. The soil samples were analyzed in the laboratory using the pipette method for texture determination. Furthermore, field tests were made to roughly estimate the texture from plasticity and other characteristics.

To facilitate comparison with the feasibility study, the soils were divided into three classes: light textured (primarily the fraction sizes coarse silt to gravel), intermediate textured (organic, slightly clayey 5–15% and silty soils) and heavy textured (clay >15% and fine silt).

### Treatment of gathered information

The compilation and treatment of the results from the questionnaires and soil samples were made with the aid of GIS tools. The soil types from the laboratory analyses were compared with the digital soil map information used in the feasibility study. The material was partitioned into: rank (1) good agreement, rank (2) moderate agreement and rank (3) poor agreement. In rank (2), the results were not as exact as the map, but it was still possible to relate the imperfect agreement with surrounding soils, e.g. sites lying in the transboundary zone between areas with contrasting soil types. Rank (3) means large differences between analyzed texture class and mapped soil type, e.g. the textural analysis indicating a clay soil whereas the soil map showed a sand.

## RESULTS

### Feasibility study

A total of more than 726,000 ha agricultural land was included in the study (Table 2). About two-thirds of this land was situated in Skåne, 16% in Halland, 5% in Blekinge and 13% in Kalmar. About 60% of the agricultural land was classified not suitable due to low water permeability or slope gradients >2% (Table 3). Thus, a large part of the area, 40% or 289,000 ha, was estimated to be suitable for controlled drainage. The largest proportion was found in areas with very high suitability (classes 1–2), about 100,000 ha, and in areas with moderate suitability (classes 5–6), 91,000 ha. Areas with high (classes 3–4) or marginal (classes 7–8) suitability composed 6–7% of the total area. Kalmar had the largest proportion of suitable agricultural land (Table 3). The proportion of the agricultural land that is classified non-suitable is, on average, similar in Blekinge, Skåne and Halland, between 62–71%. In Kalmar, only 31% was non-suitable for controlled drainage.

In Halland, the agricultural land is concentrated in the western part of the county, where a relatively large part of the studied area had a high suitability for controlled drainage (Figure 5). It was mainly in the Laholm and Falkenberg regions that the potential was highest, with 25% of the agricultural land classified as non-suitable due to low water permeability and 47% due to high slope gradients.

In Skåne, the land with highest suitability was spread across the entire region, with a certain concentration on the eastern side around the cities Kristianstad, Bromölla andÅhus. In this county 62% of the land was classified as non-suitable due mainly to high slope gradients (42%) and low water permeability (20%).

In Blekinge, the largest areas with highest suitability were found on Listerlandet. High slope gradients (51%) were found to be the major constraint in this county, but also low water permeability was limiting (11%).

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**Table 2** | Potential area (ha) for controlled drainage in the study zones

| Suitability class | Halland | Skåne | Blekinge | Kalmar | Total areal (ha) |
|---|---|---|---|---|---|
| Class 1 (very high) | 8,754 | 31,522 | 2,671 | 12,384 | 55,331 |
| Class 2 (very high) | 6,403 | 26,652 | 2,106 | 8,753 | 43,917 |
| Class 3 (high) | 1,861 | 14,357 | 926 | 12,421 | 29,565 |
| Class 4 (high) | 1,277 | 13,099 | 1,022 | 6,739 | 22,137 |
| Class 5 (moderate) | 7,995 | 36,676 | 2,054 | 9,708 | 56,433 |
| Class 6 (moderate) | 4,750 | 23,375 | 1,490 | 5,019 | 34,634 |
| Class 7 (marginal) | 1,636 | 19,505 | 1,430 | 6,452 | 29,023 |
| Class 8 (marginal) | 1,086 | 13,489 | 977 | 2,196 | 17,748 |
| Poor drainage capacity | 29,306 | 98,192 | 3,794 | 7,654 | 138,946 |
| Slope gradient >2% | 55,387 | 204,950 | 16,987 | 21,196 | 298,520 |
| Sum agricultural land | 118,458 | 481,817 | 33,457 | 92,522 | 726,254 |
| Other land | 389,216 | 620,469 | 258,108 | 505,723 | 1,773,560 |

In Kalmar, the largest proportion of agricultural land was concentrated along a 10 km stretch of coast on the mainland as well as along the coast of Öland. However, for the areas situated on Öland, with the exception of the Mörbylånga area, most of the land is composed of relatively stony and shallow soils which are drained with open ditches, indicating that subsurface drainage is neither required nor possible to implement.

It is important to remark that, in general, the areas named above are located in high intensive agricultural production districts and close to hot spot areas along the coasts with serious eutrophication problems.

## Validation study

### Information about drainage conditions

On average, 67% of the agricultural land with potential for controlled drainage in the feasibility study (classes 1–8) was found within areas with drainage network associations, a total of 193,000 ha (Table 4). A large proportion of this land, approximately 140,000 ha, was found in Skåne, as compared to Halland (21,000 ha), Kalmar (22,000 ha) and Blekinge (10,000 ha). The total area with high suitability (classes 1–4) was about 98,000 ha and constituted 13.5% of the agricultural land or 21% of the agricultural land within areas with drainage network associations. The remaining moderately and poorly suitable land constituted about 95,000 ha. The relative proportions of classes 1–4/classes 5–8/non-suitable agricultural land were fairly similar: 0.21/0.20/0.59 (98,000/95,000/278,000 ha) in the present study and 0.21/0.19/0.60 (151,000/138,000/438,000 ha) in the feasibility study.

### Questionnaire

A compilation of the results from the questionnaire study is presented in Table 5. It was found that the dominating soil types in the areas were sand and coarse silt with the

**Table 3** | Proportions of suitability classes in the counties (percentage of agricultural land)

| Suitability class | Halland | Skåne | Blekinge | Kalmar | All counties |
|---|---|---|---|---|---|
| Classes 1–2 (very high) | 13 | 12 | 14 | 23 | 14 |
| Classes 3–4 (high) | 3 | 6 | 6 | 21 | 7 |
| Classes 5–6 (moderate) | 11 | 12 | 11 | 16 | 13 |
| Classes 7–8 (marginal) | 2 | 7 | 7 | 9 | 6 |
| Not suitable | 71 | 63 | 62 | 31 | 60 |

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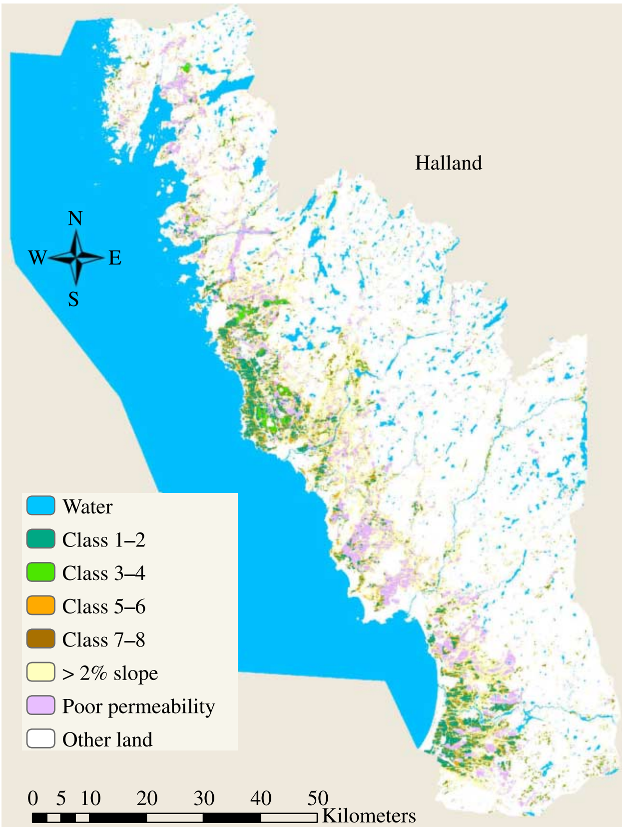


**Figure 5** | Example of a suitability map for controlled drainage: Halland.

occurrence of clay and fine silt. Only five of the land users responded that the proportion of clay and fine silt soils constituted more than 60% of their agricultural land. The majority of the land users in Halland, Skåne and Blekinge indicated that a large proportion of their agricultural land was in demand of drainage. In Kalmar, 60% of the land users stated that less than 30% of their agricultural land was in demand of drainage. The dominating soil types with drainage demands, in the whole study area, were of intermediate texture.

The land users in Halland reported the largest proportion of systematically drained land, whereas the land users in Kalmar reported that less than 30% of their land was systematically drained. Most of the land users in Halland, Blekinge and Kalmar had poorly permeable layers in the soil profiles and a normal groundwater level within 2 m below the soil surface. In Skåne, the majority responded that they did not have or did not know if they had poorly permeable layers in the soil profiles and a normal groundwater level within 2 m below the soil surface. Most of the land users in this study did not have knowledge about controlled drainage. Only 5 of them responded that controlled drainage might be suitable on their land, while 10 answered that they did not know whether the method was suitable or not.

Responses with information on maps of which fields were presently drained or in demand of drainage were obtained from 17 land users in Halland, 13 in Skåne and 10 in Blekinge. These results in digital form were used to complement the information about drainage network associations. From the map material it could be concluded,

**Table 4** | Potential area (ha) for controlled drainage in the areas of drainage network associations

| Suitability class | Halland | Skåne | Blekinge | Kalmar | Total area |
|---|---|---|---|---|---|
| Class 1 (very high) | 6,170 | 23,812 | 667 | 4,470 | 35,119 |
| Class 2 (very high) | 4,077 | 20,234 | 553 | 2,727 | 27,591 |
| Class 3 (high) | 1,497 | 12,931 | 281 | 5,660 | 20,369 |
| Class 4 (high) | 800 | 11,457 | 297 | 2,535 | 15,089 |
| Class 5 (moderate) | 4,649 | 27,097 | 6,545 | 2,714 | 41,005 |
| Class 6 (moderate) | 2,575 | 16,666 | 934 | 1,158 | 21,333 |
| Class 7 (marginal) | 800 | 16,586 | 379 | 2,236 | 20,001 |
| Class 8 (marginal) | 457 | 11,250 | 253 | 612 | 12,572 |
| Slope gradient >2% | 20,249 | 142,764 | 4,440 | 4,287 | 171,740 |
| Poor drainage capacity | 16,153 | 86,478 | 1,145 | 2,248 | 106,024 |
| Sum agricultural land | 57,427 | 369,275 | 15,494 | 28,647 | 470,843 |
| Other land | 65,342 | 243,895 | 31,190 | 35,848 | 340,427 |

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**Table 5** | Results (number) from questionnaires to land users in the study areas

| County | Halland | Skåne | Blekinge | Kalmar |
|---|---|---|---|---|
| *Dominating soil type (question no. 1)* | | | | |
| Light textured | 14 | 13 | 7 | 13 |
| Intermediate textured | 12 | 7 | 10 | 16 |
| Clay and fine silt | 3 | 4 | 2 | 3 |
| *Proportion light textured soils (no. 2)* | | | | |
| <30% | 6 | 5 | 3 | 7 |
| 30–60% | 7 | 4 | 7 | 7 |
| >60% | 5 | 9 | 1 | 5 |
| *Proportion intermediate textured soils (no. 3)* | | | | |
| <30% | 8 | 13 | 2 | 5 |
| 30–60% | 7 | 3 | 7 | 11 |
| >60% | 3 | 2 | 2 | 3 |
| *Proportion clay and fine silt soils (no. 4)* | | | | |
| <30% | 13 | 15 | 9 | 17 |
| 30–60% | 2 | 2 | 2 | 1 |
| >60% | 3 | 1 | 0 | 1 |
| *Proportion agricultural land with drainage demands (no. 5)* | | | | |
| <30% | 1 | 5 | 3 | 12 |
| 30–60% | 4 | 6 | 3 | 7 |
| >60% | 13 | 7 | 5 | 0 |
| *Dominating soil type with drainage demand (no. 6)* | | | | |
| Light textured | 9 | 5 | 3 | 4 |
| Intermediate textured | 11 | 10 | 7 | 11 |
| Clay and fine silt | 2 | 10 | 5 | 1 |
| Not defined | 2 | 1 | 3 | 5 |
| *Proportion systematically drained land (no. 7)* | | | | |
| <30% | 1 | 7 | 3 | 13 |
| 30–60% | 5 | 5 | 4 | 2 |
| >60% | 11 | 6 | 3 | 2 |
| Not defined | 1 | 0 | 1 | 2 |
| *Poorly permeable layers and groundwater level within 2 to 6 m depth (no. 8)* | | | | |
| Yes | 11 | 6 | 7 | 11 |
| No | 2 | 7 | 2 | 3 |
| Do not know | 4 | 5 | 1 | 3 |
| Not defined | 1 | | 1 | 2 |
| *Normal groundwater levels (no. 9)* | | | | |
| <1.5 m | 7 | 7 | 2 | 1 |
| 1.5–2.5 m | 7 | 7 | 6 | 3 |
| >2.5 m | 1 | 2 | 0 | 5 |
| Do not know | 3 | 4 | 3 | 8 |
| Not defined | 1 | 0 | 1 | 2 |
| *Knowledge about controlled drainage (no. 10)* | | | | |
| Yes | 8 | 8 | 2 | 4 |
| No | 9 | 10 | 8 | 13 |
| Do not know | 1 | 0 | 1 | 2 |
| Not defined | | | | |
| *Knowledge about suitability of controlled drainage on own land (no. 11)* | | | | |
| Yes | 3 | 1 | 1 | 0 |
| No | 2 | 4 | 1 | 1 |
| Do not know | 3 | 4 | 0 | 3 |

like in the questionnaire study, that the largest proportion of agricultural land in demand of drainage was found in Halland (94%) (Table 6). In Skåne and Blekinge approximately 2/3 of the agricultural land was in demand of drainage.

## Evaluation of drainage demands

The results from the responses of the land users concerning mapped drainage information, as in Figure 4 and Table 6, were evaluated against the results of suitability classification in the feasibility study and against information from drainage network associations (Table 4). A compilation of this evaluation is found in Table 7. Approximately half of the drained area in Halland (Table 6) was found in classes 1–4 (Table 7), i.e. showing a high suitability for controlled drainage. A total area of similar size was found in comparison with the evaluation of drainage network associations. Similar results were also found for Skåne

**Table 6** | Land users information of mapped drainage conditions

| | Halland | | Skåne | | Blekinge | |
|---|---|---|---|---|---|---|
| | (ha) | % | (ha) | % | (ha) | % |
| Drained area | 2,055 | 81 | 2,451 | 56 | 747 | 65 |
| Drainage demand | 319 | 13 | 278 | 6 | 81 | 7 |
| No drainage demand | 162 | 6 | 1,504 | 34 | 315 | 28 |
| Other land | 15 | 1 | 179 | 4 | 2 | 0 |
| Total area | 2,551 | | 4,412 | | 1,144 | |

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**Table 7** | Comparison of information from land users (LK) with information from drainage network associations (DF) concerning estimated area with drainage demands (ha), within suitability classes according to the feasibility study

| | | Halland | | Skåne | | Blekinge | |
|---|---|---|---|---|---|---|---|
| | | LK | DF | LK | DF | LK | DF |
| Classes 1–4 | Drained | 975 | 920 | 1,377 | 1,084 | 341 | 128 |
| | Drainage demands | 155 | 152 | 106 | 87 | 45 | 36 |
| | No drainage demands | 49 | 49 | 783 | 607 | 123 | 0 |
| Classes 5–8 | Drained | 396 | 349 | 594 | 361 | 176 | 74 |
| | Drainage demands | 84 | 78 | 51 | 35 | 0 | 14 |
| | No drainage demands | 19 | 17 | 246 | 160 | 69 | 9 |
| >2% slope | Drained | 263 | 249 | 236 | 180 | 116 | 75 |
| | Drainage demands | 36 | 33 | 38 | 36 | 2 | 2 |
| | No drainage demands | 30 | 12 | 128 | 58 | 29 | 10 |
| Poor drainage capacity | Drained | 354 | 343 | 259 | 239 | 61 | 27 |
| | Drainage demands | 18 | 17 | 64 | 63 | 14 | 11 |
| | No drainage demands | 24 | 24 | 30 | 21 | 7 | 6 |
| Sum | | 2,403 | 2,243 | 3,912 | 2,931 | 983 | 392 |

and Blekinge. In Blekinge, however, the drained area estimated from drainage network associations was underestimated in that the buffering zone around each association (Figure 3) was too small.

To summarize, at least half of the investigated area that was drained or was in demand of drainage, according to the information from drainage network associations and land users, was shown to be very highly or highly suitable for controlled drainage, according to the results in the feasibility study.

Also, concerning the occurrence of poorly permeable soil layers and groundwater levels, based on the results from the questionnaire study complemented with field investigation and interviews on some of the sites, an evaluation was made of suitable land for controlled drainage and whether the land was drained or in demand of drainage (Table 8). It was shown that, on average, more than 85% of the drained area within classes 1–4 (feasibility study) had a poorly permeable layer or occurrence of shallow water table.

### Evaluation of soil type

Generally, the soil analyses were in good agreement with soil types from soil maps in the feasibility study, with 80–88% coming out in rank 1 (Table 9). Only at two sites did the analyzed texture not agree at all with that of the soil maps.

## DISCUSSION AND CONCLUSIONS

The present study was focused on identifying potential areas for installation of controlled drainage in vast areas of southern Sweden, using a GIS-based approach considering few and fairly easily obtained parameters, and validating the mapped results with information obtained from regional authorities and land users. A possible following step would be to quantify the environmental effects of any implementation of controlled drainage in the identified areas. If more soil physical data can be made available, or can be estimated, available simulation models combined with

**Table 8** | Area of occurrence of poorly permeable layers or shallow groundwater table on land that is drained or in demand of drainage, as estimated from the questionnaire study and field investigation, within suitability classes according to the feasibility study

| | | Halland | | Skåne | | Blekinge | |
|---|---|---|---|---|---|---|---|
| | | (ha) | % | (ha) | % | (ha) | % |
| Classes 1–4 | Drained | 884 | 91 | 1,146 | 83 | 326 | 96 |
| | Drainage demands | 128 | 83 | 78 | 74 | 38 | 84 |
| Classes 5–8 | Drained | 356 | 90 | 375 | 63 | 155 | 88 |
| | Drainage demands | 53 | 63 | 35 | 69 | 0 | 0 |

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**Table 9** | Total number of sampled fields and correspondence between soil analyses and soil maps

| | Halland | Skåne | Blekinge | Kalmar |
|---|---|---|---|---|
| | 31 | 54 | 28 | 35 |
| Rank 1 | 25 | 48 | 23 | 30 |
| Rank 2 | 5 | 6 | 5 | 4 |
| Rank 3 | 1 | 0 | 0 | 1 |

GIS applications can be used to assess effects on drain outflow and nutrient leaching, such as in works by Amatya *et al.* (1997), Yanga *et al.* (2000), Fernandez *et al.* (2003, 2004, 2006) and Chescheir *et al.* (2006).

## Feasibility study

This study has revealed that there is a large need of data in standardized digital form. The technique used made it possible to handle and treat large volumes of information. However, significant time was devoted to reclassifying the soil data. Although this study has a generalized character, there are fairly detailed results since most of the information used was in the scale 1:50,000 to 1:100,000. An important requirement is that mapping demands a correct representation of the properties in the study area. However, natural borders are usually not as sharp as shown on the maps, and therefore consideration should be given to trans-boundary zones at field scale.

The feasibility study has shown that there is a large potential for applying controlled drainage in the coastal areas of southern Sweden. However, the extent of suitable areas may differ to a certain degree for individual fields if additional parameters are considered. Such parameters may be actual drainage demands, occurrence of groundwater table or poorly permeable layers at depth. The results of this feasibility study was therefore tested in the validation study using detailed information on soils, actual drainage demand, data from existing drainage network associations and results from questionnaires from land users.

## Validation study

In the present study a number of farms within each sub-area were chosen for detailed studies. This approach was preferred instead of investigating a area chosen beforehand, for example within a $5 \times 5\,\text{km}^2$ grid, since it would not be certain that the whole of the latter area would have potential for controlled drainage. Furthermore, it would not be sure that all land users within the $5 \times 5\,\text{km}^2$ grid would like to participate in the investigation. Likewise, in the case of the present study not all contacted land users wanted to participate, but by choosing several farms a representative number of cases could be defined.

Information from drainage network associations was a useful source of data for the evaluation of all study areas. However, the available information was of variable quality and extent. Complementary treatment has been carried out within our project, which has facilitated a more extensive use of the information. In spite of these limitations, the information was sufficient for an overall evaluation in all counties except Blekinge. In the case of Blekinge, each drainage network association was marked simply with a dot, whereas in the other counties there existed a fair correlation between the classified size of area in the study of drainage network associations and the questionnaire study. Based on this correlation, the data given in Tables 5 and 6 can be regarded as approximately correct, with reservations for Blekinge which generally had too small an area (Table 7) due to the uncertainties in the data.

The questionnaire study showed it to be a simple and efficient tool to get information on the actual drainage conditions of the fields and the actual knowledge status concerning controlled drainage and the eagerness to implement it. The actual acquaintance with the technique was found to be fairly limited. More information needs to be given concerning necessary aspects to consider in order to construct a well-functioning system, the expected positive effects on water and nutrient economy, characterization of potential areas, advices on maintenance, costs and financing.

Concerning the evaluation of occurrence of poorly permeable layers and groundwater levels as determinants for controlled drainage, it was found that a large proportion of the evaluated area being drained or having drainage demands also had poorly permeable layers or a shallow groundwater level. This implies that the light textured soils on planar faces with drainage demands, which dominated

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in the investigated areas, had some type of obstacle in the soil profile. From this study it was found that these prerequisites, i.e. being drained or having drainage demands, were occurring on 85% of the area mapped with high suitability for controlled drainage.

The texture of the soil samples did, to a large degree, agree with corresponding map information of soil types. Thus, the map information of soil types as compiled in the feasibility study has a large significance. To get a better appreciation of the actual drainage conditions on different fields and their influence on water and nutrient flows, it is necessary to develop a more appropriate dataset which conveniently describes the actual drainage network infrastructure. This is essential because the natural infrastructure is highly influenced by the drainage network associations and other drainage installations. A dataset is needed which includes the layouts of existing drainage ditches and the fields that are affected. Additionally, a certain control of the current status of the listed drainage network associations is needed, and also that the existing permissions become documented in digital form. It is important to be able to follow up the effects of different management measures, both in time and space.

To summarize, this study showed that 67% of the area classified as suitable for controlled drainage in the feasibility study was actually drained or had a drainage demand. This is a fair accuracy considering the relatively few parameters used. The results from the questionnaire study were, regarding the percentage of suitable area, of the same order of magnitude as those estimated from the drainage network association networks in all cases except one. An estimated extension of area which had high potential for controlled drainage in the investigated counties amounted to approximately 90,000 ha. The area estimated to have moderate or marginal potential was of the same order of magnitude.

The methodology in the present study is promising and can, after some modifications, also be applied in other regions with similar conditions. For some parameters, local adaptions are needed, e.g. the rating of drainage capacity based on soil types. There is a need of further development of dataset infrastructures to better suit these kinds of studies.

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