The Danish Pesticide Leaching Assessment Programme

Site Characterization and Monitoring Design

Bo Lindhardt, Christian Abildtrup, Henrik Vosgerau, Preben Olsen, Søren Torp, Bo V. Iversen, Jørgen Ole Jørgensen, Finn Plauborg, Per Rasmussen, and Peter Gravesen.

Geological Survey of Denmark and Greenland
Ministry of Environment and Energy

Danish Institute of Agricultural Sciences
Ministry of Food, Agriculture and Fisheries

National Environmental Research Institute
Ministry of Environment and Energy

GEUS

Editor: Bo Lindhardt
Cover: Peter Moors
Lay-out and graphic production: Authors and Kristian Ander Rasmussen
Printed: September 2001
Price: DKK 500.00

ISBN 87-7871-094-4

Available from
Geological Survey of Denmark and Greenland
Thoravej 8, DK-2400 Copenhagen, Denmark
Phone: +45 38 14 20 00, fax +45 38 20 50, e-mail: geus@geus.dk
www.geus.dk

Tables of Contents

Preface

The Geological Survey of Denmark and Greenland (GEUS), the Danish Institute of Agricultural Sciences (DIAS), the National Environmental Research Institute (NERI), and the Danish Environmental Protection Agency (DEPA) have been requested by the Danish Government to set up and run a programme to assess the risk of pesticides leaching into surface waters and groundwater when applied in the prescribed manner. The programme was designed and the test sites established during 1999. This report describes the selected sites and the monitoring equipment installed.

The programme is managed by a project committee comprising:

Bo Lindhardt, GEUS
Jeanne Kjaer, GEUS (replaced Peter Gravesen as of 1 August 2000)
Svend Elsnab Olesen, DIAS
Arne Helweg, DIAS
Ruth Grant, NERI
Betty Bügel Mogensen, NERI
Christian Ammitsøe, Danish EPA
Christian Deibjerg Hansen, Danish EPA

Bo Lindhardt
August 2001

1. Introduction

There is a growing public concern in Denmark regarding pesticide contamination of groundwater and surface waters. The Danish National Groundwater Monitoring Programme (GRUMO) has revealed the presence of pesticides and their degradation products in approx. 30% of the monitored screens (GEUS, 2000). The increasing detection of pesticides over the past 10 years has raised doubts as to the adequacy of the existing approval procedure for pesticides. As the water sampled under the groundwater monitoring programme is usually more than 5 years old and often more than 20 years old, the results are of limited value as regards evaluation of the present approval procedure.

EU and hence Danish assessment of the risk of pesticide leaching to the groundwater is based mainly on data from laboratory or lysimeter studies. However, these types of data assessment do not provide satisfactory characterization of the leaching that might occur under actual field conditions. Soil (chemical properties and biological processes) and hydrogeology can vary significantly within as well as between fields, and climate conditions can vary during pesticide use. Furthermore, agricultural practice also varies between fields. Many of these parameters are not covered by laboratory or lysimeter studies as presently performed.

Laboratory and lysimeter studies provide little if any information on the inherent variability of the soil parameters affecting leaching. This is of particular importance for silty and loamy soils, where preferential flow may occur. Field studies abroad have demonstrated considerable transport of several pesticides to 1 m b.g.s. (**b**elow **g**round **s**urface) in loamy soils under conditions comparable with those in Denmark. The inclusion of field studies, i.e. test plots exceeding 1 ha, in risk assessment of pesticide leaching to the groundwater is considered an important improvement in risk assessment procedures. The US-EPA has requested such field studies to support the registration of pesticides suspected of potentially being able to leach to groundwater. Over the past decade, studies of more than 50 pesticides have been conducted. Based on this experience the US-EPA has published a set of guidelines for field studies (US-EPA, 1998). In Europe, EU Directive 91/414/EEC, annexe VI (Council Directive 97/57/EC of 22 September 1997) enables field study results to be included in the risk assessments.

1.1 Objectives of the programme

The aim of the Pesticide Leaching Assessment Programme (PLAP) is to monitor whether pesticides or their degradation products leach to groundwater under actual field conditions when applied in the prescribed manner. The programme is designed such that the findings can be evaluated in relation to the drinking water quality criterion, i.e. 0.1 μg/l.

The programme encompasses six test sites selected to represent the dominant soil types and the climatic variation in Denmark. To provide early warning of unacceptable leaching, the sites were selected where the groundwater was located 1-4 m below the ground surface, thus ensuring a short response time. Pesticides are applied to the test fields as part of routine agricultural practice and in accordance with the current regulations, thereby enabling the occurrence of pesticides or their degradation products in the groundwater downstream of the test field to be related to the current approval conditions pertaining to the pesticides.

The programme will only include pesticides used in arable farming. Pesticides used in forestry, fruit orchards and horticulture are not encompassed by the programme.

1.2 Schedule

Work on designing the programme started in August 1998. The six sites were selected during 1999 and the equipment for sampling drainwater and groundwater was installed the same year. This report presents the site characterization and the monitoring design of each site. Monitoring was initiated between May 1999 and April 2000. The results will be published in forthcoming reports.

1.3 Structure of the report

Chapter 2 provides a detailed description of the criteria used in selecting the test sites. Chapter 3 describes the monitoring equipment and methods while Chapter 4 presents the geological and pedological methods used to characterize the sites. Chapter 5 briefly describes the six test sites with regard to instrumentation, pedology and geology. For a more detailed characterization of each site the reader is referred to the accompanying annexes. Finally, Chapter 6 presents the pesticides encompassed by the programme.

2. Site selection

Selection of the sites is critical with respect to ensuring that the results are generally applicable and hence can be utilized in the pesticide approval procedures. The risk of groundwater contamination by pesticides mainly depends on soil type, hydrogeology, climate and agricultural practice. Site selection depends not only on these parameters, but also on such factors as site access, i.e. permission from the owner, all year round road access, access to electric power and, in the case of drained sites, an old and well described tile drain system. This chapter presents the site selection criteria used and briefly summarizes the six selected sites.

2.1 Soil type

The Danish EPA requires that pesticide testing is conducted under "worst case" conditions. The test sites consequently need to be located on "vulnerable" soil types as regards possible groundwater contamination. Coarse-textured sandy soils with a low organic matter content were previously considered to be among the most vulnerable soils. Over the past decade, however, evidence has accumulated that pesticide leaching also occurs on structured soils (Flury, 1996). The findings of the Danish National Groundwater Monitoring Programme (GRUMO) also indicate that pesticides can leach to the groundwater in regions dominated by structured soil types (GEUS, 2000). Only a few studies have tried to compare the mass flux of pesticides from different soil types under identical agricultural practices and climate conditions. At present, no information is available concerning how to identify the most "vulnerable" soil types in Denmark as regards leaching of pesticides to the groundwater. As suitable scientific documentation on which to base selection of the most "vulnerable" soil types and hence the "worst case" scenarios is lacking, we decided to select a number of sites representing the soil types on which pesticides are most commonly applied in Denmark.

The geological composition of sediments down to 5-10 m b.g.s. in Denmark is known from geological maps, profiles, excavations, well data and sometimes also geophysical measurements. The composition of the uppermost metre of deposits is mainly known from the systematic mapping of Quaternary deposits carried out by GEUS. This started in 1888 and is still going on, about 80% of the Danish land area now having been mapped. At deeper levels, knowledge of the geological deposits is mainly based on well data. The deposits commonly vary considerably in grain size, internal structure and mineralogical and geochemical composition over short distances in both the vertical and horizontal directions. In addition, glaciotectonic activity has commonly overprinted and dislocated the deposits.

The map of Quaternary deposits shows that 40% of Denmark's land area consists of clay till, 28% of meltwater sand, 12% of Post-Glacial and Late-Glacial marine sand and aeolin sand, 12% of Post-Glacial freshwater sand, 3% of sand till and 7% of different subordinate Quaternary deposits. Pre-Quaternary deposits account for less than 1% of Denmark's surface. In considerable areas, however, Cretaceous and Danian limestone and Tertiary clay are reached within a depth of 5 m b.g.s. In view of the above-mentioned distribution it was decided that the sites should be located in both areas with Quaternary clay and areas with Quaternary sand.

2.1.1 Areas with Quaternary clay

Clayey sediments occurring near the ground surface are dominated by clay till deposits. These characteristically consist of a very unsorted sediment with a clay content exceeding 12–14%. The till deposits were formed in contact with ice, either laid down beneath the ice (lodgement till) or deposited from the surface of the ice as it melted (ablation and flow tills). Lodgement tills are more consolidated than ablation and flow tills due to the heavy burden of the ice during their deposition. Clay tills are generally chararacterized by containing fractures formed by glaciotectonic forces or by desiccation and freeze-thaw processes. Subsurface Pre-Quaternary deposits may considerably affect the composition of the overlying till. For instance, the clay or chalk content may be very high in the case of a clay till deposited by a glacier that has passed an area with exposed Tertiary clay or Cretaceous chalk. The till deposits which form the ground surface in Denmark were generally deposited by ice advances that occurred 20–14,000 BP during the Late Weichselian Period. In western Jutland, however, an older glacial landscape occurs as hill islands in the Weichselian outwash plains. The meltwater and till deposits that form part of this landscape were deposited during the Saalian period 140,000 BP, and hence have been exposed to weathering, erosion and soil-forming processes for a very long period.

2.1.2 Areas with Quaternary sand

The meltwater sediments were transported and deposited by meltwater from glaciers. Grain size thus diminishes from meltwater gravel to meltwater sand with increasing distance from the former ice front. They are subdivided into glacial meltwater sediments, which are sometimes deformed by subsequent ice advances, and Late-Glacial extramarginal meltwater sediments, which have not been overridden by glaciers. The extramarginal meltwater sediments form large outwash plains east of the Main Stationary Line marking the westernmost extension of the Weichselian ice sheet in Jutland.

Post-Glacial and Late-Glacial marine sand was formed when land areas were flooded due to an interplay between isostatic uplift and eustatic sea level rise caused by melting of local and global icecaps, respectively. Today these sediments form raised seafloor plains in the landscape as a result of subsequent isostatic uplift.

Aeolian sediments were deposited in the Post-glacial period and consist of well sorted, fine-grained sand deposited as dunes, mainly in coastal regions, and as coversand when deposited inland.

Freshwater sand was mainly deposited along streams and in lakes during the Post-glacial period.

2.2 Climate

Together with soil type, one of the most important parameters controlling pesticide leaching is the precipitation. The most common way to express the regional variation in precipitation is by the annual mean. The annual mean precipitation in Denmark during the period 1961–90 was 712 mm/year, varying from 550 mm/year in the Store Bælt region to 900 mm/year in the southern part of Jutland (Frich et.al., 1997). The inter-annual variation in annual mean precipitation at individual single sites varies by a factor two. Thus while the annual mean precipitation ranged from 456 to 744 mm/year during the period 1988–97 in the Roskilde region, it ranged from 557 to 1,032 mm/year in the Jyndevad region.

The variation in pesticide leaching cannot be ascribed to the variation in annual mean precipitation alone. The transport of pesticides through unsaturated soil is controlled by a complex interaction between the degree of saturation and the intensity of the precipitation. This interaction is not a useful parameter for selecting sites. Only the annual mean precipitation is of practical usefulness when selecting site location.

Other climate parameters that affect pesticide leaching, e.g. temperature and evaporation, do not vary much in Denmark. Thus only the variation in precipitation has been taken into account when selecting the sites.

The sites may not be further than 8 km away from an automatic climate station in order to ensure access to additional good quality climate data and historical time series. Precipitation is also measured at the sites along with soil temperature and soil water content.

2.3 Hydrogeology

The depth of the water table is an important site selection factor. In order to ensure a rapid response in the groundwater downstream of the test field and to facilitate sampling, the water table must be as near to the surface as possible and no deeper than 5 m b.g.s. The Danish EPA defines groundwater as water that leaves the root zone 1 m b.g.s. In large parts of Denmark, the water table is less than a few metres below the surface.

The sites must be located inside the infiltration area and have a downward gradient. To ensure a stable response in the monitoring well, a steady hydraulic gradient is required. Sites located within the radius of influence of irrigation or production wells have thus been as far as possible avoided. Where this is not possible it is necessary to obtain information on the production from the wells.

The infiltration of water and hence leaching of pesticides is influenced by surface runoff. To minimize surface runoff the selected sites have a low topographic slope – less than 2% slope in general.

The sites with structured soil have to be drained and the tile drain system must be well known and only cover the test field. Moreover, the tile drains must be more than 10 years olds so that the overlying soil has had time to consolidate, thereby avoiding artificial infiltration to the drain system. The base flow must be as low as possible to avoid dilution of the response. In order to facilitate sampling of the drainwater it is important that the drainage system feeds into a single outlet.

2.4 Site area

The size of the test field is crucial. On one hand it needs to be sufficiently large to adequately cover the variation in soil structure, particularly on clay soils where preferential flow is expected to form the key route for pesticide transport down through the unsaturated zone. On the other hand, the area must not be too large because the variation in the soil structure would then complicate interpretation of the results. That sampling costs increase with increasing test field size also points to the selection of as small a site as possible. The test field should only encompass single soil series, with a small spatial variability in the soil parameters. Test sites between 1 and 4 ha are assumed to be an acceptable compromise. The US-EPA guidelines for prospective groundwater monitoring studies requires test sites of equal size (US-EPA, 1998).

To eliminate artificial flow patterns it is important to select sites with undisturbed soil. Areas where sampling by drilling has taken place or where excavation has been performed should thus be avoided.

2.5 Site history

The previous crop rotation on the site is expected to influence the fate of the pesticide. The test field should previously have been subjected to conventional agricultural practices as regards crop rotation and soil tillage, thus excluding the use of fields with minimal or conservation tillage, organic farming, horticulture and set-aside.

We prefer fields that have been cultivated as one parcel with the same crop within recent years, and exclude sites that have been used for plot experiments or have been disturbed by excavation, drilling or deep soil sampling.

Pesticide use at the sites must have been recorded for at least the previous 5-year period.

2.6 Site access

Pesticide leaching studies are typically conducted over a 2–3 year period for each application. As the present programme will run for a period of up to 10 years, sites could only be included if a long-term lease was possible.

For practical reasons there must be good road access to the sites all year round to enable sampling. Moreover, in order to obviate the necessity to establish an on-site power supply to run the sampling equipment, mains electricity had to be within reasonable reach.

The sites also had to be located within approx. 10 km of a state experimental farm such that the pesticides and tracers could easily be applied by trained personnel from the state experimental farms. However, standard agricultural operations such as soil tillage, sowing and harvesting could be done by the landowner when deemed appropriate.

2.7 The six selected sites

The programme encompasses six sites. This number of sites is a compromise balancing monitoring intensity with the number of different soil types represented by the programme. Two of the sites are located on sandy soil and four on clayey soil. The key data for each of the six sites are presented in Table 2.1. The location of each site is shown in Figure 2.1.

Three of the sites (1 sandy and 2 clayey) are in regions with relatively high precipitation, while the other three are in drier regions. A brief description of each site is given in Chapter 5.

Table 2.1. Key data for the six selected sites encompassed by the Danish Pesticide Leaching Assessment Programme.

Name	**Tylstrup**	**Jyndevad**	**Silstrup**	**Estrup**	**Faardrup**	**Slaeggerup**
Location	Brønder-slev	Tinglev	Thisted	Vejen	Slagelse	Roskilde
Crop						
1999	Potatoes					
2000	Spring barley	Winter rye	Fodder beet	Spring barley	Winter wheat	Spring barley
2001	Winter rye	Maize	Spring barley	Peas	Sugar beet	Peas
2002		Spring barley	Winter wheat	Winter wheat	Spring barley	Winter wheat
B x L, m	70 x 166	135 x 184	91 x 185	120 x 105	160 x 150	165 x 130
Area, ha	1.1	2.4	1.7	1.3	2.3	2.2
Soil type	Fine sand	Coarse sand	Clayey till	Clayey till	Clayey till	Clayey till
Deposited by	Saltwater	Meltwater	Glacier	Glacier	Glacier	Glacier
Tile drain	No	No	Yes	Yes	Yes	Yes
Precipitation, mm/year[1)]	668	858	866	862	558	585

1) Yearly normal based on a time series from 1961-90

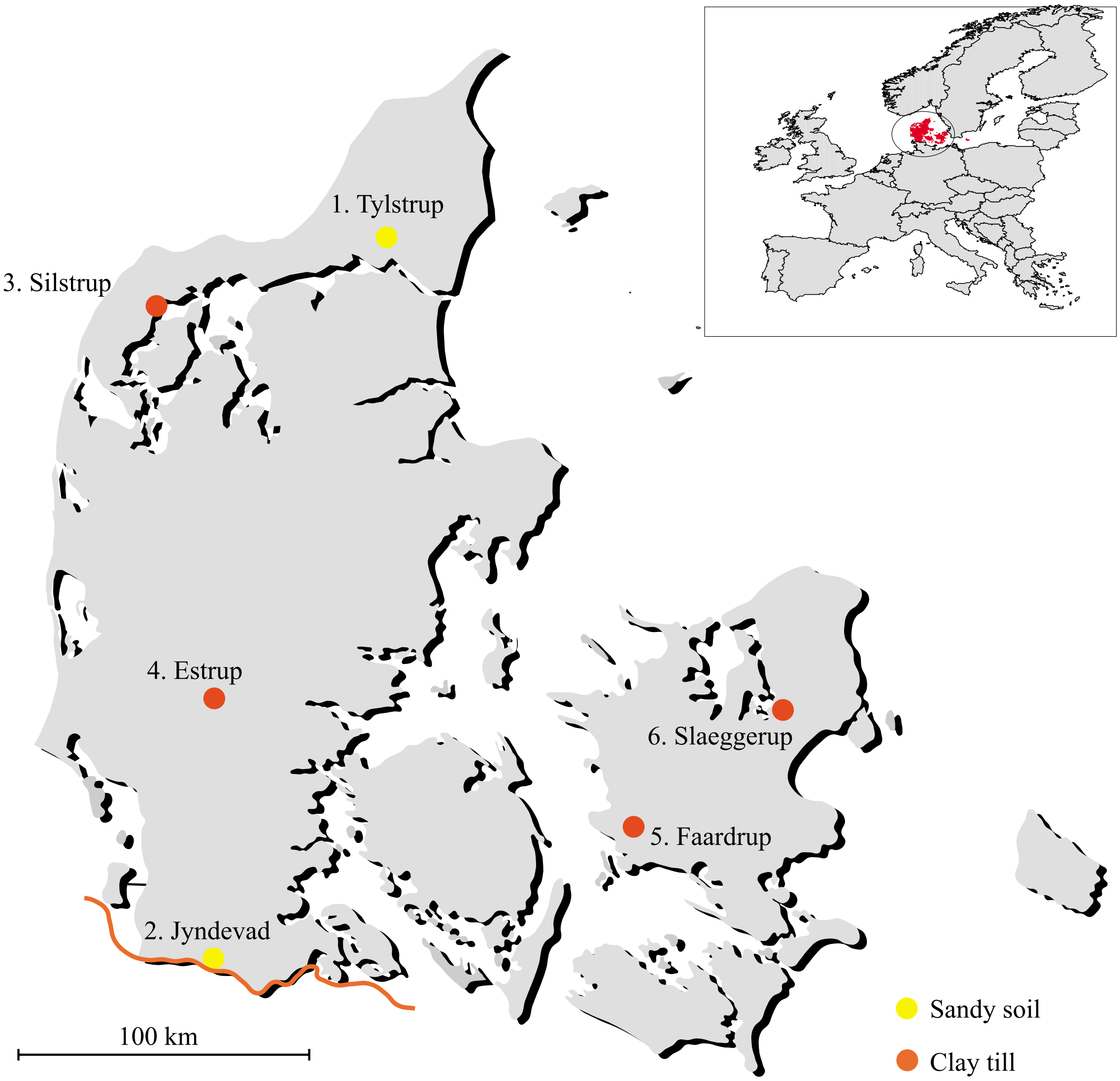


Figure 2.1. Location of the six test sites in Denmark.

3. Monitoring design

Characterization and instrumentation of the sites was carried out in an integrated manner with the soil cores from the monitoring well boreholes being used to develop a conceptual hydrogeology model for the sites. The different types of devices installed at each site are described here.

The monitoring equipment used and aspects monitored include:

- Piezometers – potentiometric pressure of the groundwater
- Vertical and horizontal monitoring wells – sampling of groundwater
- Suction cups – water samples from unsaturated soil
- Automatic ISCO samplers – sampling of drainwater
- Weather stations – precipitation
- TDR-probes – soil water content
- Pt-100 sensors – soil temperature
- Pressure sensors – barometric pressure

Figure 3.1 shows the typical lay-out of monitoring devices at a site.

To avoid any artificial leaching of pesticides, drilling and excavation have not been carried out inside the plot used for pesticide treatment. All installations and soil sampling deeper than 20 cm b.g.s. are restricted to a buffer zone around the treated plot.

3.1 Groundwater monitoring

3.1.1 Piezometers

Four multiple-level piezometers each with three separate piezometer screens have been installed at each site. The casings and the screens are made of the same material and have the same dimensions. High-density polyethylene (HDPE) pipes from Filter Jensen (DK) with an outside diameter of 63 mm and a wall thickness of 5.8 mm were used. The screens are 50 cm long and contain two 0.5 mm aperture slits per cm.

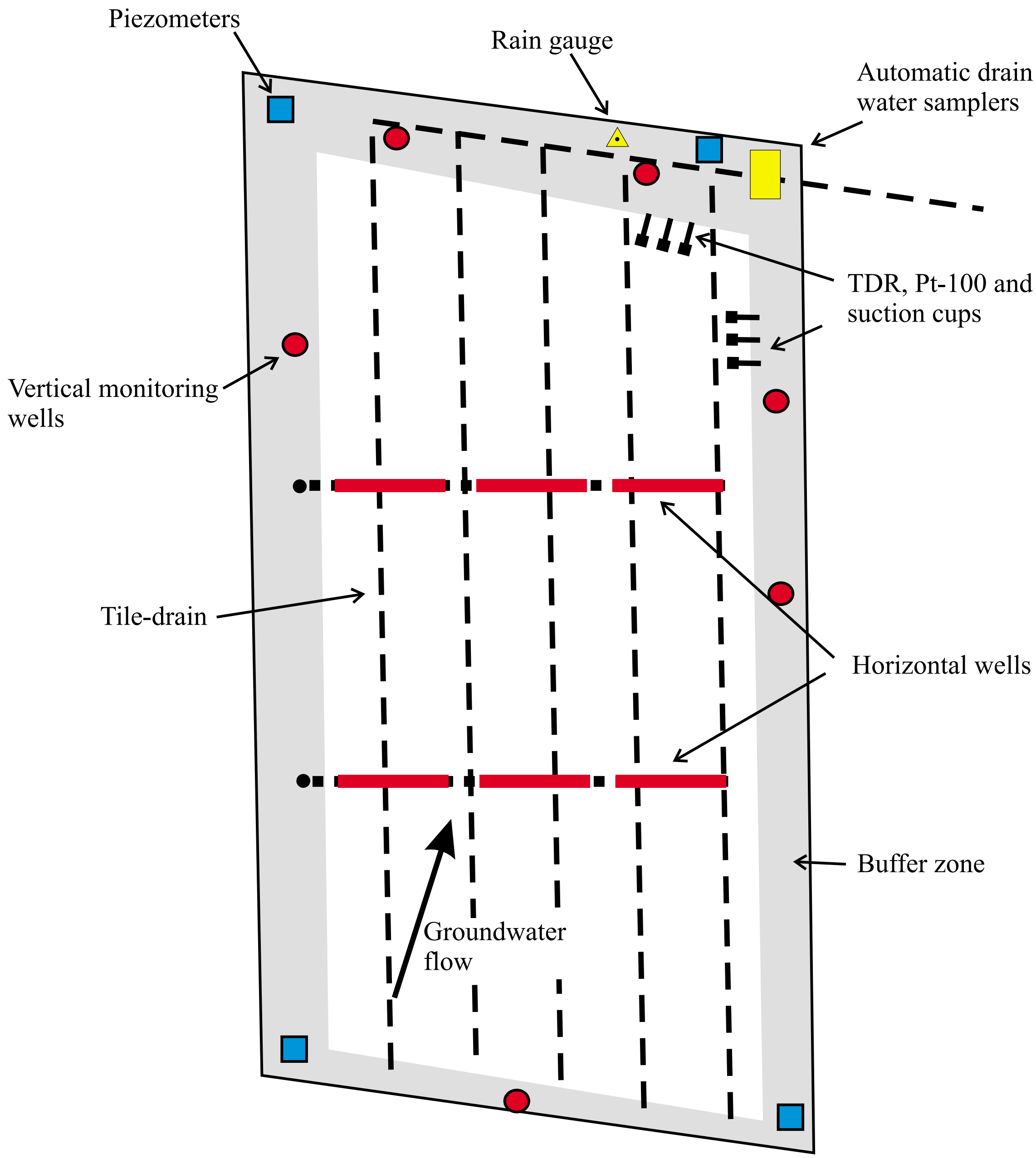


Figure 3.1. Typical lay-out of monitoring devices at a tile-drained site.

The three screens of each piezometer are installed in the same borehole. The diameter of the borehole is 152 mm (6"). In the clay soils drilling was carried out with a solid stem auger while a bailer technique was used below the water table in the sandy soils. Surface casing was used when necessary. For filter packing we used Grejs No. 2 (0.7–1.2 mm) (Grejsdalens Filterværk, DK). A filter pack seal of at least 100 cm bentonite (Pellerts, QS, Cebro, NL) was installed approx. 10 cm above each screen (Figure 3.2). Each nest of multiple-level piezometers is protected at the surface by a 0.6 m dia. concrete ring closed by a padlocked metal cover.

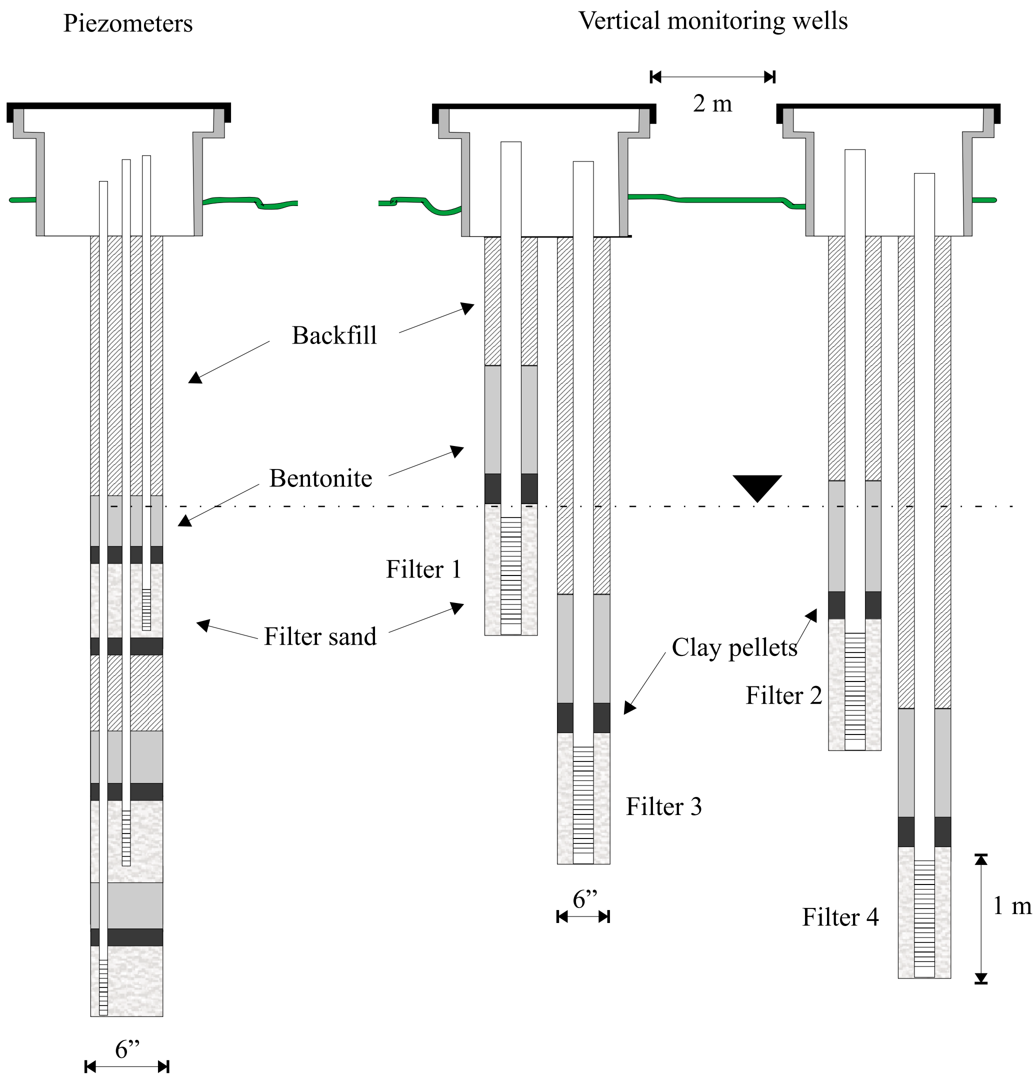


Figure 3.2. Construction of a multiple-level piezometer and monitoring well at a clay till site.

The lower screen in each nest is located between 11.5 and 12 m b.g.s. The top screen is located such that the water table is expected to be permanently above the screen. At the clay sites the screens are placed in the most sandy horizon.

The water level is measured either manually by using a “water level indicator” or continuously using one of three different transducer-logger systems. Every time samples are collected, the water level in all the piezometers is measured manually. In the piezometer closest to the “shed” the water level is measured on-line every hour using a differential pressure transducer (Druck, Limited, UK) connected to a Campbell datalogger. At the sandy sites, the water level is monitored in one screen. At the clay sites two Druck transducers are installed – one in the upper screen and another in the lower screen. The water level in the piezometer diagonally opposite the corner where the shed is located was initially measured continuously every hour using an Orphimedes-logger (OTT, D). In early spring 2000, this system was exchanged for a D-diver (RoTek a/s, DK), which is a pressure transducer and a data-logger. As the D-diver does not take into account changes in barometric pressure, the raw data have to be corrected using the barometric pressure measured at each site.

3.1.2 Vertical monitoring wells

For sampling groundwater, seven vertical monitoring wells were installed at each site. The drilling techniques and the materials used for the casings and screens are the same as for the piezometers. Sorption of pesticides to the HDPE piping is expected to be insignificant (Fetter, 1999; US-EPA, 1998). The pipe material was tested for release of any compounds that could contaminate the water samples and no evidence was found of any contamination that might interfere with analysis of the 39 different pesticides included in the Danish Groundwater Monitoring Programme (GEUS, 2000).

Each monitoring well consists of four screens. The length of each screen is 100 cm. The screens are placed so that they cover the upper 4 metres of the groundwater. The top of the upper screen is placed above the highest seasonal water table. To avoid vertical movement of water along the casing, each screen is installed in its own borehole. To optimize sealing, clay pellets (Tonkugeln, Duranit VFF; D) were used as back-fill. Monitoring well construction is shown in Figure 3.2.

For water sampling, a Whale pump (GP9216, 13 l/min, 72 watt, 12 V, RoTek a/s, DK) was permanently installed in each screen connected to a PE-tube (6 x 1 mm or 10 x 1 mm, RoTek a/s, DK).

One monitoring well is located upstream of the test field, while the other six are distributed downstream of the test field (Figure 3.1).

3.1.3 Horizontal monitoring wells

The water flow transporting the pesticides is difficult to monitor in areas with clayey till because of the effect of vertical preferential flow and the frequent occurrence of sandy lenses, which can cause lateral flow. To overcome these difficulties a number of horizontal monitoring screens have been installed approx. 3.5 m b.g.s. inside the treatment plot at the four sites on clayey till.

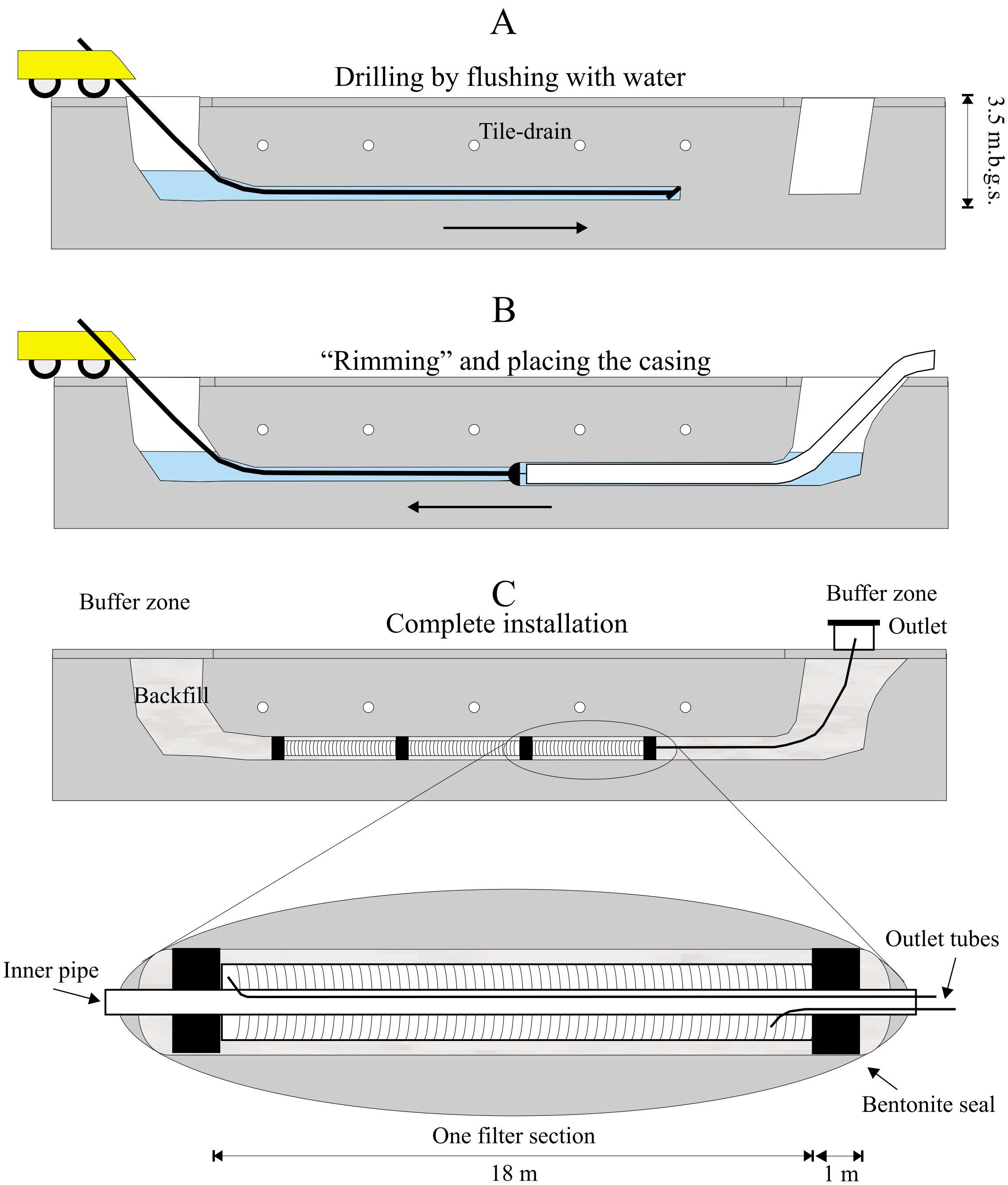


Figure 3.3 Installation of horizontal monitoring wells and a section of the horizontal screen.

The horizontal screens are installed by drilling from the buffer zone on one side of the treated plot to the buffer zone on the opposite side without causing any disturbance to the topsoil inside the plot. The technique used for drilling these horizontal boreholes is well known from installing power cables or pipelines beneath roads, etc. The drilling rig is placed on the surface and drilling performed in two steps: Firstly, forward drilling by a water flushing technique and secondly, reaming whereby the rod is drawn back. The diameter of the final boreholes is 200 mm. In the first step the drilling rod can be steered by changing the position of the rod head, which is continuously monitored at the surface by a radio signal. The sediments are released by flushing with water and transported out of the borehole by the water flow. The diameter of the borehole made by forward drilling is 110 mm. To reduce the water pressure, a mud pit is excavated at the entrance to the borehole just outside the test field in the buffer zone (see Figure 3.3A). When the rod has traversed the treated plot and penetrated an excavation on the other side a reamer is installed on the rod together with a 160 mm o.d. casing. The screens with bentonite packers are placed inside the casing and the casing then drawn into the borehole at the same time as the "rimming" takes place (Figure 3.3B). At the specific positions the screens are fixed by retaining them with a wire while the casing is drawn out of the borehole. The complete installation procedure is shown in Figure 3.3C.

The screens are 18 m long with an outer diameter of 125 mm and a wall thickness of 5.8 mm. The screens have two 0.5 mm aperture slits per cm. Two tubes are installed at each screen. The outer diameter of the inside pipe is 63 mm (Figure 3.3) while tubes are 10 mm in diameter with wall thickness of 1 mm. The screens are made of HDPE and the tubes of PE. Three individual screens are installed in each borehole separated by 1 m bentonite seals.

Sampling from the screens is performed with a peristaltic pump on the surface.

3.2. Drainwater collection

The four clayey till sites are located in areas with an existing tile drainage system. As a criterion for selecting the sites the drainage system had to be systematically described and easily isolated to represent a well-defined monitoring area. At all four sites it was necessary to cut off some drainpipes and/or to install additional pipes to ensure a defined catchment area. The modifications made at each site are described in the accompanying Annexes 1–6.

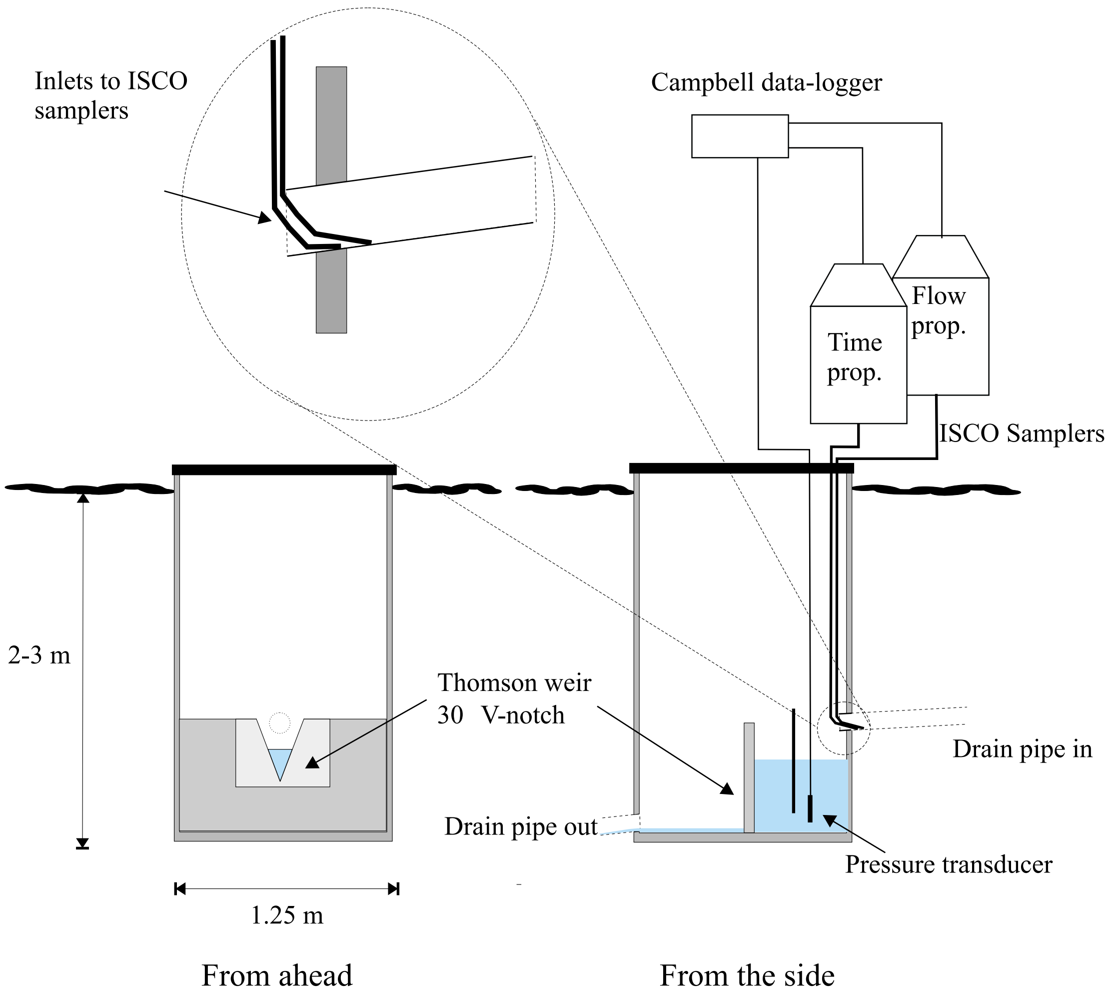


Figure 3.4. Drainwater monitoring well with Thomson weir and water sampler.

In order to enable the measurement of drainage runoff and the collection of drainwater samples a concrete monitoring well was established at the outlet of each drainage system. The wells are 1.25 m in diameter and 2–3 m deep.

The monitoring wells are constructed with a sharp-crested V-notch weir (Thomson weir) made of 5 mm galvanized iron plate. The Thomson weir is the most exact profile for measuring runoff with a large variation in flow rate (Bos, 1976). A 30° V-notch angle was chosen as a compromise between high precision at relatively low flow rates and low sensitivity to blockage of the notch. The height of the notches is not less than 30 cm.

Table 3.1. Infiltration per ha vs. flow in the drainage system.

Height above the Thomson weir, cm	Flow in drain, Q (l/s)	Infiltration, q mm/ha/day
5	0.23	2
10	1.2	10
20	6.8	59
30	19	164

A Thomson weir requires a free fall from the weir notch of at least 25 cm. The water level above the V-notch is monitored using a pressure transducer (Druck PDCR 1830, Druck Limited, UK). The transducer is mounted in a stainless steel tube (length 1,100 mm, diameter 21.5 mm) fixed to the wall of the well by means of a stainless steel clamp (Figure 3.4). To protect the transducer from turbulent water at high flow rates, it is placed in a special chamber behind the weir and as far away from the drain inlet as possible (Figure 3.4). The pressure transducer is connected to the central Campbell datalogger.

The water samples are collected using ISCO 6700 (Isco, Inc. US) samplers equipped with eight 1,800 ml glass bottles (boron silicate), teflon suction tubes and intakes of stainless steel. The intakes are placed a few centimetres into the inlet of the drainpipe so as to ensure sampling of flowing drainwater and particulate matter. Two samplers are used at each site: One for time-proportional sampling and one for flow-proportional sampling. The time-proportional sampler is equipped with refrigerated bottles such that the water samples can be collected over a 7-day period. The flow-proportional sampler is only activated during storm events and sampling is carried out for 1–2 days depending on the intensity of the event.

The monitoring wells are each located inside a shed so as to protect the equipment from the weather. Two electrical heaters in each shed prevent the temperature from dropping below 5°C.

3.3 Soil water sampling

Soil water in the unsaturated zone is under tension, and hence cannot flow into a well as groundwater does. Monitoring of soil water in the unsaturated zone thus requires the use of suction cups, etc.

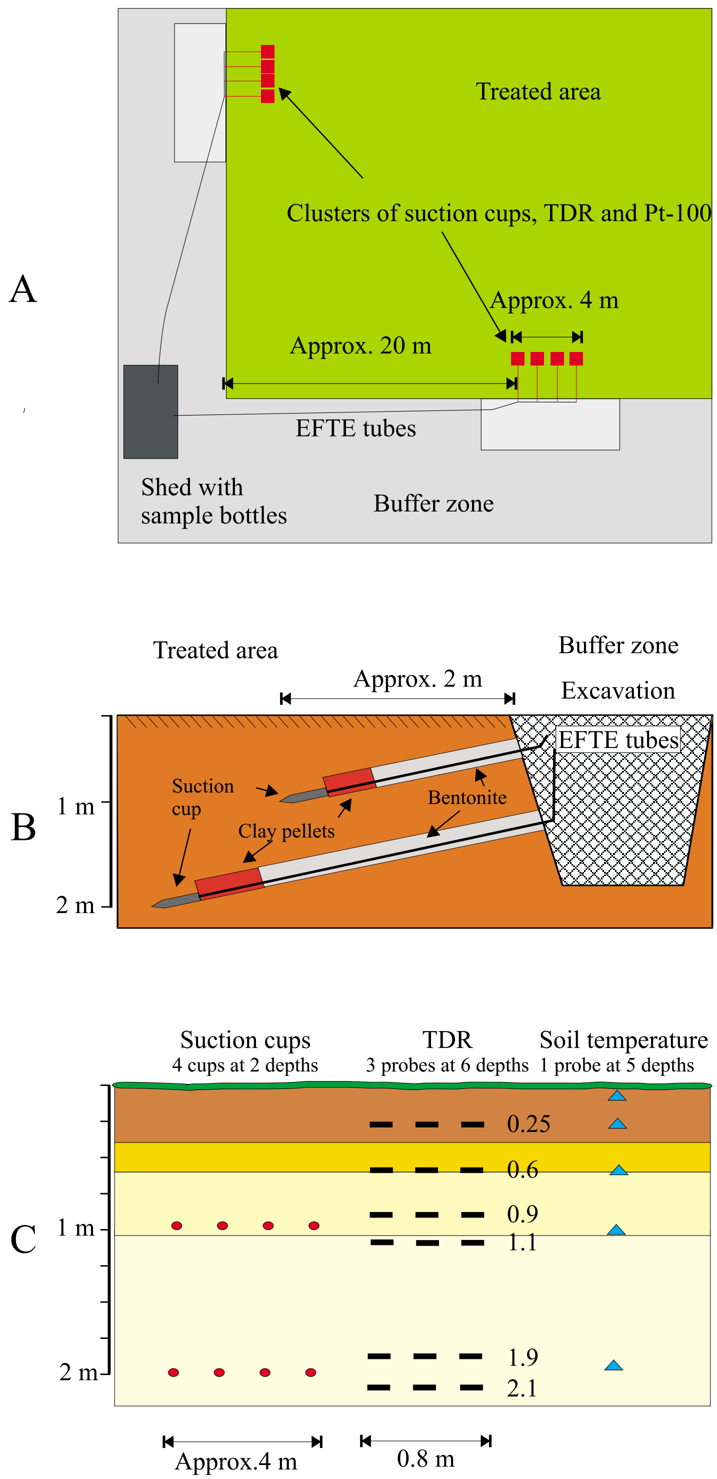


Figure 3.5. A) Location of suction cups, TDR and soil temperature probes, B) a cross section showing the installation of the suction cups, and C) a plan view of an excavation wall indicating the location of the suction cups, TDR and soil temperature probes.

A total of 16 suction cups have been installed at two locations at each site – one on each side of the test field about 20 meters from the downslope corner (Figure 3.5A).

At each location, four suction cups are installed at a depth of 1 m b.g.s. and four at a depths of 2 m b.g.s. (Figure 3.5B/C). The horizontal distance between suction cups installed at the same depth is 1 m while that between suction cups installed at different depths is 0.5 m.

The suction cups were installed from two excavation pits at the edge of each test field via holes drilled obliquely to the desired depth. This procedure ensures that the soil directly above the suction cups remains undisturbed.

The suction cups installed at a depth of 1 m are located at a horizontal distance of 2 m from the edge of the test field while the suction cups installed at a depth of 2 m are located at a horizontal distance of 2.5 meters from the edge of the field. The installation holes were drilled from 0.5 m b.g.s. in the case of the suction cups installed at a depth of 1 m and from 1 m b.g.s. in the case of those installed 2 m b.g.s.

The installation holes were drilled with a 50 mm air-driven hand auger to the desired length minus 20 cm. The final 20 cm of the installation holes were completed using a 21 mm steel rod corresponding to the diameter of the suction cup.

100 ml of a thick slurry of water and silica flour was poured to the bottom of the hole just before installation of the suction cup. Immediately after installation of the suction cup a further 100 ml of the slurry was poured into the installation hole, which was then sealed with 20 cm of clay pellets before being back-filled with bentonite pellets.

Each suction cup is connected to the sampling bottle via a single length of PTFE tubing. From the excavation pit to the shed the PTFE tubes run through a protective tube buried in a 70 cm deep trench. The sampling bottles are located in a refrigerator in the shed. The soil water is extracted using a continuous vacuum technique.

The suction cups used are PRENART SUPER QUARTZ (Prenart, DK) consisting of porous PTFE mixed with quartz. The soil water sampler is 21 mm in diameter and 95 mm in length with 2 micron pores. The tubes used consist of 1/8" x 2.0 mm PTFE tubing. The sampling bottles are 1 or 2 litre glass bottles. All fittings that come into contact with water are made of stainless steel.

3.4 Climate parameters

An automated monitoring system has been installed at each site for measurement of precipitation, barometric pressure, soil temperature, soil water content and soil water pressure. At the four sites on clayey till, the system also controls two drain water sampling devices (Section 3.2).

The automated system consists of various items of hardware and sensors and commercially available software tools in which dedicated software codes have been implemented. The central unit is a Campbell CR10X 2M datalogger (Campbell Sci, UK). User communication from office PC to this datalogger is established via modem using fixed telephone lines or GSM phone transmission. The data are collected automatically every night.

Precipitation

Precipitation is measured on site with a tipping bucket rain gauge (Type 1518Wilh. Lambrecht, BmbH, D). The gauge is accurate to 0.1 mm and is well suited for measuring high precipitation intensity. Sampling is carried out every minute and hourly values are stored.

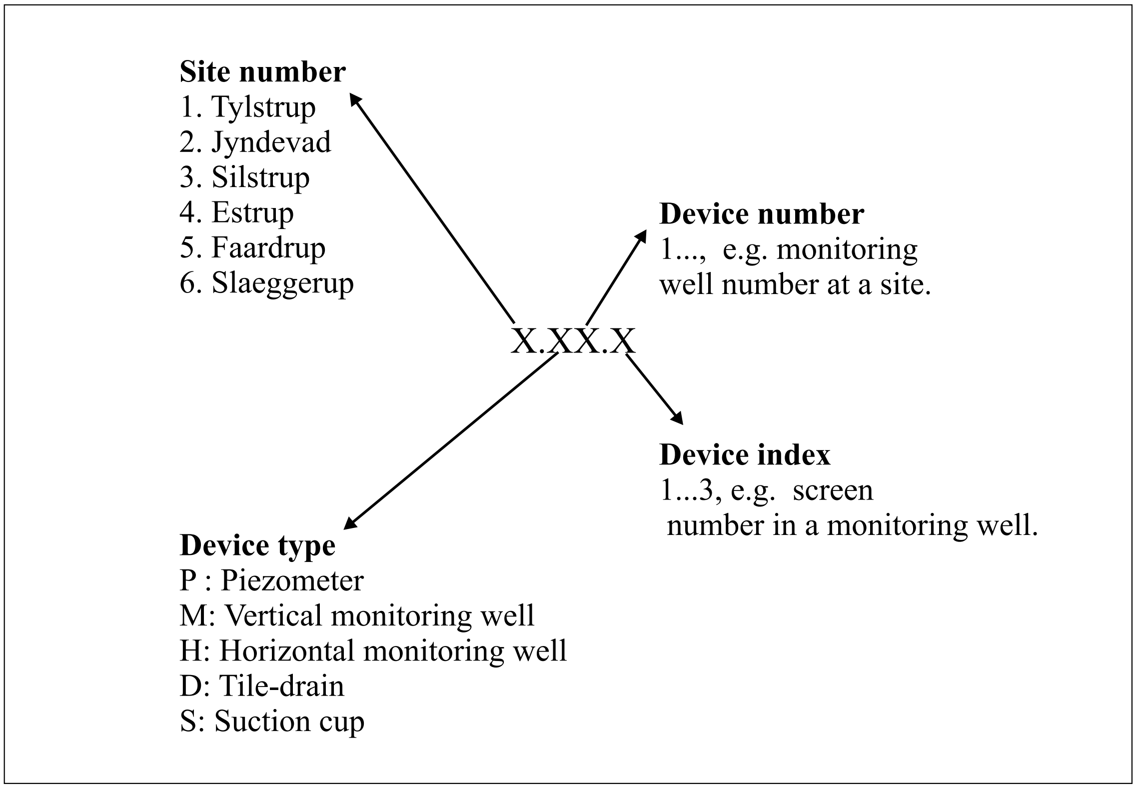
Soil moisture

Soil moisture is measured using a CR10X-controlled Time Domain Reflectometry (TDR)-system. The central unit in the TDR-system is the cable tester from Tektronix 1502C (Tektronix Inc., Beaverton, OR, USA). The soil water probes are developed at Research Centre Foulum and consist of a 40 m coaxial cable (Mikkelsen Electronic A/S, DK) connected through a solid plastic box to three 30 cm steel rods spaced about 2 cm apart. The accuracy of the soil water measurements is around ±1 vol %.

Soil water content is measured in two profiles at each site at the depths of 0.25, 0.6, 0.9, 1.1, 1.9 and 2.1 m (Figure 3.5C), with three replicate probes at each depth. Soil water content is measured and stored every hour.

Soil temperature

Soil temperature is measured with platinum resistance thermometers (Pt-100, length 10 mm and diameter 5 mm). The accuracy of the measurements is ±0.1°C. Soil temperature is measured in two profiles at each site with one sensor at each of the following depths: 0.1, 0.25, 0.6, 1.0 and 2.0 m (Figure 3.5C). The temperature is measured and stored hourly.



Barometric pressure

The barometric pressure is measured with a pressure sensor (PTB101B, Vaisala, SF) with an accuracy of ±2 mB. Measurements are taken and stored hourly.

3.5 Monitoring device codes

To ensure unique identification of all samples collected in this programme, all sampling points are described by a code that includes the site identification, the type of sampling device, and the number of sample points in each device. The code system is illustrated in the box above.

By way of example, a vertical monitoring screen on the Tylstrup site will have the code 1.M4.3, indicating screen number 3 in vertical monitoring well (M) number 4 at site number 1.

The screens in the vertical monitoring wells and the piezometers are coded with increasing numerical value from the surface and downward.

4. Geological and pedological methods

4.1 Geological methods

4.1.1 Geological field work

The initial field work at the sites included drilling of one to four shallow boreholes with a hand auger in order to determine whether the desired geology was present. Subsequently, four 12 to 23 m deep wells each fitted with three piezometers were drilled to monitor the potential head of the shallow groundwater flow and determine the direction of flow. Once the direction of flow had been determined, seven monitoring well clusters were established – six downstream of the test field and one upstream.

A geologist in the field supervised all drilling and the geology was described in the field in accordance with Larsen *et al*. (1995). Samples were taken for each 0.5 m or at least one sample from each described layer. All well data and the geological description are stored in the GEUS water well database JUPITER.

Test pits

At the four clay till sites (Silstrup, Estrup, Faardrup and Slaeggerup) a 5 m deep 10 x 10 m test pit was excavated in the buffer zone with profiles perpendicular to each other at three levels: 0.5–2.0 m, 2.0–3.5 m and 3.5–5.0 m. This test pit structure enabled all fracture orientations to be observed. The profiles were described according to Klint and Gravesen (1999). The test pits were used for the following tests and investigations: field vane tests, fracture description and characterization, fabric analysis and lithological description. Samples were collected for grain size analysis, total organic carbon (TOC) and $CaCO_3$ content, clay mineral analysis and exotic stone counts.

4.1.2 Laboratory analyses at GEUS

Total organic carbon (TOC)

TOC content was determined as follows: 300–500 mg of sample was treated with 5–6% H_2S0_3 to remove carbonate minerals and then combusted in a LECO CS 200.

$CaCO_3$

Each bulk sample was gently crushed sufficiently to pass a 2 mm sieve. 25 ml 0.5 M hydrochloride acid and demineralized water was then added and the sample heated to boiling point for 20 minutes. Thereafter the suspension was titrated with 0.5 M sodium hydroxide using phenolphthalein as indicator.

Grain size

Grain sizes larger than 0.063 mm were determined by sieving according to DS 405.9 but with a ½ phi sieve column.

Material smaller than 0.063 mm was sieved through a 0.1 mm sieve cloth and the material larger than 0.1 mm dried, treated with 50 ml 0.005 M $Na_4P_2O_7$ x 10 H_2O and centrifuged. After 12 hours of shaking the sample was measured using a Micromeritics SediGraph 5100.

Permeability

The plug dimensions were measured with a calliper and the plug then mounted in a special Hassler core holder at a confining sleeve pressure of 1.75 bar. The required fluid and fluid upstream pressure of 0.2–1.5 bar was delivered by a constant flow rate pump. At least one pore volume of liquid was allowed to flow through the sample before the measurements were initiated. The flow rate was measured volumetrically over a period ranging from a few hours to more than one day.

Porosity and grain density

The porosity was measured in cleaned and dried samples by subtraction of the measured grain volume and the measured bulk volume. The grain volume was determined using the helium technique (Boyle's law) applying a double-chambered helium porosimeter with a digital readout. The bulk volume was measured by submersion of the plug in a mercury bath using Archimedes' principle. Grain density was calculated from the grain volume measurement and the weight of the cleaned and dried sample.

Porosity by weight loss

The porosity of loosely consolidated sediments, e.g. till samples that are saturated to 100% with a liquid, can be analysed by drying at 110°C and recording the weight loss. The weight loss was recalculated to a liquid volume equal to the pore volume. The sample bulk volume was determined from calliper measurements of the saturated sample before drying.

Clay mineralogical analysis

The samples were gently crushed to pass a 2 mm sieve and treated with sodium acetate at a pH of 5 to remove carbonates. The sand and silt fraction was then removed by elutriation and centrifugation, and the 2-30 µm fraction and clay fraction < 2 µm were separated in a particle size centrifuge. The clay fraction was saturated with Mg^{2+} and K^{+} prior to X-ray diffraction analysis.

Oriented specimens were prepared by the pipette method and the following specimens analysed:

Mg^{2+} – saturated, air dry.
Mg^{2+} – saturated, glycolate.
K^{+} – saturated, air dry.
K^{+} – saturated , heated to 300°C.
X-ray diffraction was carried out with Co-Kα radiation, β-filter and pulse height selection.

Fine gravel analysis (Ehlers, 1978)

4.2 Pedological methods

4.2.1 Pedological field work

Excavation and description of soil profiles

Two or three soil profiles were excavated at each site to a depth of approx. 1.6 m using a backhoe. Major excavations performed by GEUS and used for geological site descriptions were also used to describe the upper 1.6 m of the soil profile.

Pedological description of all identified soil horizons was carried out in accordance with Madsen and Jensen (1988). Field reports from the sites included detailed maps showing the succession of identified and described soil horizons. Profile descriptions, photographs and drawings are presented in the annexes.

Soil samples from every identified horizon were collected for laboratory analysis. About 10 litres of bulk soil from each horizon were dried and stored at DIAS. The soil samples were analysed at the DIAS. A detailed description of the laboratory analysis methods used can be found in Hansen and Sørensen (1996). The most important methods and procedures are briefly summarized in Table 4.2.

Table 4.2. Summary of methods and procedures used in the laboratory analyses of soil samples.

Parameter	Description
Soil texture	Particle size analysis subdivided the soil samples into the following classes: clay <2 µm, silt 2–20 µm, coarse silt 20–63 µm, fine sand 63–125 µm and 125–200 µm, medium sand 200–500 µm, and coarse sand 500–2,000 µm.
TOC	The total organic carbon (TOC) content was determined using dry combustion. Soil samples containing significant amounts of calcium carbonate (exceeding 1%) were also analysed for $CaCO_3$ content.
pH	pH was measured following suspension of the soil in 0.01 M $CaCl_2$.
Fe and Al	Fe and Al were extracted using an ammonium oxalate solution and determined by atomic absorption spectrophotometry.
Total-P	Phosphorous content was determined spectrophotometrically following destruction of the soil by perchloric acid-sulphuric acid.
Total-N	The soil sample was combusted in an atmosphere of pure oxygen at 900°C. Water and CO_2 were removed and the nitrogen oxides were reduced to free nitrogen, which was then measured in a chemical conductivity cell.
Exchangeable cations	Exchangeable cations were extracted using ammonium acetate buffered at a pH of 7.0. Ca and Mg were determined using atomic absorption spectrophotometry. Na and K were determined by flame emission. Exchangeable hydrogen ions were determined by titration to equilibrium in a 0.06 M-nitrophenol solution.
CEC	CEC was calculated as the sum of cations.

The soil profiles were classified both according to the Danish system (Madsen and Jensen, 1985) and the USDA Soil Taxonomy (Soil Survey Staff, 1999). Nomenclature for textural classes in this investigation follows the Danish system, illustrated in Figure 4.1. The description and the analysis results from all the profiles have been stored in the DIAS soil profile database (Den Danske Jordprofil Database – DDJD (The Danish Soil Profile Data Base)).

Soil core descriptions

The soil core samples for description were retrieved to a depth of 1 m b.g.s. using a hand auger or until 1.2 m b.g.s. by using a hydraulic soil auger provided by DIAS. Soil horizons and soil texture have been described for approx. every 25 metres along the edge of the test field. The position of each described soil core was geo-referenced using DGPS to an accuracy of 0.2 m. Soil cores retrieved with the hand auger were determined using local fix points.

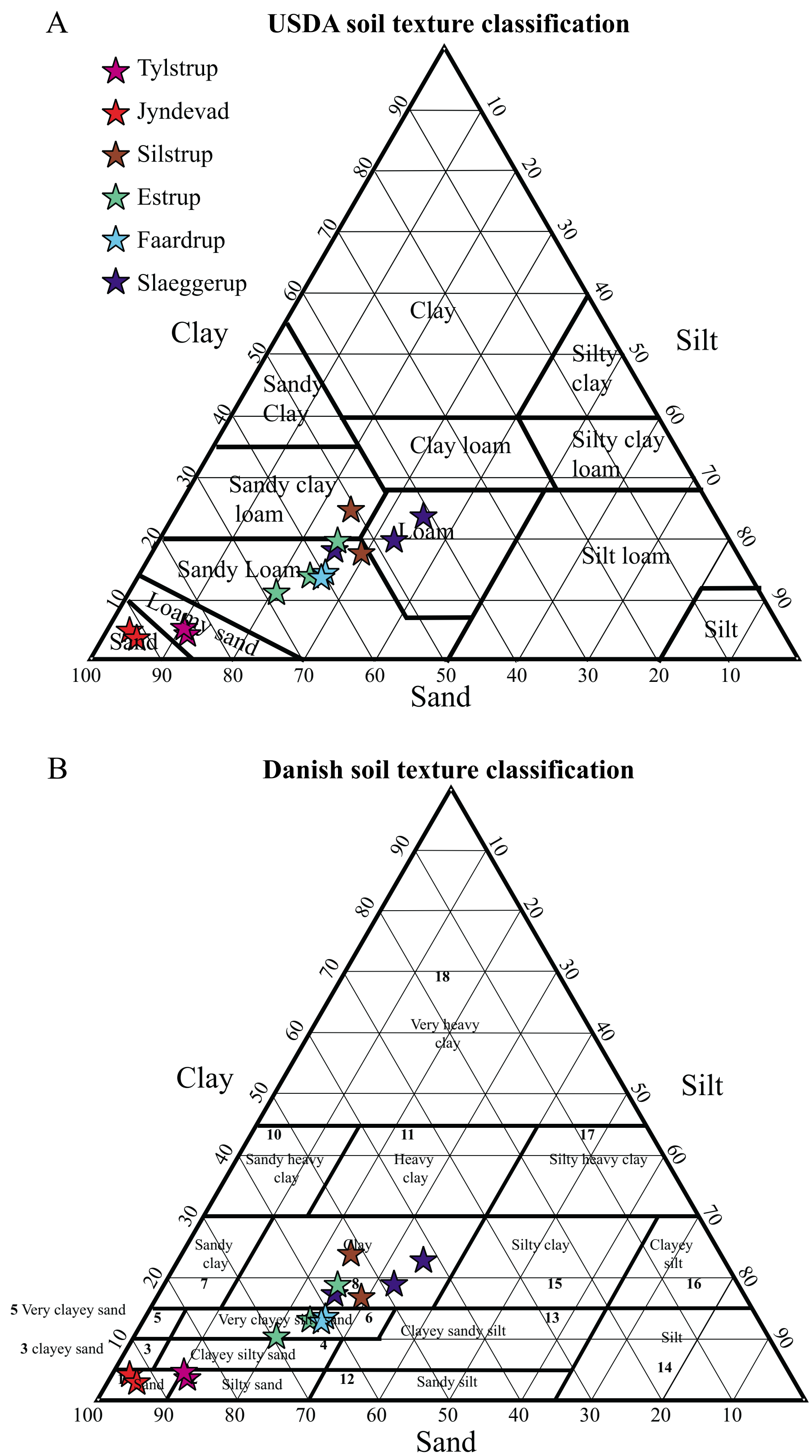


Figure 4.1. A) USDA (Soil Survey Staff, 1999) and B) Danish (Madsen and Jensen, 1988) soil classification triangel. Samples from the A-horizon taken at the soil profiles on each of the six fields.

Description of excavated trenches

Trenches excavated in order to establish the cut-of drainage pipes were used for mapping soil horizons and for determination of soil texture. Soil horizons and soil texture were described for every 25 m along the 0.8–1.6 m deep trenches.

Total carbon mapping

The topsoil (0–25 cm) at each site was sampled in a 20 m grid. Nine soil samples were collected at each grid point – one point exactly at the grid point and the other eight points arranged symmetrically around the grid point at a distance of 1 m. The nine samples were then pooled and the total organic carbon content determined at the Department of Analytical Chemistry, DIAS (Tabatabai and Bremner, 1970).

4.2.2 Soil hydrology

At all six sites, soil cores were taken from within three levels of the soil profiles corresponding to the A-, B-, and C-horizons. Five 6,280 cm^3 soil cores (large cores) and nine 100 cm^3 soil cores (small cores) were collected from each horizon. The nine small cores were divided into three groups with each group being collected near and around one of the large cores. To collect the large cores a large sampling cylinder was forced into the soil by means of a hydraulic press mounted on a tractor. To collect the small cores a small sampling cylinder was forced into the soil with a hammer using a special flange. All samples were protected from evaporation and stored at 2-5°C until analysis.

Analysis of large cores

In the laboratory the large cores were placed on a ceramic plate and saturated with water from below. The samples were then drained to a soil water potential of -50 cm. H_2O and air permeability were measured using a portable air permeameter (Iversen *et al*., 2001). The samples were then left to re-saturate and the near-saturated hydraulic conductivity was measured using a drip infiltrometer (van den Elsen *et al*., 1999). This works automatically and measures the hydraulic conductivity in the soil under steady-state water flow conditions at different soil water potentials. The soil column was placed on a sandbox and five ceramic cups connected to transducers were placed in the soil column. When steady-state water flow was reached, a measurement was conducted and the measurement continued at lower water potential. Upon completion of the drip infiltrometer measurements the samples were re-saturated and the saturated hydraulic conductivity measured using the constant-head method (Klute and Dirksen, 1986). Near-saturated hydraulic conductivity and air permeability were only measured on three out of five samples, whereas saturated hydraulic conductivity was measured on all five samples.

Analysis of small cores

Small soil cores were placed on top of a sandbox and saturated with water from below. Soil water characteristic were determined by draining the soil samples successively to soil water potentials of -10, -16, -50, -100, -160, and -1,000 cm H_2O (pF 1, pF 1.2, pF 1.7, pF 2, pF 2.2, and pF 3.0) using a sandbox for potentials from -10 to -100 cm H_2O and a ceramic plate for potentials from -160 to -1,000 cm H_2O. Soil water characteristics were also determined at a soil water potential of -15,850 cm H_2O (pF 4.2) after the soil had been ground and sieved through a 2 mm sieve (Klute, 1986). Air permeability was measured at a soil water potential of –50 cm H_2O using the same device as for the large soil cores. After the soil water characteristic had been determined the samples were re-saturated and the saturated hydraulic conductivity measured using the constant-head method (Klute and Dirksen, 1986). Finally, the soil samples were oven-dried at 105°C for 24 hours and weighed in order to determine the dry weight.

All analyses were carried out at the Department of Crop Physiology and Soil Science, DIAS except for the pF 4.2 analysis, which was carried out at the Department of Analytical Chemistry, DIAS.

4.3 Geophysical mapping

Geo-electrical mapping of the sites was performed using an EM-38 sensor and a CM-031 ground conductivity meter. Both instruments measure the apparent specific conductivity by electromagnetic induction (Durlesser, 1999). The electromagnetic conductivity of the soil is a function of such factors as the content of salts, clay and water (Rhoades and Corwin, 1981).

EM-38 mapping

Simplified maps generated by means of the EM-38 sensor delineate soil types according to their clay content (Nehmdahl, 2000). The measurement unit is millisiemens per metre (mS/m) and the penetration depth of the sensor is 1–1.5 m.

The mapping system developed at DIAS consists of a 4-WD motorcycle equipped with a GPS receiver and data-logger, pulling a sledge on which the EM-38 is mounted together with a GPS antenna.

Data from the EM 38 and GPS were stored simultaneously with a frequency of 1 measurement per second while navigating in parallel lines separated by a distance of approx. 10 m. Measurements were made at approx. 10 m intervals and used to produce interpolated maps of the soil electrical conductivity.

Conductivity meter (CM-031)

The electrical conductivity from 1 to 6 m b.g.s. was mapped at five of the six sites using a CM-031 ground conductivity meter (Geofyzika, Czech). A local 10 m by 20 m grid was established at the site and measurements made with both vertical and horizontal dipole orientations. The vertical dipole orientation corresponds to a penetration of 5.5–6 m whereas the horizontal dipole orientation corresponds to a penetration of approx. 1 m. The data were automatically stored in a HP palmtop during field work.

Note that the resistivity values at depths down to 1 m were measured with EM 38 whereas the measurements at 2.5–3 m b.g.s. and 5–6 m b.g.s. were made using the CM-031. The two instruments are operated at different heights above the ground surface.

Ground-penetrating radar (GPR)

To detect any larger sand or gravel lenses or other geological anomalies and obtain information about internal structures such as bedding plane, the area was mapped with ground-penetrating radar in a 20 to 30 m grid using a 100 MHz antenna. The GPR mapping was performed by FAXE Kalk A/S, DK.

5. Site characterization

In this chapter each of the six sites is described briefly in respect to instrumentation, pedology, and geology. For a detailed characterisation of the sites the reader is referred to the relevant Annexe.

5.1 Site 1: Tylstrup

This test field is situated at Tylstrup in northern Jutland. It covers an area of 1.08 ha and the width of the buffer zone is approx. 2 m towards the northeastern, 3 m towards the southeastern, 22 m towards the southwestern and 4.5 m towards the northeastern. Windbreaks run along the western and eastern side of the buffer zone and a road runs along the northern side of the site. All installations are shown in Figure 5.1.

Instrumentation

Four wells each containing three piezometers were installed in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 4.5–12 m b.g.s. An additional two piezometers consisting of ¾" electroplated pipes were also installed in the buffer zone and two were installed approx. 150 m south of the test field. The groundwater table fluctuates between 3 and 4 m b.g.s. Based on the groundwater potential in the piezometers in spring 1999 it was concluded that the direction of groundwater flow is towards west-southwest. The monitoring wells were therefore placed such that 6 of the 7 monitoring well clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering approx. the depth interval 2–6 m b.g.s. on the western side of the site and 1.6–5.6 m b.g.s on the eastern side.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the southwestern corner of the site, i.e. the downstream corner of the test field in relation to the direction of the groundwater flow.

Geology

The Tylstrup site is located on Late-Glacial fine-grained marine sand deposited in a shallow Arctic sea – the Yoldia Sea – approx. 15,000 BP. The area has subsequently

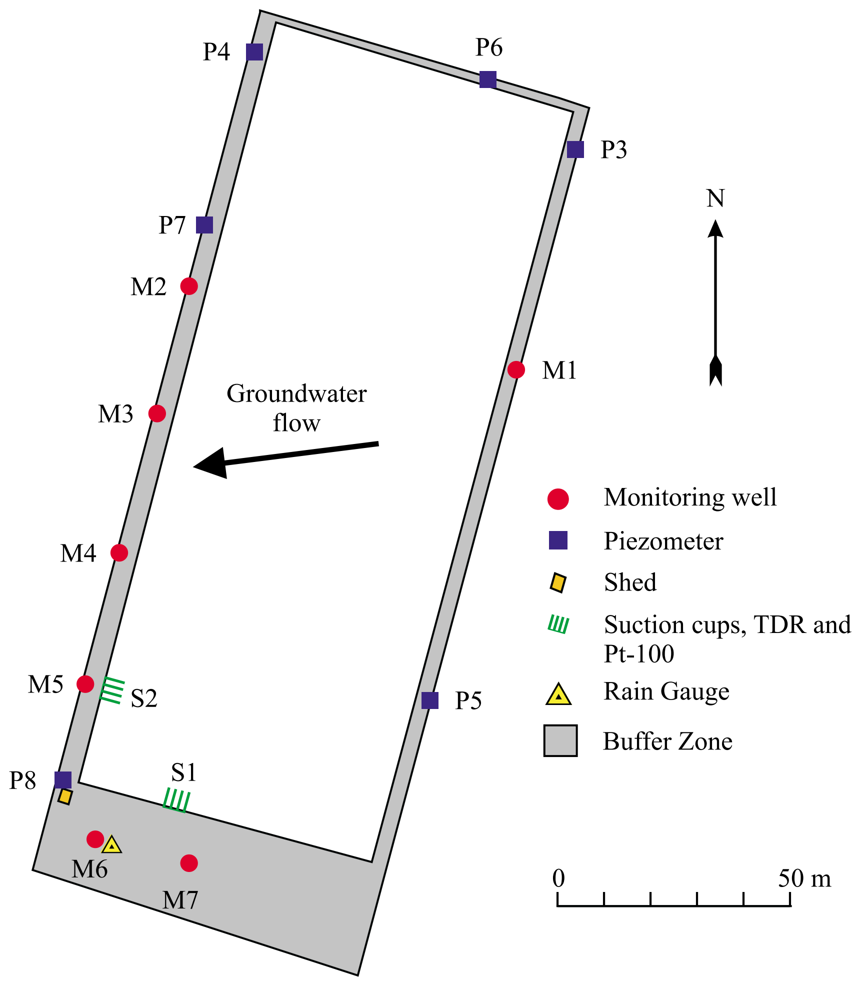


Figure 5.1. Sketch of the Tylstrup field showing the test and buffer zones, location of installations and the direction of the groundwater flow.

been subject to isostatic uplift and the Late-Glacial marine deposits are now found as one in a series of raised seafloor terraces.

The pattern of sediment distribution at the site indicates the presence of more fine-grained material, i.e. silt and clay layers, in the northern end of the field. The geophysical mapping is in good accordance with the well data and the field can be described as homogeneous. The pedological profiles at the site are classified as Typibrunsols. A geological-pedological model has been established on outcrop, borehole and geophysical data. The four units are presented below. A borehole croos section from the site is illustrated in Figure 5.2.

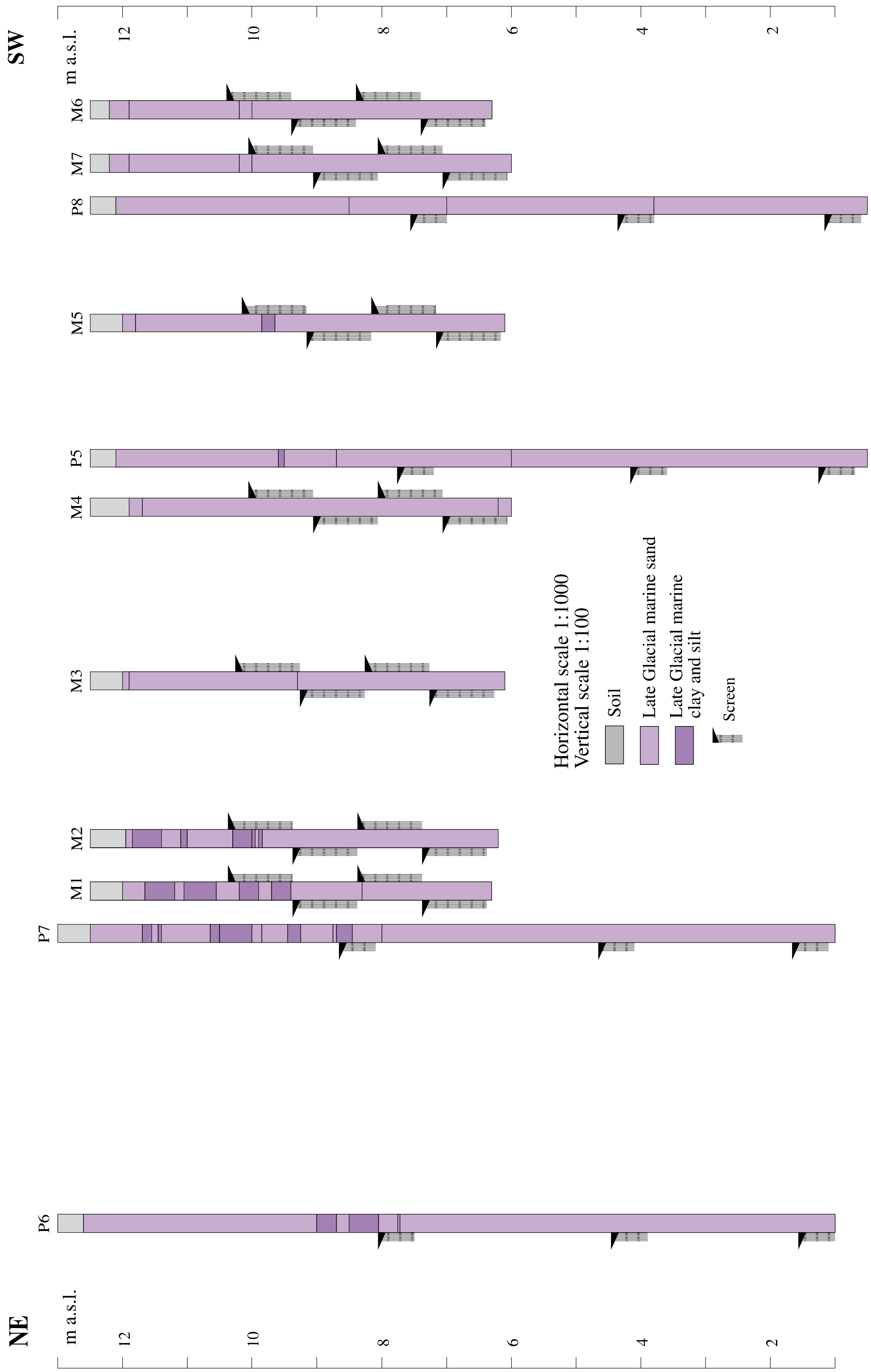


Figure 5.2 NE-SW cross section based on wells at the Tylstrup site. The location of the wells is shown in Figure 5.1.

Unit 1: Topsoil. 0–0.4 m b.g.s.

The very dark greyish brown sandy topsoil (loamy sand) contains humus (1.7–2.3% TOC), a varying content of burrows and roots, and is an Ap horizon. The material is noncalcareous. On the lee side of the windbreaks, Ap2 horizons are present, formed as a result of eolian sediment transport. The saturated hydraulic conductivity ranges from 10^{-6}–10^{-5} m/s.

Unit 2: Oxidized noncalcareous weathered fine-grained silty sand. 0.4–1.6 m b.g.s.

This unit is a yellowish brown, brownish yellow or dark olive brown silty sand classified as a Bv and a Bc horizon with wormcasts and roots to a depth of 1.6 m. The TOC content is approx. 0.3–1.5%. Placic horizons and hydromorphic characters are also present in the unit. Sedimentary structures are obscured as a result of soil formation processes. In the northern half of the field the unit can be expected to contain some silt and clay layers. The saturated hydraulic conductivity is approx. 10^{-5} m/s.

Unit 3a: Oxidized noncalcareous silty sand. 1.6–approx. 4 m b.g.s.

The silty sand in the unit is yellow or light yellowish brown, fine grained and silty. In outcrops it contains a variety of sedimentary structures such as lamination cross-bedding and erosive surfaces. The TOC content is less than 0.1%. In the top part of this unit the saturated hydraulic conductivity ranges from 10^{-5}–10^{-4}m/s.

Unit 3b: Oxidized noncalcareous silty sand with clay and silt layers. 1.6–approx. 4 m b.g.s.

This unit is confined to the northern half of the field. It consists of interbedded sand, silt and clay layers. The sand in the unit is yellow or light yellowish brown and the clay-silt layers are light olive brown. The different lithologies often appear as heterolithic beds, i.e. thin alternating layers. Silt layers typically have a lateral extension of approx. 10 m. The TOC content is less than 0.1%.

Unit 4: Oxidized weakly calcareous silty sand. 4–12 m b.g.s.

This unit consists of light yellowish brown silty sand with very few silt or clay layers. The $CaCO_3$ content is approx. 1.5–2.0% and TOC content is less than 0.1%.

Regional aquifer

The regional aquifer in the area is an extensive 20–30 m thick meltwater sand and gravel unit of Weichselian age located approx. 3–20 m b.g.s.

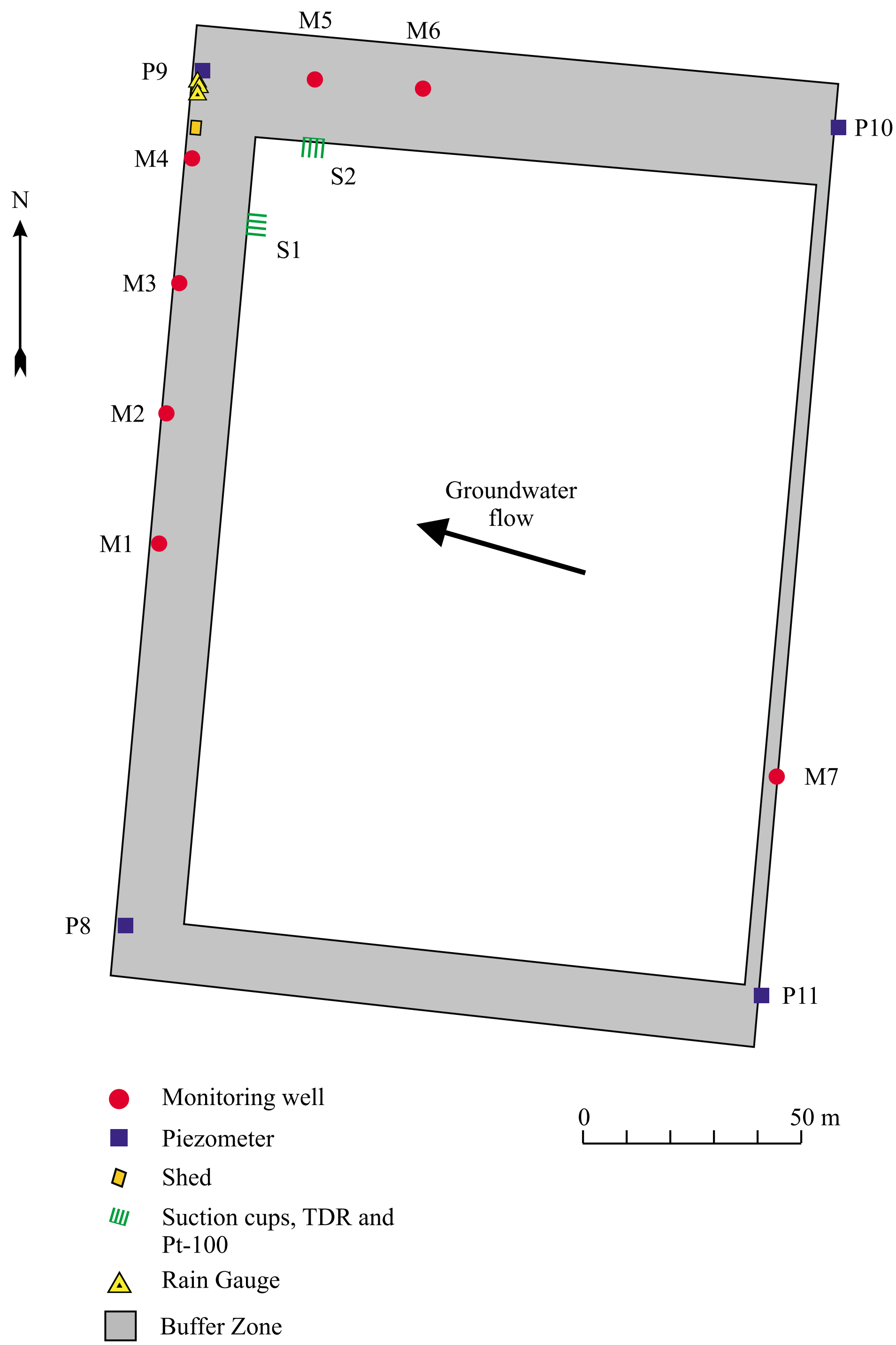


Figure 5.3. Sketch of the Jyndevad site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

5.2 Site 2: Jyndevad

This test field is situated at Store Jyndevad in southern Jutland. It covers an area of 2.39 ha and the width of the buffer zone is 24 m towards the north, 16 m towards the west, 14 m towards the south and 3 m towards the east. A windbreak borders the field to the east. All installations are shown in Figure 5.3.

Instrumentation

Four wells each containing three piezometers were installed in each corner of the site in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 3.4–11.5 m b.g.s. An additional seven piezometers were installed at a distance of up to 900 m from the site. The groundwater table fluctuates between 1 and 2 m b.g.s. Based on the groundwater potential in the piezometers in summer 1999 the direction of groundwater flow was concluded to be west-northwest. The monitoring well clusters were therefore placed such that 6 of the 7 clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering the depth interval 0.6–5.4 m b.g.s. at the western side of the site and 1.6–5.6 m b.g.s at the eastern side.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northwestern corner of the site, which is the downstream corner in relation to the direction of the groundwater flow.

Geology

The site is located on a Late Weichselian outwash plain west of the Main Stationary Line marking the westernmost extension of the Weichselian ice sheet. The outwash plain consists of meltwater sand and gravel locally draped by Post-Glacial eolian sand. Meltwater sand and gravel with a few silt and clay layers dominate the site. The meltwater sand unit in the area is at least 25 m thick and the Pre-Quaternary surface is located at a depth of approx. 30–40 m.

The three soil profiles at the site have been classified as Typipodsols. equivalent to a Humic Psammentic Dystrudept.

The geophysical mapping is in good accordance with the well data and the field can be described as very homogeneous. A geological-pedological model has been established on outcrop, well and geophysical data. The four units are described below and cross sections are illustrated in Figure 5.4.

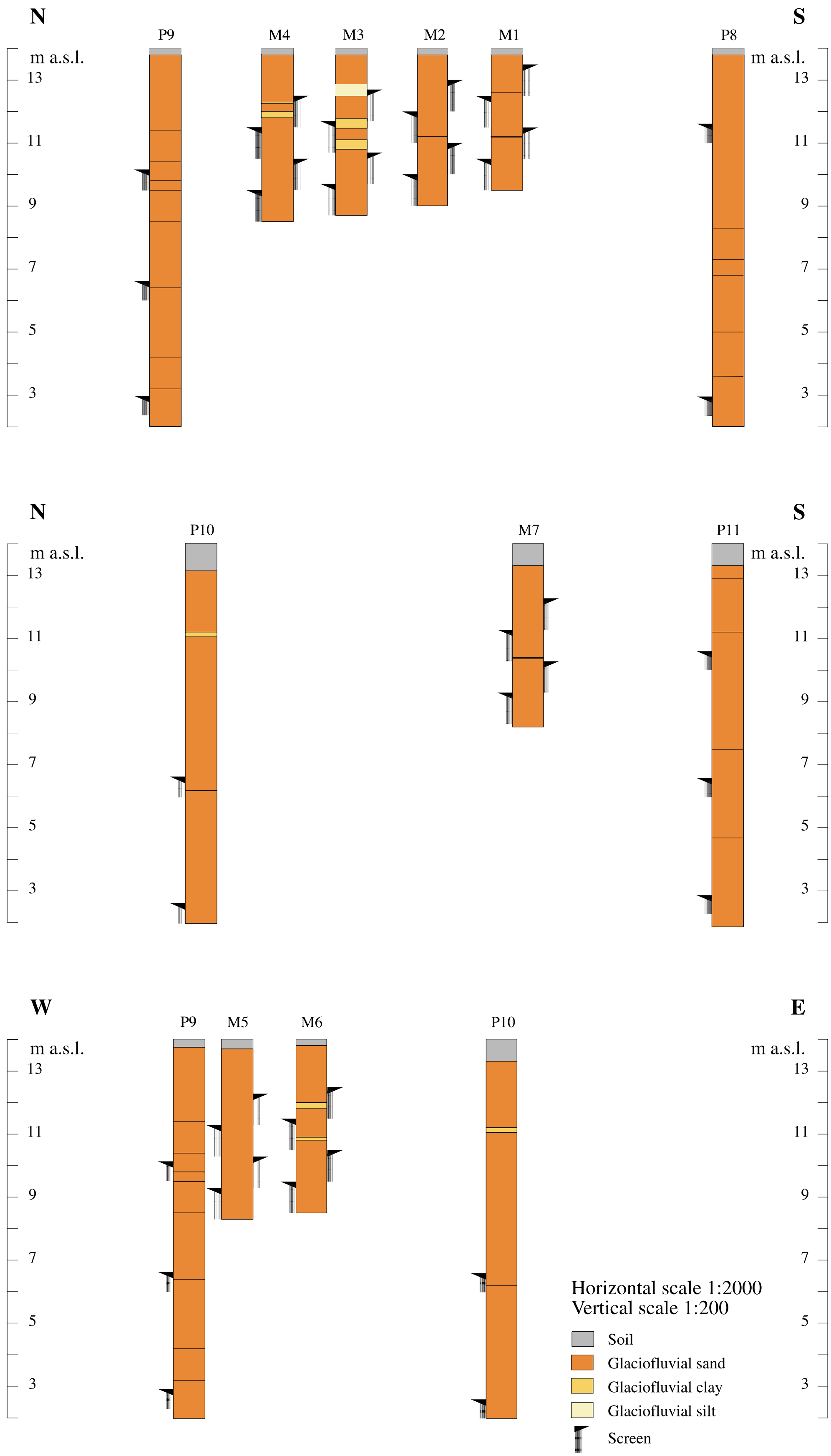


Figure 5.4. Cross sections based on wells at the Jyndevad site. The location of the wells is shown in Figure 5.3.

Unit 1: Top soil. 0–0.3 m b.g.s

The black topsoil consists of sand with a content of TOC at 1.5–2.5%, and is an Ap horizon. The saturated hydraulic conductivity ranges from 10^{-5}–10^{-4} m/s.

Unit 2: Weathered noncalcareous meltwater sand. 0.3–1.2 m b.g.s.

The black to yellowish brown unit consists of sand with small amounts of clay and silt. It contains three horizons: Bhs, Bs and BC. Remains of sedimentary structures such as cross-bedding and lamination can be observed. The TOC content is 0.25–0.75% and the saturated hydraulic conductivity is approx. 10^{-4} m/s.

Unit 3: Noncalcareous meltwater sand. 1.2–5.5 m b.g.s.

This unit is dominated by alternating beds of fine to medium-sized meltwater sand and medium- to coarse-grained meltwater sand. A few thin clay silt layers are present as well. Sedimentary structures such as cross-bedding and ripple lamination can be observed in the sand. Clay and silt account for less than 10% of the sand matrix. TOC content is lower than 0.2%. The saturated hydraulic conductivity ranges from 10^{-4}–10^{-3} m/s.

Unit 4: Unweathered weakly calcareous meltwater sand. 5.5–>12 m b.g.s.

This unit is similar to unit 3, but has a $CaCO_3$ content of 0–4.5%. The transition from oxidized to reduced conditions as indicated by colour changes is in good agreement with water well data from 10–12 m b.g.s.

Other deposits

In monitoring wells M3, M4 and M6, one or several clay and silt layer beds and stringer are present. In M3 the stringers are present to such an extent that the lithology takes on a heterolithic character.

Regional aquifer

The regional aquifer consists of extra-marginal meltwater deposits and to some extent more deep-lying Miocene quartz sand deposits.

5.3 Site 3: Silstrup

This test field is situated at Silstrup south of Thisted in northwestern Jutland. It covers an area of 1.69 ha and the width of the buffer zone is 18 m towards the west and east, 5 m towards the south (where a small road acts as an additional buffer zone) and more than 10 m wide towards the north. All installations are shown in Figure 5.5.

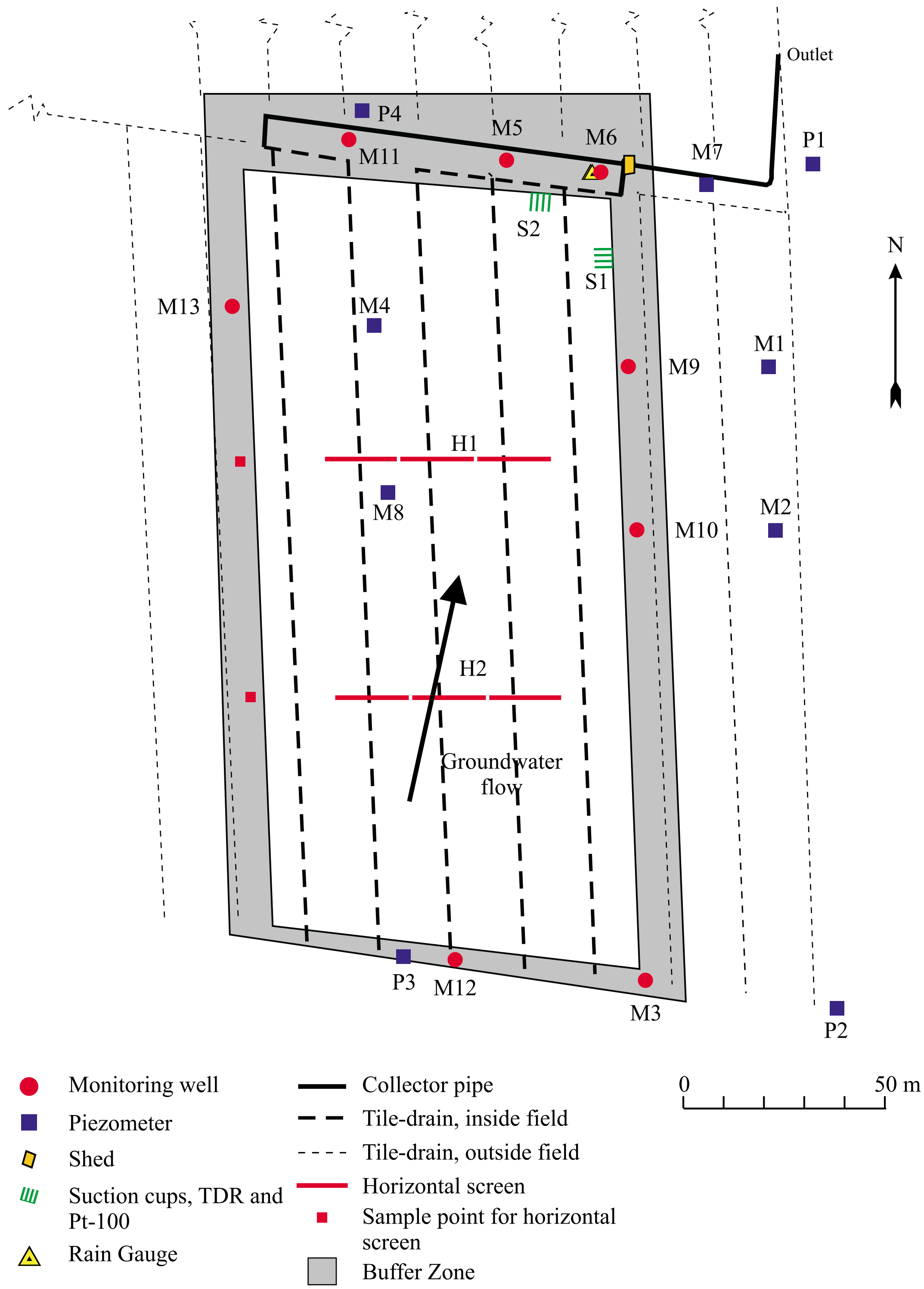


Figure 5.5. Sketch of the Silstrup site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

Instrumentation

Four wells each containing three piezometers were installed in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 2.0–12.0 m b.g.s. Based on the groundwater potential in the piezometers in summer 1999 it was concluded that the direction of the groundwater flow is towards the north. The monitoring wells were therefore placed such that 6 of the 7 clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering the depth interval 1.5–5.5 m b.g.s.

The drainage system at the site was installed in the 1960s. The design of the drainage system in the test field was simple, consisting of 5 parallel field drains running from south to north connected to two transverse collector drains at the northern end. All existing drainpipes are clayware. The lateral drains are 6.5 cm i.d. while the main drains are 8 cm and 10 cm i.d. The laterals appeared to have an envelope of seashells (mussels) to improve permeability.

The monitoring chamber was placed in the northeastern corner of the field. The two easternmost pipes exited towards the west, where a new 98 m PE pipe had to be laid along the northern boundary of the field to lead the water from the northwestern corner to the measuring chamber in the northeastern corner.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northeastern corner of the site, their positions being determined by that of the drainwater monitoring chamber.

Two 58 m long horizontal sampling wells H1 and H2 were also installed at Silstrup. Each consisted of three 18 m screen sections separated by 1 m bentonite seals. The first screens (H1.1 and H2.1) of both wells are situated within a lateral distance of 17 m from the edge of the test field.

The wells were drilled perpendicular to the edge of the field with the screens 3.5 m b.g.s. According to the drilling company, part of H2 follows a "pavement" probably comprised of a clay till rich in stones and boulders.

Geology

The Silstrup site is located north of the Main Stationary Line of the Weichselian Glaciation. Weichselian glacial clay till deposits dominate the site and only few thin bodies of

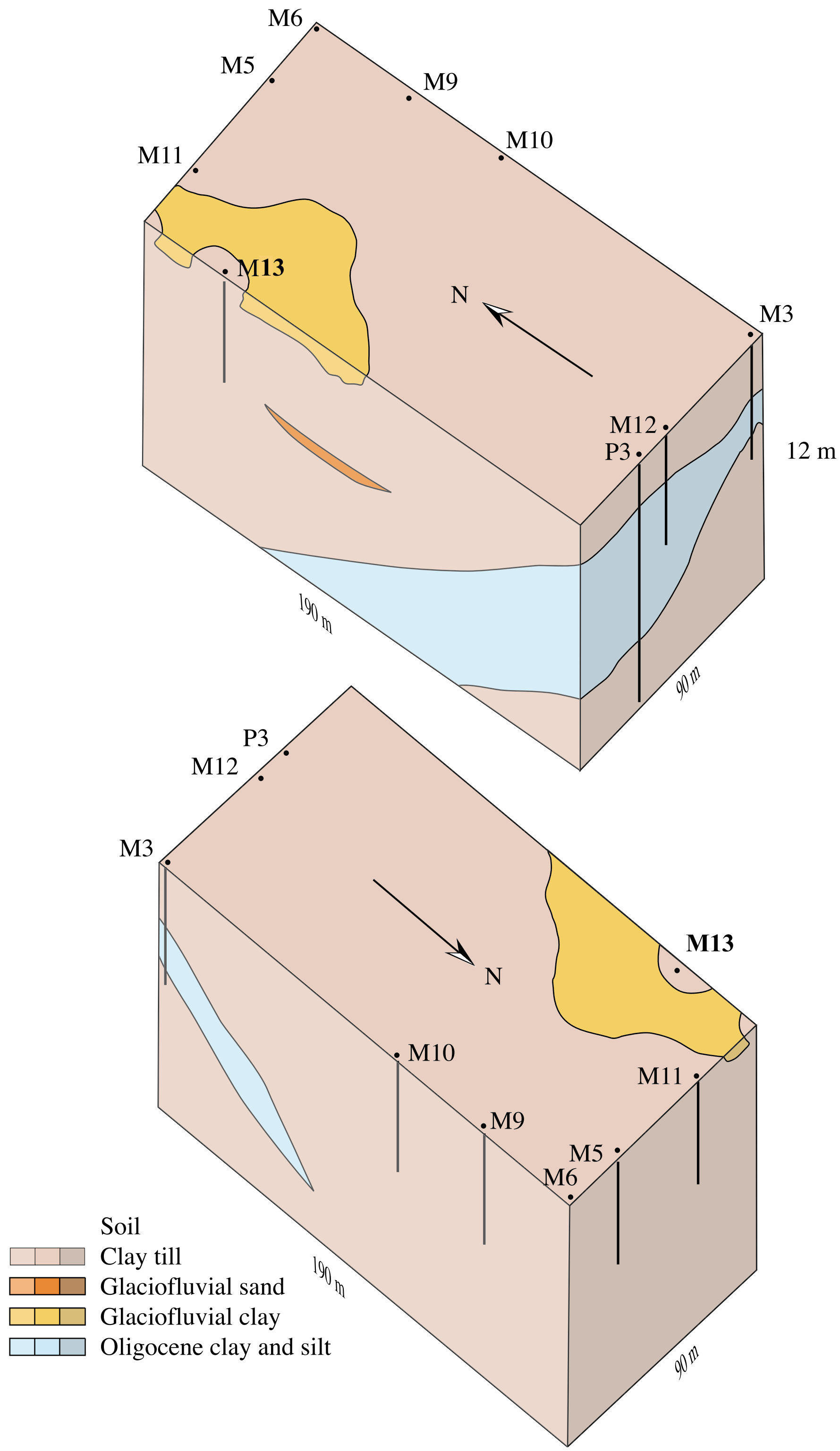


Figure 5.6. A geological model for the Silstrup site.

meltwater sand are present. Dislocated Oligocene clay and silt are present in the till along the southern rim of the test field. The site is situated in an area of glaciotectonic thrust faults and the coastal cliff east of the site contains dislocated Palaeocene and Oligocene deposits deformed by glaciers from the NNE and N.

The geophysical mapping is in good accordance with the well data and the field can be described as homogeneous.

A geological-pedological model comprised of the four units described below has been established on outcrop and borehole data and is illustrated in Figure 5.6.

Unit 1: Topsoil. 0–0.5 m b.g.s.

The dark grey brown to black sandy clayey topsoil (sandy clay loam/sandy loam) contains humus (1.9-2.4 % TOC) and numerous burrows and roots. The unit is also heavily fractured by vertical desiccation fractures. It is an Ap horizon and the material is non-calcareous. The saturated hydraulic conductivity ranged from 10^{-6}–10^{-4} m/s.

Unit 2: Noncalcareous oxidized clay till. 0.5–1.3m b.g.s.

The oxidized yellow brown clay till is penetrated by roots and burrows mainly in the upper part. The till is generally noncalcareous but some spots at the site are calcareous. Several horizontal-subhorizontal fractures are present. The till is weathered and the B horizon consists of Bv and Bt with clay illuviation in the lower part. The saturated hydraulic conductivity ranges from approx. 10^{-5}–10^{-4} m/s.

Unit 3: Calcareous oxidized clay till. 1.3–3.5 m b.g.s.

The brown and light yellow brown clay till is oxidized and calcareous (C- horizon). The till contains small vertical and subvertical fractures which decreases in amount with increasing depth. Additional sparse horizontal to subhorizontal fractures occur in this unit. Dislocated Oligocene clay and silt are included along the southern rim of the site. Saturated hydraulic conductivity values range from 10^{-7}–10^{-5} m/s

Unit 4: Calcareous reduced clay till. 3.5–13 m b.g.s.

The olive grey clay till is calcareous and contains chalk and chert gravel. Only very few vertical fractures exist at this depth while horizontal and subhorizontal fractures are more abundant.

Other deposits

At the southern end of the field, dislocated Oligocene clay and silt layers are found interbedded in the clay till. Since the clast fabric in the clay till indicates a deformation from the north, it is likely that the dislocated Oligocene layers strike approx. 90° and dip towards the north. The clay content of these layers ranges from 20–30% and the silt content from 40–80%. The TOC content is 1.0–2.1%.

Regional aquifer

The sparse well data available for the area reflect the fact that there is no primary aquifer below the Silstrup site. However, the chalk is found at a depth of at least 100 m.

5.4 Site 4: Estrup

This test field is situated west of Vejen in central Jutland. It covers an area of 1.26 ha and the width of the buffer zone is 10 m towards the north and west, 5 m towards the south (where the railroad is) and 15 m towards the east. All installations are shown in Figure 5.7.

Instrumentation

Four wells each containing three piezometers were installed in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 1.5–21.9 m b.g.s. Based on the groundwater potential in the piezometers in autumn 1999 it was concluded that the direction of groundwater flow is to the northeast. The monitoring wells were therefore placed such that 6 of the 7 clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering the depth interval 1.5–5.5 m b.g.s.

The drainage system was established in 1965. It is thought to be constructed of 6.5 cm drains. To prevent water outside the test field from entering the drainpipes in the test field, a cut-off drain was installed along the south and east boundary of the site. The monitoring chamber was placed in the northeastern corner of the site. A 85 m long pipe running 1–2 m from the edge of the ditch collected discharge from the two 8 cm pipes that originally led to the ditch. Water from the main drainage system was conveyed to the monitoring chamber by a 5 m long pipe. The two branches join as a T-junction right outside the chamber.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northeastern corner of the site, their positions being determined by that of the drainwater monitoring chamber.

Due to the prevailing geological conditions, only one of two planned horizontal wells were installed. Three 18 m screen sections and four 1 m bentonite seals were installed

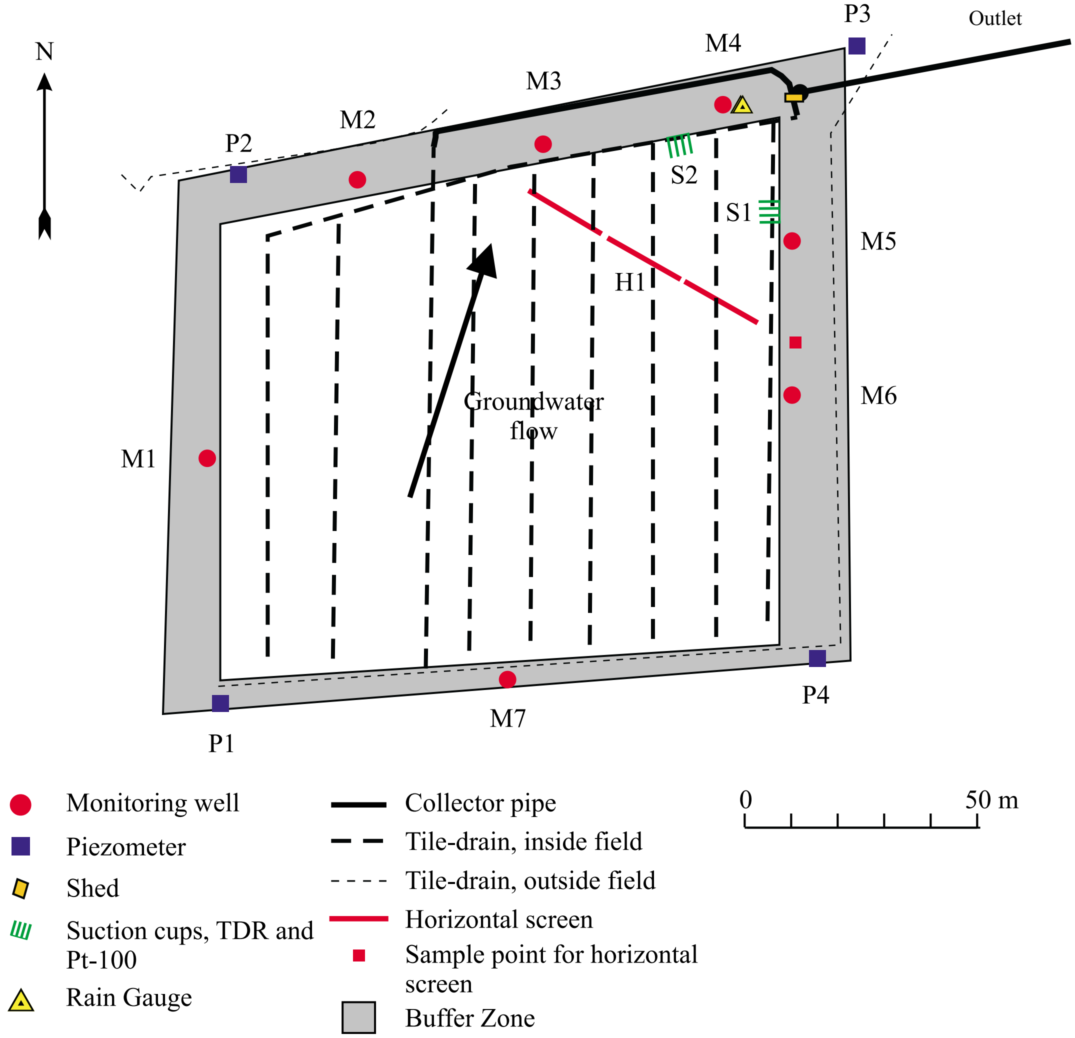


Figure 5.7. Sketch of the Estrup site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

3.5 m b.g.s. beneath the northeastern corner (H1). The samples are collected from the southern end of the well. A second attempt was made to drill a horizontal well from a position 7 m west of M2 to 13 m north of M6, but the borehole had to be abandoned after 15 m of drilling in sand.

Geology

The Estrup site is located west of the Main Stationary Line of the Weichselian Glaciation and the clay till that dominates the site is therefore Saalian. The site has a complex geological structure comprising a clay till core with deposits of different age and com-

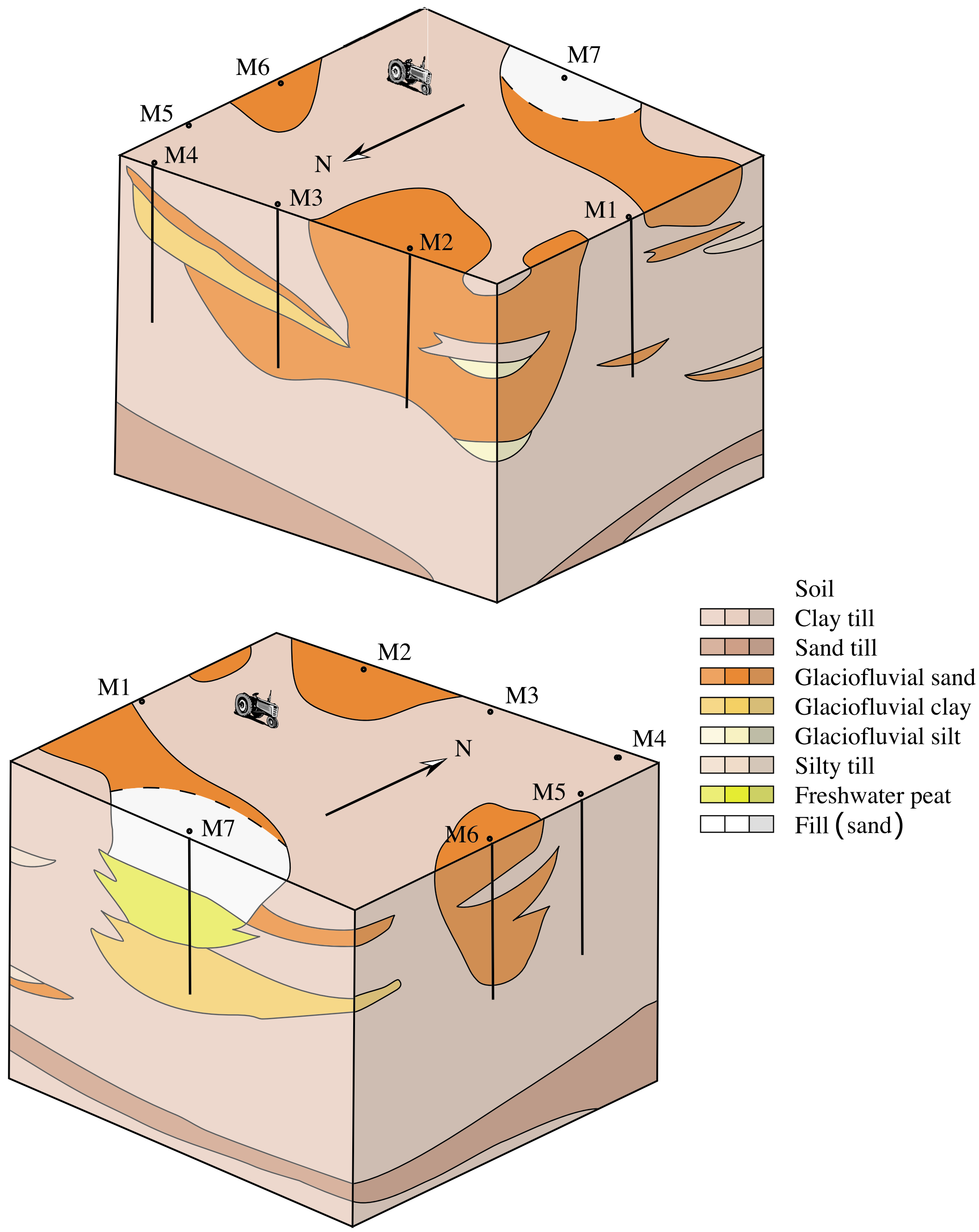


Figure 5.8. A geological model for the Estrup site.

position (Figure 5.8). At the southern rim of the site, shallow Post-Glacial peat is depositedupon a meltwater clay above the till. In the northwestern corner, a Saalian meltwater sand basin with intercalation of till and silt layers is present. Along the eastern rim of the area there is a small meltwater sand body. In the northeastern corner, a small lacustrine basin filled with clay and gyttja rests on the clay till. The age of the deposits could be Weichselian Interstadial or Eemian Interglacial. Small bodies of black micaceous clay (not shown on Figure 5.8) with a high content of organic material are considered to be glacially dislocated Miocene sediments.

The soil profiles developed in the clay till at the site are classified as Pseudogleytypilessive, whereas the soil profiles in the meltwater sand are classified as Lessive Pseudogleytypipodsol.

The Estrup site is heterogeneous with different lithologies of Saalian, Weichselian and Post-Glacial ages. The long exposure of the sediments to weathering during the glacial-interglacial-glacial cycle has resulted in pedological development of acidification, decalcification and transport of fines and organic matter resulting in leached upper horizons.

The clay and sand till body is the most important lithology as regards the geological model. It is difficult to incorporate all the lithologies in one single model, and a geological-pedological clay till model has therefore been established and relationships to the other sediments are mentioned. The four units of the model are described below and a conceptual 3-D model is illustrated in Figure 5.8.

Unit 1: Topsoil. 0-0.4 m b.g.s.

The topsoil consists of very dark greyish brown clay and clayey sand (sandy loam) with a TOC content between 1.7 and 7.3%. It is an Ap horizon and is noncalcareous. The saturated hydraulic conductivity ranges from 10^{-6}–10^{-4} m/s.

Unit 2: Noncalcareous clay till. 0.4–1.0 to 4.0 m b.g.s.

The yellow brown clay till is noncalcareous and oxidized. Root channels reach down to a depth of 2 m in this zone and occur together with randomly oriented small desiccation fractures. From 2.0 to 4.0 m the fractures are still randomly oriented, but systems of small vertical fractures and horizontal-subhorizontal fractures also occur. A few large fractures are found. The till is heavily weathered and has an upper BE-horizon with clay evaluation , a middle Bt horizon with clay and Fe and Mn oxide illuviation, and a lower C horizon. The saturated hydraulic conductivity is 10^{-7}–10^{-5} m/s. Other sediment bodies present at the site are in contact with unit 2 and may influence the upper part of the hydraulic system of the Estrup site.

Unit 3: Non calcareous/calcareous clay till. 4– approx. 12 m b.g.s.

The light yellow to brown grey sandy clay till is oxidized. The calcareous content varies through the unit due to the occurrence of chalk rafts. Abundant large vertical fractures and horizontal fractures occur and form a three-dimensional pattern. The saturated hydraulic conductivity ranges from 10^{-9}–10^{-7} m/s. The meltwater sand bodies are in contact with unit 3.

Unit 4: Calcareous clay and sand till. >12 m b.g.s.

This unit consists of alternating reduced calcareous grey clay till and sandy till beds with some sand veins.

Other deposits

In addition to the deposits included in the clay till model, the site also includes the following:

- Noncalcareous Saalian meltwater sand in the northeastern corner of the site. A glacial raft of Miocene micaceous clay with a TOC content of 10% is found in the southeastern corner at a depth of approx. 2 m.
- South of the site 2 m of Post-Glacial peat was found with a TOC content of 50% and no $CaCO_3$. East of the site there is a 5 m thick glaciofluvial sand body with a clay till bed. Northwest of the site there is a 7 m thick sequence of glaciofluvial sand with clay till and silt beds.

Regional aquifer

The regional aquifer is located approx. 20 m b.g.s. and consists of meltwater sand.

5.5 Site 5: Faardrup

This test field is situated at Faardrup south of Slagelse on Zealand. It covers an area of 2.33 ha and the width of the buffer zone is >11 m towards the north, 12 m towards the west (where the road adds another 4 m to the buffer zone), 17 m towards the east and >11 m towards the south. All installations are shown in Figure 5.9.

Instrumentation

Four clusters of piezometers were installed in each corner of the test field, in the buffer zone. Each cluster consisted of three 0.5 m long screens distributed over the depth interval 1.5–13.2 m b.g.s. Based on the ground water potential in the piezometers during summer 1999 it was concluded that the direction of groundwater flow was towards the west. The monitoring wells were then placed such that 6 of the 7 monitoring well

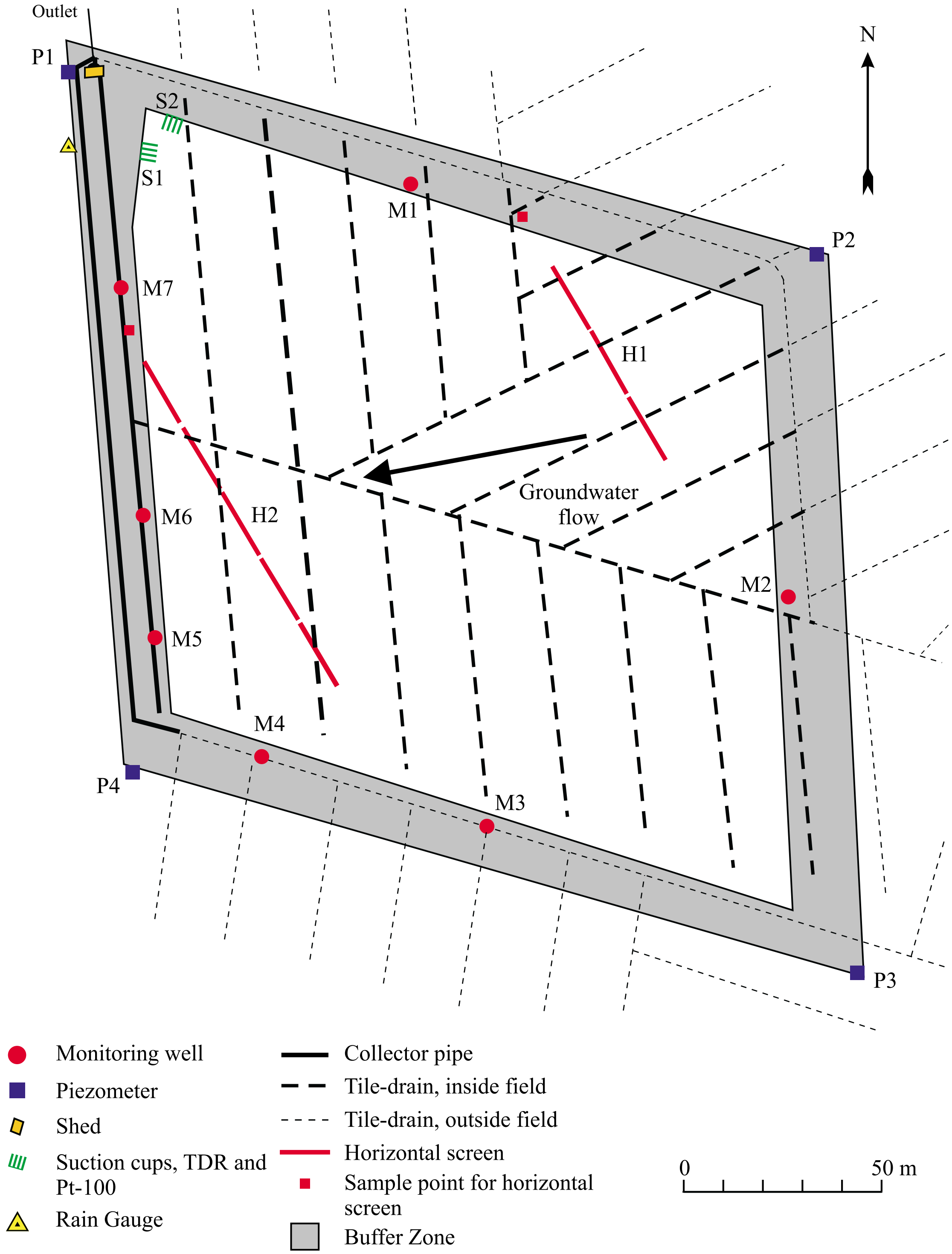


Figure 5.9. Sketch of the Faardrup site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

clusters were located downstream of the test field. Each cluster contained four separate 1 m screens covering the depth interval 1.5–5.5 m b.g.s.

The drainage system at Faardrup was installed in 1944. The map from 1944 shows a traditional systematic drainage system. The drainage water from the test field and the adjacent fields is collected in a 15 cm main drain that runs along the western side of the area. The drainage system in the test field is a "herringbone system" with a collector drain that runs down westwards from the hills to the east, crosses the middle of the field and ends in the 15 cm main drain. All the drainpipes are clayware – 5.5 cm i.d. laterals and 6.5 cm and 10 cm i.d. collector drains. The monitoring chamber was placed in the northwestern corner of the site.

To isolate the test field drainage system, two cut-off drainpipes were installed. South of the test field there is a smaller, independent drainage system which also exited at the top end of the 15 cm main in the southwestern corner of the experimental field. This system was disconnected at this point and the water lead downstream via a new watertight pipe installed along the western boundary, parallel to the old main. A second cut-off drain made of perforated, corrugated pipes with an envelope of gravel was installed to the north and the east of the test field to prevent water from running into the test field from its upstream side. All the existing drains intersected were closed off with a brick towards the experimental field, and their upstream parts were connected to the new drainpipe via a T-junction.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northwestern corner of the site, their positions being determined by that of the drainwater monitoring chamber.

Two horizontal sampling wells were installed at Faardrup. Both wells were planned to consist of five 18 m screens separated by 1 m long bentonite seals, total length 96 m, including a 1 m bentonite seal at each end. Due to technical difficulties, however, H1 only consists of three 18 m long screens separated by 1 m bentonite seals.

H1 was drilled under the northeastern corner of the field. The overall drilled length is 160 m, of which 120 m lie beneath the test field. The screens are positioned from 3.35 to 3.70 m b.g.s. The samples are collected from the northern end of H1. Well H2 intersects the southwestern corner of the field. The overall drilled length is 158 m, of which 110 m lies beneath the test field. The screens are positioned from 3.2 to 3.7 m b.g.s. The samples are collected from the northern end of H2.

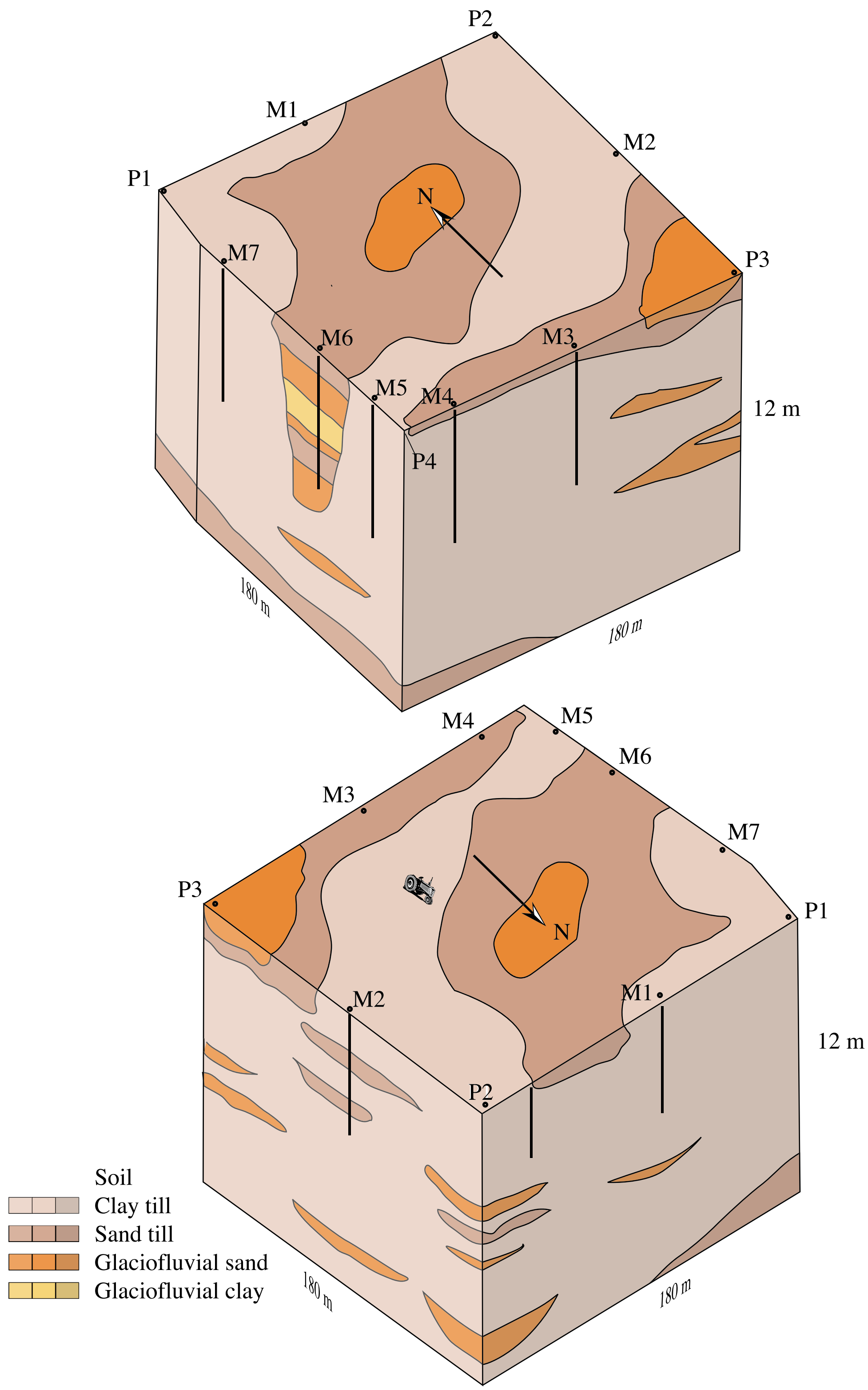


Figure 5.10. A geological model for the Faardurp site.

Geology

The Faardrup site is dominated by Weichselian clay till deposits more than 18 m thick and overlying a regional meltwater sand aquifer. The till deposits are covered by a clayey topsoil 0.3-0.4 m thick. The upper part of the till is classified as sandy-clayey till as the clay content is about 12%. This part is heavily weathered, bioturbated and fractured. The underlying clay till consists of an upper oxidized unit down to 4.1 m b.g.s. and below a reduced unit. Borehole information shows that the clay till body contains small channels or basins consisting of meltwater clay and sand (Figure 5.10).

The two of the soil profiles developed in the more or less clay-rich till are classified as Pseudogleytypilessive and one as Degralessive.

The geophysical data are in accordance with the well and outcrop data and the test field can be described as relatively homogenous representing the variability of the till plain. A geological-pedological model for the clay till has been established consisting of the 4 units described below. A conceptual 3-D model is illustrated in Figure 5.10. The meltwater sand and clay layers are not included in the model.

Unit 1: Topsoil. 0–0.4 m b.g.s.

The dark brown topsoil consists of clay and sand (loam/sandy loam) with TOC content between 1.2-1.8% and is an Ap horizon, of sandy loam. The material is noncalcareous. The deposits contain numerous wormholes and root channels. Saturated hydraulic conductivity ranges from 10^{-6}–10^{-3} m/s.

Unit 2: Noncalcareous sandy clay till. 1.1–1.8 m b.g.s.

The yellow brown sandy-clayey till with sand lenses is oxidized and noncalcareous. Numerous burrows and roots are present but decrease in number with increasing depth. Vertical fractures (desiccation cracks) occur through the whole unit. The till is heavily weathered, often with an upper BE horizon showing eluviation of clay and a lower Bvt horizon showing illuviation of clay and Fe and Mn oxides. The saturated hydraulic conductivity of the till is relatively high (compared to till deposits), ranging from 10^{-5}–10^{-3} m/s.

Unit 3: Calcareous clay till. 2–4.2 m b.g.s.

The olive brown and yellow clay till is oxidized and calcareous. Few deep roots penetrate down into this unit. The unit is dominated by a network of fractures: Numerous horizontal to subhorizontal fractures, many small fractures and few large fractures penetrating down to at least 5 m b.g.s., i.e. into Unit 4. The saturated hydraulic conductivity ranges from 10^{-6}–10^{-5} m/s in the upper part (1.5m) and 10^{-9} m/s in the lower part.

Unit 4: Reduced clay till. 4–>18 m b.g.s.

The olive grey reduced clay till with sand lenses and layers of sandy till is calcareous. The till contains few large subhorizontal fractures crossed by few large vertical fractures that can be followed into unit 3. The saturated hydraulic conductivity is 10^{-9} m/s at 5.0 m b.g.s.

Other deposits

Well M6 contains a sequence of glaciofluvial sand, silt and clay 5 m thick that appears to be an infilled erosive channel. There is good reason to believe that glaciofluvial sediments of the same origin can be found under the topographic depression in the eastern part of the field.

Regional aquifer

The regional aquifer is located approx. 15–25 m b.g.s. beneath the clay till. According to local water well data, it consists of meltwater sand and gravel.

5.6 Site 6: Slaeggerup

This site is situated at Slaeggerup northeast of Roskilde on Zealand. It covers an area of 2.17 ha and the width of the buffer zone is >12m towards the northwest and northeast, and >10 m towards the southwest and southeast. All installations are shown in Figure 5.11.

Instrumentation

Four wells each containing three piezometers were installed in the buffer zone. Each cluster consists of three 0.5 m long screens distributed over the depth interval 2.0–13.5 m b.g.s. Based on the groundwater potential in the piezometers in summer 1999 it was concluded that the direction of the shallow groundwater flow is towards the northwest, following the topography. The monitoring wells were thus placed such that 6 of the 7 clusters were located downstream of the test field. Each cluster contained four separate 1 m long screens covering the depth interval 1.5–5.5 m b.g.s.

The exact age of the drainage system is unknown, but the system is shown on a map of several other drainage systems dated 1963. The systems exit to a ditch, a small stream running 30-40 meters from the eastern boundary of the experimental field. The drainage materials used are traditional clayware – 5.5 cm i.d. laterals and 8 cm and 10 cm i.d. main drains. The field is systematically drained. The spacing between the field drains

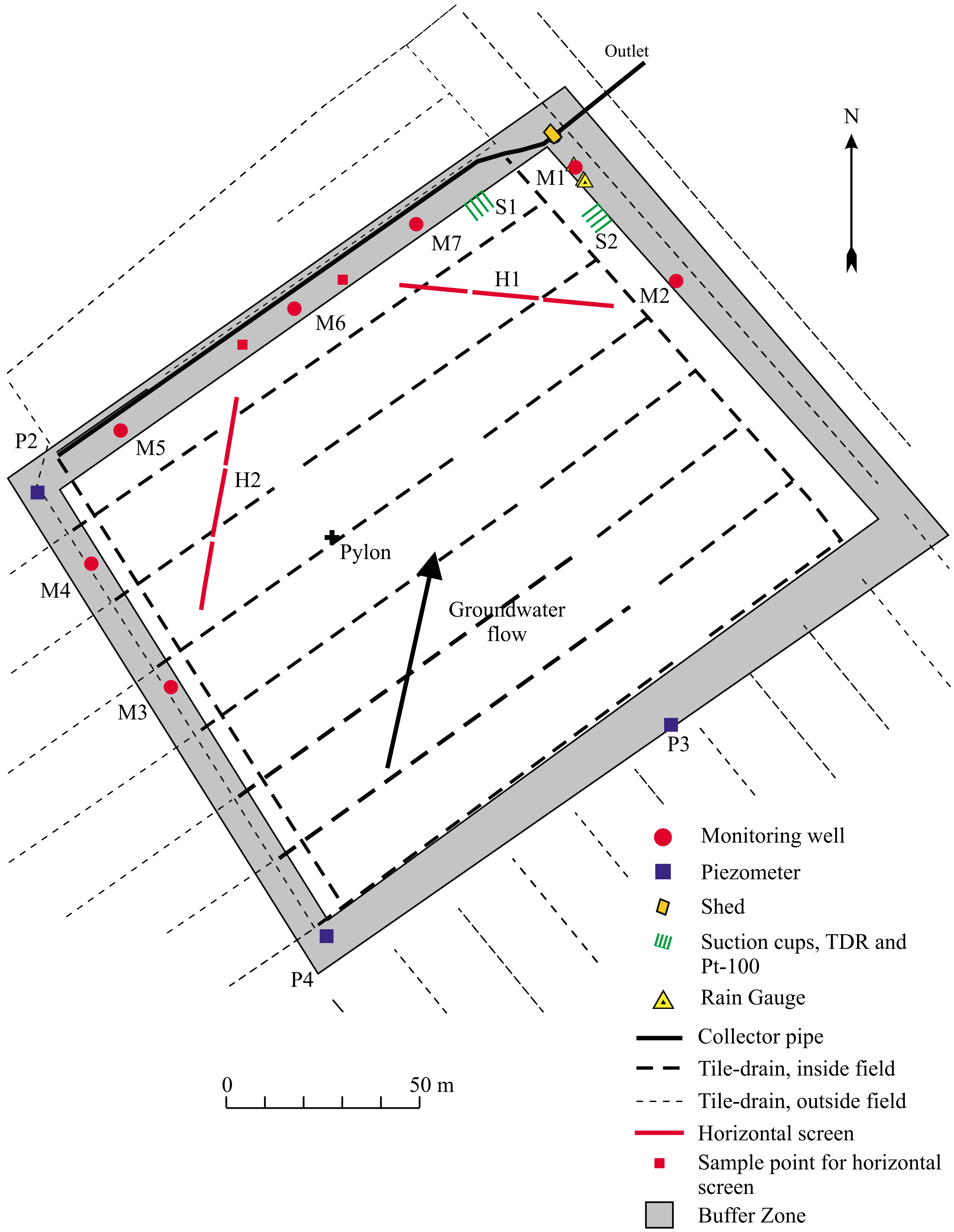


Figure 5.11. Sketch of the Slaeggerup site showing the test and buffer zones, location of installations and the direction of the groundwater flow.

(laterals) is 20 m. Since the field has a hilltop on the middle, the field drains are connected to a main drain on either side of the hill.

The monitoring chamber was placed in the northeastern corner of the site. Along the northwestern side of the test field a new PE pipe was installed to connect the two main drains to the monitoring chamber. The main pipe on the southwestern side of the hill has side drains attached from both sides. Eight drains approaching from the west were cut off along the western border of the field by a new main drain laid parallel to the old main drain at a distance of 8 m.

Two groups of suction cups, TDR-probes and Pt-100 sensors were installed at the northeastern corner of the site, their positions being determined by that of the drainwater monitoring chamber.

Two horizontal monitoring wells were installed at the site each containing three 18 m screens separated by 1.0 m bentonite seals. Well H1, which intersects the northern corner of the field, was installed 3.5 m b.g.s. Well H2 was installed in the western corner. During the process of drilling the well, upward transport of drill water was recorded in two places, one approx. 32 m from the southwestern boundary and 5 m east of the well trajectory and the other approx. 48 m from the southwestern boundary and 9 m east of the well trajectory. When the PVC liner was drawn out of the well, a far larger force than usual was needed, thus indicating the presence of a gravel/boulder bed in the well path with hydraulic contact to the surface in the well path. The screens of well H2 were also installed 3.5 m b.g.s.

Geology

The Slaeggerup site consists of Weichselian glacial deposits. Layers of clay and sand till dominate. Meltwater clay, sand and gravel cover the till in the main part of the area and clay till is only present just below the topsoil in the southeastern corner of the site. A meltwater lacustrine basin on the top of the tills is filled lowermost with a sand-gravel body having an erosive base, and uppermost by a clay veneer that is only missing to the east (Figure 5.12).

The three soil profiles at the site are classified as Brunjordstypilessive.

A geological-pedological model has been established consisting of the six units described below. A conceptual 3-D model is illustrated in Figure 5.12.

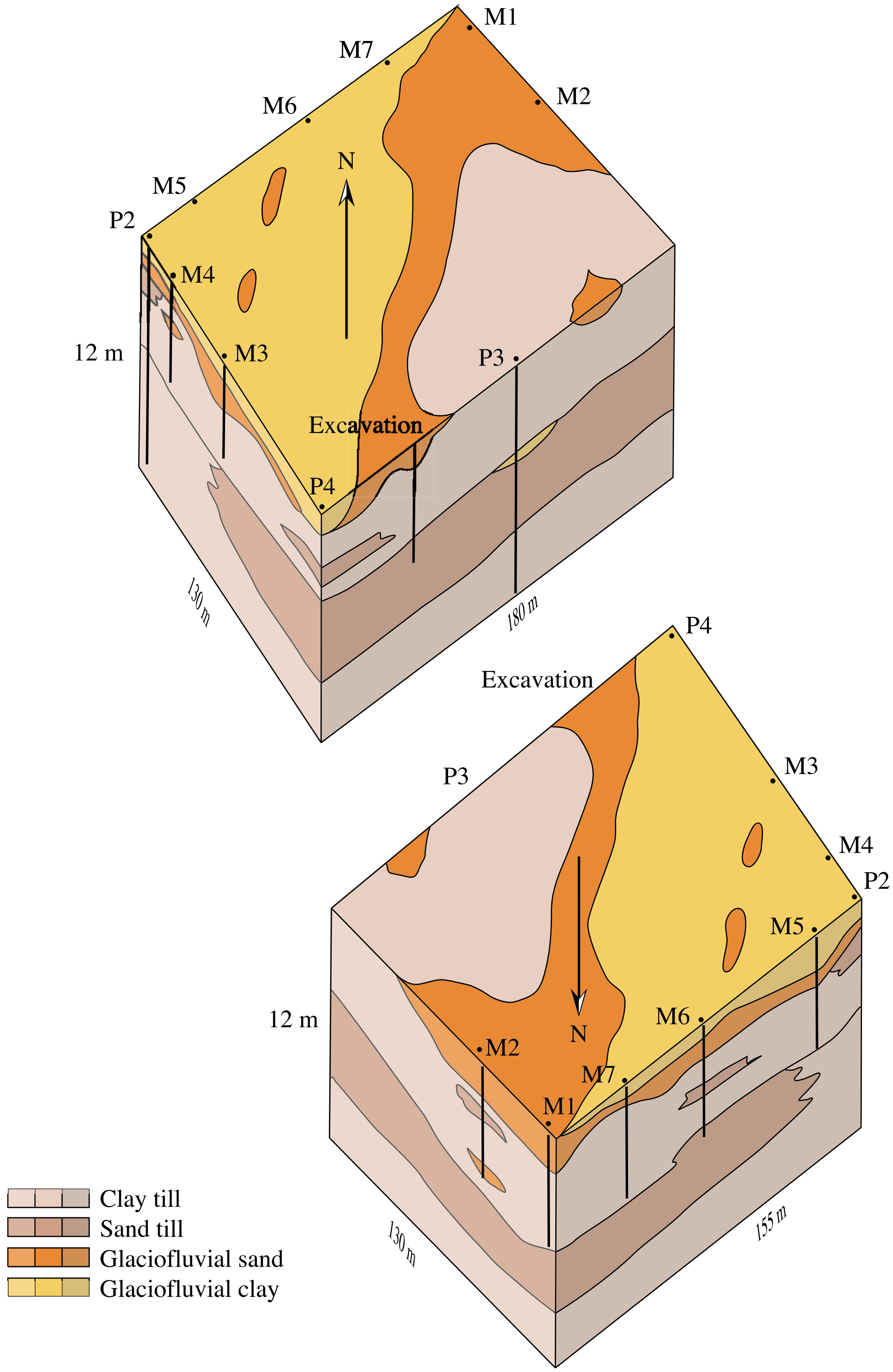


Figure 5.12. A geological model for the Slaeggerup site.

Unit 1: Topsoil. 0–0.3 m b.g.s.

The topsoil is a very dark grey brown clay (loam and sandy loam) containing 1.0-1.7% TOC. It is noncalcareous and contains small roots and burrows. It is an Ap horizon. The saturated hydraulic conductivity ranges from 10^{-6}–10^{-4} m/s.

Unit 2: Meltwater clay. 0.3–1.8 m b.g.s.

The meltwater clay is up to 1.8 m thick and overlies meltwater sand and gravel (unit 3, below) with a gradational boundary. The clay content is 40-55%. In the lower part of unit 2 the clay is commonly sandy and strongly silty whereas it is weakly sandy and silty in the upper part. Small roots, wormholes and vertical desiccation fractures are common. The clay is strongly calcareous except down to approx. 0.7 m b.g.s. where it is noncalcareous. Down to approx. 0.7 m b.g.s. the clay has a yellow brown colour indicating oxidized conditions whereas greyish colours in deeper levels indicate reduced conditions. The soil horizon consists of a Bv or a Bvt with clay illuviation and Fe and Mn oxide nodules. The saturated hydraulic conductivity in the horizons ranges from 10^{-5}- 10^{-4} m/s.

Unit 3: Meltwater sand and gravel. 0.3–2.5 m b.g.s.

The meltwater sand and gravel erosively overlies a clay till (unit 4, below). The deposits are up to 1.8 m thick and consists of gravelly sand with scattered stones overlaid by alternating beds of sand, silt and clay. The sand beds are commonly cross laminated whereas the clay and silt beds are horizontally laminated. Small vertical and horizontal fractures are abundant in the clay and silt beds. The colours of the sediments are generally yellow brown and light yellow brown indicating oxidized conditions. The soil horizon is a Cc with unweathered sediments. The unsaturated hydraulic conductivity ranges from 10^{-7}- 10^{-5} m/s.

Unit 4: Oxidized/reduced clay till.0.3–7 m b.g.s

The calcareous, sandy clay till contains lenses of silt and sand. The clay till is yellow brown and oxidized down to 3.5 m, where it gradually changes into a reduced environment. The clay till has large vertical tectonic fractures and some horizontal-subhorizontal fractures. The $CaCO_3$ content is 20–30% and the TOC content ranges from 0.06-0.6%. The saturated hydraulic conductivity is approx. 10^{-8}-10^{-9}m/s.

Unit 5: Reduced sand and clay till. 4.7–>14 m b.g.s.

The unit is at least 8.5 m thick. It consists of a strongly sandy clay till overlaid by a sand till. Lenses of meltwater sand and clay are common. The till deposits are calcareous and have greyish colours indicating reduced conditions. However, locally the sand till has a light yellowish brown colour in its uppermost part indicating oxidized conditions. The

TOC content in the till deposits ranges from 0.08-0.13%. The saturated hydraulic conductivity is approx. 10^{-8} m/s in the sand till. Based on water well data the till deposits rest directly upon Danian limestone, which forms the regional aquifer at a depth of approx. 15-20 m b.g.s.

5.7 Comparison of the sites

The six sites were selected on the basis of the available information on the pedology and geology of the sites. The key data on the six sites is summarized in Table 5.1.

The total organic carbon (TOC) content of the topsoil at the sites ranges from 1.5 to 2% except at Estrup, where it varies markedly from 1.7 to 7.3% within the test field.

The sandy sites – Tylstrup and Jyndevad – represent two different types of sandy soil. The soil at Jyndevad is coarse-grained sand, with a low content of clay and silt, whereas that at Tylstrup is fine-grained sand with some silt and hence is characterized as a loamy sand. The two soils also different as regards pH. Thus the pH is 4-4.5 at Tylstrup but around 6 at Jyndevad. The saturated hydraulic conductivity is one order of magnitude higher at Jyndevad than at Tylstrup. The upper part of the groundwater is aerobic at both sites.

Of the four sites dominated by clay till, the clay content of the topsoil is lowest at Faardrup (14–15%) and highest at Silstrup and Slaeggerup (18–26%). Soil texture varies considerably within each site, both horizontally and vertically. The clay content is shown versus depth for two to three profiles per site in Figure 5.13. Considerable variation with depth is seen at Estrup and Silstrup. In some parts of the Estrup site the clay content is as much as 50%.

The saturated hydraulic conductivity in the C horizon is approx. 10^{-5}–10^{-6} m/s at the three clay sites (Silstrup, Faardrup and Slaeggerup), but two orders of magnitude lower at Estrup.

At Silstrup, Faardrup and Slaeggerup the calcareous matrix is located 1 m b.g.s., and the reduced matrix occurs 4 to 5 m b.g.s. At Estrup the calcareous matrix is located from 1–4 m b.g.s., and the reduced matrix occurs at more than 5 m b.g.s.

The fracture intensity at 3–4 m b.g.s. is 0–4 fractures m^{-1} at Silstrup and Faardrup compared with the much higher figure of 11–12 fractures m^{-1} at Estrup and Slaeggerup. The

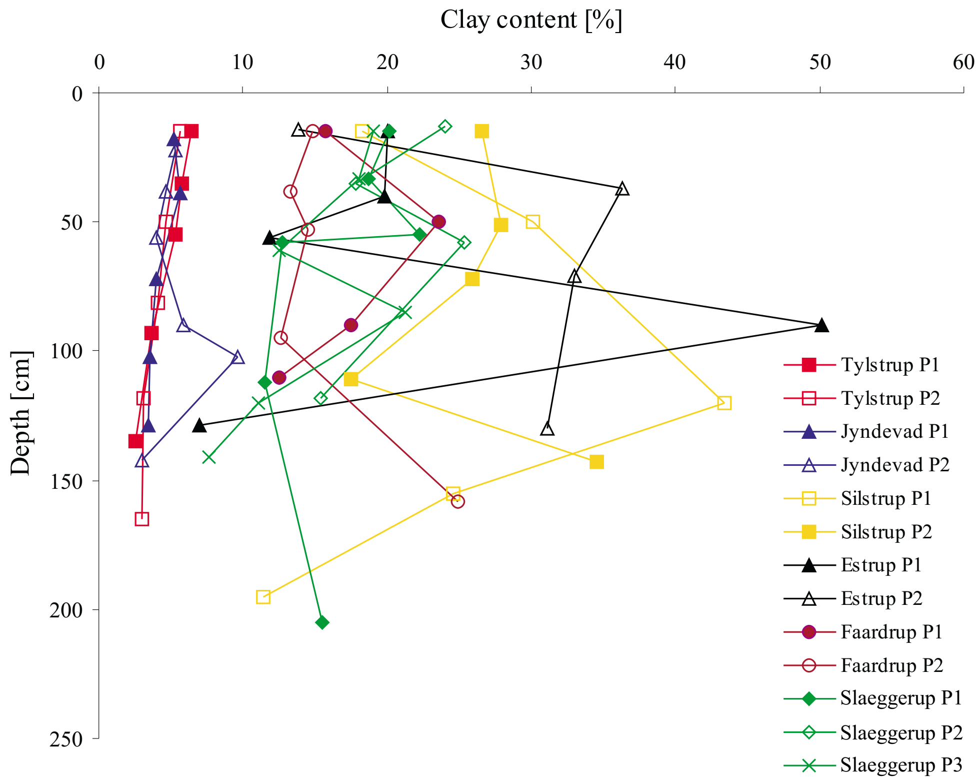


Figure 5.13 Clay content versus depth for two to three profiles per site.

maximum depth of the fractures is 4–5 m b.g.s. at Silstrup and Slaeggerup, but more than 5.5 m b.g.s. at Estrup and 8 m b.g.s. at Faardrup.

Table 5.1. Key data for the six selected sites encompassed by the Danish Pesticide Leaching Assessment Programme.

Name	**Tylstrup**	**Jyndevad**	**Silstrup**	**Estrup**	**Faardrup**	**Slaeggerup**
Location	Brønderslev	Tinglev	Thisted	Vejen	Slagelse	Roskilde
Precipitation, mm/y[a]	668	858	866	862	558	585
Potential evaporation, mm/y	741	742			785	
B x L, m	70 x166	135 x 184	91 x 185	120 x 105	160 x 150	165 x 130
Area, ha	1.1	2.4	1.7	1.3	2.3	2.2
Tile drain	no	no	yes	yes	yes	yes
Depth to ground water, m	3-4	1-2				
Deposited by	Saltwater	Meltwater	Glacier	Glacier/ meltwater	Glacier	Glacier
Soil type	Fine sand	Coarse sand	Clayey till	Clayey till	Clayey till	Clayey till
DGU-symbol	YS	TS	ML	ML	ML	ML
Topsoil characteristics						
–USDA-classification	Loamy sand	Sand	Sandy clay loam/sandy loam	Sandy loam	Sandy loam	Loam/sandy loam
– DK-classification	JB2	JB1	JB7	JB5/6	JB5/6	JB7
– Clay content, %	6	5	18–26	10–20	14–15	20–24
– Silt content, %	13	4	27	20–27	25	25–33
– Sand content, %	78	88	8	50–65	57	41–54
– pH	4–4.5	5.6–6.2	6.7–7	6.5–7.8	6.4–6.6	6–6.3
– TOC, %	2.0	1.8	2.2	1.7–7.3	1.4	1.4
Subsoil characteristics						
K_s, in C horiz., m/s[b]	$2.0 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$3.4 \cdot 10^{-6}$	$8.0 \cdot 10^{-8}$	$7.2 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$
Depth to the calcareous matrix, m b.g.s.	6	5–9	1.3	1–4[c]	1.5	0.7
Depth to the reduced matrix, m b.g.s.	>12	10–12	5	>5[c)]	4.2	3.7
Max. fracture depth in excavation and wells m b.g.s.	–	–	4	>6.5	8	4.7
Fracture intensity 3–4 m depth (fractures m^{-1})	–	–	<1	11	4	11

a) Mean precipitation for the period 1961–90 in the region where each site is located.
b) Determined on large soil samples (6,280 cm^3).
c) Large variation within the field

6. Pesticide selection

The purpose of the Danish Pesticide Leaching Assessment Programme is to assess the risk of leaching among pesticides approved for use in Denmark. In 1998, 72 pesticides were approved for use in the cultivation of plants, not counting fungicides for use on seed corn. Pesticides used in forestry, fruit growing and horticulture are not encompassed by the programme. As it is not possible to include all 72 of these pesticides in the programme, 18 of the 72 pesticides have been selected for study during the first three growing seasons by the Danish Environmental Protection Agency on the basis of expert judgement.

Based on the 18 selected pesticides, four different crop rotations were established involving three crops. Two of the crop rotations were for sandy soils and two for clayey soils (Table 6.1).

Table 6.1. Crop rotations.

	Clayey soil		Sandy soil	
Year	C1	C2	S1	S2
1	Beets	Spring barley 1	Potatoes	Winter rye
2	Spring barley 1	Peas	Spring barley 2	Maize
3	Winter wheat	Winter wheat	Winter rye	Spring barley

To run these four crop rotations it was necessary to add a further six pesticides to the programme to give 24 pesticides in all (Table 6.2 and Figure 6.1). The sorption coefficient K_{oc} and degradation rate DT_{50} given for each pesticide in Table 6.2 are median values where possible or otherwise the midpoint between the minimum and the maximum value.

The reasons for selecting the specific pesticides are explained below.

Bentazone

Bentazone is considered to be highly mobile in the soil under Danish conditions. For this reason the permitted dose was reduced to 300 g active ingredient per ha in 1996. Bentazone was included in the programme to evaluate whether the reduction in the permitted dose is adequate.

Table 6.2. Pesticides encompassed by the Danish Pesticide Leaching Assessment Programme.

Pesticides, common names	Type[1]	Product name in Denmark	Selected by DEPA[2]	GRUMO [3]	Consumption in 1998, tonnes[4]	Treated area in 1998, 1,000 ha[5]	K_{oc} l/kg	DT_{50} days
Bentazone	H	Basagran 480	x	X	69	11	13[6]	52[6]
Bromoxynil	H	Oxitril	x	X	80	200	371[10]	10[8]
Desmedipham	H	Betanal Optima			0.9	1.3	370[7]	49[7]
Dimethoate	I	Dimethoat 400	x	X	37	82	30[7]	16[7]
Ethofumesate	H	Betanal Optima		0	22	54	150[7]	37[7]
Fenpropimorph	F	Tilt Top	x	X	219	292	3,700[7]	67[7]
Flamprop-M-isopropyl	H	Barnon Plus	x		12	20	400[8]	116[9]
Fluazifop-P-butyl	H	Fusilade X-tra	x		6.2	23	30[8]	5[8,9]
Fluroxypyr	H	Starane 180	x		31	222	62[7]	27[7]
Glyphosate	H	Roundup	x	X	618	491	3.400[6]	16[6]
Ioxynil	H	Oxitril	x	0	81	202	278[10]	38[10]
Linuron	H	Afalon			8.0	7.3	233[7]	131[7]
Mancozeb	F	Dithane DG	x	(X)	294	196	>2.000[9]	11[8]
Metamitron	H	Goltix WG	x	X	189	54	207[6]	14[6]
Metribuzin	H	Sencor WG		X	5.3	22	16[8]	83[8]
Metsulfuron-methyl	H	Ally	x		0,8	132.	56[6,8]	45[6]
Pendimethalin	H	Stromp SC	x	X	374	294	725[6]	34[6]
Phenmedipham	H	Betanal Optima			31	43	826[7]	45[7]
Pirimicarb	I	Pirimor G	x	X	5.7	44	821[7]	108[7]
Propiconazole	F	Tilt Top	x	0	41	324	688[6]	96[7]
Pyridate	H	Lentagran			13	15		5[7]
Terbuthylazine	H	Gardoprim 500W	x	X	42	52	220[8]	73[8,9]
Triasulfuron	H	Logran 20 WG	x		0,3	64	9[6]	19[9]
Tribenuron-methyl	H	Express	x		1.5	207	67[8]	7[8,9]

1) H: herbicide, I: insecticide, F: fungicide.
2) Pesticide selected by the Danish Environmental Protection Agency (DEPA).
3) Pesticide included in the Danish National Ground Water Monitoring Programme (GRUMO), X: detected in Danish groundwater, 0: Not detected (GEUS, 2000).
4) Amount used in Denmark in 1998 in the cultivation of plants expressed in 1,000 kg active ingredient (Miljøstyrelsen, 1999).
5) Estimated area treaed in 1998 with the pesticide, 1,000 ha (Miljøstyrelsen, 1999).
6) Lindhardt *et al*., 1998
7) Linders *et al*., 1994
8) Roberts, 1998
9) Tomlin, 1997
10) Miljøstyrelsen

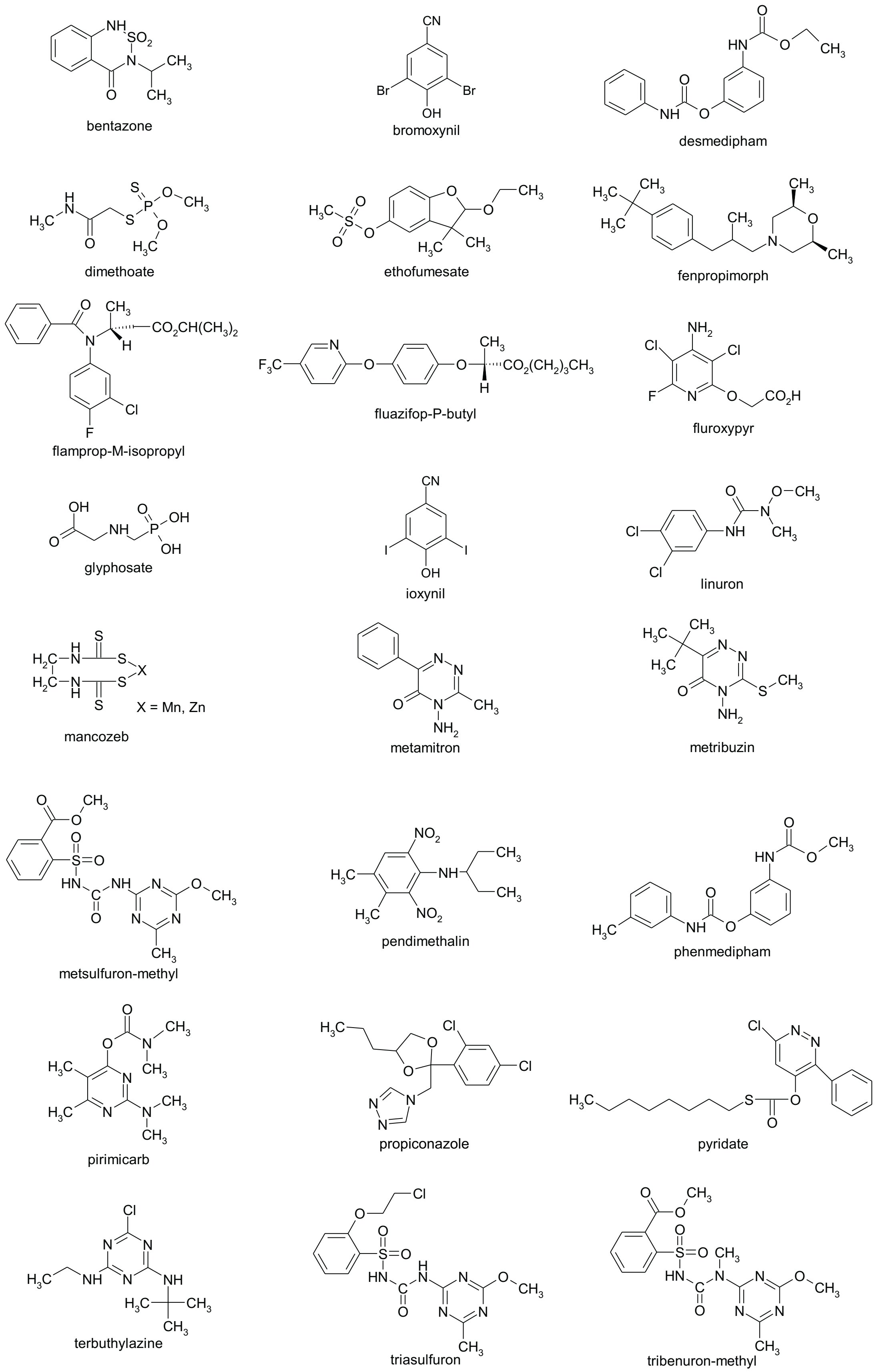


Figure 6.1. Structure of the selected pesticides.

Bromoxynil

Based on the sorption and degradation properties, the pesticide is considered to be immobile. It was selected for inclusion in the programme because it is used on large areas and primarily in autumn, which increases the risk of leaching in Denmark.

Desmedipham

Desmedipham is one of the active ingredients of the product Betanal Optima, which is used to control weeds in beet crops. The compound itself is not expected to leach because of hydrolysis. Knowledge of the fate of the degradation products is insufficient, however.

Dimethoate

Dimethoate was the most used insecticide in Denmark in 1998 in terms of quantity, and the second most used in terms of treated area. The compound was selected for inclusion in the programme because it is considered to be mobile.

Ethofumesate

Ethofumesate is also an active ingredient of the product Betanal Optima, and is considered to be reasonably mobile in soil under Danish conditions.

Fenpropimorph

Fenpropimorph was the second most used fungicide in Denmark in 1998. The compound is expected to sorb strongly to the soil and hence is not considered to be mobile. Some studies indicate that fenpropimorph is degraded in soil by oxidation of the tertiary butyl group to *cis*-4-[3-[4-(2-carboxypropyl)-phenyl]-2-methylpropyl]-2,6-dimethylmorpholine, called "fenpropimorph acid". This degradation product is expected to be mobile in soil under Danish conditions.

Flamprop-M-isopropyl

Flamprop-M-isopropyl is considered to be reasonably mobile in soil under Danish conditions because of its low degradation rate. The major degradation product is expected to be the carboxylic acid flamprop-M, which is also considered to be mobile in soil under Danish conditions.

Fluazifop-P-butyl

Degradation of fluazifop-P-butyl occurs rapidly in soil, the major transformation product being fluazifop-P. Fluazifop-P is considered to be mobile in soil under Danish conditions.

Fluroxypyr

Fluroxypyr is used on relatively large areas in low dose. It was selected for inclusion in the programme because it is considered to be mobile, which is the reason for selecting it to the programme.

Glyphosate

Glyphosate is expected to be immobile based on its sorption and degradation properties. It was selected for inclusion in the programme because of the large amount used. It is the most used pesticide in crop production in Denmark in terms of both quantity and applied area.

Ioxynil

Based on the sorption and degradation properties ioxynil is considered to be relatively immobile. It was selected for inclusion in the programme because it is used on large areas and primarily in autumn, which increases the risk of leaching in Denmark.

Linuron

Linuron was included in the programme because it is used for weed control in potatoes. Consumption in Denmark only amounts to a few thousand kg per year. Based on its properties and low degradation rate it is expected to leach out of the root zone.

Mancozeb

Mancozeb is a dithiocarbamate that is readily hydrolysed in neutral and alkaline soil and further degraded into ETU (ethylenethiourea). ETU is highly mobile. It is uncertain whether ETU is persistent in subsoil. The dose of mancozeb used in potatoes is extremely high compared to other pesticides, as much as 20 kg per ha per year being used in some years. Mancozeb was included in the programme because of the high dosage and uncertainty as to whether ETU is persistent in subsoil.

Metamitron

Metamitron was the fourth most used herbicide in Denmark in 1998 in terms of quantity used. It is applied in relatively high doses and is considered to have "medium" mobility in soil. Metamitron is very rapidly degraded on the soil surface and in water by photodecomposition, resulting in desamination to desamino-metamitron (3-methyl-6-phenyl-1,2,4-triazin-5-one).

Metribuzin

Metribuzin is used in relatively small quantities in Denmark. Based on its properties it is expected to leach out of the root zone. Metribuzin is degraded by desamination to form desamino-metribuzin (6-tert-butyl-4,5-dihydro-3-methylthio-1,2,4-triazin-5-one) or diketo-metribuzin (4-Amino-6-tert-butyl-4,5-dihydro-1,2,4-triazin-3,5-dione). This are further transformed to desamino-diketo-metribuzin (6-tert-butyl-4,5-dihydro-3-methylthio-1,2,4-triazin-3,5-dione). All of these degradation products are expected to be mobile.

Metsulfuron-methyl

Even though the total amount used in Denmark is low, the area treated with metsulfuron-methyl is relatively high because the compound, like the other sulfonylureas, is applied in low doses (10–20 g per ha). Metsulfuron-methyl degrades in soil by cleavage of the sulfonylurea linkage to yield methyl 2-(aminosulfonyl)benzoate and 4-methoxy-6-methyl-2-amino-1,3,5-triazine as the major degradation products. The latter is called triaziamin. Laboratory tests indicate that triazinamin can be persistent in soil. It is for this reason that metsulfuron-methyl was included in the programme.

Pendimethalin

Pendimethalin sorbs strongly to soil, for which reason it is not considered to be mobile. It was included in the programme because of its extensive use. It was the third most used herbicide in 1998 in terms of both quantity used and treated area.

Phenmedipham

Phenmedipham is also an active ingredient of the product Betanal Optima. The compound itself is not expected to leach because of relatively rapid hydrolysis. In alkaline soils, hydrolytic degradation of phenmedipham results in MHPC (*N*-(3hydroxyphenyl)carbamate) as an intermediate and 3-aminophenol as the end product. Knowledge of the fate of these degradation products is insufficient.

Pirimicarb

Pirimicarb was the second most used insecticide in 1998 in Denmark. Pirimicarb is expected to be moderately mobile, but the documentation is considered to be incomplete. When slow degradation occurs in soil, the major degradation product is dimethyl-pirimicarb (2-(methylamino)-5,6-dimethyl-4-pyrimidinyl-dimethylcarbamate).

Propiconazole

Propiconazole was the most used fungicide based on treated area in 1998. The compound is considered to be moderately mobile. The degradation product 1,2,4-triazole is mobile.

Pyridate

Pyridate was selected for the programme because of uncertainty of the mobility of the principal degradation product, 3-phenyl-4-hydroxy-6-chloropyridazine.

Terbuthylazine

Based on the sorption and degradation properties of terbuthylazine it is expected to be mobile. Lysimeter studies indicate leaching of a number of degradation products.

Triasulfuron

See metsulfuron-methyl.

Tribenuron-methyl

Tribenuron-methyl is included in the programme for the same reasons as metsulfuron-methyl and triasulfuron. Tribenuron-methyl is the most used sulfonylurea. Tribenuron-methyl degrades rapidly in acidic soil by hydrolysis and forms triazine-methyl (4-methoxy-6-methyl-2-methylamino-1,3,5-triazine).

References

Andersen, S. & Sjørrring, S. (1992): Det nordlige Jylland, Geologisk set, En beskrivelse af områder af national geologisk interesse – Geografforlaget, Miljøministeriet, Skov- og Naturstyrelsen.

Bos, M.G. (1976): Discharge Measurement Structures. International Institute for Land Reclamation and Improvement, Publication no. 20. Wageningen, Netherlands

DS 405.9 (1978): Testing of sand, gravel and stone materials, sieve analysis. Dansk Standardiseringsråd

Duchafour, P. (1979): Pedology – George Allen & Unwin, London.

Durlesser, H. (1999): Bestimmung der Variation bodenphysikalischer Parameter in Raum und Zeit mit elektromagnetischen Induktionsverfahren – FAM-Bericht, Technische Universität München, Shaker Verlag.

Ehlers, J. (1978): Fine Gravel Analysis after the Dutch method as tested out on Ristinge Klint, Denmark. Bulletin Geological Society of Denmark, 27, 157 – 165.

Ernstsen, V. (1998): Clay minerals of clayey subsoils of Weichselian Age in the Zealand –Funen area, Denmark. Bulletin of the geological Society of Denmark, 45, 39 – 51.

Ernstsen, V., Binnerup, S.J., & Sørensen, J. (1998): Reduction of Nitrate in Clayey Subsoils Controled by Geochemical and Microbial Barriers. Geomicrobiology, 15, 195-207.

Eyles, N. (1983): Glacial Geology for Engineers and Earth Scientists, Pergamon, New York.

Eyles, N. (1984): Glacial Geology - University of Toronto, Canada. Pergamon Press, Toronto.

Fetter, C.W. (1999): Contaminant hydrogeology. Prentice Hall. New York.

Flury, M. (1996): Experimental evidence of transport of pesticides through field soils – a review. Journal of Environmental Quality, 25, 25-45.

Frich, P. Rosenørn, S., Madsen, H. & Jensen, J.J. (1997): Observed precipitation in Denmark 1961-90. DMI, Techical report 97-8

GEUS (2000): Grundvandsovervågning 2000. Danmarks og Grønlands Geologiske Undersøgelse, København, Danmark.

Greve, M. Helweg, A., Yli-Halla, M.. Eklo, O.M., Nyborg, Å.A., Solbakken, E., Øborn, I., & Stenstrøm J.(1998): Nordic Reference Soils - In: E. Tiberg (Ed.) 1998: Nordic Reference Soils – Nordic Council of Ministers, TemaNord 1998: 537, Environment.

Gry, H. (1940): De istektoniske forhold i moleromrāder. Med bemærkninger om vore dislocerede klinters dannelse og om den negative askeserie. Medd. Dansk Geol. Foren., 9.

Hansen B. & Sørensen, N. K. (1996): Metodereferencer til Centrallaboratoriets analyser – Centrallaboratoriet, intern rapport fra Statens Husdyrbrugsforsøg Nr. 96.

Hansen, J.M. & Håkansson, E. (1980): Thisted strukturen et neotektonisk skoleeksempel. Dansk geol. Foren. Årsskrift for 1979.

Hansen, L. (1976): Soil types at the Danish Experimental Stations – Særtryk af Tidskrift for Planteavl 80, 742-758.

Hansen, S. (1989): Geologisk kort over Danmark. Geological map of Denmark. 1:100 000. Kortbladet/Mapsheet Tinglev. Jordarts kort & Glacial-morfologiske kort/Soil map & Glacial morphological map. Danmarks Geologiske Undersøgelse, Kortserie 9 & 10.

Harremoës, P., Moust Jacobsen, H. & Krebs Ovesen, N., (1984): Lærebog i Geoteknik, 5. udg. Polyteknisk Forlag. Copenhagen.

Heidmann, T. (1989): Startkarakterisering af arealer til systemforskning IV. Resultater fra arealet ved Jyndevad – Statens Planteavlsforsøg, Beretning nr. S 2021.

Henriksen, H.J., Christiansen Barlebo, H., Ernstsen, V., Hansen, M., Harrar, B., Jakobsen P. R., Klint, K. E. & Troldborg, L (2000): Anvendelse af regionale pesticidmodeller som prognoseværktøj Pesticider og Grundvand - Temanummer fra Grundvandsgruppen. Miljøforskning 42, April 2000, Det Strategiske Miljøforskningsprogram, 40-42.

Hermansen, B. & Jacobsen, P.R. (1998): Danmarks digitale Jordartskort 1:25.000. Version 1.0 GEUS.

Houmark-Nielsen, M. (1987): Pleistocene stratigraphy and glacial history of the central part of Denmark. Bull. geol. Soc. Denmark, 36, 1-189.

Iversen, B.V., Schjønning, P., Poulsen, T. G. & Moldrup, P. (2001): In situ, on-site and laboratory measurements of soil air permeability: Boundary conditions and measurement scale. Soil Science, 166, 97-106.

Jacobsen, E.M.(1984): En råstofgeologisk kortlægning omkring Roskilde. Dansk geol. Foren., Årskrift for 1984, 65-78.

Jacobsen, O.H. (1989): Unsaturated hydraulic conductivity for some Danish soils, metods and characterization of soils – Statens Planteavlsforsøg, Afdeling for Kulturteknik, Jyndevad, Beretning nr. S 2030.

Jessen, K. & Milthers,V. (1928): Stratigraphical and Paleontological Studies of Interglacial Freshwater-deposits in Jutland and Northwest Germany. D.G.U. II Række, nr 48, 1-379 + Atlas.

Klint K.E.S. & Pedersen, S.A.S. (1995): The Hanklit Glaciotectonic Thrust Fault Complex, Mors, Denmark. Danmarks Geologiske Undersøgelse, DGU serie A, 35, 1-30.

Klint, K.E.S. & Gravesen, P. (1999): Fractures and Biopores in Weichselian Clay Till Aquitards at Flakkebjerg, Denmark. Nordic Hydrology, 30, 267-284.

Klute, A. & Dirksen, C. (1986): Hydraulic conductivity and diffusivity: laboratory methods. In: Klute, A. (ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, 2nd edition, Amer. Soc. Agron., Madison, WI, 687-734.

Klute, A. (1986): Water retention: Laboratory methods. In: Klute, A. (ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, 2nd edition, Amer. Soc. Agron., Madison, WI, 635-656.

Langohr, R. (1993): Types of Tree Windthrow, their impact on the Environment and their importance for the understanding of Archeological Excavating Data – Helinium, XXXIII/1, 36-49.

Larsen, G., Frederiksen, J, Villumsen, A., Fredericia; J., Gravesen, P., Foged, N., Knudsen, B. & Baumann, J. (1995): Vejledning i Ingeniøgeologisk prøvebeskrivelse. Danish Geotechnical Society Bull. 1, rev. 1.

Linders, J.B.H.J., Jansma, J.W., Mensink, B.J.W.G. & Otermann, K (1994): Pesticides: Benefaction or pandora's box ? National institute of public health and environmental protection, The Netherlands. Report no. 679101014.

Lindhardt, B., Brüsch, W., Fomsgaard, I. S. & Bossi, R (1998): Vurdering af pesticiders udvaskelighed på grundlag af tilgængelige data for sorption og nedbrydning. 15th Danish Plant Protection Conference, 1998, 43-52.

Madsen, H.B. (1983): Himmerlands jordbundsforhold – Landbrugsministeriet, Arealdata-kontoret, Vejle.

Madsen, H.B. (1988): Geografiske forskelle i landbrugsjordens reaktionstal – Agrologisk Tidsskrift 12/88.

Madsen, H. B. & Jensen, W.H. (1983): Et pedologisk jordbundklassifikationssystem baseret på danske jorde, manual – Landbrugsministeriet, Arealdatakontoret, Vejle.

Madsen, H.B. & Jensen, N.H. (1985): Jordprofilundersøgelsen – Landbrugsministeriet, Arealdatakontoret Vejle.

Madsen, H.B. & Jensen, N. (1988): Vejledning til beskrivelse af jordbundsprofiler – Landbrugsministeriet, Arealdatakontoret, Vejle..

Mertz, E.L. (1924): Oversigt over de sen- og postglaciale niveauforandringer i Danmark. Danmarks Geologiske Undersøgelse, II. Rk., 41.

Miljøstyrelsen (1999): Bekæmpelsesmiddelstatistik 1998. Orientering fra Miljøstyrelsen nr. 5 1999. København, Danmark.

Nehmdahl, H. (2000): Kortlægning af jordbundsvariation – geoelektriske målinger med EM38. GeologiskNyt 2/00, 18-19.

Nielsen, J.D. & Møberg, J.P. (1985): Klassificering af jordprofiler fra forsøgsstationer i Danmark – Tidsskr. for Planteavl 89, 157-167.

Pedersen, S.A.S. (1989): Glacitectonite: Brecciated sediments and cataclastic sedimentary rocks formed subglacially. In Genetic Classification of Glacigenic Deposits,(Goldthwait and Matsch (eds.)) Balkema, Rotterdam.

Rasmussen, H.W. (1968): Danmarks geologi – Gjellerups liniebøger, Gjellerup.

Rhoades, J.D. & Corwin, D.L. (1981): Determining Soil Electrical Conductivity-Depth Relations Using an Inductive Electromagnetic Soil Conductivity Meter – Soil Sci. Soc. Am. J., 45, 255-260.

Roberts, T (1998): Metabolic pathways of agrochemicals. The Royal Society of chemistry, Cambrige, UK.

Rosenbom, A.E., Klint, K.E.S. & Fredericia, J. (2000): Pore-to-core scale-up studies of the transport properties of organic pollutants with natural attenuation. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2000/79. Copenhagen: GEUS.

Skov- og Naturstyrelsen (1987): Geofysik og råstofkortlægning. Råstofkontorets kortlægningsserie 5, pp 7-207. Skov- og Naturstyrelsen.

Soil Survey Staff (1999): Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Agriculture Handbook Number 436. Second Edition, United States Department of Agriculture, New York.

Stamp, L.D. (1966): A glossary of geographical terms. New York Wiley.

Statens Planteavlsforsøg (1996): Geographic data at the Department of Landuse – Ministry of Agriculture and Fisheries, SP report, No. 6.

Tabatabai, M.A. & Bremner, J.M., (1970): Use of Leco Automatic 70-Record Carbon Analyser for total carbon analysis of soils. Soil Sci. Soc. Amer. Proc., 34, 608-610.

Tomlin, C.D.S. (1997): The pesticide manual. British Crop Protection Council, Surrey, UK.

US-EPA (1998): Guidance for prospective ground water monitoring studies. Environmental fate and effects division, Office of Pesticide Programs. U.S. Environmental Protection Agency.

van den Elsen, E., Stolte, J. & Veerman, G. (1999): Three automated laboratory systems for determining the hydraulic properties of soils. In: Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media, Part 1. M. Th. Van Genuchten, F. J. Leij, and L. Wu (Eds.). Riverside, CA. U.S. Salinity Laboratory, USDA, ARS. Department of Environmental Sciences, University of California. pp. 329-340.

Washburn, A.L. (1979): Geocryology, A survey of periglacial processes and environments 2nd ed. Edward Arnold (Publishers) Ltd.