GEOCHEMICAL INVESTIGATION OF THE LATE NEOLITHIC WELL OF KOLHORN (PROVINCE OF NOORD-HOLLAND)

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ABSTRACT: Some 4000 years ago, people of the Single Grave Culture dug a well c. 2 m deep to water their cattle. The well was sunk into the central part of a 30 m wide levee, which was part of a system of tidal flats. An active tidal salt-water creek was situated at a distance of about 700 m. The local creek adjacent to the levee had fallen dry.

At the time, the levee had a modest fresh-water lens. Evidently the Neolithic people knew about this fresh-water occurrence. Moreover, they had knowledge of how to construct a well, which is demonstrated by the application of charred reed as a filter material. The yield of the well varied from 100 to 300 l/day depending on the season. The water had no saline taste and it was very hard.

The quality of the groundwater extracted was probably not affected by the waste from the settlement.

KEYWORDS: Single Grave Culture, tidal flats, salt marsh, geochemistry, hydrology, water well.

1. INTRODUCTION

At the request of Professor J.D. van der Waals a preliminary study of the Late Neolithic well at Kolhorn, with the emphasis on geochemical and geohydrological aspects, was carried out by the Department of Geochemistry of the University of Utrecht.

The purpose of the investigation was to find out what knowledge and experience people of the Single Grave Culture had of the occurrence of fresh water in a salt marsh and of well construction. After describing the methods of investigation we will give the results of the chemical analyses. These results will be discussed, and finally some conclusions will be given.

2. METHODS

The location, discovery and excavation of the two tidal estuary settlement sites of the Single Grave Culture is described by van der Waals (1989a). Figure 1 shows these sites. The settlements were eventually flooded, during the Calais IVB and the Zuiderzee transgression phases, respectively. Nowadays the site lies within a polder; the water level in the ditches is 2,80 m below mean sea level.

The basis of this study is the analysis of the extent of alteration of soil characteristics due to processes of desalinization, leaching of lime and decay of organic matter. Our field work was restricted to the southern settlement where the water well had been discovered. Approximately at right angles to the levee, two sections were chosen. These sections were graduated in accordance with the B.A.I. grid (van der Waals, 1989a). In figures 1 and 2 these two sections are shown. They are the 222 m section and the 270 m section respectively. In these sections samples were collected by means of hand auger borings, or with a gouge. To sample the groundwater we used plastic filter tubes. A limited number of samples were taken in pF-rings in order to determine the bulk density (in contrast to the particle density).

The sampling took place in September 1984. Depending on the cohesion of the soil we sampled either beneath the plough-soil horizon, or beneath the peat deposit and/or the culture layer (black soil). As a rule the deepest samples were taken in the zone beneath the presumed fresh-water lens, in the tidal sediments. In a lateral direction we bored in the former creek, levees and basins of the salt marsh. Van der Waals provided soil samples from a cut profile at a distance of 30 cm from the well. The locations of the samples are shown in figure 2.

In the field the samples were described in terms of the following variables: texture, stratification, class of maturity, groundwater level, presence of organic matter and the transition from oxidized to reduced conditions.

The analytical measurements in the laboratory were (appendix 1):

1. The texture or grain-size distribution. The fractions <50 μm were determined by sedimentation; the

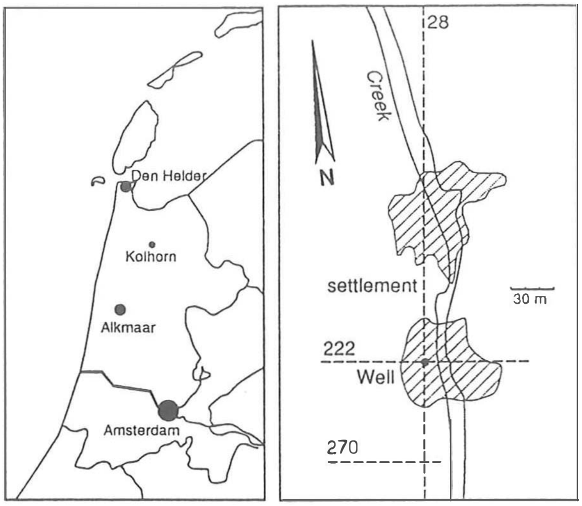


Fig. 1. Location of the Kolhorn Late Neolithic estuary sites in the province of Noord-Holland (left). The two sites are situated on a levee which is bordered by a local creek (right). The well was found in the southern settlement. The two studied sections refer to a local grid as given by van der Waals (1989a). The section in the north intersects the well, the other section was chosen as a background reference. After Banga & van Dijk (1979).

sand fractions 50-200 µm by dry sieving. The soil was pretreated with H_2O_2 and HCl (0.2 M). The data are expressed in weight % of the pretreated sample.

2. Organic carbon. Acid-dichromate digestion (Walkley-Black method); the data are expressed in weight % of the oven-dried, untreated sample.

3. $CaCO_3$. Field-moist samples were shaken with 20% HCl with $CuSO_4$ in a Scheibler apparatus. The volume of the developing CO_2 was measured. The data are expressed in weight % of the oven-dried, untreated sample.

4. Water content. The field-moist samples were dried at 105 °C. The data are expressed in weight % of the oven-dried, untreated sample.

5. CEC: cation-exchange capacity. NaOAc (pH 7) saturation followed by NH_4OAc (pH 7) extraction. The data are expressed in meq/100 g of oven-dried, untreated sample.

6. Extractable cations (Na, K, Mg and Ca). NH_4OAc (pH 7) extraction. The data of X-H_2O are expressed in meq/100 g of oven-dried, untreated sample.

7. Water-soluble cations (Na, K, Mg and Ca). 50 g of field-moist sample suspended in 200 ml of H_2O was agitated ultrasonically during 12 hours. The extract was

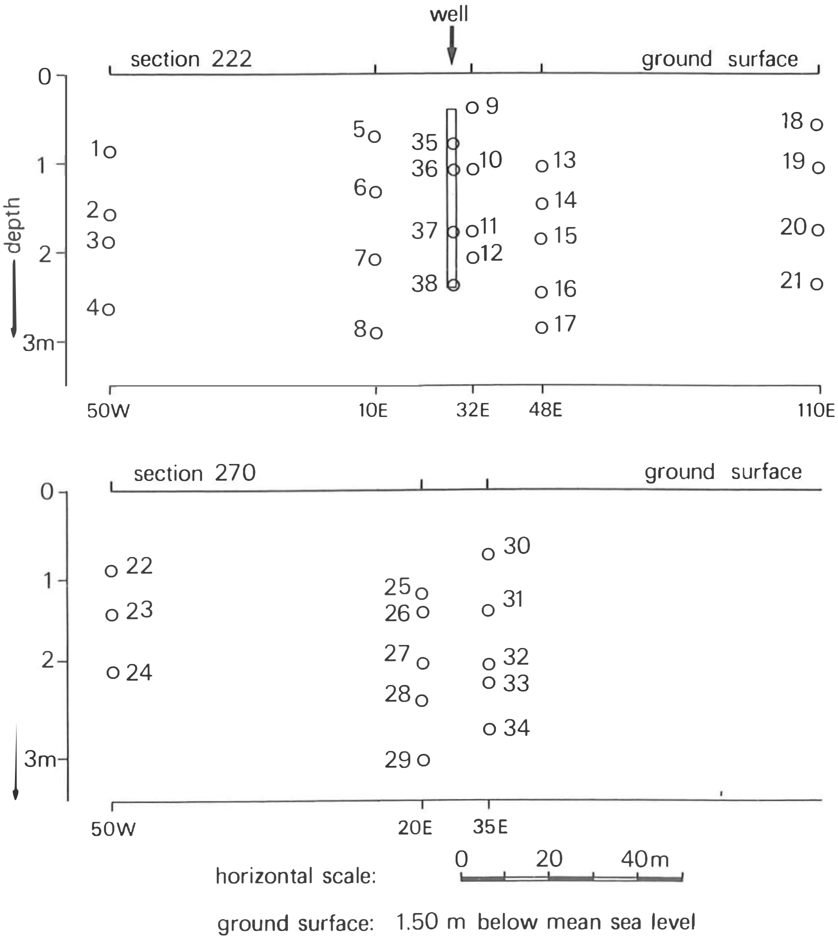


Fig. 2. Location of the samples obtained from the Kolhorn site. The numbers in the lower margin refer to the local grid. The well is shown in section 222.

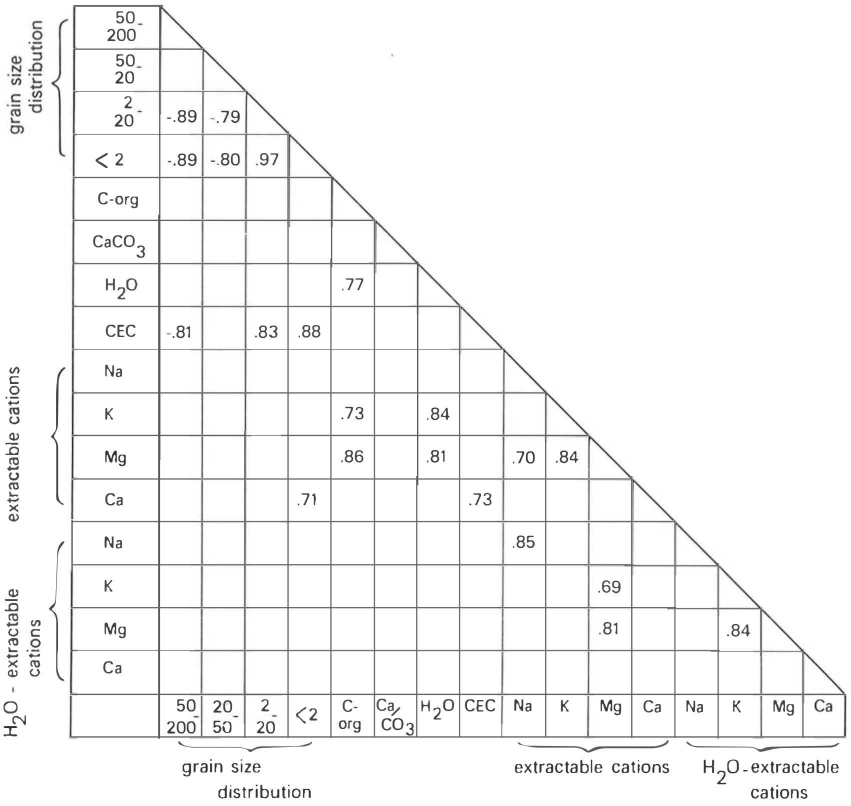
obtained by super-centrifugation. The data are expressed in mg/l of interstitial water (= field moisture content).

The measurements of Na, K, Mg and Ca were made by means of atomic absorption spectrometry (AAS).

3. RESULTS

The data are tabled in appendix I, grouped according to the sampled sections and arranged according to depth. The samples taken at the well are grouped separately.

In order to gain some insight into the interrelationship between the variables and the data, we carried out Principal Component Analysis (Nie et al., 1975) on the whole data set. The correlation coefficients of the components are given in figure 3. Because of the limited amount of samples only the higher values of correlation coefficients are shown. It is evident that many variables to some extent are linked together, for example the texture parameters. Two important correlations are presented in scattergrams. Figure 4 shows the positive



		50-200	20-50	2-20	<2	C-org	Ca/CO$_3$	H_2O	CEC	Na	K	Mg	Ca	Na	K	Mg	Ca
grain size distribution	50-200																
	50-20																
	2-20	-.89	-.79														
	< 2	-.89	-.80	.97													
	C-org																
	CaCO$_3$																
	H_2O					.77											
	CEC	-.81		.83	.88												
extractable cations	Na																
	K					.73		.84									
	Mg					.86		.81		.70	.84						
	Ca				.71				.73								
H_2O - extractable cations	Na									.85							
	K											.69					
	Mg											.81			.84		
	Ca																

Fig. 3. Correlation coefficients among 16 variables based on 38 samples. Correlation coefficients lower than c. 0.7 are not shown.

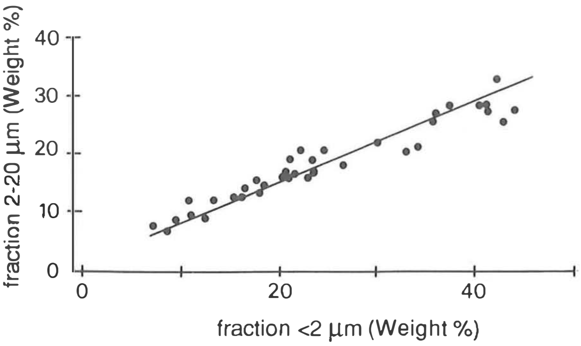


Fig. 4. Correlation between the fractions <2 µm and 2-20 µm of the Kolhorn samples. This constant ratio is normal for all Dutch marine sediments (Kooistra, 1978).

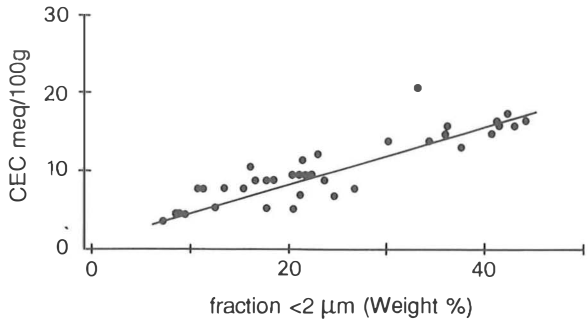


Fig. 5. Correlation between the fraction <2 µm and the Cation Exchange Capacity.

correlation between the fractions <2µ m and 2-20 µm. This correlation is characteristic of a particular type of sedimentation environment, such as the transformation into dry land with the silting up of the local creeks. In figure 5 the dependence of the CEC on the fraction <2 µm is shown, which also is a clearly positive correlation.

The interrelationship of the variables becomes clearer if we look at the components which emerged from the Principal Component Analysis. The variables which contributed highly to any one component can be considered together as an independent new variable which can be compared with other new variables. The components are:

1. Water content, K-extractable, Mg-extractable, C-organic, fraction <2 µm.
2. Na-H_2O, Na-extractable.
3. Ca-H_2O, Mg-H_2O.
4. $CaCO_3$.

The CEC and three grain-size fractions were omitted from this calculation because of their strong correlations. It must be noted that the CEC should belong to the first component. Indifferent behaviour was found for Ca-extractable and K-H_2O.

More specific Principal Component Analysis and Discriminant Function Analysis (D.F.A.) are discussed in section 4.2.

In the following section we shall present the contour patterns of the variables in the field sections and an interpretation of these distributions.

4. DISCUSSION

4.1. The salt marsh

The ratio between the grain-size fraction 2-20 µm and the fraction <2µm has a value of about 0.75 and is fairly constant (fig. 4). This is a common phenomenon of all Dutch marine sediments (Kooistra, 1978).

The range of textures of the investigated samples varies from clay to sandy loam; no sand was found. We found that the bulk densities vary from 0.8 to 1.2 g/cm³, which indicates that the soil profiles nowadays are

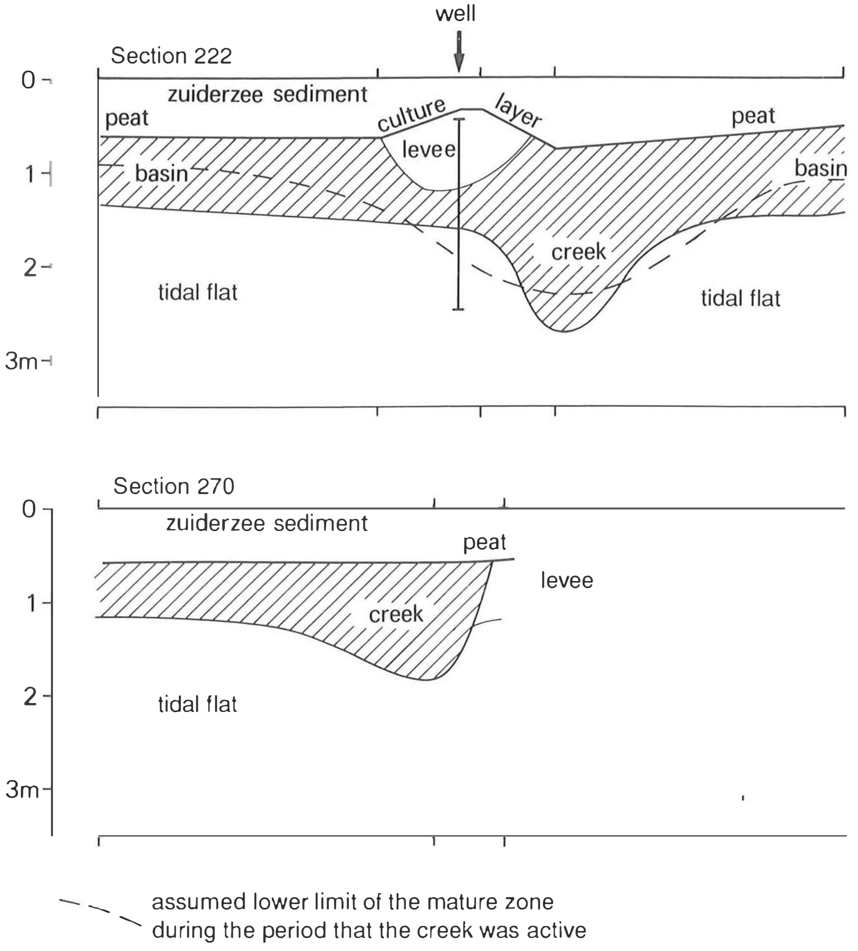


Fig. 6. The sedimentology of the Kolhorn site. Regression of the sea resulted in a change from a tidal environment to a salt marsh. This salt marsh was dominated by creeks, levees and basins. The settlement flourished during the high salt-marsh stage at the border of a silted-up, no longer active, local tidal creek.

fairly mature. The distribution of the textures in our sections is shown in figure 6.

On the basis of these textures we have reconstructed the sedimentological environment. An earlier study by Banga & van Dijk (1979) was very helpful for this interpretation. The deepest part of the profiles was found to be composed of tidal sediments with a texture varying from sandy loam to clay loam. Detailed observation shows fine laminations.

During marine regression the tidal sediments were cut by a system of tidal creeks; along the borders of which locally sandy loam sedimented. At the site of the future settlement levees were formed, especially on the western bank of the creek in its last stage of activity. The levee is composed of quite homogeneous sandy loam to clay loam. The levee was about 30 m wide, which can be observed in section 222 (fig. 6). The creek's width was only a few metres. In section 270 another creek appears. This creek is interpreted as a tributary of the creek in section 222. Behind the levee a basin was formed. The soil in this basin is composed of partly laminated, partly homogeneous clay. The regression finally left a high salt marsh in which the creek first functioned as a discharge channel and subsequently was filled up through surface run-off. The creek sediment consists of material derived from the salt marsh, mainly homogeneous clay with a high content of organic matter. Figure 7 shows the correlation between the C-organic content and the amount of Mg-extractable. The ratio of these components is constant, which possibly indicates that the organic matter in the creek sediment consists of halophilic vegetation.

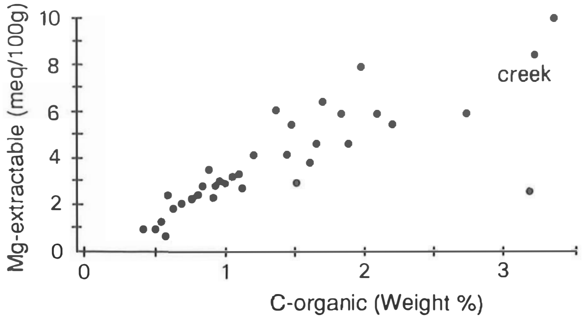


Fig. 7. Correlation between C-organic and Mg-extractable. The correlation emphasizes the impact of organic matter on Mg-extractable. The similar results for both the creek sediments and the other types of sediment possibly indicate the presence of halophilic vegetation at the time of the creek's silting up.

The subsequent growth of peat started around the time the settlement was established. This growth of peat and the later sediments of marine transgressions are beyond the scope of this study.

4.2. General desalinization

We shall here discuss Principal Component Analysis in greater detail, using a two-component model and 37 samples. The first factor is composed of the following variables: water content, K-extractable and Mg-extractable. The second factor is composed of the variables K-H_2O and Mg-H_2O. In figure 8 the component scores of the first component are plotted against the component scores of the second component. These components both describe the texture, the CEC and the salinity of the sediment. Component 1 also describes the ripening of the sediment expressed in some degree by the water content.

In the component plot it is possible to distinguish several CEC and salinity classes. The most saline zone is zone III, whereas zones II and I represent progressive desalinization. The position of these zones in the sections is shown in figure 9.

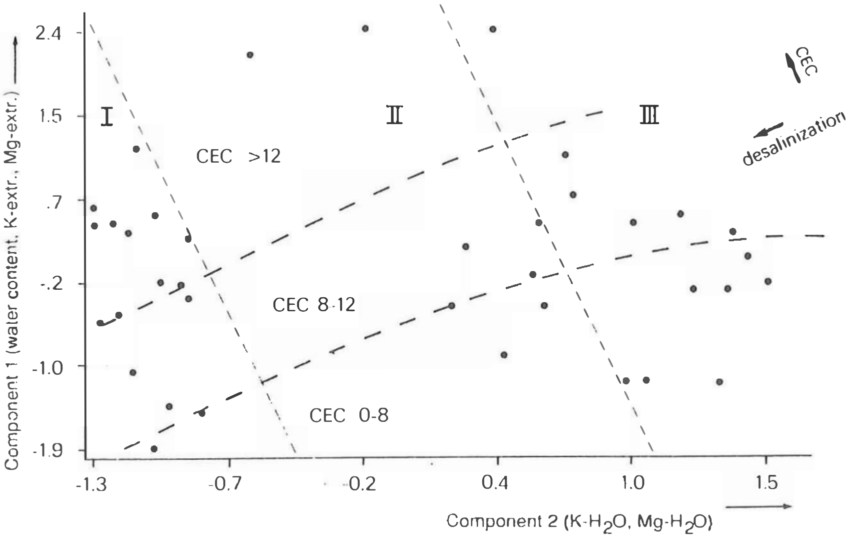


Fig. 8. Correlation between the componentscores of Principal Component Analysis using 5 variables of 37 samples in a two-component model. Rotation of the axes provides a division into desalinization stages of the soil.

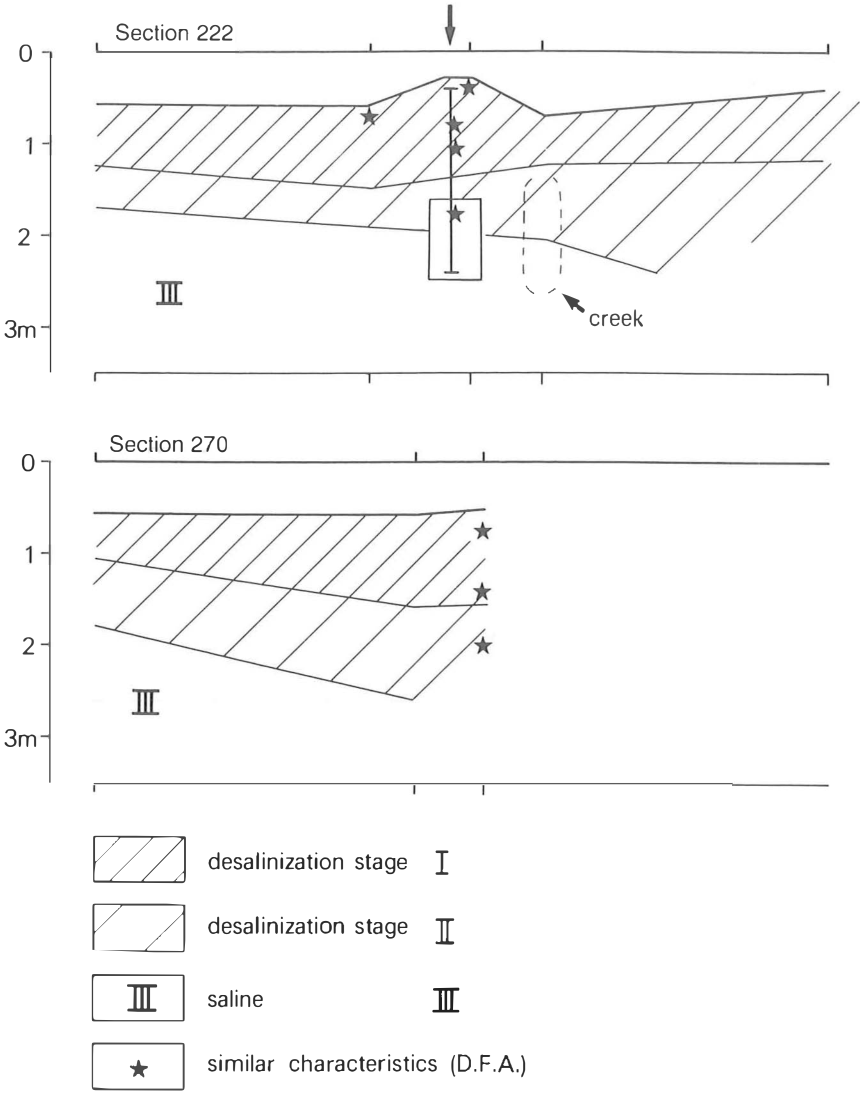


Fig. 9. The desalinization stages that could be distinguished in figure 8 are shown in the two Kolhorn sections. Apart from some interference at the well-site, a general vertical zonation of desalinization was found. Stars indicate the group of samples with similar characteristics according to D.F.A.

In this figure the zone influenced by the well has not been considered. General desalinization appears to be determined by the location of modern ditches, showing no trace of any former fresh-water lens. Thus the components 1 and 2 are not useful for our purpose.

Another type of statistical analysis, the Discriminant Function Analysis (D.F.A.) (Nie et al., 1975), assumes a priori knowledge of the grouping, and tests whether this grouping is statistically significant (training set). If the grouping is significant, D.F.A. can assign other samples to a specific group (testing set).

In this study all variables and all samples are used. Our training set was composed of those samples which were part of the assumed fresh-water lens (sample Nos 5, 9, 30, 35, 36, 37).

The outcome of the D.F.A. was that the training set was indeed composed of similar samples and that from the testing set two additional samples (Nos 31 and 32) had similar characteristics. Although the position of the related samples, which is shown in figure 9, produces a shape that can be interpreted as a fresh-water lens, it may also be a consequence of the difference in texture between the levee and the underlying tidal sediments.

In the statistical analysis definite clues to the former presence of a fresh-water lens were not found, because of the recent desalinization. We therefore have to quantify the effect of the recent desalinization, before an estimation can be made of the former desalinization.

4.3. Recent desalinization

Several of our data are evidently determined by the recent dealinization, which is shown in figure 10. The chemical composition of the group of water samples extracted by means of filter tubes reveals the phreatic table and the salinity of the groundwater. More detail is

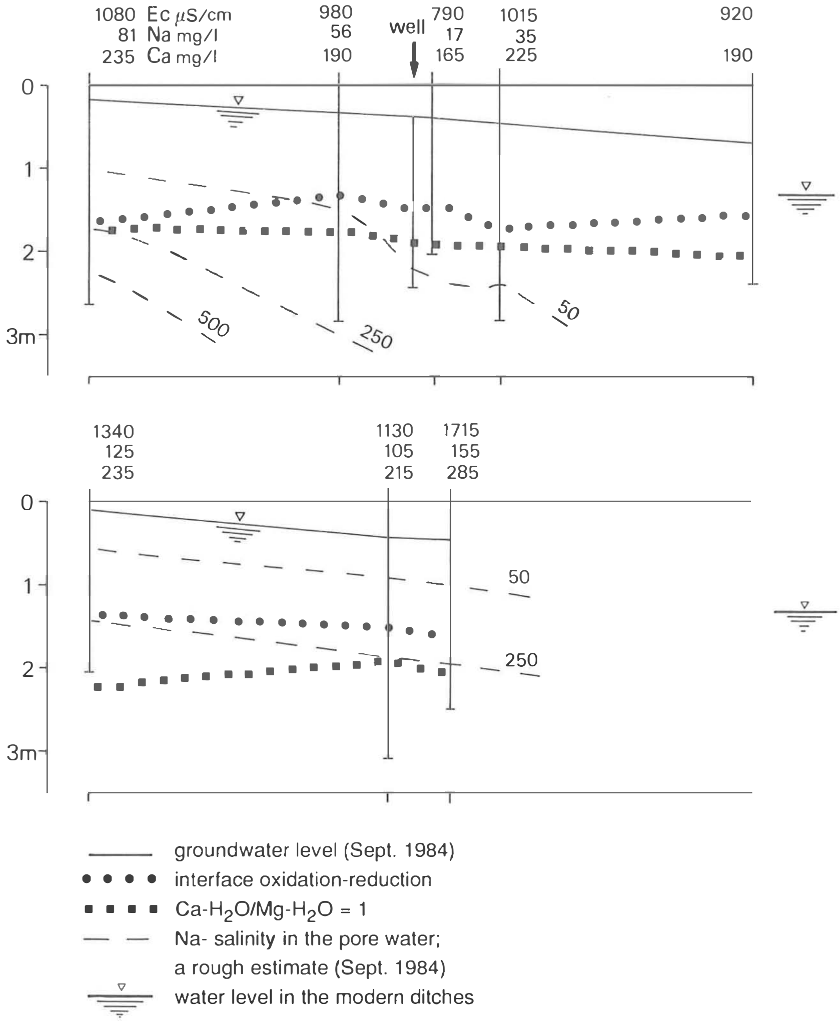


Fig. 10. Variables which are definitely determined by modern drainage of the Kolhorn area are the groundwater level, the salinity of the groundwater, the Ca-H_2O and Mg-H_2O ratios and the redox interface in the sediment.

given by the composition of the pore water in the soil samples. We assume that the sodium concentration in the pore water equals 1/2 Na-H_2O. This concentration depends on the stage in the soil water balance, and reflects therefore only the situation at the time of sampling.

More important for the actual degree of desalinization of the soil are two other variables: 1. the redox interface oxidation-reduction as it is observed in the field and 2. the interface formed by a notable increase in the concentration of Mg-H_2O with increasing depth. This interface is reflected by Ca-H_2O/Mg-H_2O values in the range of 3 up to 6. This systematical behaviour is determined mainly by the decrease of Mg-H_2O during desalinization.

In figure 10 the inclination of the phreatic level and the graduation of the sodium content of the pore waters both reveal an increase in desalinization from east to west and from south to north. Thus nowadays the drainage generally occurs in a north-easterly direction in accordance with the pattern of modern ditches. The redox interface and the pattern of the Mg-H_2O values possibly reflect a somewhat older desalination stage. But none of the contours of these variables show any sign of a former fresh-water lens.

4.4. Former desalinization

The degradation of organic matter is a quite effective process in an aerated soil, but its rate diminishes rapidly as soon as the sediment becomes permanently reduced. In the reduced zone there is still some degradation of organic matter, which is indicated by the precipitation of iron sulphide. Normally one finds a positive correlation between the fraction <2 µm and the fraction C-organic (Kooistra, 1978; van de Meent, 1982). In figure 11 we have plotted these two variables. It appears possible to distinguish two groups of samples. The lower slope, which represents one group, can be interpreted as the result of degradation of organic matter in

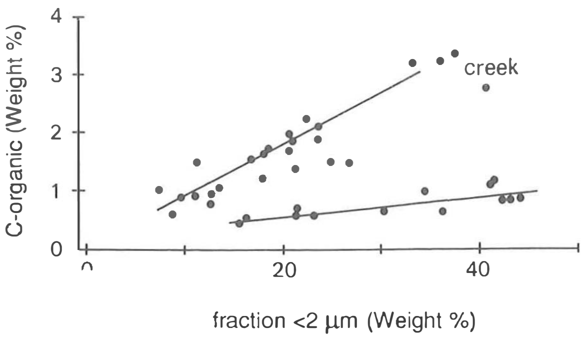


Fig. 11. Correlation between the fractions of <2 µm and C-organic. During sedimentation this ratio is constant. Due to microbial decay of organic matter, particularly in aerated sediment, the ratio increases.

the aerated soil. In the soil sections three groups can be distinguished by their clay size fraction/C-organic ratio (fig. 12). The highest values of this ratio are found in the upper part of the soil. At the site of the levee we find that the aerated zone has a deeper extension. The shape of this zone with high ratios is similar to that of a fresh-water lens.

Decalcification of the soil is a very slow process. Figure 13 shows the zone in which the lime content is lower than 15 weight %. Kooistra (1978) stated that the decrease of lime through dissolution is associated with the degradation of organic matter and takes place mainly in the basins of the salt marsh. In our sections the greatest decrease of lime content occurred in the levee, if we assume a fairly homogeneous distribution of lime in our sections during the deposition of the sediment.

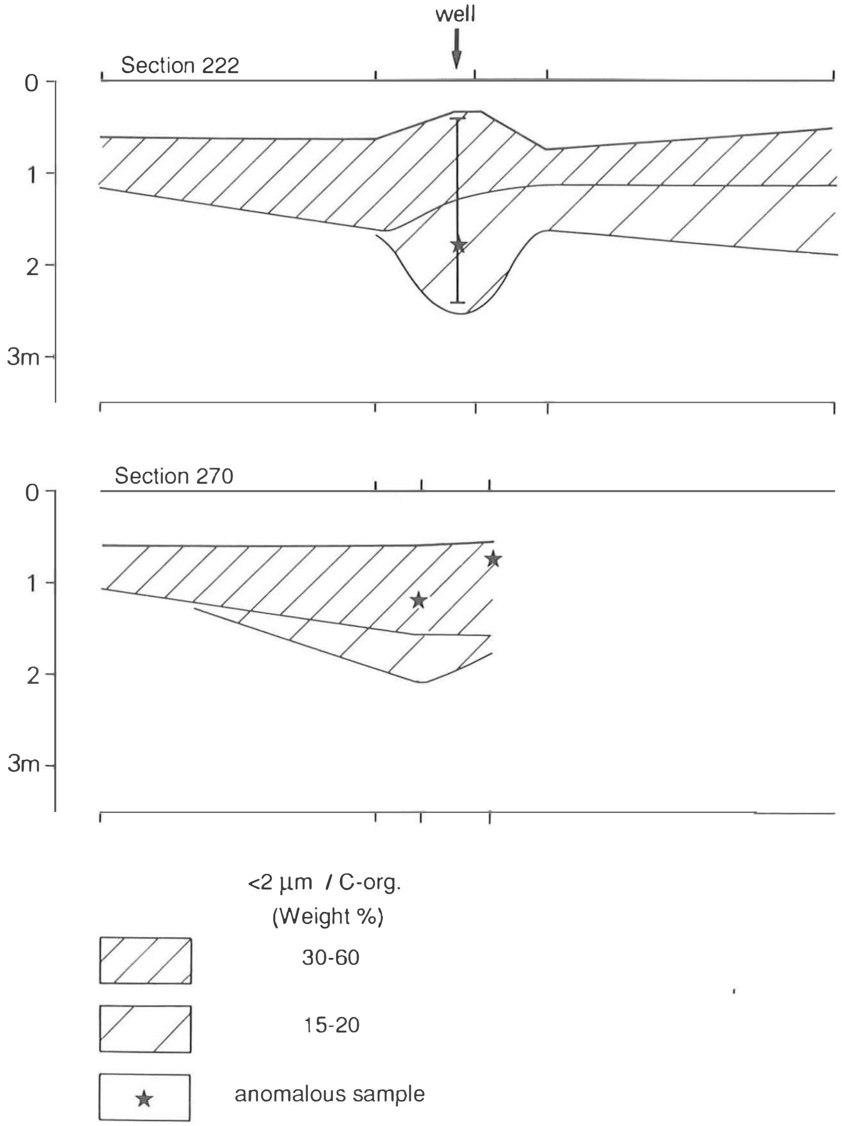


Fig. 12. The ratio between the fractions of <2 µm and C-organic is fairly indicative of the stage of decay of organic matter. The contours of two stages in aerobic decay are shown in the Kolhorn sections. Not only a vertical zonation is visible, but also the shape of a fresh-water lens. Samples which interfere with the presented contours are indicated by a star.

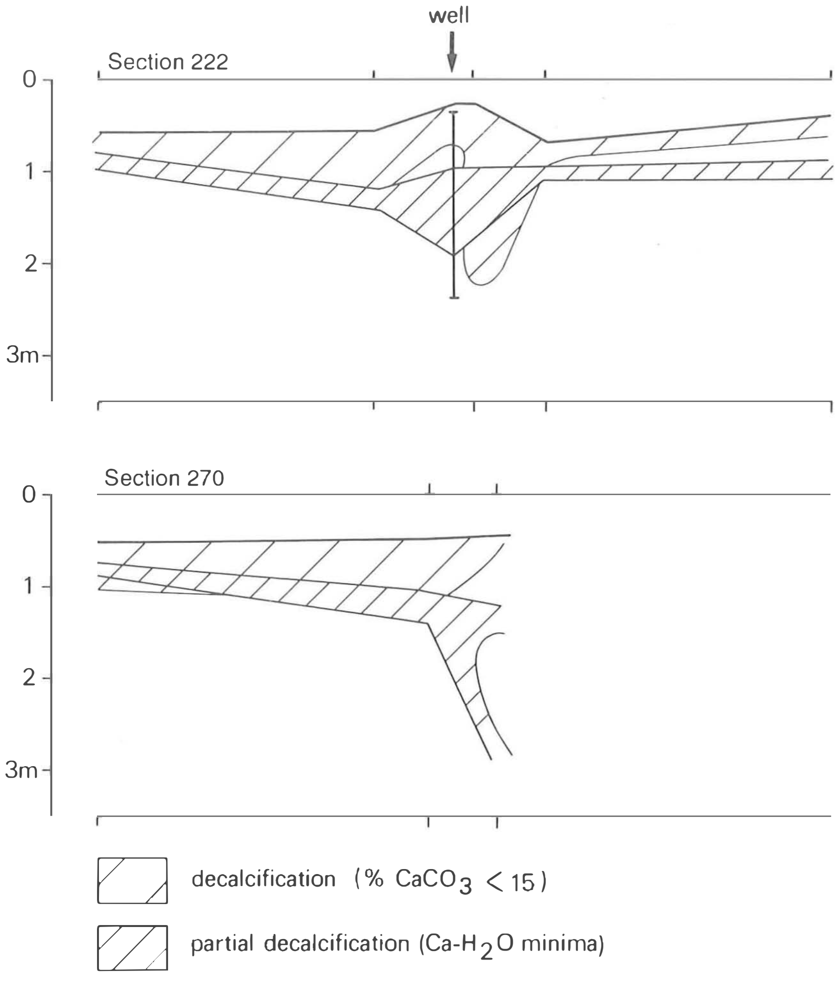


Fig. 13. The stage of decalcification of the soil is a measure for the extent of leaching. The contours of two stages in decalcification are shown in the Kolhorn sections. In the upper zone the content of lime decreased to values lower than 15 weight % of $CaCO_3$. The lower zone is marked by minimum values of Ca-H_2O. The configuration of the two zones is similar to that of a fresh-water lens. At the well site a distortion of the $CaCO_3$ zonation is found.

Apart from the process described by Kooistra (1978) there must be another process lowering the lime content of the levee. This could be the percolation of meteoric water in the course of many centuries (Reynders, 1984, mentioned a leaching rate for $CaCO_3$ of 1 weight %/100y). At the well-site, higher $CaCO_3$ contents were found locally. This will be discussed in the next section.

Ca-H_2O appears to have a minimum value at a certain depth in the soil. This minimum is interpreted as the result of the leaching out of the most reactive type of lime. The zone of these minimum values, which too has the shape of a fresh-water lens, is presented in figure 13.

The extent of the zone characterized by the decay of organic matter as well as the extent of the zones characterized by the leaching of lime and the partial leaching of lime at the site of the levee are interpreted as resulting from the presence of a fresh-water lens during many centuries. It should be noted that the establishment of such a fresh-water lens occurred quite rapidly, early on in the prehistoric period of first desalinization. From that time on, the dimensions of the fresh-water lens remained practically constant.

4.5. Deviating samples

Some variables occasionally display values which do not fit into the already described models. These variables are:

1. K-extractable (Nos 11 and 37);
2. K-H_2O (No. 12);
3. Mg-H_2O (Nos 12 and 38);
4. Ca-H_2O (No. 38);
5. % $CaCO_3$ (Nos 35, 36 and 37).

Three of these outliers are shown in figure 14. In figure 14a the correlation between K-extractable and Mg-extractable is given. The samples Nos 11 and 37 appear to be out of line. Figure 14b shows the relation between Mg-H_2O and Ca-H_2O. Sample No. 38 clearly deviates. All these samples are found to have been taken in the neighbourhood of the well (fig. 15).

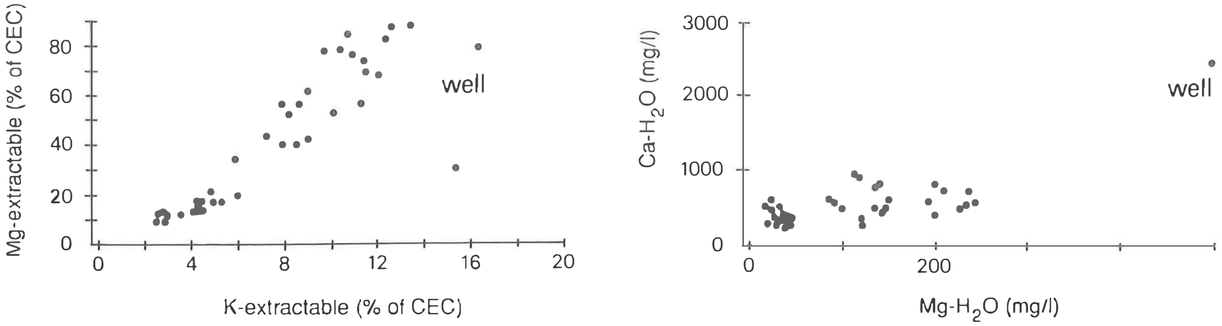


Fig. 14. Deviating values of four variables from sediment samples in the immediate vicinity of the well, indicating the local chemical disturbance of the sediment by the well. a. Correlation and deviating values of K-extractable and Mg-extractable. b. Correlation and deviating values of Mg-H_2O and Ca-H_2O.

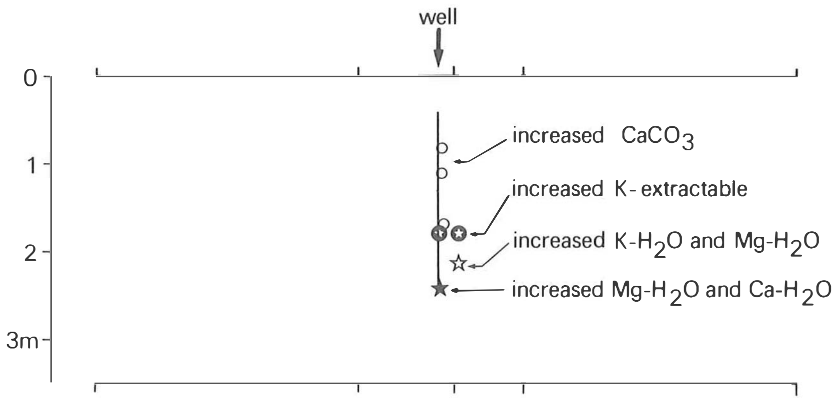


Fig. 15. The location of the samples with exceptional values of specific variables at the well site. These variables are K-extractable, K-H_2O, Mg-H_2O, Ca-H_2O and weight % of $CaCO_3$. The exceptional concentrations indicate a reequilibrium between the sediment and water in the soil after disturbance of the soil through the digging, use and eventual decay of the well.

4.6. Water chemistry

The following processes determine the water chemistry: 1. Composition of meteoric water; 2. Desalinization stage of the soil; 3. Evapotranspiration; 4. Mineralogical composition of the soil; 5. Organic matter in the soil; 6. Reduction-oxidation.

Ad 1. The settlement was situated 15-20 km from the coastline (Kielman, 1983). Therefore, the chloride content of the rainwater was about 10 mg/l. This is caused by the absorption of sea-spray salt. Meteoric water can be caught by the vegetation cover. This water will evaporate, leaving dry salts. These dry salts when dissolved are an additional factor in the composition of infiltrating meteoric water. This leads to an increase of K and Ca.

Ad 2. In the soil we distinguish open and closed pore spaces. Formerly they were all filled with saline water. Through groundwater flow, fresh water replaces the saline water in the open pore space. The closed pores preserve the saline water. The infiltrating meteoric water can mix to some extent with the remaining salt water. The same goes for the exchangeable cations Na, K and Mg, which are replaced by Ca, H and Al.

Ad 3. The evapotranspiration of the soil water under normal conditions results in a two- to fivefold increase of the dissolved solids. In the dry season the result may be a complete evaporation and salts such as $CaSO_4.2H_2O$, $CaCO_3$ and NaCl will precipitate. In the recharge period, leaching of these salts can cause high concentrations in groundwater.

Ad 4. $CaCO_3$ is a very reactive mineral. It is possible to establish a decrease of several per cent in a relatively short time (hundreds of years). Fresh water especially will dissolve $CaCO_3$.

Ad 5. Degradation of organic matter produces CO_2, which stimulates not only calcite dissolution, but also the ionic exchange.

Ad 6. Infiltrating, aerated water oxidizes iron sulphides, resulting in an increase of dissolved sulphate and calcium. Under stagnant conditions microbial decay will result in reduction of the water. The dissolved sulphate diminishes and iron and manganese will dissolve.

4.7. Yield of the well

In order to calculate the yield of the well we employed a range of different methods and used estimated values.

The sediments exposed in the well are from bottom to top (fig. 6): 1. Loam, with semi-confined or phreatic water; 2. Impermeable clay; 3. Mature loam with varying soil-moisture conditions (depending on the season). The levee's width is about 30 m; its length was not determined but is at least 50 m.

Methods for estimating the yield of the well:

1. Logan's method (Kruseman & de Ridder, 1970). Assumptions: thickness of the aquifer 1.7 to 1.3 m; hydraulic conductivity 0.5 to 2 m/day; drawdown in the well 0.34 to 1.7 m; effective discharge 30% of the calculated discharge. Effective discharge $Q_{eff} = 55$-670 l/day;

2. Extraction of uppermost phreatic water by means of shallow wells (van der Valk, pers. comm.). $Q_{eff} =$ several dozen to a few hundred l/day;

3. Seepage water during the digging of the well. Assumptions: seepage water equals 10% of the removed sediment; digging 1.5 m into the phreatic zone took 4 hours. $Q_{eff} = 240$ l/day;

4. The water volume in the well. High water level: $Q_{eff} = 240$ l; low water level: $Q_{eff} = 98$ l;

5. Available precipitation. Assumptions: effective precipitation 200 mm/y; circular catchment area with radius of 15 m; effective discharge 50%. May-September: $Q_{eff} = 100$ l/day; October-April: $Q_{eff} = 270$ l/day.

5. CONCLUSIONS

Although the data which were at our disposal were very limited, we yet are able to reconstruct the geohydrology, the hydrochemistry and the construction of the Neolithic well.

A long time before the settlement was established, the Kolhorn site was a tidal-flat environment which became dry land. During the successive stages from low salt marsh to high salt marsh there was no cultivation. But in these stages the location of the later settlement was predetermined through the development of creeks, levees and basins. The levee of the Kolhorn site was characterized by a somewhat coarser sediment in comparison with the basin. Through the drainage of the levee by the adjacent creek, the levee matured, resulting in an increase of particle cohesion. By the high salt-marsh stage its elevated position and higher permeability had resulted in a noticeable desalinization of the levee and the development of a fresh-water lens. The water in the levee, however, still had a saline taste.

During the following regression period the area was no longer flooded by saline water. Surface runoff, carrying particulate matter including halophilic vegetation, drained into the local creeks, which finally silted up. In the levelled relief of the area the systems of creeks, levees and basins remained visible to some extent. In this environment a general desalinization occurred, which was accompanied by the growth of peat. The drainage of the area was poor (the drainage base was determined by a tidal creek at 600-800 m distance) so that maturation of the soil proceeded only to a shallow depth. At the Kolhorn site the tidal fluctuations had lost their influence on the soil-water balance.

At the beginning of the period of peat growth the settlement at Kolhorn was established. At the time of the digging of the well the general desalinization was not far advanced. Our chemical data indicate a desalinization of the sediment as shown in figure 16. The desalinization of the sediment and the formation of a fresh-water lens was most pronounced at the site of the levee. The desalinated sediment was about 30 m wide and up to 2.5 m deep. Its longitudinal extent was also determined by the levee.

The well (fig. 17) was sunk into the central part of the levee (fig. 16). Given the depth of the well, we concluded that its digging probably occurred in the dry season at low groundwater level. Obviously the upper part of the soil had matured at an earlier stage, resulting in increased grain cohesion. This facilitated the digging of the well. Just above the clay layer some seepage water entered the well. This clay layer also could be removed

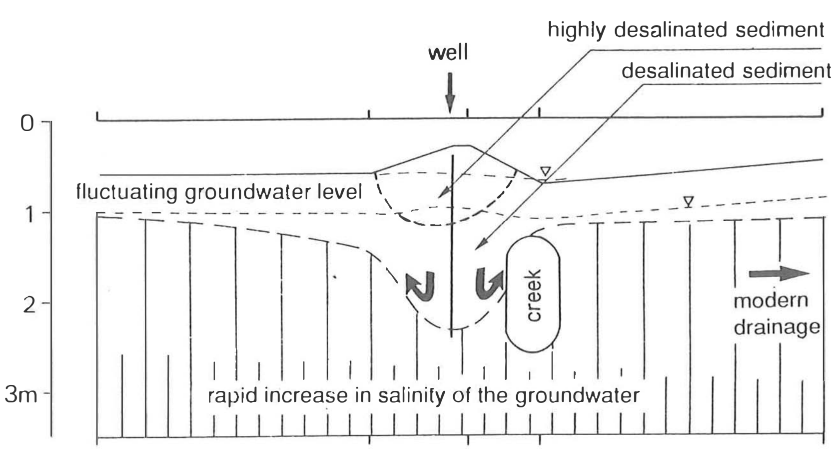


Fig. 16. Geohydrological reconstruction of the Late Neolithic well at Kolhorn. The progression of long-term processes such as decalcification and microbial decay of organic matter was used to estimate the dimensions of the fresh-water lens in the levee of the ancient settlement. The dimensions of the fresh-water lens at that time (pronounced desalinization of the sediment) were a depth of about 2 m and width of about 30 m.

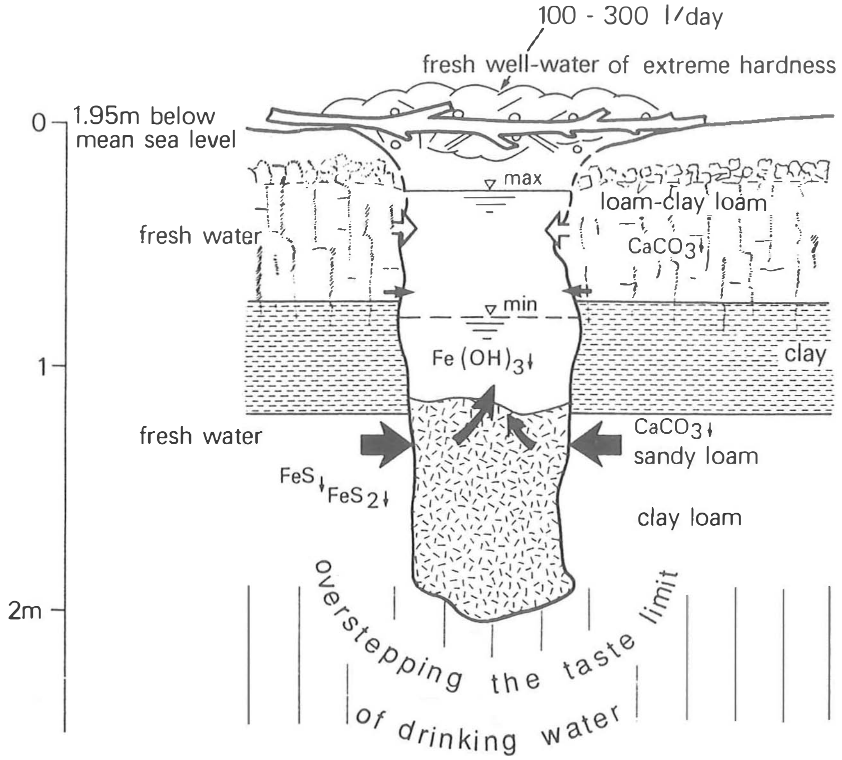


Fig. 17. Experience with recent salt marshes is the basis of the reconstruction of the digging and the use of the well. The digging was facilitated by previous maturing of the creek-border sediments in which the well was constructed. The deepest aquifer was supported by filter material consisting of charred reed fragments. The well was protected by a covering bundle of brushwood. In the dry season some water emerged from the base of the mature soil; the main discharge, however, originated from a sandy loam layer which produced semi-confined water from under a clay layer. The water contained c. 200 mg/l of chloride which is just below the taste-limit, and had a very high total and permanent hardness (Ca, Mg-HCO_3 and Ca-SO_4, respectively). The yield of the well ranged from 100-300 l/day.

without problem. Underneath the clay layer the seepage increased, particularly from the sandy loam horizon.

Having reached a depth of about 2 m, people decided that a deeper excavation was not favourable. The following considerations may have played a role: 1. The seepage increased sufficiently to guarantee an adequate yield of the well; 2. The sediment became progressively immature, which caused subsidence of the walls; 3. The sediment began to have a saline taste, and 4. The amount of the preparated filter material (charred reed) was limited.

It must be noted that the filling in with filter material had to be carried out immediately after finishing the digging, in order to prevent subsidence of the wall. The upper level of the filter material was determined by the fact that drawing water must remain possible. People knew that the deeper part had to be supported with permeable material. They chose a material which was present in the neighbourhood and which would not affect the water quality.

The diameter of the well is only 60 cm. Several considerations can be given: 1. Optimal production seemed better quaranteed by deep penetration of the phreatic zone than by a shallow well with a large diameter; 2. Optimal use of the restricted amount of preparated filter material, and 3. A firmer construction of the well.

The actual digging was done by a small person, possibly a child.

The construction of the well – the use of the filter material to protect the lower aquifer and covering the well with a bundle of brushwood – prevented direct damage. Therefore, it is quite well possible that the well was used for several years.

The yield of the well depended on the soil water balance, which means that in the wet season a maximum yield (from both aquifers) was possible, whereas near the end of the dry season the yield came entirely from the deepest aquifer. The yield of the well is estimated at 100 to 300 l/day. The water production was sufficient for the watering of three or four cows and domestic use by the inhabitants of the settlement.

Obviously the water in the tidal creek at a distance of about 700 m was too salty for consumption by cattle or people. Verhoeven et al. (1978) found that the drinking water for cattle nowadays in salt marshes may contain 4000-5000 mg Cl/l. During periods of high groundwater level (January-April) the well produced fresh water with a chloride content below the taste limit (200-250 mg Cl/l). From spring till the end of summer the groundwater level would fall and finally through capillary rise salts might precipitate. These salts are $CaCO_3$, $CaSO_4.2H_2O$ and NaCl. During the period of recharge (October-December) it is possible that for a short period the chloride content of water withdrawn from the mature soil exceeded the taste limit, due to the dissolution of these salts.

At low groundwater level, the water of the well was extracted entirely from the deepest aquifer. Probably this aquifer was not contaminated by settlement waste.

Generally we may state that the water of the well was fresh; its chloride content was around the taste limit. The water had a very high total hardness (Ca and Mg) and its permanent hardness (SO_4) was considerable.

The well was indeed productive, which is proved by the accumulation of $CaCO_3$ in the wall. This is the result of evaporation or CO_2 release from the soil water.

We assume that after a few years of use, the well fell into disrepair. Finally the brushwood cover collapsed and vegetation started to grow in the well. The result was that the well changed from an extraction point to an infiltration site of meteoric water. The rapid decay of the brushwood enriched the infiltration water with potassium, which resulted in an ionic exchange in favour of potassium in the sandy loam aquifer. This was a short-term process. The runoff water carried soil and detritus from the settlement. This finally resulted in the silting up of the well.

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APPENDIX I. Analytical results of the Kolhorn samples

Sample code		Grain Size Distribution				C-Org	$CaCO_3$	H_2O	CEC	Extractable Cations				H_2O Extractable Cations			
grid-depth		(weight %)								(meq/100 g)				(mg/l)			
(m) (cm)	No.	50-200	20-50	2-20	< 2μm	(%)	(%)	(%)	(meg/100 g)	Na	K	Mg	Ca	Na	K	Mg	Ca
Section 222																	
050-W -090	01	2	22	33	43	0.81	15	37	17.39	0.70	0.70	2.38	52.00	90	19	39	369
-160	02	19	56	12	14	1.06	20	34	7.83	1.51	0.67	3.15	49.50	348	165	118	903
-195	03	20	47	15	19	1.71	15	37	8.70	4.00	0.99	6.39	50.80	747	250	237	729
-270	04	35	45	9	11	1.49	13	35	7.83	5.83	0.90	5.41	44.70	1259	256	245	570
010E -070	05	17	44	16	23	0.56	9	27	12.17	0.21	0.35	1.16	49.10	48	4	24	500
-135	06	5	26	28	41	1.10	15	43	16.52	0.74	0.99	3.30	50.80	70	52	42	268
-210	07	14	43	19	24	2.10	16	39	8.70	1.37	1.05	5.90	45.90	263	263	193	595
-290	08	20	42	17	21	1.98	15	41	9.57	2.70	1.18	7.87	49.40	418	226	123	245
032E -042	09	33	38	13	16	0.52	12	25	10.43	0.28	0.27	0.92	50.10	84	9	24	601
-110	10	12	36	22	30	0.61	13	37	13.91	0.37	0.73	2.38	49.90	46	43	45	343
-180	11	22	44	16	18	1.21	13	35	5.22	0.37	0.86	4.10	48.60	60	288	150	605
-210	12	23	39	16	21	1.38	13	37	6.96	0.51	0.88	6.07	46.80	54	252	236	547

APPENDIX I. (Cont.).

Sample code grid-depth (m)	(cm)	No.	Grain Size Distribution (weight %) 50-200	20-50	2-20	< 2µm	C-Org (%)	$CaCO_3$ (%)	H_2O (%)	CEC (meg/100 g)	Extractable Cations (meq/100 g) Na	K	Mg	Ca	H_2O Extractable Cations (mg/l) Na	K	Mg	Ca
048E	-105	13	8	23	27	42	1.13	15	39	15.65	0.45	0.78	2.67	60.10	55	27	29	337
	-150	14	7	23	28	41	2.73	19	50	14.78	0.81	1.18	5.90	58.10	55	91	87	609
	-190	15	9	29	26	36	3.21	22	52	14.78	1.02	1.28	8.36	57.50	44	126	133	488
	-250	16	8	26	28	38	3.36	20	50	13.04	1.18	1.44	10.00	58.90	103	158	209	739
	-290	17	29	34	16	21	1.84	20	40	9.57	0.78	0.86	5.90	53.00	113	196	201	808
110E	-060	18	3	33	27	36	0.63	14	29	15.65	0.15	0.56	1.82	60.00	22	2	26	492
	-110	19	7	24	26	43	0.81	20	38	15.65	0.30	0.68	2.39	59.60	34	14	33	362
	-180	20	28	51	9	13	0.76	19	32	5.22	0.19	0.47	2.20	45.80	32	150	90	562
	-240	21	22	46	13	18	1.62	20	38	8.70	0.30	0.64	3.77	46.70	24	152	136	784
Section 270																		
050W	-090	22	2	26	27	44	0.84	9	37	16.52	0.87	0.72	2.79	53.20	166	20	31	280
	-140	23	14	54	14	17	1.52	20	35	8.70	1.80	0.51	2.95	50.50	493	88	115	941
	-205	24	37	42	9	13	0.95	19	30	5.22	1.57	0.42	2.95	44.40	78	174	141	824
020E	-122	25	10	36	20	33	3.18	10	33	20.87	0.70	0.54	2.46	55.30	250	20	34	363
	-140	26	8	36	21	35	0.97	22	40	13.91	2.09	0.67	2.95	49.00	390	41	39	232
	-200	27	9	46	18	27	1.46	21	40	7.83	2.78	0.65	4.10	47.90	619	150	99	499
	-240	28	18	41	17	24	1.88	17	39	8.70	2.96	0.88	4.59	44.40	678	196	121	359
	-310	29	43	42	8	7	1.01	18	30	3.48	1.39	0.37	2.95	42.90	623	156	143	418
035E	-075	30	43	41	7	9	0.59	17	22	4.35	0.03	0.12	0.59	44.50	21	5	17	511
	-140	31	26	36	16	22	0.70	21	33	11.30	0.47	0.49	2.03	48.80	138	26	39	347
	-200	32	16	41	21	23	2.21	22	39	9.57	1.57	1.08	5.41	36.00	461	195	149	502
	-220	33	26	37	16	21	1.67	20	38	5.22	1.22	0.70	4.59	39.30	661	254	227	502
	-275	34	45	37	9	10	0.89	20	30	4.35	0.78	0.45	3.44	41.30	638	191	197	379
Well																		
029E	-081	35	33	38	13	16	0.43	17	25	7.83	0.13	0.23	0.92	43.30	38	8	32	510
	-110	36	26	34	19	21	0.55	19	32	9.57	0.11	0.43	1.25	43.50	53	16	20	287
	-180	37	27	50	12	11	0.92	24	31	7.83	0.35	1.20	2.31	42.70	135	406	36	386
	-240	38	24	31	21	25	1.47	19	37	6.96	0.40	0.68	5.41	49.50	104	255	499	2436