Wetland Restoration: from Polder to Tidal Marsh

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Summary

After a non repaired breach in the Selenapolder closing dike (SW Netherlands), a new tidal wetland has been reverted out from a former polder (Sieperdaschor). Since depoldering along the Westerschelde estuary is a topic of discussion, the development of this new born wetland has been studied. This paper reflects some of the hydrodynamical and morphological developments that a depoldered area experiences within the first 6 years of tidal restoration. The focus of the study is on the relations between the tidal propagation and the creek morphology, land use and erosion/sedimentation areas, soil structure and chemistry.

The area was considered to behave in a different way depending on the different land use during the polder period. The Sieperdaschor can be differentiated in 4 regions on the longitudinal axis. On the basis of a flux survey, soil sampling and topographical surveys over a number of years, the development in each of the selected regions can be reconstructed. The results are summarized as follows.

Tides showed local energy dissipation from the mouth inwards. It was also founded a two-weekly cycle of water run on/run off. The rear part of the polder, which lays at a lower topographical level, stores water over a spring tide period, which can not drain out by the diurnal tide. During a neap tide period, this water is able to leave the standing water area and the watershed, draining out towards lower areas. A secondary drainage system must be present, maybe underneath the ground, trough the ripening cracks formed after the reclamation of the marsh.

The bridge which constraints the main gully has a negative effect in the water circulation, since it definitely hampers the flow, particularly during neap tides, when low tide can not reach this bridge' sill level. For the flood, there is also an alternative way for the incoming water, which is over the road.

The peculiar elongated and narrow shape of the Sieperdaschor and the topographical relieve do influence its development. The restoration pattern goes slow because of this. Nevertheless, an increase in better restored area has been found with regards to earlier studies. Within the standing water areas, an interesting area of active marsh development occurs. These pools accumulate fine sediment and are preferred foraging site for birds from Saeftinghe. From the pools there is a water stream seepages towards lower areas through a compact, cracked and ripened soil layer.

The topography seems a relevant feature which strongly influences the restoration pattern. In fact, active deposition and erosion zones were found at areas placed deep inside the Sieperdaschor. The cause of this appears to be the relative increase of tidal range in comparison with land topography, that becomes smoother and softer on entering the marsh. Bare mudflats are a response to this need of dissipation of the tidal wave.

The entire Sieperdaschor might behave as a sediment importer from the Westerschelde. Its surface grew up in the vertical more than 6 cm in 4 years' time, yet this pattern varies depending the location. We consider a rather low sedimentation zone about 1800 m long (from the rear part of the polder frontwards). The proximal part of the polder accumulates sediment in a faster way, partially due to redistribution of local materials. Lower areas, where water remain stagnant and isolated, trend to become siltated. This pattern is not repeated all the lower areas through; some irrigation ditches silt up whilst some others enlarge. A lot of this has to do with the position of these creeks interconnecting pools or creeks, yielding to a more active role in marsh formation.

The existence of a previous land use has very much conditioned the present development of the marsh. Land ploughing seems to be the driving cause for the appearance of a hard layer that hampers the redistribution of materials according to the newly created conditions. Tidal forcing must be larger to rebuild an effective drainage network. That results in a clear waterlogging process every now and then when overmarsh floodings cover the Sieperdaschor.

0 Preface and Acknowledgements

This report is the result of a cooperation between the National Institute for Coastal and Marine Management (Rijksinstituut voor Kust en Zee / RIKZ) and Ricardo Sanchez from the University of Cadiz. This research is executed in 1996 as a 3 months internship, within the PhD program of Ricardo Sanchez. The subject of that PhD program is the study on a large former wetland in the Bay of Cadiz.

Due to the relative short time and the fact that the field work period coincided with the regular summer holidays in The Netherlands, our ambitions had to be readjusted. Therefore we had to skip some work on the hydrodynamical model and on laboratory analyses. The final report has been produced much later that expected. Due to the fact that Ricardo went back to Spain and Kees found another job Harm had to finish the work at home, resulting in the late production of this report.

We want to thank Fred Tank, Annemiek van der Pluijm, Dick de Jong, Ad Langerak, Kees van der Male, Tom Pieters and Fred Geijp, who are all working at the National Institute for Coastal and Marine Management, for their contributions and support during the field work period and for the "gezelligheid" (coziness).

The hydrodynamical measurements were swiftly and adequately executed by the Survey Department of Rijkswaterstaat Direction Zeeland (Meetdienst Zeeland). Special thanks to David Louws, Jan van 't Westende en Piet de Rijke. The Survey Department Delft (Meetkundige Dienst Delft) has provided all the geographical positioning.

This research has kindly been granted permission for the work in the Sieperdaschor by the the conservator of the Stichting het Zeeuws Landschap, Jos Neve.

Very special thanks to Marina Delgado for executing the laboratory work and drawing of Figures and Adella Ranggong for her help with the lay out of the text and tables.

1 Introduction

The Sieperdaschor is a 100 ha's wide tidal marsh situated in the brackish zone of the macro tidal Scheldt estuary, near the Belgium-Dutch border (Figure 1.1). This tidal marsh has undergone two "metamorphoses" within the last 3 decades (Figure 1.2).

Before 1966 it was part of the tidal marsh "Het Verdronken Land van Saeftinghe" (from here on referred to as Saeftinghe). These 3000 ha's of tidal flats and marshes is the only tidal marsh of this size left over in the SW of The Netherlands. The Saeftinghe marshes are declared protected area since 1975 and became recently a RAMSAR area. Saeftinghe and the Sieperdaschor are both managed by the "Stichting het Zeeuws Landschap", a regional nature conservator.

In 1966 a sand dam was constructed on the marsh, parallel to the existing sea wall, containing several pipelines. The former owner closed of the area between the sea wall and the pipeline dam with an additional dike along the river Scheldt. This was how the Selenapolder, an area of 98 ha's. After leveling of the surface and implementation of the drainage system consisting of ditches and a sluice at the dike, this polder was used for cattle grazing and some agriculture.

The dike was relatively low, only 4 m above NAP[1], and as a result the polder was frequently flooded during winter storms coinciding with spring tides. The dike breached twice, in 1976 and in 1985, but in both cases was immediately repaired. On February 26, 1990, a severe storm struck the area and water levels reached 5.0 m above NAP. The dike breached again, but due to combined efforts of nature conservation groups and local authorities, reparation works were discouraged. From then on, the tides have had rather free access to the area. The artificial ditches are altered and reverted into creeks and the surface is colonized by marsh vegetation. In 1993 the "Stichting het Zeeuws Landschap", gave a new name to the altered area: the "Sieperdaschor"[2].

The objective of this research is to describe changes in the Sieperdaschor after breaching of the dike in terms of: hydrodynamics, sediment budgets, creek morphology and soil structure. We will try to analyze these changes in relation to each other and to former land use. With a simple one-dimensional hydrodynamic model, a prediction is made of the evolution of the tidal flushing and creek morphology on a medium-long term. This kind of information is crucial to policy makers which consider wetland restoration as an option of the integral coastal and water management.

This "accident" proves to be a perfect one to one scaled "experiment" of how a polder changes into a tidal marsh after tidal action is restored. It provides us with a better understanding of the physical and chemical processes. This is fortunate while recently both marsh creation and marsh restoration have become an important issue in coastal and estuarine management. For instance in East-England, former polders have been reverted into marshes (Pethick, 1994). This so called "managed retreat" is an alternative strategy for sea defense while at the same time the area of wetlands increase and therefore environmental potential of the coastal zone is increased. In near future tidal activity will be restored in a few polders in the Dutch Wadden Sea. In the Scheldt estuary marsh restoration is being discussed as one of the alternatives to compensate for environmental losses due to deepening of the navigation channel. Apart from increasing wetland area and restoring natural borders, it also can improve the dissipation of the tidal wave energy and lower the high waters peaks.

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[1] NAP (= Normaal Amsterdams Peil) is the Dutch ordnance level and is abour mean sea level

[2] The former owner, a Belgium dredging contractor, decided to sell the polder to "Stichting het Zeeuws Landchap" in June 1993. The money was partly provided by a legacy of Mr. Sieperda, former president of the Court of Middelburg and a well-known bird watcher

2 Research area and historic evolution

The Sieperdaschor is a leg-shaped narrow and elongated area. It is 200 to 500 m wide and about 3,500 m long. The surface topography lies between 2.40 and 2.80 m above NAP. The marsh is connected to the estuarine channel on the north-eastern side. The southern border is formed by the sea wall, which protects the Prosperpolder. The western and northern borders are formed by a sand dam, dividing the Sieperdaschor from Saeftinghe (Moermond, 1994).

In the first half of this century it was a common policy in the SW of the Netherlands accelerate marsh accretion and consequently land reclamation. Plantings of *Spartina anglica*, the installation of brushwood groins and small dams and the improvement of tidal flushing by artificial rectification of creeks locally led to accretion rates of 0.1 m/year. These reclamation works were also implemented in Saeftinghe and the area of the Sieperdaschor. Some of these rectified creeks were matched into the drainage network once the polder was reclaimed. This feature is still noticeable. In fact, the present morphology of the Sieperdaschor and its soil structure are remnants of the pre-reclamation period (Figure 2.1).

After construction of the dam and dike in 1966, a main ditch was created alongside the dam, connected to a sluice in the dike. A secondary drainage system was implemented perpendicular to the main ditch, along with the surface gradient towards the NW (Figure 1.2). This complex of ditches drained the polder from surplus rainwater and tidal floodings. The sluice in the dike is opened during low tide. The tidal flooding occurred. when severe (western) storms coincided with spring tides.

The topography and soil of the Selenapolder was far from homogeneous. The part with a more dense drainage network corresponds with the relative lower and more clayey soils. These were the back marsh areas before reclamation. On the other hand, the parts with fewer ditches are higher and sandier and correspond with the location of former creeks and levees. The major part of the polder was used as pasture land for cattle. Only the sandier parts in the center were used for agriculture, especially corn. It is interesting to note that differences between pasture and arable land can easily be detected using processed LANDSAT images.

The summer dike was breached in the beginning of a storm period of several days, with water levels which occur 1 in every 80 too 100 years. After the storm, it was clear that considerable costs had to be made to close the breach. It was then decided not to repair the dike.

After breaching of the dike, the area was flooded frequently during spring tides. Tidal flow was restricted mainly to the existing drainage network. The main parallel ditch was the preferential route for both flood and ebb flow. Most ditches were too small for the new tidal discharges. The creeks readjusted to the higher discharges and creek bank erosion was common feature in the eastern part of the marsh, proximal to the estuary channel. In the western part and along the sea wall, along the southern border of the area, drainage was insufficient and waterlogging occurred.

The change from polder to marsh posed different "users" of the area with several problems. Creek bank erosion was undermining the dam, endangering the pipeline integrity. To prevent damage sand bags and later stone revetments were used. The access road to a cattle farm in Saeftinghe crossed the polder about 500 m westwards from the former dike. Being the only access road, it had to be maintained. First an extra culvert was placed in the main channel (parallel ditch) to accommodate filling and drainage of the area. But this soon proved to be insufficient, and both culverts were blown out, obstructing the access road. In December 1992 a provisional bridge was built.

However, both creek banks and bridge still needed constant maintenance and local authorities together with the manager of the pipeline dam wanted a more solid solution.

In February 1993 a creek was dug in the center of the marsh and a new and wider bridge was constructed. The former ditch was closed where it crossed the road. As a result creek bank erosion along the dam decreased to manageable proportions. Another important change was that cross section at the new bridge was larger than the former one. Tidal action was less hampered and tidal influence was given a new impulse, with respect to tidal flow and creek enlargement within the marsh. Tidal flow has used the former drainage pattern. Some ditches have silted up and new creeks have been formed. Still, six years after inundation, the drainage pattern resembles the former ditch network (Figure 2.2).

3 Research objectives

The objective of this research is to describe changes in the Sieperdaschor after breaching of the dike in terms of: hydrodynamics, sediment budgets, creek morphology and soil structure. We will try to analyze these changes in relation to each other and to former land use. In this research developments in flora or fauna, which are an evident and interesting feature, have hardly been taken into account.

Four regions or zones have been discerned (from east to west) within the Sieperdaschor where different hydrodynamical and morphological developments are expected (Figure 3.1). Each zone has different distinct environmental features related to tidal action, creek morphology and hydroperiods (Moermond, 1994). The first "reference" zone is the undisturbed tidal marsh, extending from tidal flat along the river Scheldt channel towards the breached dike. The second zone is situated between the dike and a ditch situated at about 400 m from the road (with the bridge). Because this part of the polder had not been leveled, it still had the pre 1966 marsh topography. Together with the fact that tidal action is not hampered, the tidal marsh is almost completely restored even after the short duration of 6 years. Within the third zone, from the road sample up to about 2/3 of the area, tidal action is still increasing and restoration of the marsh is in progress. The fourth zone is about the rear half of the area. Here tidal action is too weak to cause noticeable morphological alterations. Apart from inundation during spring tides this zone shows the fewest changes since 1990.

The concept of the zonation is used as a framework when dealing with the research questions and hypothesis which are categorized in several subjects.

vertical tides
Tidal action is the engine for the morphological and ecological dynamics and therefore it is the dominant factor. How did the vertical tidal change since 1990? How does the tide propagate through the marsh and what is the importance of the obstruction at the bridge? What will be the tidal regime in about a decade and in 50 years time?

horizontal tides
Horizontal tides are responsible for the morphological shaping of the marsh and for the transport of sediments. What are the present fluxes of water in different sections of the marsh? Can this flux be expected to change in the near or far future?

creek and marsh morphology
Tidal action is still actively reshaping the morphology of this young marsh. In turn, the altered creek pattern will modify tidal propagation. How exactly does creek enlargement take place? When will an equilibrium state have formed between creek dimensions and discharge?

sedimentation/erosion
Did the Sieperdaschor have a net export or a net import of sediments in its first six years? Is there an internal redistribution of sediments taking place? If so, how does that occur?

soil structure and chemistry
What can be said of the soil structure and soil chemistry six years after inundation? How important was former land use for the present developments?

4 Methods and Instrumentation

4.1 General method

basic topographical chart

During preparation of the field work an accurate topographic map of the Sieperdaschor has been constructed on a scale of 1:5.000 (Figure 4.1). The basis of this map was formed by a full coverage topographic map on a 1:2.000 scale. This map was produced with data from a detailed height survey of 1994, which were interpolated by DIGIBEELD[3],This map has an estimated accuracy of about 0.15 m on the marsh surface. The reproduction of the creeks is less accurate, due to the erratic creek patterns. Therefore, from aerial photographs with a scale of 1:5.000 (infra red- false color, 19/6/1995) a detailed contour map was produced, showing all the relevant creeks, gullies, ditches and pools. Additional vegetational information was included using the draft version of the vegetation map (dated 7/96) of the Survey Department Delft. Aerial photographs themselves were employed as helping tool in the field, due to the lack of significant reference points to get oriented.

positioning measurements

All relevant measuring locations were positioned by the Meetkundige Dienst Delft (Survey Department Delft), using a D-GPS. The XY coordinates are determined with an accuracy of decimeters and the Z coordinate with an accuracy of about 1 cm. Apart from solitary locations, transects, such as some creek profiles and the soil-transects, were measured as well.

4.2 Tidal survey

vertical tides

The propagation of the tidal wave (celerity and amplitude) was measured for complete neap-spring tide cycles in 1992, 1993 (2 times), 1995 and 1996 (reports from the Survey Department Zeeland). These measurements were all carried out with pressure sensors, placed at the bottom of the creeks.

For this research only the 1992 and the 1996 measurements have been used to illustrate the changes in the vertical tide over these 4 years. Due to the artificial changes in the drainage network in 1993, the measuring site at the bridge has been relocated (Figure 4.2). This means that that location is not useful for the interpretation.

horizontal tides

In 1996 tidal currents are measured during complete tidal cycles in two creek sections; one at the bridge and one in the main creek along the dam. These two sites were chosen for their strategic locations, in between zone 2 and 3 (bridge) and zone 3 and 4 (ditch) (Figure 4.3). The measurements were done twice: during a weak developed spring tide on July 17 (High Water 296 cm above NAP) and July 18 (HW 296 cm above NAP) and during a high spring tide on July 31 (HW 328 cm above NAP) and August 1 (HW 333 cm above NAP). The measurements are executed with OTT C-31 propeller current meters. The current meters were placed at 3 to 5 different heights in the vertical (Table 1 and Figure 4.4).

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[3] DIGIBEELD is an interpolation program which is used by Rijkswaterstaat for all depth charts in the Zeeland region

In combination with the cross sectional areas (Figures 4.5 and 4.6) and water depth, flood and ebb water fluxes are calculated. Integrated over a flood and ebb period the total fluxes are ascertained

At both sections flow through tributary creeks and gullies (including seepage) is expected to be limited during most tidal conditions. However, during high spring tides, overmarsh flow will occur, and considerable amounts of water will flow in and out the marsh without being measured by our sensors. In those situations our flux measurements underestimate the real water (and sediment) fluxes.

Visual water levels measurements were taken at the bridge location, using two scaled poles placed both at the outer and at the inner side of the bridge (referred to NAP). These readings were used for calibration of the pressure sensor and also gave an impression of the influence of resistance at the bridge bottleneck experienced by the tide.

Table 4.1. Position above the ground of the different surveying instruments.

Sensors (above creek bottom)	July 17	July 18	July 31	August 1
OTT 1	30 cm	30 cm	30 cm	30 cm
OTT 2	80 cm	60 cm	60 cm	80 cm
OTT 3	130 cm	100 cm	100 cm	150 cm
OTT 4	200 cm	-	-	200 cm
OTT 5	-	-	-	300 cm
Pressure	15 cm	20 cm	40 cm	20 cm

one-dimensional hydrodynamical model

The contour map of 1994 with additional information of monitoring transects has been used to schematize a one-dimensional hydrodynamical model for the polder. The creek pattern was updated with information of the aerial photographs and field observations. Therefore the model represents the present (=1996) situation. For this purpose the DUFLOW 2.02 modeling package[4],was used. The model is calibrated with water level and flux measurements from the spring of 1996. After calibration the model is used for sensitivity analysis.

4.3 Creek and marsh morphology

A combined field and desk study was performed to track the changes on creek morphology. The marsh surface morphology and creek pattern of 1995/1996 are determined with the contour map of 1994, the vegetation map of 1995 and an interpretation of aerial photographs (stereoscope) of 1995. Additional information is gathered with respect to the land use of the polder just before inundation in 1990.

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[4] This computer software is developed by Rijkswaterstaat, Delft University of Technology and Delft Hydraulics

Heights of longitudinal and cross transects (Figure 4.7), measured since 1992 on a yearly basis, are the only real quantitative data we could use. Still these are only rough indicators for the overall changes in creek dimensions and marsh surface.

In the field some creek profiles and horizons of hard and cohesive sediments have been studied with special interest. The results are qualitative. At some cliffs reference sticks were placed at the start of the field work in July to monitor the rate of progress within the three months of the research.

4.4 Sediment budgets

sediment fluxes
Simultaneously with the discharge measurements sediment fluxes were determined. From 3 to 4 different depths water samples were pumped every 15 minutes and stored in 1 liter plastic bottles. These were analyzed at the RIKZ laboratory for total suspended load (mg/l) by determining the dry weight of the sediment on 2µm filters. The sediment load was calculated as the water flux times the sediment concentration.

budget calculations
From aerial photographs areas with net sedimentation or erosion were determined, using topographical data and 'in situ' observations. We tried to assess patterns in the field which show either erosion or sedimentation. In addition cores were taken to check whether distinct layers could be observed. The idea was, that the pre and post 1990 sediments could be discerned clearly.

The monitoring heights transects are the only quantitative information with which net sedimentation and erosion of the marsh and creeks can be estimated. A net sediment budget is made per section, with lengths of 500 m each, with the 1992 and 1996 surveys. The sediment budgets are first calculated for the creeks and marsh surface respectively. The average depth change times area gives the change in sediment volume on the marsh. The average change in creek cross sections times the creek length give the change in sediment volumes in the creeks. When the differences between eroding and accreting ditches is rather high, separate calculations were done for a better result. After all, areas with similar accretion or erosion rates have been discerned.

sediment composition
The sediment composition of suspended sediments is assessed on September 27, 1996 during a well developed spring tide for five situations; twice during the flood period, once during high water slack and twice during the subsequent ebb period. In order to obtain enough sediment for the analysis (minimal required amount of sediment was 20 mg), for each sample 200 liters of water were pumped and immediately centrifuged. This took about 20 min. per sample, using a mobile truck-lab combination from the Survey department. The sediments samples were stored in glass bottles and analyzed for grain size distribution, organic and carbonate contents. It was originally planned to take these samples together with the flux measurements. However, due to logistic limitations, this could not be achieved.

4.5 Soil structure and soil chemistry

general

Soil maps are not available at the moment for the area, although there is one surveys which indicates how the soil properties vary throughout the marsh (Stikvoort, 1995). This was used as additional data in a survey which was carried out to find out the present soil conditions at different locations within the polder. Twelve transects were selected to carry out the soil survey at representative sites, which were selected after desk and field examinations. In each transect at least three cores have been taken, with a hand-corer. The maximum drilling depth was about 100 cm; the diameter about 5 cm. These cores were first described in the field on visual characteristics. Then the first 30 cm's was sampled at every 5 cm interval (in total 6 depths). This was analyzed in the RIKZ laboratory on moisture content, organic content and carbonate content. Some of the cores were analyzed following a different scheme of depths, taking two or three depths in one sample and averaging the result.

Height profile of the transects was determined with D-GPS in the topographical survey for the accurate micro-topography and positioning of the sampling locations. This is important in order to correlate layers, strata and soil properties. This information is attached on annex 1.

visual description

Every core is described in terms of soil structure, color, marks of oxidization, grain size estimations, compaction and additional features such as shells or roots and bioturbation marks. Although Reineck & Sing (1975) define several bedding types (homogeneous, interlayered, rippled, lenticular, mottled and laminated) for tidal sediments. In these sampled cores, mainly two patterns were present: homogeneous (no bedding structure) and interlayered.

Sediment color varies both with grain size and with the degree in ground aeration. This was, therefore, an indicator to assess the presence of the boundary line limiting the reduced and oxidized sediment layers. Thus, oxidized sediments appeared with rather light colors if they were fresh and not yet reduced, and red/orange mottled (if they were re-oxidized). Reduced deposits showed darker tones.

For sediment grain size, simple visual in situ techniques were employed. For the scope of the research that was enough. So, a distinction following the U.S.D.A. triangle was made among (from fine to coarse) clay (corresponding material below 2 microns grain size), silt (2-50 microns), and sand (50-2,000 microns).

Compaction was ascertained using a modification of the de Bakker & Schelling (1966) ripening classes (Table 4.2). The ripening classes rank the consistency of soils that have been formed under wet conditions or that are permanently or periodically saturated with water (Kooistra, 1978). We also give 'ripening' the meaning of a micro slumpy-easily crackable (or already cracked) material, which, due to water losses, organogenic and physical-chemical aeration and microbial oxidization, has changed properties.

In order to relate all this information to ecological and environmental variables, geomorphologic information of the sites were described together with the most relevant vegetation species.

Table 4.2. Ripening classification (after Kooistra, 1978, and own elaboration).

our code	de Bakker and Shieling code	class name	consistence
1-2	1	whole unripened	very weak. Material runs through the fingers
3-4	2	nearly unripened	weak, material can be squeezed through the fingers
5-6	3	half ripened	rather weak, material can still be squeezed through the fingers
7-8	4	nearly ripened	rather firm, material can be squeezed through the fingers with difficulty
9-10	5	ripened	firm

The soil structure (texture, layering, ripening, oxidation/reduction) were described from cores and bare cliffs along the creek banks. A selection of the cores were photographed. Locations were also positioned in the field with D-GPS (Figure 4.8). In the 4 "regions" 12 transects were selected, sampled and described, of which finally 10 were processed in the laboratory.

5 Tides and hydrology

5.1 Observed vertical tides

tidal propagation in the marsh

The Sieperdaschor is situated in the brackish part of the macro tidal Scheldt estuary near to the region where maximum tidal range is. The tidal range varies from 4 m during ordinary neap tides to nearly 6 m during spring tides. The tidal curve is a slightly asymmetric sinusoidal wave with shorter flood than ebb duration .

The tidal wave propagates throughout the marsh creeks into the Sieperdaschor, gradually dissipating tidal energy due to friction and dispersion of flood water. The high water levels decrease from MP4 near the mouth of the marsh, towards MP1 at the rear (Figure 5.1). There is a time lag of about 2 - 3 hours between these measuring locations, which are about 2300 m apart from each other.

The tidal wave becomes more asymmetrical entering the marsh. On March 20, a relative high spring tide flood and ebb durations at MP4 are 3 hours 20 minutes and 8 hours 15 minutes respectively (Figure 5.2). At MP3, flood and ebb durations are about 2 hours and 11 hours respectively. At MP1 flood duration during spring tides took only 1 hour 30 minutes. The remaining period water levels were dropping slowly.

water levels in MP1, MP3 and MP4

The propagation of the tidal wave depends strongly on the tidal range. During neap tides water levels at MP1 do not change (Figure 5.3). Only when high water level at the mouth exceeds 2.38 m above NAP, a small tidal range of about 0.1 m. is observed. This means that at the end of the marsh tidal energy is almost entirely dissipated.

Water levels at MP3 show that during neap tides drainage of the marsh can be completed before the next flood starts. During spring tides this is not the case. For example, on March 14 (neap) low water level stabilizes at the end of the ebb in an asymptotic way at about 0.33 m above NAP, which is the level of the stone revetments at the bridge. However, on March 21 (spring tide) this low water level never gets below 0.68 m+NAP. Water is still flowing out when the current turns as the next flood enters the marsh. Likewise, on a spring tide, the slope of the tidal curve during ebb is much steeper than during neap tide.

hydraulic head between MP3 and MP4

During a neap tides (Figure 5.3) maximum hydraulic head between MP4 and MP3 occurs very soon after the start of the flood. After this short peak, with a maximum of about 15 cm, the hydraulic head reduces gradually. After high water, the head is still slightly positive. This would mean that water would flow out against a slope. We think that this inconsistency is caused by a small error in the z-level of the instruments. Only at the end of the ebb period hydraulic head starts to build up, especially after MP3 has reached the minimum level of 0.33 m above NAP.

During spring tides, the hydraulic head between MP4 and MP3 differs completely (not shown here). In the first part of the flood, water levels rise sharply at MP4. At this moment water levels are still lowering in MP3 and water is flowing out. When water levels exceed 0.33 m above NAP a hydraulic head is formed between MP4 and MP3 and water is flowing into the marsh. In both MP4 and MP3 water levels rise fast. But at the moment that the marsh starts to be flooded and water disperses from the creek onto the marsh, the rise in water levels at MP3 slows down. This "shoulder" in the tidal curve is a well known phenomenon of a tidal wave in estuaries (Bayliss-Smith et al., 1979). It is normally observed at the moment when a large proportion of tidal flats are submerged. The sharp rise continuous at MP4, which leads to an increase in hydraulic head just before high water is reached. We observed that, when a water level of about 3.00 m above NAP is exceeded, flood water flows into the Sieperdaschor over the road, using the complete width of the marsh. However, we have not observed any peculiar effects on the hydraulic head between MP4 and MP3 because of that.

Just after high water, the hydraulic head reverses. A hydraulic head is formed from MP3 to MP4 with a maximum of about 15 cm. It is typical that after this peak, which lasts for about 1 hour, hydraulic head diminishes, at March 21 even to zero. This is the result of a period during ebb when water levels at MP3 decrease faster compared to MP4. We are not quite sure why this occurs. Perhaps the first peak occurs as the reservoir behind MP3 is emptying. When this reservoir is drained, water levels in the marsh are determined by drainage of the main channel. The flow around the bridge during this period of the ebb is probably driven mostly by momentum.

water fluxes during spring neap tidal cycles

From neap to spring there is a net flux of water entering the Sieperdaschor. The marsh gradually fills in, resulting in somewhat higher water levels at the end of the marsh and large areas of standing water all over the marsh at the top of the spring tide cycle. From spring to neap there is a net outward flux of water. At MP1 this is shown by an almost continue lowering of the water level.

At the bridge, in between MP4 and MP3, the creek floor is fixed by stone revetments at 0.3 m above NAP. At the rear end of the marsh creek floor is about 2.5 m above NAP, but the creek practically never dries up. In the period from March 5 until April 4, 1996, minimum water level was 2.2 m above NAP. The 0.33 m above NAP level at the bridge is therefore the governing key particularly for the drainage. We believe that this constrain influences its morphological evolution significantly.

water levels Prosperpolder compared with MP4 in the Sieperdaschor

Water levels at the tide gauge Prosperpolder are always lower than those in MP4. This is physically impossible. It would mean that water enters the marsh against the slope in the water table. Given the curve in the hydraulic head we estimate that the waterlevels in MP4 are about 15 to 20 cm higher. The tide gauge at Prosperpolder is derived from Belgium authorities and has been measured in a different manner. From further work a correction should be used.

In Figure 5.8 and 5.9 we show water levels at Prosperpolder and at the bridge, measured both with a pressure gauge and visually with leveling poles. The data of July 17 show clearly that the water level from Prosperpolder correspond with about the mean of both visual water level data (outside and inside). The water levels derived from the pressure gauge are about 20 cm higher. The observations on August 1 show less regular curves. Then only during the ebb period the pressure gauge showed higher levels compared to the other data.

Given these figures we must conclude that the data from the pressure gauges within the Sieperdaschor must be systematically higher than real water levels. This is probably due to insufficient calibration. The Survey Department has guaranteed that the gauges are automatically corrected for atmospheric pressure changes.

Fortunately, the results of the three pressure gauges inside the Sieperdaschor are consistent relative to each other. Therefore we can use them for the purpose of describing the propagation of the tidal wave, within the marsh. But it is clear that we can not use the water levels at Prosperpolder in comparison with the data in the Sieperdaschor. This should be take into account when calibrating the hydrodynamical model, when these different sets of data are used.

5.2 Observed horizontal tides

horizontal tide at the bridge

As expected there is only a slight layering in the vertical velocity distribution. This homogeneous flux is the result of the very turbulent situation and the extreme roughness of the creek floor, due to stone revetments. During the overmarsh flood episode, main and maximum peaks are observed short before and after the high water slack. A similar trend is observed for the non overmarsh flood episode, yet there is no real flood peak.

From our data collection it can be seen that stream velocities show a sharp increase during overmarsh flooding with regards to non overmarsh flooding (Figure 5.4 and 5.5). Let us have a look at the following table:

Table 5.1. Maximum current velocities (cm/s) at the bridge location

tidal phase date	**flood 17/7/96**	**ebb 17/7/96**	**flood 1/8/96**	**ebb 1/8/96**
30cm +ground	59.4	59.9	100.8	151.6
80 cm +ground	69.7	86.3	181.9	190.4
130 cm +ground	71.4	87.2	not measured	not measured

The first difference between these two spring tide measurements, is the enormous difference in current velocities. Due to the flooding of the marsh on August 1, considerable more water had to enter the marsh through this creek. Also when the marsh is flooded, maximum current velocities occur during the ebb period. Water enters the marsh over a broader cross section during flood. When this overmarsh flooding takes places, water is pushed over the marsh but due high flow friction of the vegetation, current velocities are low. During the following ebb, the gravity driven flow concentrates in the creeks. Compared to the flood period, water is more constrained in the creeks. This reduction in cross section results in higher current velocities during ebb. So both tidal range and high water level strongly influence the pattern of current velocities, for both the ebb and flood period. Dankers et al. (1984) describe how overmarsh flow during high spring tides and during storm tides, have an influence in this speed distribution. They described two peaks in both flood and ebb period, a similar to that of August 1.

On July 17, an average tide, a flood peak is observed soon after start of the flood at the height of 30 cm above the ground (Figure 5.4). After this peak, velocities fade out at this depth, probably due to frictional terms. Then there is a long interval where velocities reach a maximum value but not a real second flood peak. During the ebb, maximum current velocities occur very soon after high water slack. After a subsequent reduction in velocities, a stabilization and even another increase is observed at the end of the ebb. Dankers et al. (1984) found the second ebb peak when the marsh was flooded only. However, despite the whole marsh was not flooded at July 17, this second ebb peak is observed. These higher current velocities in the second part of the ebb are the result of a strongly decreasing cross section at the bridge. At the same time, the hydraulic head between both sides of the bridge is building up again. The levels in the marsh can't drop below the threshold of the revetments, whereas downstream of the bridge water levels will continue to lower.

On August 1, a well developed spring tide, we have only observed one real peak in velocities, about 1 hour before high water slack (Figure 5.5). This peak coincides with the moment that the marsh is flooded. As noted in the former paragraph, at that moment hydraulic head is maximum. Again, during the ebb period, a second ebb peak is observed. The limited cross section at the bridge has a large effect on current velocity distributions through this main creek. This obstruction results in higher velocity peaks and longer drainage duration, both increasing with higher water levels. With the numerical hydrodynamical model we will be able to show how important this constraint at the bridge is for the tidal flow in the marsh, both during flood and ebb periods.

horizontal tides at the ditch

At the ditch current velocities are always slower for the ebb than for the flood, even though the first one is aided by gravity (Figure 5.6 & 5.7). The vertical distribution of velocities at this site is more homogeneous than at the bridge, probably because relative low bottom friction. Anyway a slight vertical gradient of velocities is observed increasing from bottom upwards.

Table 5.2. Maximum current velocities (cm/s) at the ditch location

tidal phase date	flood 18/7/96	ebb 18/7/96	flood 31/7/96	ebb 31/796
30cm +ground	56.9	84.8	78.2	-
60cm +ground	51.6	54.8	85.5	69.3
100cm +ground	48.8	51	-	-

At this location distinct flood peak velocities only occurred during overmarsh flood episodes. This feature was also observed at the location bridge. Higher velocities were observed on the July 31 when high water level was higher (Table 5.2). Second peaks are clearly observed on the non overmarsh flood. Shoulder-typed curves also appear when the overmarsh flooding takes place. During the survey at the ditch we had the same problem as at the bridge when the flood came short after the instruments were set up and few data could be collected over that early period.

We suggest that the long ebb flow at this location is partly caused by the retention of water in the rear part of the Sieperdaschor in pools and cracks which drains only slowly during ebb. In a way, the rear part of the Sieperdaschor can be compared to a is sponge.

It was remarkable to notice water levels dropping already 12 cm, before current direction changed from flood to ebb. This indicates that at this location, a clear phase lag is present between the vertical and the horizontal tide, whereas at the bridge these almost coincide. Therefore we conclude that an inward momentum exceeds the gravitational force outward during this period around high water slack. This pattern normally occurs when the tidal wave takes the form of a solitary wave.

translation waves caused by ships

At the bridge location, and particularly on the high spring tide measurement, an irregular pattern is observed in both current velocities and water levels (Figure 5.4 & 5.5). These are translation waves, which are caused by ships passing through the main channel, at a distance of some 500 m. A moving ship has apart from the short periodic waves in its wake, a longer periodic wave with an amplitude up to 0.5 m and a wave length of several hundreds of meters (Kornman, 1991). These translation waves can travel far into the creeks like miniature tidal waves. They influence water levels, hydraulic heads and therefore current velocities in the marsh creeks.

5.3 Changes in tidal propagation form 1992 to 1996

Since waterlevels were first measured in 1992, both tidal propagation and creek configuration have changed significantly in the Sieperdaschor. The increase in tidal volume for instance has probably occured in a "shock-wise" manner.

From 1990 to 1992 tidal flow was obstructed by a culvert, where the creek (former main drainage ditch) crossed the road. Although we have no waterlevel dat from that period it can be concluded that tidal flow was very limited. Only after storm tides, when the marsh was filled completely with a column of for example 1 m water, very high current velocities must have occurred during the next ebb. It was on those occasions that the culverts were undermined by local scour.

After the culvert had been wiped out for the second or third time, a provisional bridge was constructed at that place (Moermond, 1994) in December 1992. This already improved tidal flow during normal tidal conditions. Creek enlargement in the marsh continued which led to the already described problems along the sand dam. It was during this period that water level measurements were started by Rijkswaterstaat (April-May 1992). Two locations were strategically chosen in the main creek (former drainage ditch); one at the rear end of the marsh (MP1) and one just inside of the bridge (MP2). Prosperpolder was supposed to be the reference at the mouth of the creek. Moermond (1994) has processed these data. Tidal range in MP2 was about 1 m during spring tides. At MP1 tidal range had a maximum of 0,3 m. The phase difference between MP1 and MP2 at high water was 130 minutes.

In the February 1993, a central creek was dug with a cross section of 18 m (at Marsh level), about twice the size of the former creek width. MP2 was then located in a dead end. From the water levels of April 1993, it is clear that (maximum) tidal range at MP1 was about the same, whereas at MP2 this increased from 1 to 2 m with higher high waters and lower low waters. The phase difference between MP1 and MP2 at high water was a bit shorter: 120 minutes. However, as Moermond (1994) has reported, this average is influenced by meteorological circumstances

In 1995 it was decided to abandon MP2 and two new locations where chosen: MP3 about 300 m westward of the bridge and MP4 at the breach in the summer dike. Creek dimensions have continued to grow, but since 1992 completely due to creek bank erosion. The effects can be seen at MP1 where high water levels have strongly increased. Correspondingly drainage during ebb has improved, illustrated by the lower water levels at the end of the ebb period at MP2 and later MP3. In 1996 low waters at MP3 during neap tides were 0,5 m above NAP. This means that the creek bed has almost reached the erosion basis, formed by the level of the revetments at the bridge at 0,3 above NAP. The average phase difference between MP1 and MP3 at high water was 120 minutes in 1996. These data show that the tidal propagation was still developing in the Sieperdaschor; lower low waters, faster tidal propagation and increasing tidal prism.

Clearly, hydrological end morphological developments have interacted. Therefore, increase in tidal activity will continue as long as significant creek enlargement takes place. Eventually, the constraint at the bridge will provide a finite maximum configuration of the creek pattern in the Sieperdaschor. In the long run tidal prism will reduce, due to sedimentation on the marsh surface.

5.4 Results of the hydrodynamical model; the 1996 situation

A one-dimensional numerical hydrodynamic model, Duflow 2.02, has been used to simulate tidal flow in the Sieperdaschor. For its application, a topographical schematization of the study area was made. This was realized according to the 1994 topographical chart, complemented with extra topographical data.

Since this model is not particularly designed for marshes, where creeks can dry up, a calculation trick is employed. A deep but extremely narrow channel is included in the schematization within the creeks. The design of nodes and sections was made according to field experiences concerning the water circulation in the marsh. Only those creeks are represented which are relevant for the main flooding and drainage of the marsh. The model was calibrated for the conditions in March-April 1996, with data from MP1, MP3 and MP4.

The first results are presented in Figure 5.10, 5.11 and 5.12, for MP1, MP3 and MP4. The Duflow modelling for this schematization simulates quite well the actual patterns in water levels. Still some instabilities cause local deviations. Curious results are seen for MP1, at the end of the marsh. Here the simulated tide is both flooding and draining faster than observed in reality. The filling and draining pattern corresponding with the neap-spring tide cycle is reproduced. In the model, water levels at MP1 dry up completely during neap tide cycles, something which is not observed in reality. In fact all results for water levels below 1.97 m above NAP are fictiously generated along this 'unexisting' deep ditch.

The model does not take the vegetation on the marsh into account. Therefore the rise and fall of the tide is stronger in the simulation that in the measured situation. Another critical point is the geometry of the ditches, which have to be taken into account. Especially the smaller ditches are not well seized, yielding to errors in the schematization.

The model can still be used to evaluate the tidal storage over different parts of the marsh in relation to the neap tide - spring tide cycle. The results are for that reason usefull. As an example the discharge under the bridge and over the road is presented in Figure 5.13. This figure shows that at flood discharge only for a short time water is flowing over the road and that almost all ebb discharge is flowing under the bridge.

In the nearby future a 2D model, build for tidal wetlands by Van der Molen (1996), will be used to get a better understanding of the tidal propagation on the marsh.

6 Creek and Marsh Morphology

6.1 Topographical changes; from marsh to polder to marsh

Topographical data from 1963 and 1994 are used to make a chart with height differences (Figure 6.1). This chart shows general changes in this area for 31 years time span. It embraces a short period before reclamation in 1966 (3 years), the polder period (1966-1990, 24 years) and the most recent 4 years of tidal activity. Therefore, different processes have occurred which have resulted in these patterns. For the better comprehension of the situation, the zonation in 4 areas is also assumed for morphological evolution.

The first 3 years (1963 - 1966)were probably the least influential. We expect only some minor accretion to have taken place, give the fact that this part of the tidal marsh of Saeftinghe had already silted up to relative high level. The second period, when the marsh is reverted into a polder has left more than just a fingerprint. After reclamation soil processes such as ground water drainage, oxidization of organic matter and aerobic bioturbation, have resulted in net compaction and subsidence of the soil. These processes are described for similar areas by De Jong et al. (1994). Compaction is great for the clayey, wet and unripened sediments of the back marshes. On the contrarily, the relative high, dry and sandy sediments of the creek levees did not compact that much. As an effect, height differences should have increased after empoldering. But leveling of the surface and creek rectification did in general counteract this.

The western part of the Sieperdaschor, zone 4 in our methodology, shows a lowering of 0.2 to 0.5 m, except for some regions which have hardly changed. These correspond with locations of former creek levees. Height transects, which have been measured on a yearly basis since 1992, show that marsh surface in the westernmost part of the marsh has hardly changed. Net accretion is minor and averages about 4 cm in 4 years time. In the same period secondary drainage ditches filled up with about 20 cm (Figure 6.2 a/b/c and 6.3). In the central part somewhat higher sedimentation rates are observed on the marsh surface; about 6 cm. Deposition is observed especially in those areas which are flooded frequently and where standing water occurs, such as in drainage ditches and lower depressions which are converted into pools (Figure 6.2 b/c and 6.4). Here the compaction from 1966-1990 largely exceeds the recent accretion.

The second region is located in eastern part of the Sieperdaschor, where recent creek formation has been intense (zone 3). Here tidal action was first restored and is still most intense, as shown in the section of tidal evolution. Marsh surface has both lowered and accreted (Figure 6.2 d/e and 6.5). We conclude that soil compaction from 1966 to 1990 is more or less compensated by the deposition of new sediments since 1990 (Figure 6.1).

The closer to the breached dike, the higher the accretion rates of the marsh surface and the deeper the broadening of the creeks. Here maximum accretion of 13 to 21 cm from 1992 to 1996, or rates from 3 to 5 cm/year are observed (Figure 6.2 f/g and 6.6). The expectionally high sedimentation rate can only be explained by a large local sediment availability. Apart from the estuary itself, we assume that in this region the widening of creeks has served as an important sediment sourse. We will try to quantify this aspect in chapter 7.

The first zone fringes the estuary. This part of the marsh is located eastward of the former embankment and was never reclaimed. Average accretions of 0.2 to 0.5 m have occurred in this period of 30 years (Figure 6.1). This accretion rate of 1 to 2 cm/year is normal for the tidal marshes in the Scheldt estuary.

6.2 Creek formation after breaching

An ideal dendritic pattern, as observed in a natural created marshes, will probably never be attained in the Sieperdaschor. The artificial drainage network has played and still plays an important role in creek formation. Directly after tidal action was restored, tidal flow started to widen and deepen the main ditches. It seems that ebb is very persistent in following the artificial drainage network. The short-cuts are mostly made by the flood flow and, when deep enough, later used by the ebb flow as well. These creeks cross divert the initially expected flow.

In general, creek cross section for intermediate creek dimensions (1 to 10 m wide) in tidal marshes have a typical V-shaped. In zone 1, the natural fringing marsh, most creeks exhibit this form. But moving into the newly formed marsh, the general profile changes from V-shape to U shape. The creeks have steep creek banks and an almost flat creek bed. We link these U-shaped cross sections to all actively eroding creeks. It is in these creeks that after a storm flood, the creek bed is covered with freshly eroded lumps. These indicate that creek widening, not unexpectedly, especially occurs during these extreme situations.

With respect to the widening and deepening of creeks a special process is observed. All over the marsh steps in the creek beds are a prominent feature. These steps, both in creek bed depth and creek width, marked a place where cross sectional area changed abruptly, sometimes with a factor 5. Just downstream of the steps a deep scour hole was observed. The profile was U-shaped. But sometimes, downstream this gradually changed into a V-shaped creek profile. After visually observing flood and ebb flow around these steps, the morphological process was understood.

During flood flow, current velocities are mostly not high enough to erode the cohesive and compacted marsh soils along the creek banks. During ebb, water flow is concentrated along creeks and especially after a the marsh was flooded, high velocities occur. At the steps, cross section suddenly enlarges causing the flow to decelerate. This in turn causes highly turbulent conditions which form the deep scour hole, downstream of the step. Both creek head and banks become unstable and slump. This results in an upward movement of the cliff (the step). This process is illustrated in Figure 6.7. The surplus sediments from the scour hole and the bank slides is partly deposited downstream in the same creek. When the U shape profile, which was adjusted to the scour hole flow situation, was too large for the discharges the profile tends to fill up. Then the U-shape creek profile is reshaped into the more characteristic V-shape

During our field survey, a monitoring station was placed at the rear cliff of the main gully. There an averaged retreat of 4 cm/day was measured from July 18 to July 19 (rather high spring tide). A more continuous survey was not performed due to the unreliability of the reference stick, which had moved from its original position. On a second ditch, the retreat was measured to embrace about 4 cm over 4 days, being thrown out the rest of data due to the very lack of reliability.

6.3 Formation of marsh surface after breaching

In zone 1 nothing has really changed after the breach of the summer dike in 1990, apart from erosion along the main creek. Since 1966 the marsh topography had not changed in zone 2. In 1990 the original creek pattern was present and the surface was vegetated. Due to the old creek pattern, drainage was efficient and standing water did not occur. The vegetated surface and heavily rooted soil proved to be a stable substrate where new marsh plants, such *as Aster tripolium* [Zeeaster], *Salicornia europaea* [Zeekraal], *Elytrigia pungens* [Strandkweek], and *Phragmitus* [riet] could colonize easily.

In the third and fourth zone drainage was insufficient during spring tides and after storm floods. Standing water was formed along the southern side of the polder. This led to extreme long flooding periods with respect to marsh vegetation. As a result these pools remained unvegetated. Furthermore, waders and geese were foraging in soft muddy substrate. This bioturbation disturbs the possible colonization of marsh vegetation.

The total area of standing water and mud flat, is gradually diminishing (Figure 6.8). Drainage is improving throughout the marsh, due to the growth of the creek pattern. Also pools are accreting with imported sediments, decreasing flooding periods. We can see that especially *Phragmitus* is successful in colonizing these pools/mud flats.

As mentioned before, vegetation colonization was easier where a stable substrate was present. In the zone 3, an unvegetated part was present at the moment of the dike breach. This is shown by a processed LANDSAT image of this area of October 1989 (Figure 6.9). The vegetated (grasses) have a similar reflection pattern as the higher marshes of Saeftinghe. However two rectangular darker spots are visible in the polder which refer to the arable land (The area within the sea wall has masked [black]). The unvegetated land was directly converted into a mud flat. Vegetation colonization, especially with *Aster tripolium* and *Salicornia europaea* occurred gradually. Still, even in 1996 the central part was still unvegetated. This area is located at the end of the central creek which has experienced both erosion and sedimentation up to 0,5 m.

Towards the west grazing of the marsh has led to regions with short vegetation and a substrate which is heavily trampled by the hooves of the cows. Natural influences both with respect to morphology and vegetation are relatively small.

7 Sedimetation budgets and fluxes of water and sediments

7.1 Sedimentation budget

With the height transects of the marsh surface and creeks from 1992 and 1996 sedimentation and erosion are quantified throughout the marsh. This calculation is rather rough due to the limited amount of data in such an irregular topography. Still, this calculation will give a rough idea of the deposition and erosion in the marsh and its geographical variation. We have divided the marsh in 7 regions. The first 4 regions correspond with zone 4, region 5 corresponds with zone 3, region 6 with zone 2 and region 7 with zone 1.

Separate calculations are made for: a) the open marsh surface (Table 7.1), b) the ditch parallel to the sand dam (Table 7.2), c) the accreting ditches (irrigation ditches which have silted up; Table 7.3) and d). the eroding ditches (e.g. the irrigation ditches which have enlarged; Table 7.4).

*Table 7.1 Sediment balance for the open marsh during the last 4 years (1992-1996) *excluding the ditches and creeks.*

Zone	open marsh surface (m^2)	averaged accretion (cm)	sediment budget marsh surface (m^3)
1	88479*	3.7	3274
2	139772*	6	8442
3	85635*	5.6	4804
4	83635*	4.2	3488
5	97594*	9	8783
6	133422*	12.7	16998
7	59150*	21	12244
total	68.8 ha*/71.3 ha	8.4	58033

In total (Table 7.5) about 44,000 m^3 of sediments has accumulated over the last 4 years on the 71.3 ha's of the Sieperdaschor, which is about 156 m^3/ha/year. The total deposition on the marsh surface was 58.000 m^3, of which about 14.000 m^3 were derived from erosion in the creeks. This means that about 75% of sediments have been imported from the estuary.

The whole marsh (former polder) surface has experienced a net vertical accretion of on average 8.4 cm from 1992 to 1996. This is an average net sedimentation of the surface (without the creeks) of 1.4 cm per year. Sedimentation rates of 1 to 1,5 cm/year is comparable with sedimentation rates in the neighboring Saeftinghe marsh (Krijger, 1993).

The accretion rate of more than 2 cm/year is higher than most marshes in the Scheldt estuary. But as the figures in the Sieperdaschor point out, the net sedimentation on the marsh surface is both imported in the marsh but is also partly locally derived. Within the marsh there is a redistribution of sediments from the eroding creeks (in the eastern part) of the marsh to the marsh surface (in the eastern en central part).

Table 7.2 Sediment balance for the parallel ditch (1992-1996).

Zone	parallel ditch length (m)	parallel ditch averaged width (m)	averaged accretion (cm)	sediment budget ditch (m^3)
1	400	2.1	70	594
2	500	3	60	900
3	500	3	-10	-150
4	500	4	-30	-600
5	500	4	-50	-1000
6	500	6	-70	-2100
7	225	7.5	-140	-2308
total	3125	4	-37	-4464

Table 7.3 Sediment balance for the accreting ditches (1992-1996).

Zone	accreting ditch total length (m)	accreting ditch averaged width (m)	averaged accretion (cm)	sediment budget (m^3)
1	1947	1.3	19.3	496
2	2708	1.5	20	659
3	-	-	-	-
4	-	-	-	-
5	1009	2	15	311
6	265	3	21	195
7	-	-	-	-
total	3491	2.7	18	1661

Table 7.4 Sediment balance for the eroding ditches (1992-1996).

.Zone	eroding ditches total length (m)	eroding ditches averaged width (m)	averaged erosion (cm)	sediment budget (m^3)
1				
2				
3	133	8	18	193
4	500	3.3	47	775
	13	5	25	169
	500	8.4	21	882
5	240	2	38	182
6	177	4.2	100	740
7	133	11.3	184	2750
	300	11.5	147	5071
total	2116	6.4	79	10762

Table 7.5 Total sediment balance throughout different zones (1992-1996).

Zone	1	2	3	4	5	6	7	total
	0-500 m	500-1000m	1000-1500 m	1500-2000 m	2000-2500 m	2500-3000 m	3000-3200m	
sediment budget (m^3)	4.369	10.001	3.686	1.837	7.912	14.343	2.115	44.273

The rear half of the marsh, divided in regions 1 to 4 (zone 4), has experienced only minor sedimentation from 1992 to 1996. Region 1 (the first 500 m) and region 4 (from 1500 to 2000 m), net sedimentation of the marsh surface averages about +4 cm in 4 years. In these regions drainage ditches are filled up with about 19 cm. The second and third region, have experienced somewhat higher sedimentation rates, averaging 6 cm. Deposition is observed especially in those frequently flooded areas where standing water occurs, such as in ditches and lower depressions which are converted into pools. The higher net sedimentation rates in regions 2 and 3 are the result of the relative low topography (1,5 to 2 m above NAP) and consequently higher flooding frequencies.

In regions 5, 6 and 7 (zones 3, 2 and 1 respectively) both net accretion rates of the marsh and erosion rates in the creeks are high. These changes in sediment volumes determine largely the total sediment balance.

Moermond (1994) suggested a general leveling of the marsh surface, caused by the filling up of ditches. We agree that this might happen in the rear end of the marsh, where even the main parallel creek is accreting. Some parts of that creek have even completely overgrown with reed. However, in the rest of the marsh, creeks are still widening an deepening and have not reached their equilibrium profile so far. We assume that tidal influence will still increase for several years, reaching deeper parts of the marsh.

7.2 Flux measurements of water and sediments

Measurements at the bridge location

Due to the homogeneous vertical velocity distribution, the distribution of suspended load is also quite homogeneous all through the water column (Figure 7.1 and 7.2). At the bridge maximum fluxes of water and suspended matter (from now on: SPM) occur just before and after high water slack (Figures 7.3 and 7.4). At the normal tide (July 17, 1996) the water flux peaks for flood and ebb are almost equal (Table 7.6). Over the complete tidal cycle there is still a surplus of water entering the marsh. The SPM flux peak is higher for the ebb, but there is no appreciable net import or export of suspended matter (less than 1 % of the total flux).

At spring tide peak fluxes of both water and SPM are higher for the flood. Still flux calculations show a negative flux of water of about 7% of the total flux. The reason is that water that entered the marsh as overbank flow, is draining preferably through the creeks and passes the transect at the bridge. This is discussed in chapter 5 and also observed in other marshes (Dankers et al., 1984). Despite this negative water flux, there has been a considerable import of sediments of about 2500 kg, which is about 5 % of the total flux in SPM.

Table 7.6 Water fluxes at the bridge and in the creek

water flux (m^3)	TOTAL	FLOOD	EBB	FL-EBB	%TOTAL
bridge 17-07-96	180.119	94.160	85.959	8.201	4,6 %
bridge 01-08-96	477.017	224.044	254.973	-32.929	-6,9 %
ditch 18-07-96	37.188	21.018	16.170	4.848	13,0 %
ditch 31-07-96	92.834	44.456	48.378	-3.921	-4,2 %

Measurements at the ditch location

At the ditch location, the time pattern of water and SPM fluxes is typically asymmetrical (Figure 7.5 and 7.6). The peak at flood is high but short, whereas the outflow during ebb is longer with much lower maximums. The drainage during ebb shows several pulses which probably are caused by differential drainage of distinct sections of the marsh.

The net water flux is inward at the average tide (July 18, 1996) when only a small portion of the marsh was flooded (Table 7.7). At spring tide (July 31, 1996), the water flux in the creek is negative as observed at the bridge. Both at average tide and at spring tide a considerable SPM flux of 37 to 55% of the flood respectively have been measured. Even though the total flux at spring tide is 8 times smaller than at the bridge, the net flux of SPM is similar. This shows that the western part of the marsh is acting as a very effective sediment trap. This observation suggests no net sedimentation occurs in the marsh between the bridge and the ditch measuring sites. This contrary to our findings. Therefore we speculate that sediments are eroded in the creek systems and transported into marsh.

Table 7.7 Suspended matter (SPM) flux at the bridge and the ditch location

SPM flux (kg)	TOTAL	FLOOD	EBB	FL-EBB	%TOTAL
bridge 17-07-96	10.008	4.969	5.039	-70	-0,7 %
bridge 01-08-96	55.596	29.055	26.541	2.515	4,5 %
ditch 18-07-96	3.553	2.191	1.361	830	23,4 %
ditch 31-07-96	7.599	5.320	2.279	3.041	40,0 %

7.3 Composition of Suspended Matter

At a well developed spring tide of September 27, 1996, water samples were taken to determine the composition of de suspended solids of both flood and ebb flow. We have taken 3 samples during the flood period, one at high water slack and two more during the subsequent ebb period. The samples were taken at a depth of 0,5 m above the creek bed. For every sample 300 l of water were pumped and centrifuged to extract all suspended matter, using a mobile car-laboratory form the Survey Department. Then the samples were analyzed in the laboratory for composition and grain size distribution. The results are presented in Table 7.8.

The SPM concentrations on September 27, 1996, where more than twice as high as the SPM concentrations at the same locations two months earlier August 1, 1996, during similar tidal circumstances (well developed spring tide). We have no idea what has caused the difference. Weather conditions on both days were fair with low to moderate wind speeds.

With respect to the suspended sediment composition, we have seen different results for the flood and ebb samples, except for humus and carbonate content. The result from the sampling at high water slack, a very similar to the flood results. This is probably caused by hystheresis, which means that SPM was not yet adjusted to the lower flow velocities. These samples all have sand contents (sand fraction is larger than 63 microns)of about 55 to 60 % and silt contents of about 20%. The median grain size was about 90 to 115 microns. The samples taken during the ebb period both exhibit somewhat lower sand contents, however median grain sizes were twice as low.

Table 7.8. Total amount of SPM (in 300 l) and concentration of SPM for 6 samples at the location of the bridge; well developed spring tide 27/9/96.

Time	tidal period	total SPM g	SPM conc mg/l	sand content weight%	siltcontent weight%	Humus weight%	Carbonate weight%	D50 microns
14'00-14'20	start of flood	22	73	55,6	21,9	1,3	21,2	87
15'00-15'20	flood	86	287	66,0	16,0	1,.9	16,0	117
15'40-16'00	maximum flood	164	547	59,9	22,6	2,4	15,1	111
16'30-16'50	high water slack	66	220	53,0	28,0	1,0	18,0	116
17'40-18'00	maximum ebb	144	480	34,7	35,8	3,2	26,3	40
19'00-19'20	end of ebb	102	340	47,6	30,5	1,8	20,1	49

8 Soil structure and chemistry

8.1 General

In general, mineral soil composition of marshes can vary from sandy soils on creek levees, to very clayey soils in the back marshes (Long and Mason, 1983). Also large variations in mineralogic composition, e.g. carbonate and organic contents, are familiar on marshes. But these patters are not completely irregular. Kooistra (1978) found that organic content and percentage of the clay fraction were positively correlated for salt marshes in the Eastern Scheldt. Organic contents may vary from 50% dry weight in *Spartina alterniflora* marshes to 8% and less on a *Puccinellia maritima* dominated marsh (after Long and Mason, 1983). It is also found that organic content often shows an increase with marsh elevation.

Organic matter in marsh soils is either produced within the marsh or imported. Marsh vegetation provide (shoot) litter, whilst dead rhizomes add organic matter to the soil at various depths. Marshes are considered effective sediment traps. Vegetation reduces the water flow allowing even fine and relative light sediments to settle.

After empoldering a number of soil-related processes occur at reclaimed areas. Some are due to mechanical human activities, such as ploughing, ground surface leveling and the construction of a drainage pattern. Others are due to soil processes such as an increase in soil compaction (especially in very clayey soils) and a reduction of organic matter content (Kooistra, 1978; De Jong et al., 1994). This decrease is caused by sediment decomposition after drainage and aeration of the soils. Kooistra (1978) reports 1.4% C (from dry samples) in polders and 5.6% on adjacent salt marshes. Carbonate deficiencies, linked to sulfur oxidation reactions, eventually cause acidification of the soils. This is also often experienced in fresh empoldered areas. De Jong et al. (1994) have also observed this process after a long emersion and drying of a salt marsh in the Eastern Scheldt. The by-products of this soil process, Ferro oxides, can be observed clearly in creek beds in the Sieperdaschor and as oil-films on water surfaces. Thus, a history of the soil might be reconstructed using the observations of Kooistra (1978).

Waterlogged soils are depleted from oxygen and the soils become anaerobic. Microbial activity uses electron acceptors other than oxygen; the soil reduces and the Red-Ox potential drop.

8.2 The 1992 situation

Moermond (1994) has found two regions with different soil characteristics in the Sieperdaschor. In the first region, extending about 1,100 meters from the front part of the polder (zone 1 to 3), she found relative high contents of organic matter and antropogenic-related compounds such as iron, cadmium, copper, lead, nitrogen and phosphates. This was explained on the basis that, despite the compounds present from the pre-reclamation period, even during empolderment, this part was flooded several times per year. Estuarine sediments were deposited in the proximal part of the former polder. In the more intensely used distal part of the polder, drainage and aeration of the soils was better. Nutrients and micro pollutants were either leached out by surfacial freshwater streams or taken up by agriculture (Moermond, 1994).

8.3 The 1996 situation

Results of the soil survey are for different transects presented in Figures 8.1 to 8.11 which are all visualized relative to NAP. The explanations of the abbreviations can be found in annex I.

Aeration depth

During the visual description of the soil samples In the fieldwork evidence of the presence of pyrite and accumulations of ferric oxides were found at the interface of the reduced and oxidized environment. Normally this a strong mottling of brownish to reddish colors due to ferric compounds was observed. In this zone black mottles of manganese oxides were also found.

As can be observed from our soil coring, the extension of the aerated zone varies depending on the geomorphologic unit. For instance, on creek levees and higher areas existing of coarser sediments, are better drained and the aerated zone is deeper. In the back marshes, pools or in the creek beds, the aerated layer was smaller and sometimes even absent. These features are seen in most tidal marshes.

Nevertheless, in the Sieperdaschor, relative thick aerated layers are common all over the marsh. We consider this an artifact of former land use, when drainage led to better aeration. The formation of shrinkage cracks and soil ripening increases soil aeration in general.

When waterlogging is permanent, oxygen concentrations rapidly decrease, due to benthonic (micro-biological) activity, the soils are reduced. Mostly we found these soils to have high organic matter contents (see C10, C12 and C2). At locations C3 and C4 this is not found, because of the relative high sand contents. As expected, there is an inverse correlation between sand and organic contents for the front half of the polder (Figure 8.12). Sampling sites 1 to 5 were taken in the pools which had a higher elevation compared to sites 6 to 10, in the rear half of the Sieperdaschor.

Carbonates and organic content

Some features seem to have changed since 1992 when soil composition was described by Moermond (1994). In Table 8.1 organic and carbonate content is given for 4 zones for averaged data from the transects from Moermond (1994) and recent data. Both locations and methodology are different for these sets of data, so conclusions can only be tentative.

Table 8.1. Carbonate and organic contents for different areas in the Sieperdaschor (from Moermond, 1994, and own elaboration)

	Zone A	Zone B	Zone C	outside
% organics (Moermond, 1994)	9.14	5.17	4.65	-
% organics (here)	1.74	4.97	0.92	1.89
% carbonates (Moermond, 1994)	12.90	11.30	13.10	-
% carbonates (here)	17.28	17.09	16.39	17.57

Normally organic content should increase in depth, due to reduction processes and decrease of aerobic microbial actiivity. However, there are plenty of locations, where analyzed data show show a sharp decrease in organics with depth. We have three explanations: a) on sandy levees marsh vegetation debreis and root/rhizomes systems on the surface, b) in low basins but also on higher spots, organic accumulations (elsewhere eroded peats) can be deposited in deeper layers and c) in general newly imported sediments are expected to contain a higher organic percentage than post-reclaimed materials, particularly due to peat content of estuarine waters. When sediment is eroded in creeks inside the polder is thought to bear a lower organic content since polder soils are poor in organic content, except for peat layers.

In some environments organic matter content can be used to indicate sediment sources. However, bioturbation and for instance cattle excrement, can strongly bias these results. At transect C10A, high organic content are probably mainly caused by cattle excrement.

We have observed a general decrease of carbonate contents with depth, except for those cores where shell accumulation occurs or where bioturbation is prominent. This indicates that the newly deposited sediments have higher carbonate contents. Carbonate decrease deeper in the soil must be related to the carbonate dissolving with ground water flow, during the polder period. Then better drainage and shortage of new input of carbonates should led to these lower contents.

Soil structure.

Soil cores can be divided roughly into four types, matching with different morphological units: creek levees, creek beds, backmarshes and mudflats. The deeper parts of the cores are mostly composed by sand and silty sand. These are the former mud and sand flat deposits, before a marsh was formed centuries ago (see for instance C9A).

The part of the cores that belong to the marsh deposits, vary enormously from sandy to clayey layers. Often alternate layering is observed, evidence of successive historical episodes. It is not within the scope of this report to interpret the paleo stratigraphical records. The upper part of the cores was to us the most relevant, for it provides information of recent changes from the polder to the marsh environment.

A hard, silty layer is found, particularly on transects C2, C3, C4, C8, C10 and C12. The layer is rather dry, well ripened and oxidized. The layer is situated at about NAP +2 m (plus or minus 80 cm), at variable depths below the present ground surface. However, reconstructing the 1990 topography, we think this layer was situated at about 60 to 80 cm below former ground level. We believe this layer to have formed after reclamation of the area. The layer is a former accumulation zone of fine particles which were transported from the (ploughed) upper layer to deeper depths. This hard layer appears only in the central region of the marsh, were agricultural use has been most active. This hard layer has also a geomorphologic importance. It is often observed to form the creek bed, acting as an erosion basis.

9 Discussion

Most results have already been discussed in the previous chapters. In this chapter we will focus on the relations between the different subjects.

restoring tidal activity
The restoration of tidal activity in 1990, has set in motion a chain of processes which have changed the former polder into a tidal marsh, at least for the eastern part of the Sieperdaschor. The tide is the main "engine" for the geomorphological processes; e.g. the lengthening and widening of creeks and the accretion on the marsh surface. But in turn, we have seen that the changing creek system and topography, influence the tidal propagation as well. Tidal action has increased in these 6 years, illustrated by a larger tidal range. Human interventions have accelerated this change significantly.

human interventions
The most important human intervention was not do anything in the first place, immediately after the dike had breached in 1990. From then on new problems arose at the road and along the sand dam. First the siphons were replaced with a bridge. One year later a central creek was dug and wider bridge installed. These interventions have all led to a wider cross section at the road crossing. Pethick (1992) has shown that the dimensions of a creek system in a tidal marsh depend on the width of the creek at the mouth of the system. Indeed, in the Sieperdaschor we have observed new impulses to the widening of creeks when the limited cross section at the road crossing was widened. Even now the cross section at the bridge limits the extension of the creeks upstream. The level of the revetments under the bridge forms the erosion basis of the creek beds upstream. If the creek at this point was allowed further widening, tidal influence in the Sieperdaschor will experience an extra increase.

zonation approach (include observations on soil features)
We have found the zonation approach to work quite well. The first zone, or reference, has hardly changed within these six years, apart from some accretion of the marsh surface and erosion along the main creek. This marsh is significantly higher than the rest of the Sieperdaschor, because normal accretion took place during the period 1966-1990 when the Sieperdaschor was turn inot a polder.

In zone 2, remnants of the pre 1966 marsh were present. Still, most creeks have widened considerably, especially the main creek. Before 1990, this part of the polder was used as grazing land. Due to the low creek beds, drainage was efficient and standing water did not occur in this zone. The vegetated surface and heavily rooted soil proved to be a stable substrate where new marsh plants, such *as Aster tripolium* [Zeeaster], *Salicornia europaea* [Zeekraal], *Elytrigia pungens* [Strandkweek], and *Phragmitus* [riet] could colonize easily.

In the third and fourth zone drainage was insufficient during spring tides and after storm floods. Standing water was formed along the southern side of the polder. This led to extreme long flooding periods with respect to marsh vegetation. As a result these pools remained unvegetated. However, drainage has improved over the years. The creeks have widened and new creeks are created draining more and more former pools. The total area of standing water and mud flat, is gradually diminishing. Also pools are accreting with imported sediments, decreasing flooding periods. We can see that especially *Phragmitus* is successful in colonizing these mud flats. This will reduce the foraging possibilities for waders, ducks and geese. On the other hand, other birds will profit from the increase of reed habitat.

As mentioned before, vegetation colonization was easier where a stable substrate was present. In the zone 3, an unvegetated part was present at the moment of the dike breach. This was the arable land, with a loose soil. This part was soon converted into a mud flat after tidal activity was restored. Vegetation colonization, especially with *Aster tripolium* and *Salicornia europaea* occurred gradually. Still, even in 1996 the central part was still unvegetated. This area is located at the end of the central creek which has experienced both erosion and sedimentation up to 0,5 m.

creek widening process

An ideal dendritic pattern, as observed in a natural created marshes, will probably never be attained in the Sieperdaschor. The artificial drainage network (ditches) has played and still plays an important role in creek formation. Directly after tidal action was restored, tidal flow started to widen and deepen the main ditches. It seems that ebb is very persistent in following the artificial drainage network. The short-cuts are mostly made by the flood flow and, when deep enough, later used by the ebb flow as well. These creeks divert the initially expected flow.

All eroding creeks have steep creek banks and an almost flat creek bed. Pethick (1992) suggests that creek evolution shows a clearer response to flood, in order to dissipate this tidal prism, as a part of the mudflat system, than to ebb. That does not match with processes in the Sieperdaschor. With respect to the widening and deepening of creeks a special process is observed. During flood flow, current velocities are mostly not high enough to erode the cohesive and compacted marsh soils along the creek banks. During ebb, water flow is concentrated along creeks and especially after a the marsh was flooded, high velocities occur. At the steps in the creek bed, cross section suddenly enlarges causing the flow to decelerate. This in turn causes highly turbulent conditions which form the deep scour hole, downstream of the step. Both creek head and banks become unstable and slump. This results in an upward movement of the cliff (the step).

tidal discharges and sediment budgets

Tidal discharges are especially high when the marsh is flooded. Within the main creek there is a net export of water. Flood water which has entered overmarsh, perferably drains through the creek system. However sediment fluxes showed a clear flood surplus, indicating a net import of sediments into the marsh. This fits with, albeit rough, calculation of sediment budgets in the Sieperdaschor for the period from 1992 to 1996. In total about 44,000 m^3 of sediments has accumulated over the last 4 years on the 71.3 ha of the Sieperdaschor. The total deposition on the marsh surface was 58.000 m^3, of which about 14.000 m^3 were derived from erosion in the creeks. This means that about 75% of sediments have been imported from the estuary. The accretion rate of more than 2 cm/year is higher than most marshes in the Scheldt estuary. But as the figures in the Sieperdaschor point out, the net sedimentation on the marsh surface is both imported in the marsh but is also partly locally derived. Within the marsh there is a redistribution of sediments from the eroding creeks (in the eastern part) to the marsh surface (in the eastern en central part).

soil processes in relation to the changing hydrodynamics and morphology

Special emphasis has been given to ground water flows. In a marsh ground water flow depends on the soil texture, structure and topography. At low tide water seeps laterally, first through the lower strata and eventually through upper layers. Ground water recharges particularly where flooding is persistent, and then waterlogging occurs. As the ebb starts the process reverses and drainage starts (Long and Mason, 1983). In such high marshes, where the existence of cracked subsoil is set in evidence, a sub surgical flow is more than probable.

10 Conclusions

The restoration of tidal activity in 1990, has set in motion a chain of processes which have changed the former polder into a tidal marsh, at least for the eastern part of the Sieperdaschor.

The tide is the main "engine" for the geomorphologic processes. But in turn, the changing creek system and topography, influence the tidal propagation as well. As a result of these interactions, tidal action has increased in these 6 years, illustrated by a larger tidal range. Human interventions have accelerated this change significantly.

In the Sieperdaschor new impulses to the enlargement of the creek system occurred every time the limited cross section at the road crossing was widened. Even now the cross section at the bridge, limits the extension of the creeks upstream. If the creek at this point is allowed further widening, tidal influence in the Sieperdaschor will increase.

The artificial drainage network has played and still plays an important role in creek formation. Directly after tidal action was restored, tidal flow started to widen and deepen the main ditches. It seems that ebb is very persistent in following the artificial drainage network.

From 1992 to 1996 a total amount of about 44,000 m^3 of sediments has accumulated in the Sieperdaschor. The total deposition on the marsh surface was 58.000 m^3, of which about 14.000 m^3 were derived from erosion in the creeks. This means that about 75% of sediments have been imported from the estuary.

The accretion rate of the marsh surface is more than 2 cm/year, which is higher than most marshes in the Scheldt estuary. This is caused by the erosion of creeks in the marsh, providing an extra sediment source.

Vegetation colonization with marsh plants was more successful where a stable vegetated substrate was present. An unvegetated part, arable land at the moment of the dike breach, was soon converted into a mud flat after tidal activity was restored

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Annex I. Soil transects and corings

For this annex, this legenda must be followed:

H:	homogeneous
I:	interlayered
Fresh:	recently deposited
M:	mud
C/Cl:	clay
SA:	sand
S:	silt
P:	peat
I:	iron mottles
Red/Reduct:	reduced
Ox:	oxidized
RIP (1-10):	ripening status
Hard:	hard compaction
Loose:	loose compaction
Dry:	water absence
Wet:	water presence
Biot:	biorurbation in general
Shells:	shells presence
Roots:	roots and rhizomes
Dark tones:	reduced sediment
Light tones:	oxidized sediment
Stripped horizontal line:	limit of aeration depth

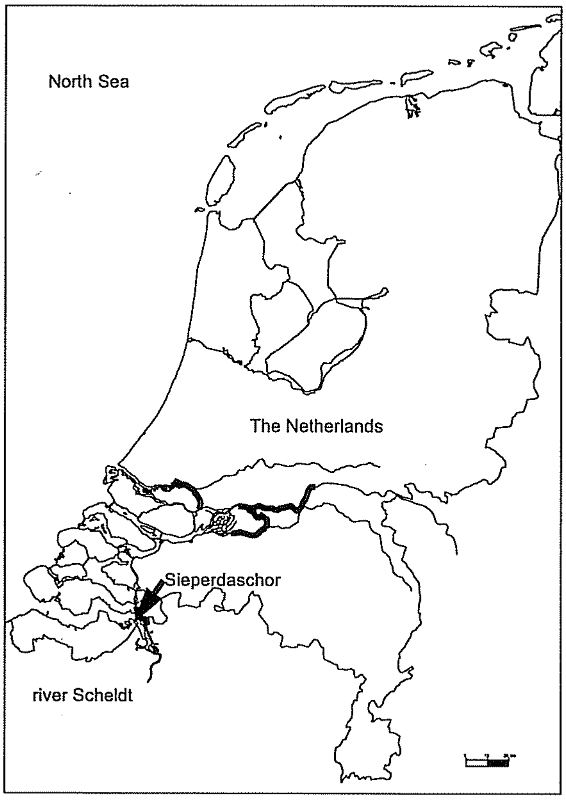

Figure1.1 **Location of the Sieperdaschor in the Scheldt estuary.**

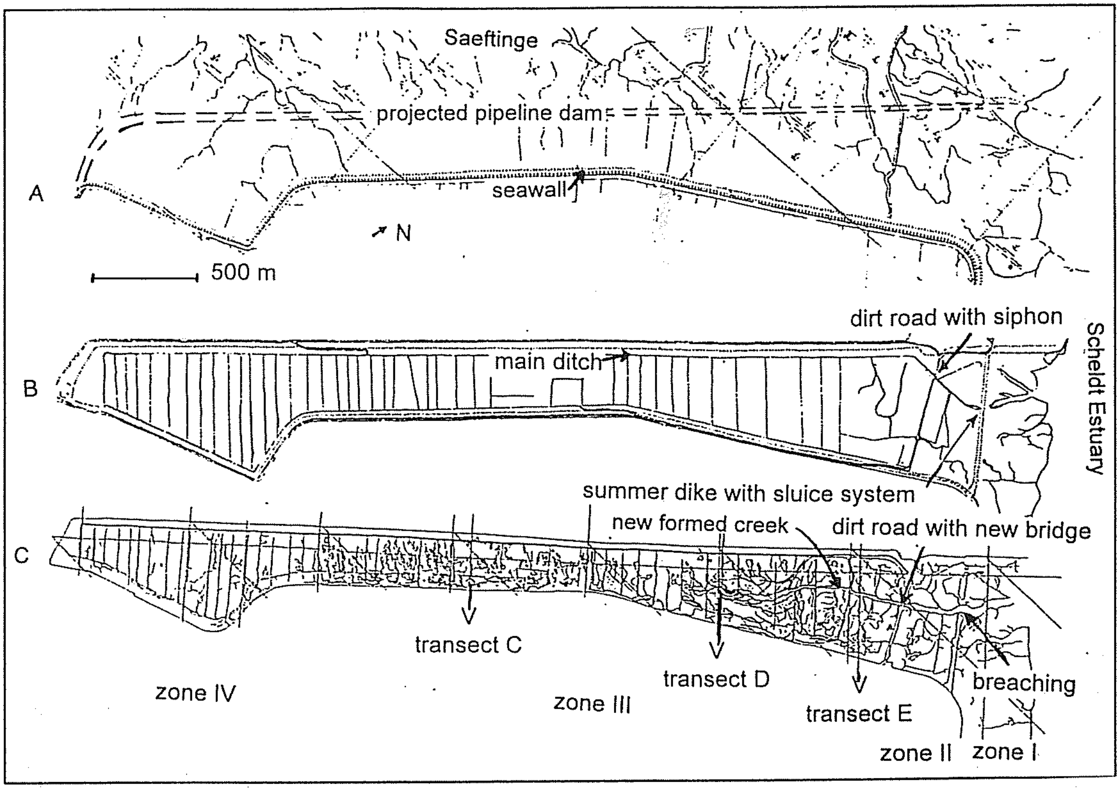

Figure1.2 **A) The area before 1966 with the projected pipeline; B) the area as a polder; C) present situation (1996); D) Location of the Sieperdaschor in the Scheldt estuary.**

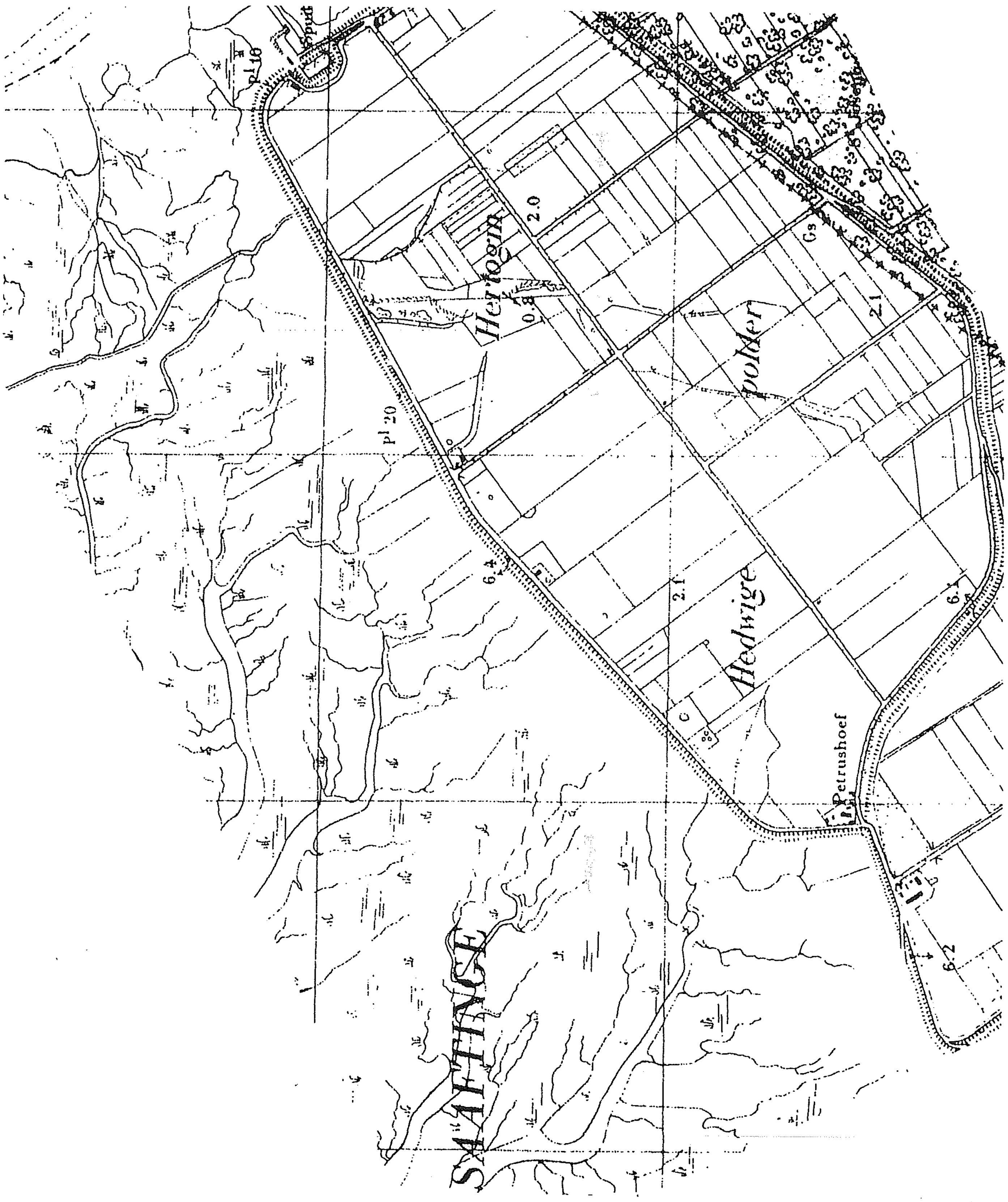

Figure 2.1 The Sierpdaschor still a part of the Saeftinghe tidal marshes; before 1966.

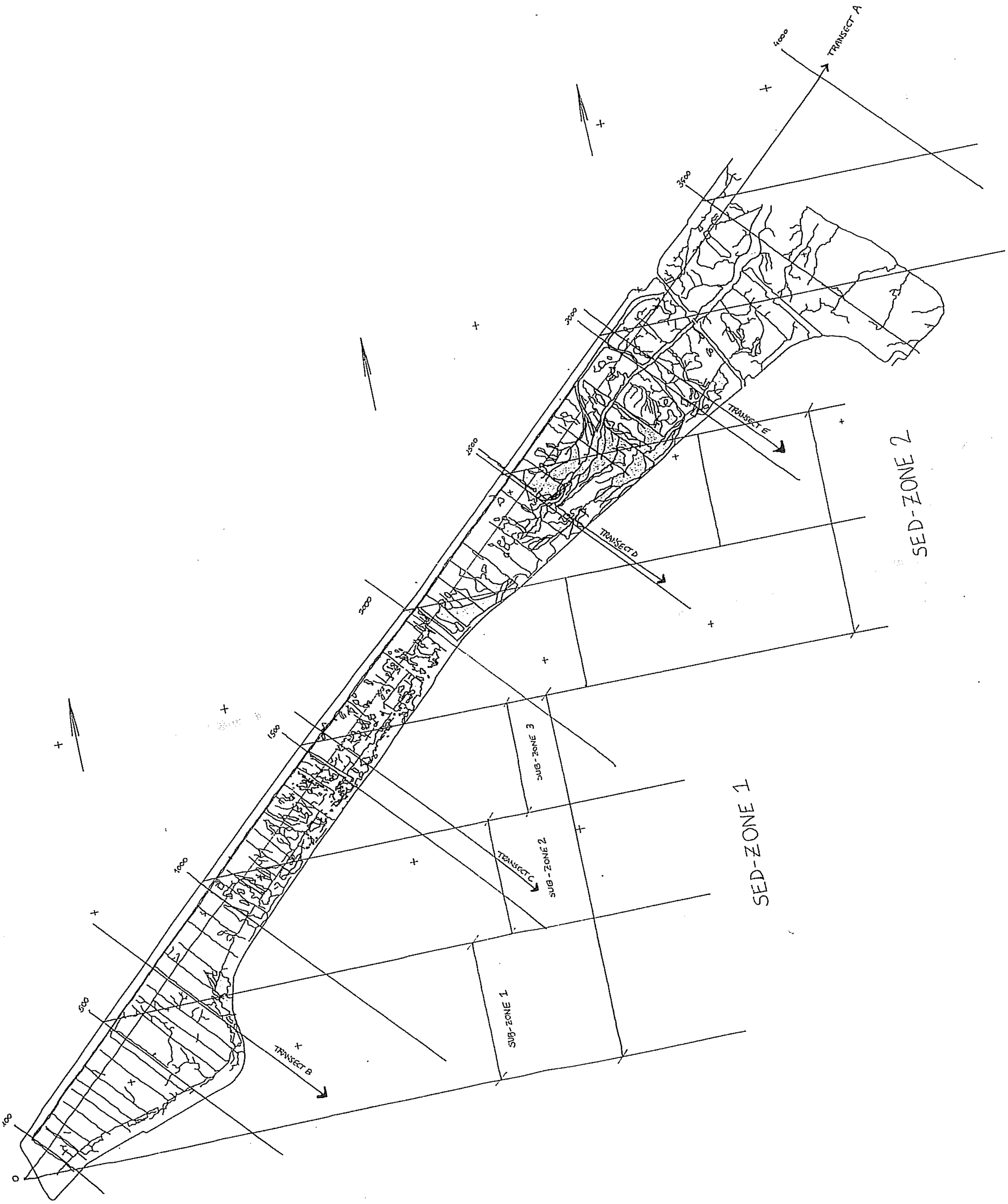

Figure 2.2 The Sieperdaschor in 1996 with creeks, ditches and mud flats (based on aerial photographs of spring 1996).

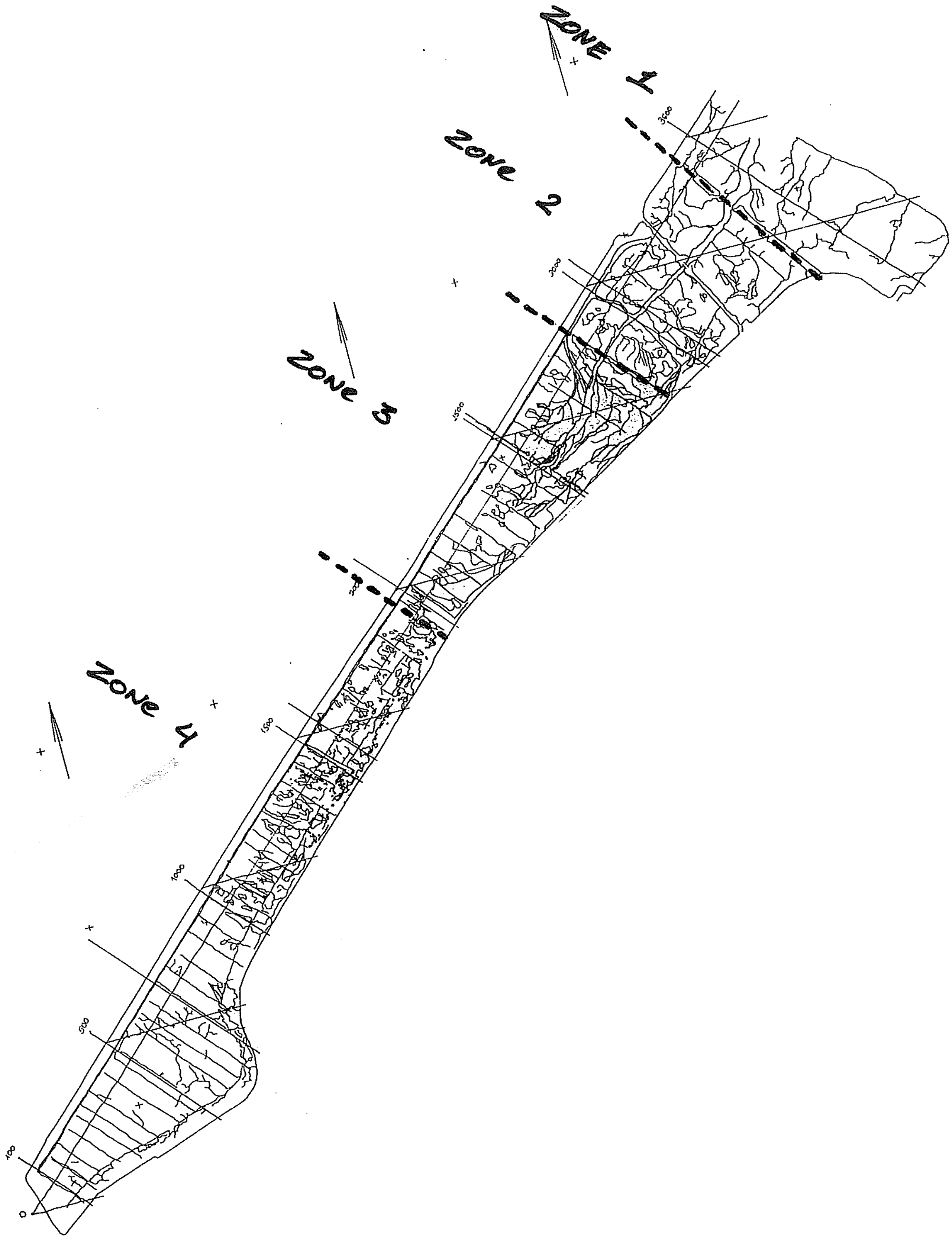

Figure 3.1 The 4 zones designated in the Sieperdaschor.

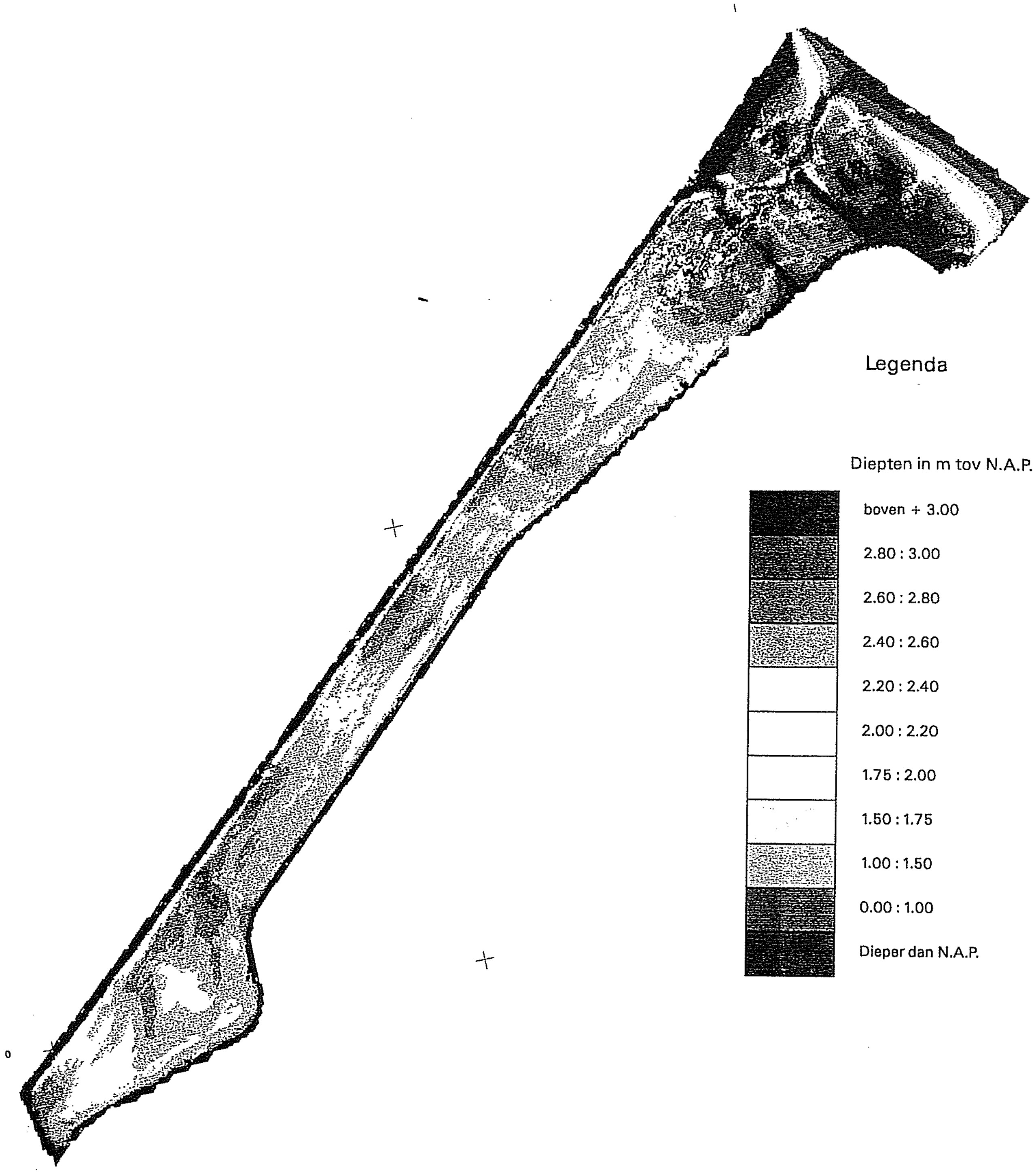

Figure 4.1 The topography of the Sieperdaschor in 1994.

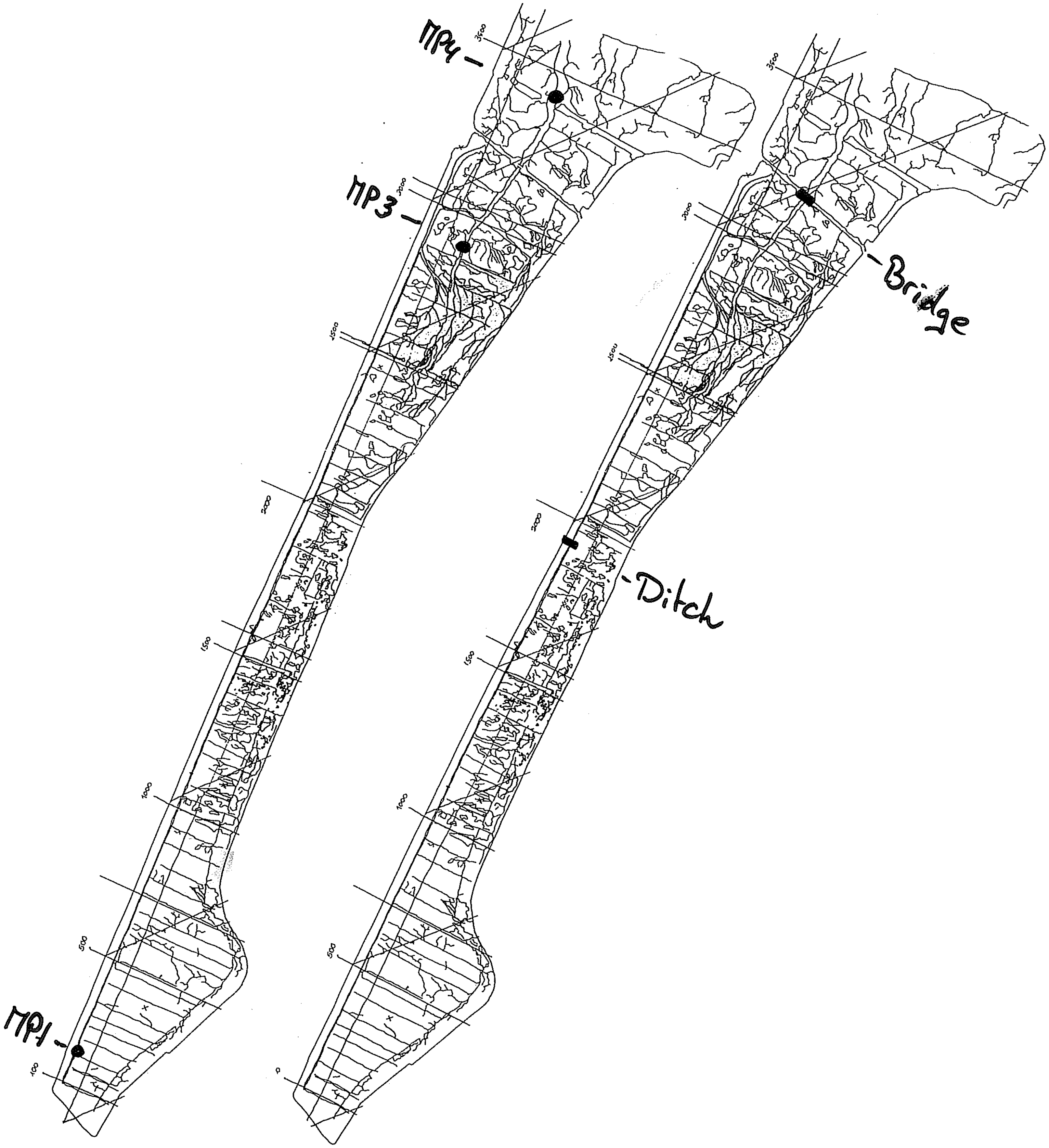

Figure 4.2 Measuring positions of water levels in Sieperdaschor: MP 1, MP3 and MP4.

Figure 4.3 Measuring locations of the flux measurements in the Sieperdaschor: bridge location and ditch location.

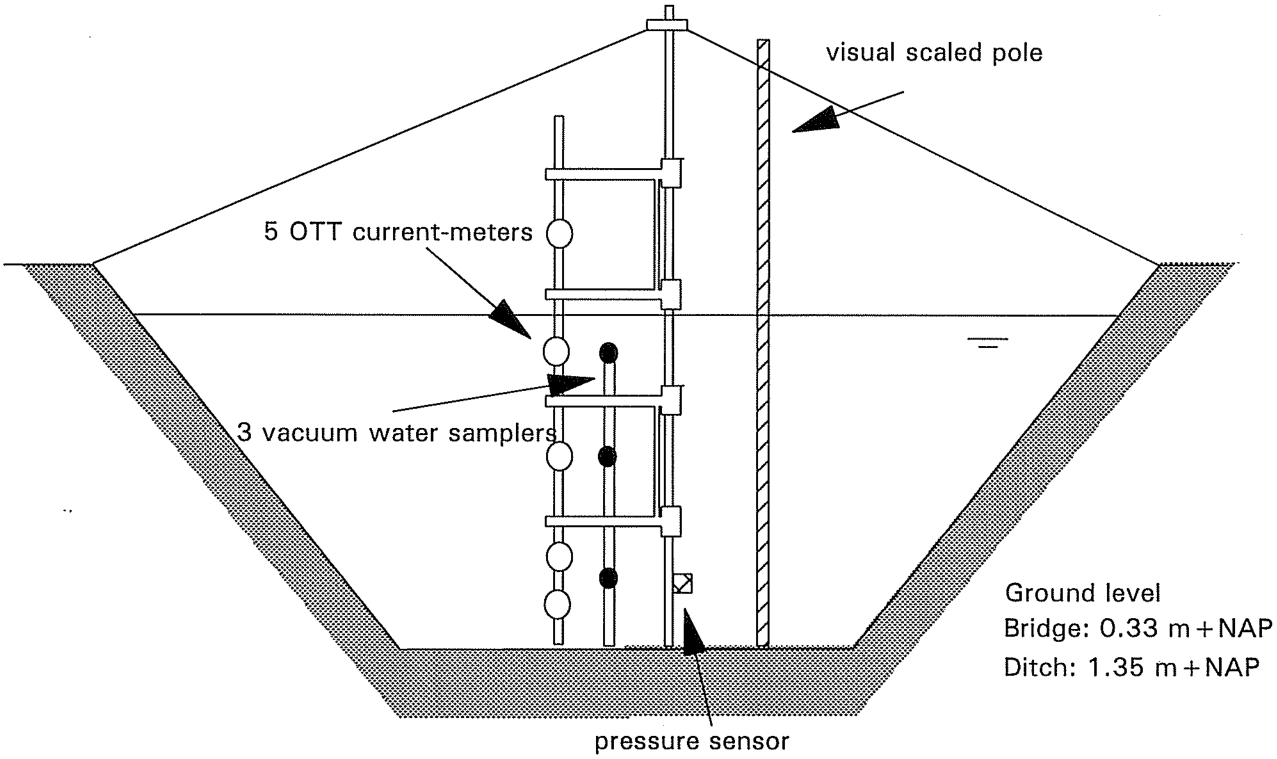

Figure 4.4 The standard arrangement of the instrumentation during flux measurements.

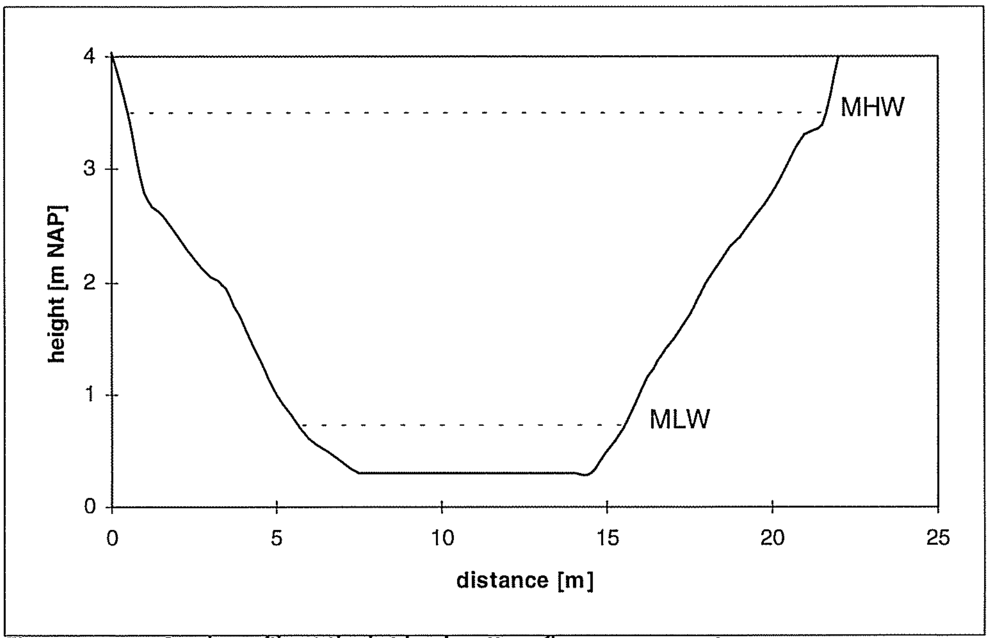

Figure 4.5 Creek profile at the bridge location; flux measurments.

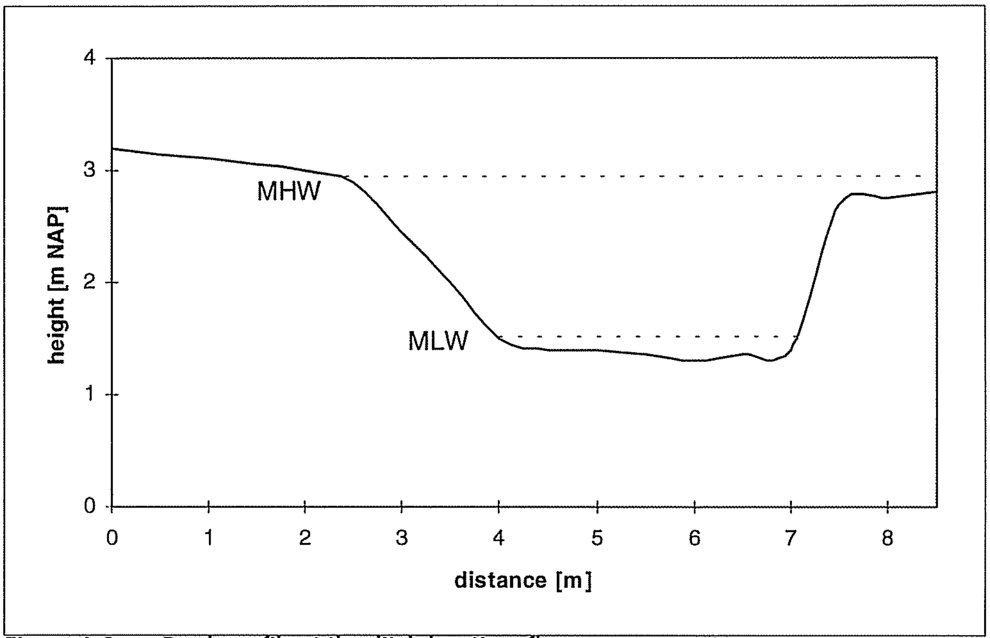

Figure 4.6 Creek profile at the ditch location; flux measurements.

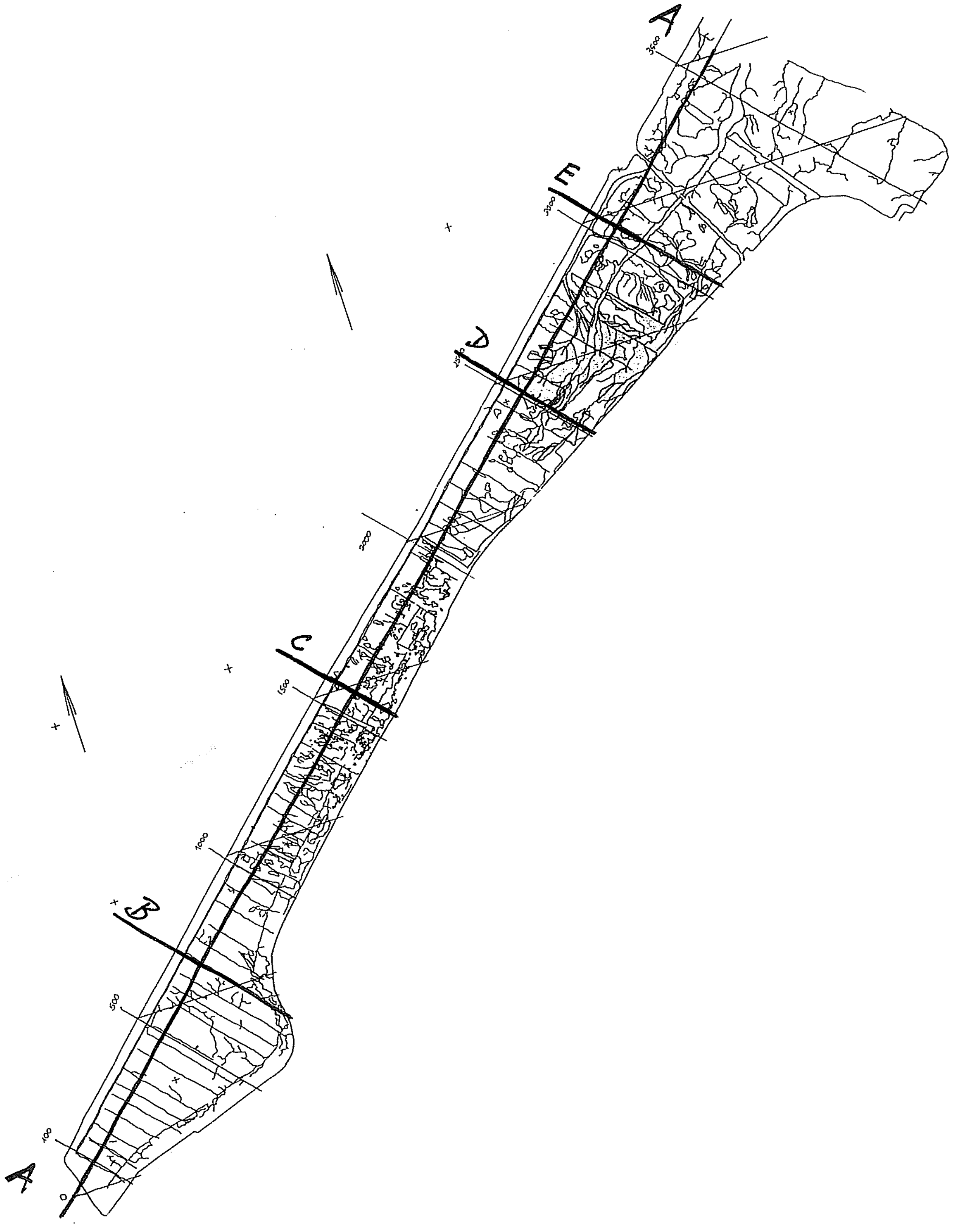

Figure 4.7 Height transects A, B, C, D and E in the Sieperdaschor.

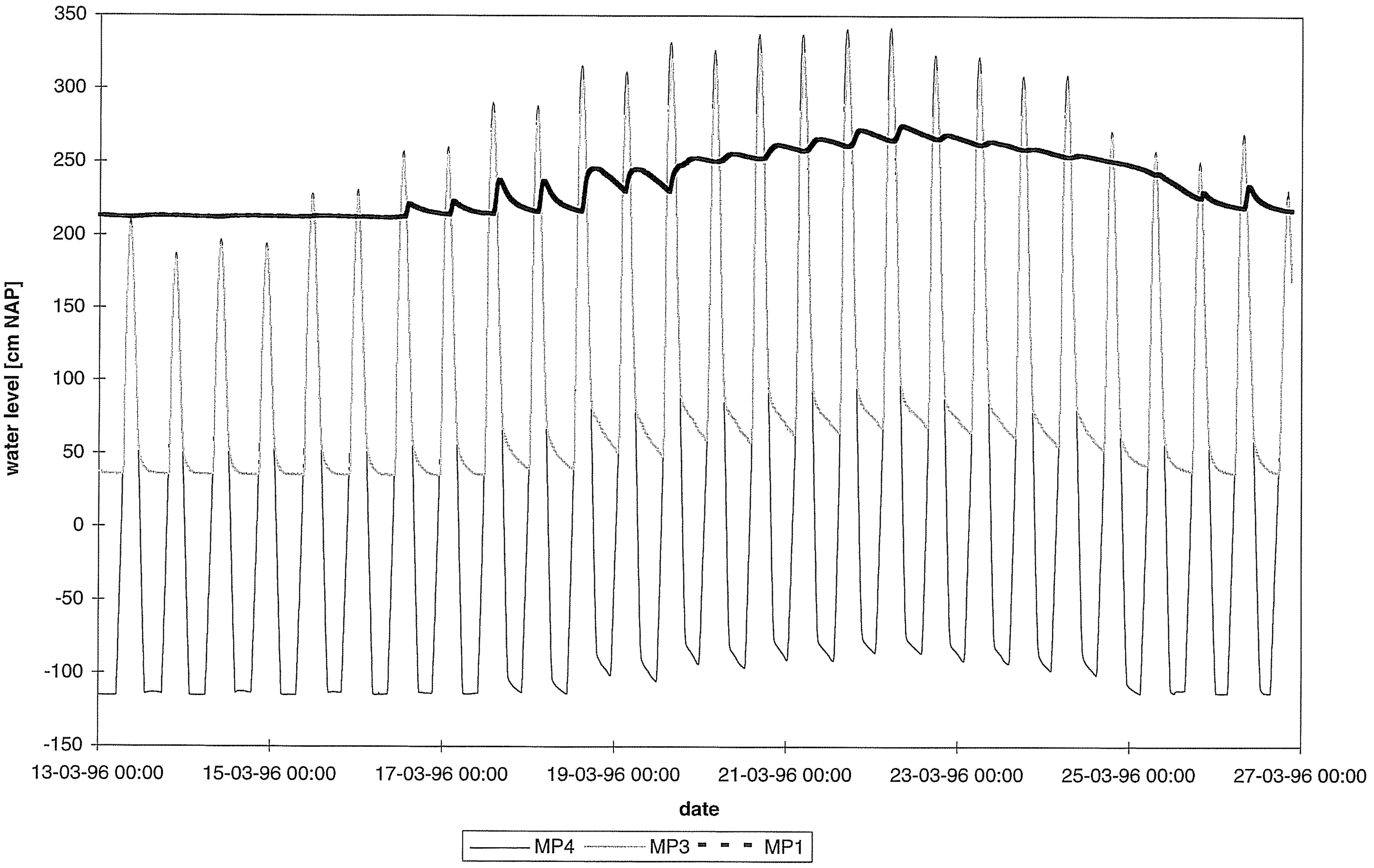

Figure 5.1 Water levels for MP1, MP3 and MP4 in the Sieperdaschor over a spring tide - neap tide period; March 13 to 27, 1996

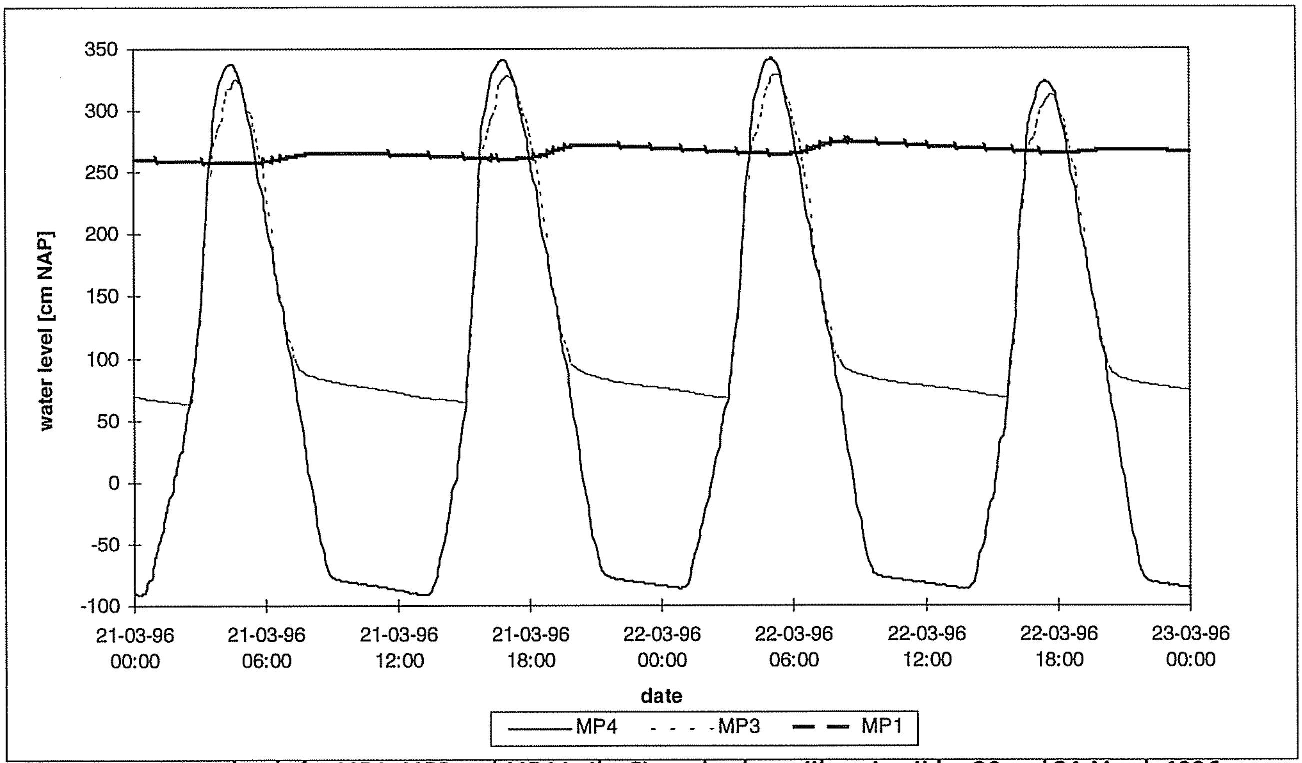

Figure 5.2 Water levels for MP1, MP3 and MP4 in the Sieperdaschor with spring tide ; 20 and 21 March 1996.

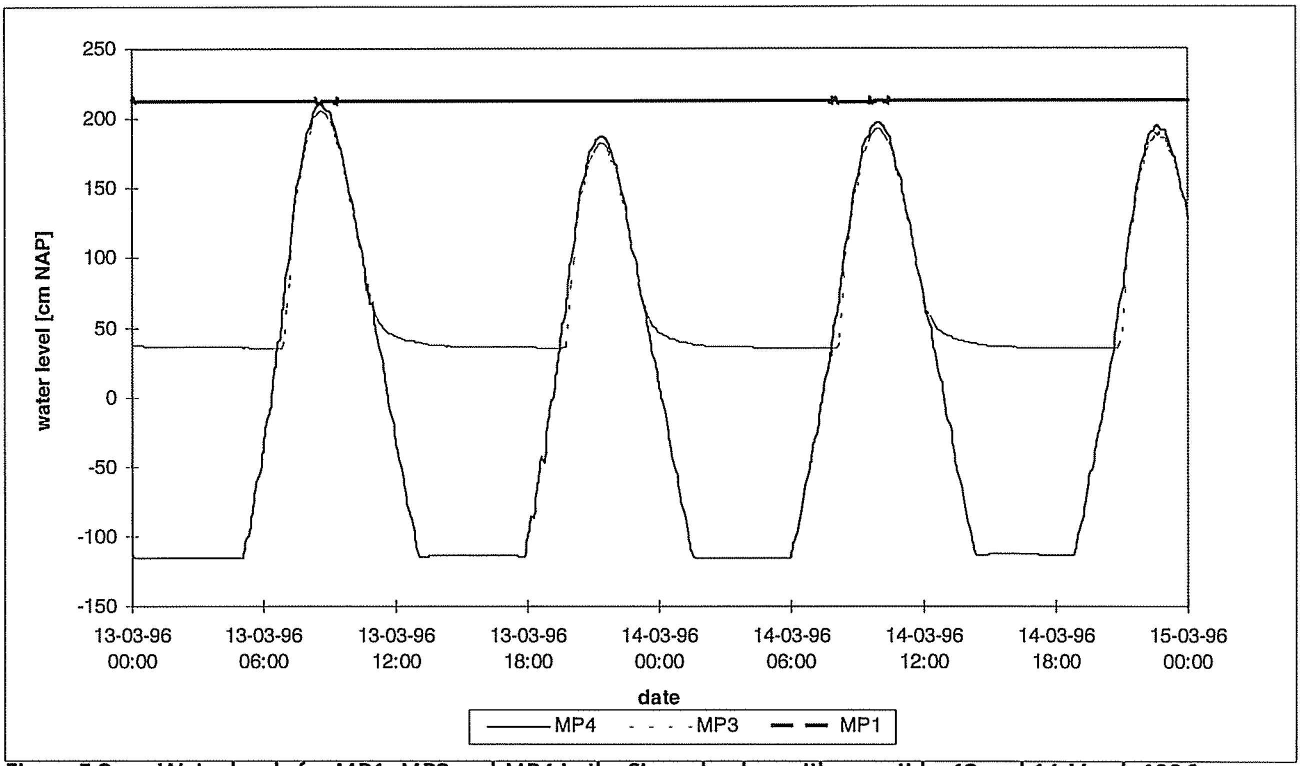

Figure 5.3 Water levels for MP1, MP3 and MP4 in the Sieperdaschor with neap tide; 13 and 14 March 1996.

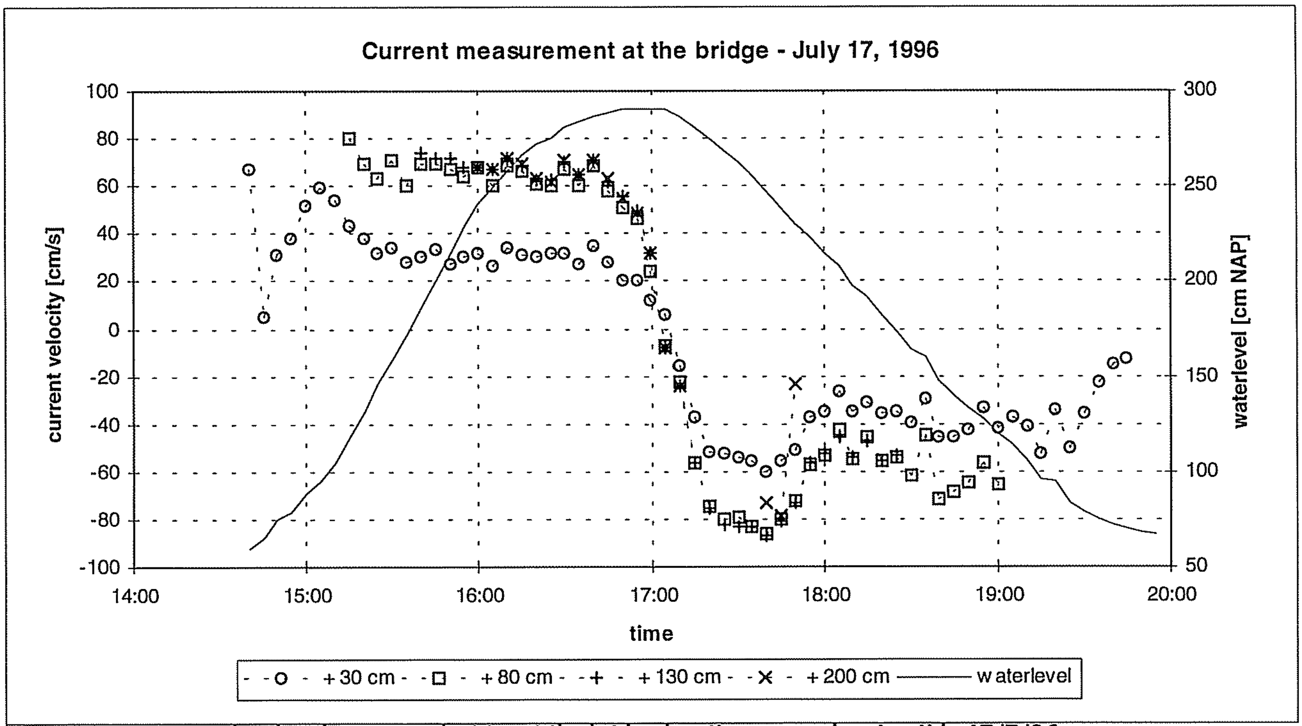

Figure 5.4 Water level and current velocities at the bridge location; normal spring tide 17/7/96.

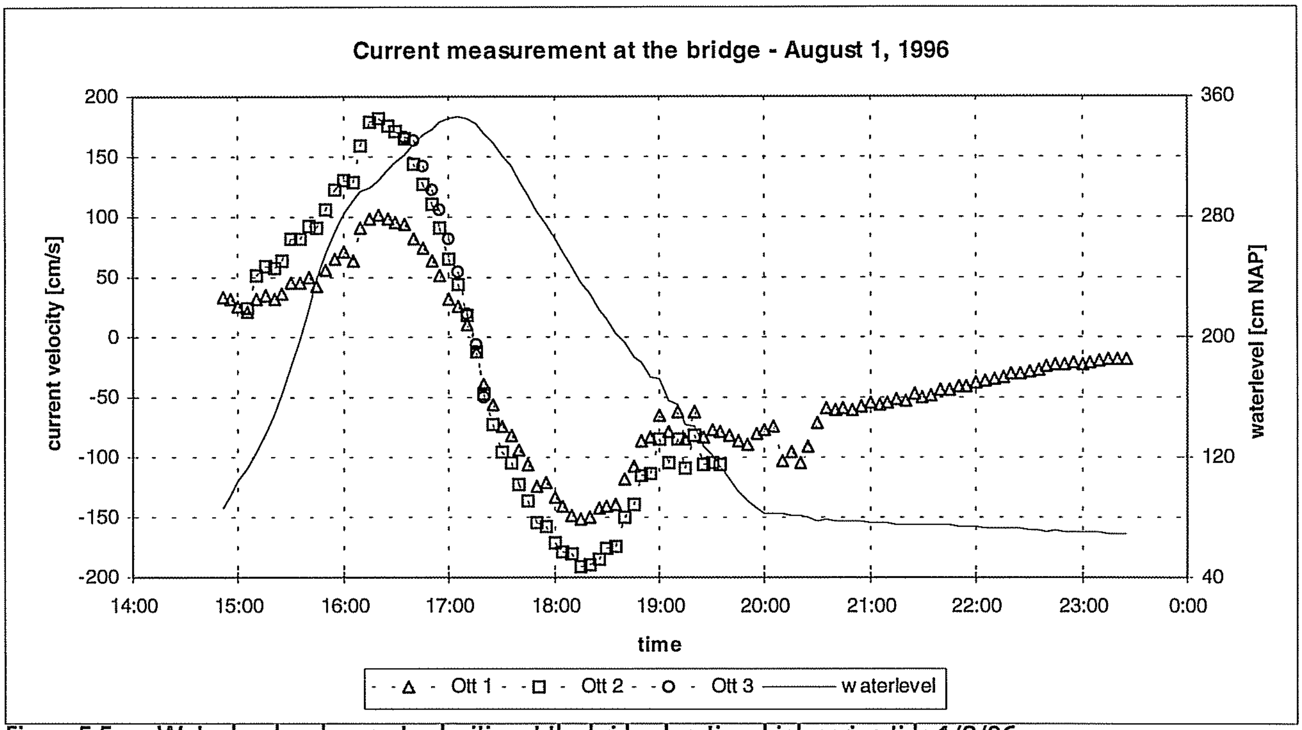

Figure 5.5 Water level and current velocities at the bridge location; high spring tide 1/8/96.

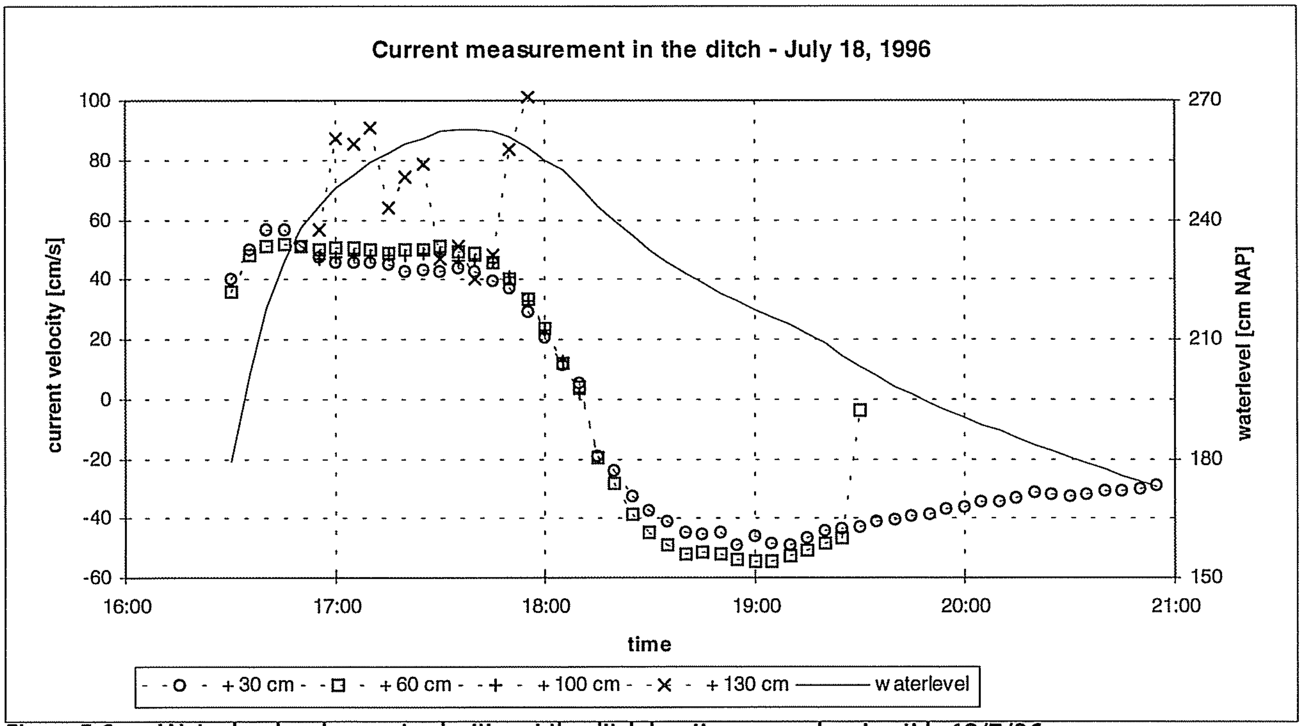

Figure 5.6 Water level and current velocities at the ditch location; normal spring tide 18/7/96.

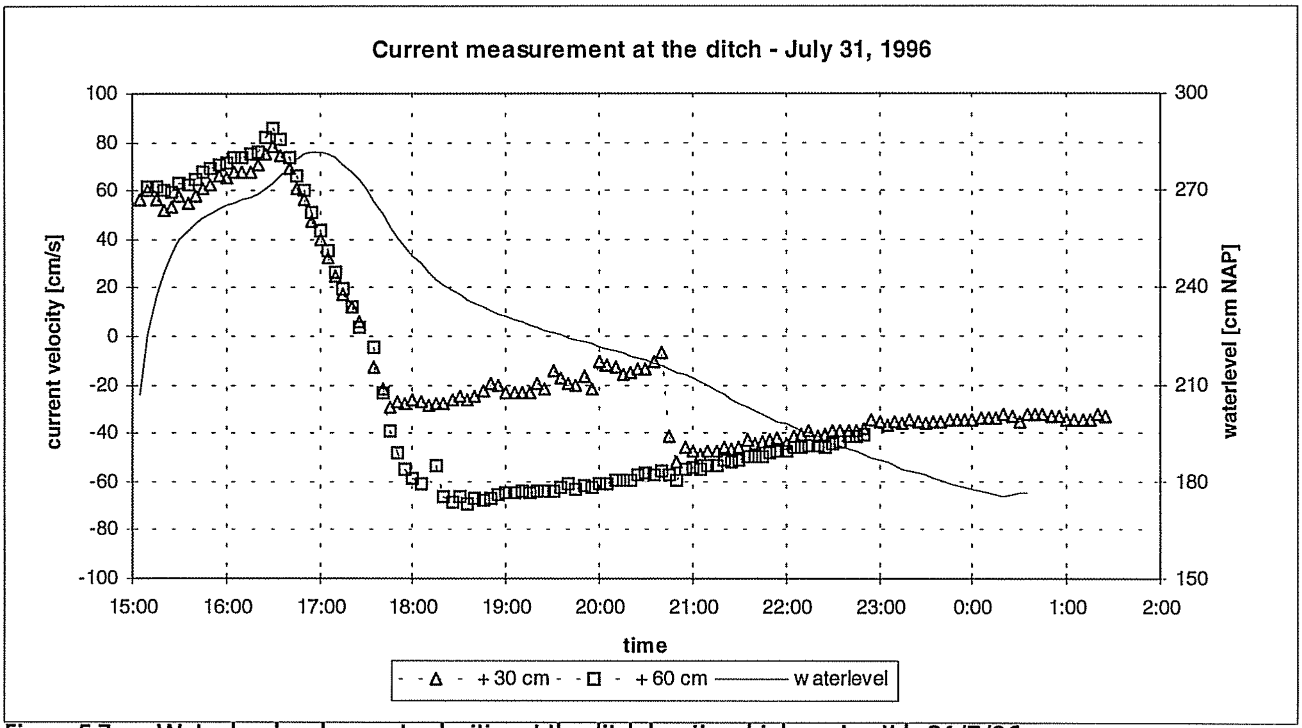

Figure 5.7 Water level and current velocities at the ditch location; high spring tide 31/7/96.

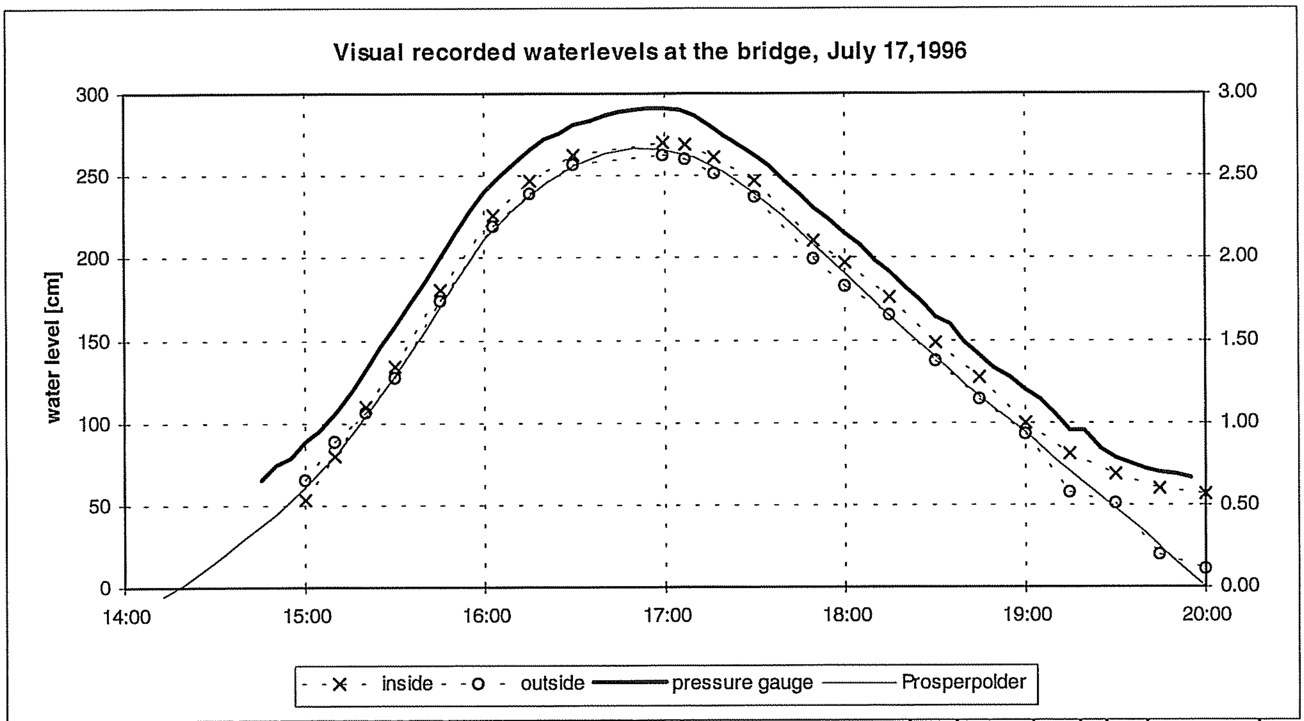

Figure 5.8 Water levels at the bridge location measured with pressure sensor and with visual scaled poles; normal spring tide 17/7/96.

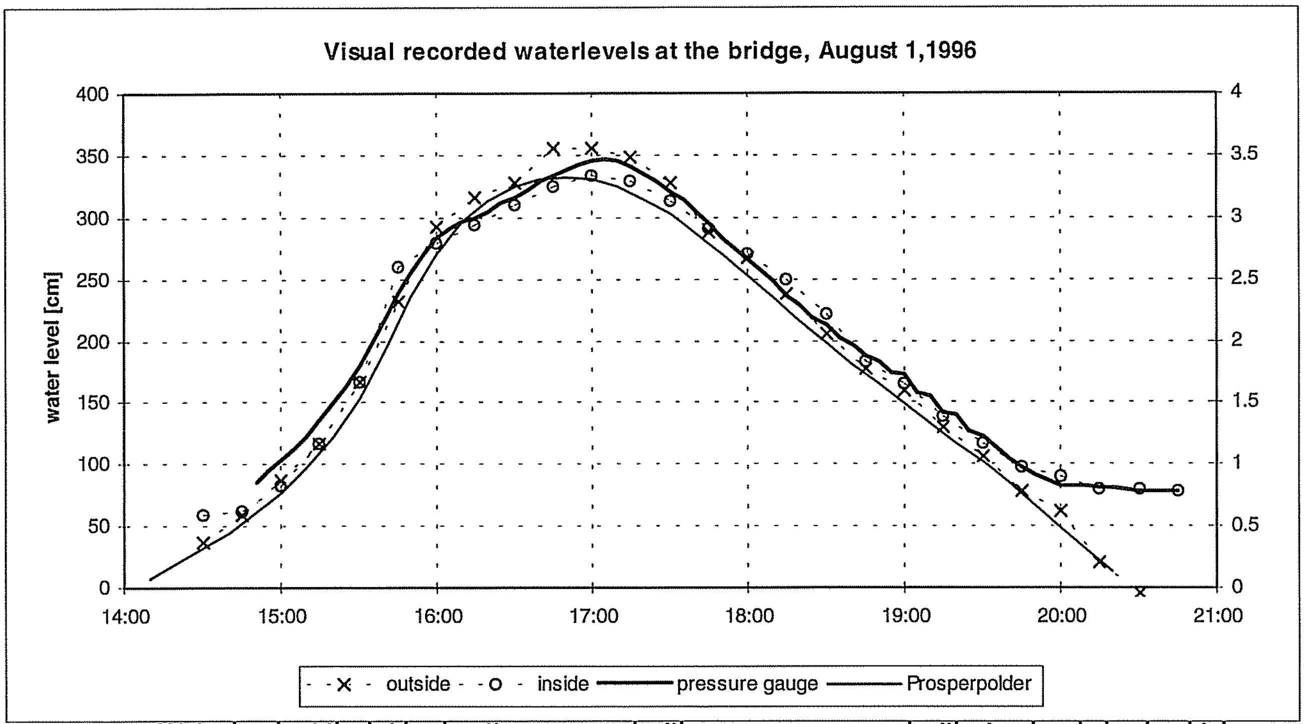

Figure 5.9 Water levels at the bridge location measured with pressure sensor and with visual scaled poles; high spring tide 1/8/96.

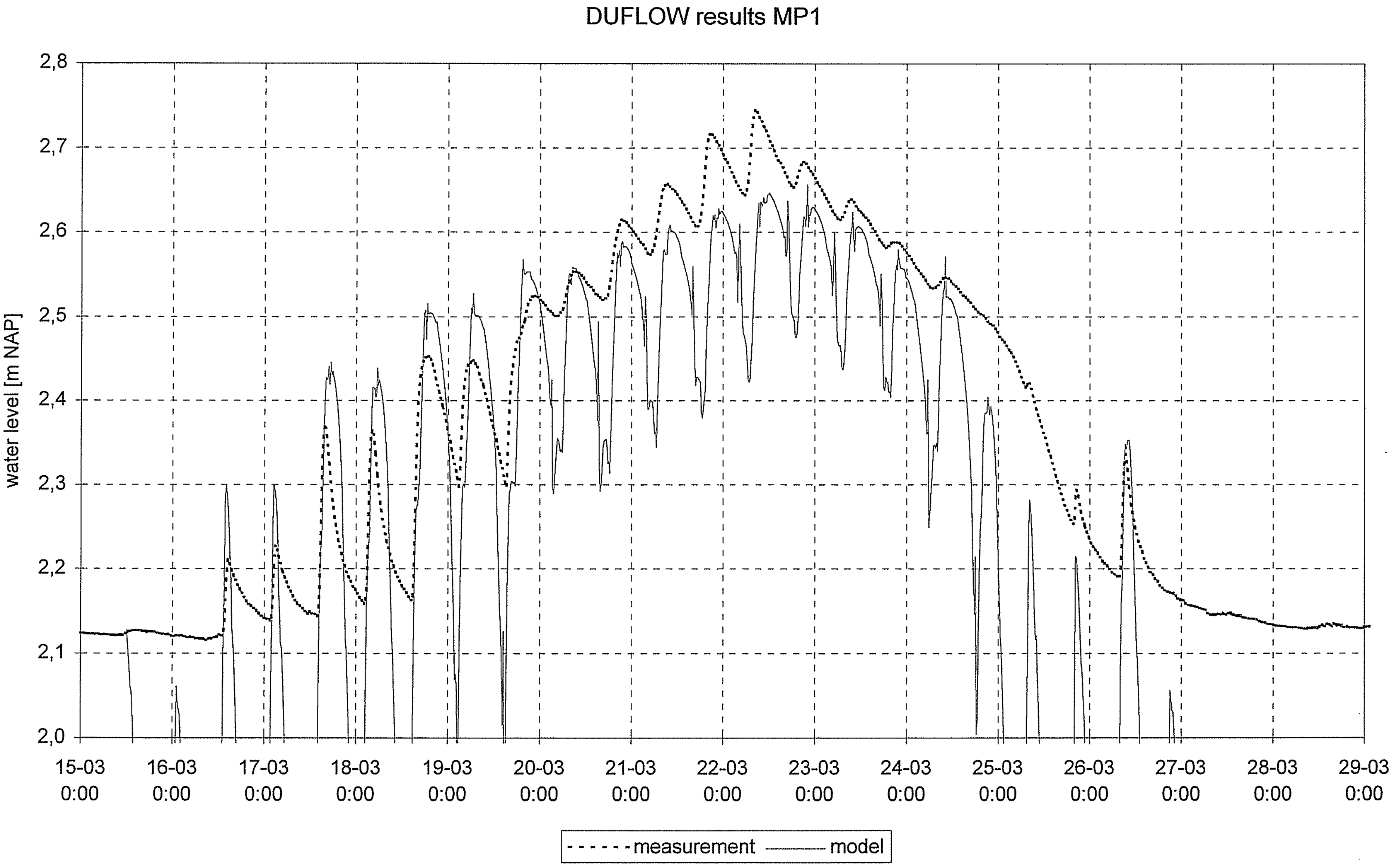

Figure 5.10 Calculated and observed waterlevels at MP1 for March 15 until March 29, 1996

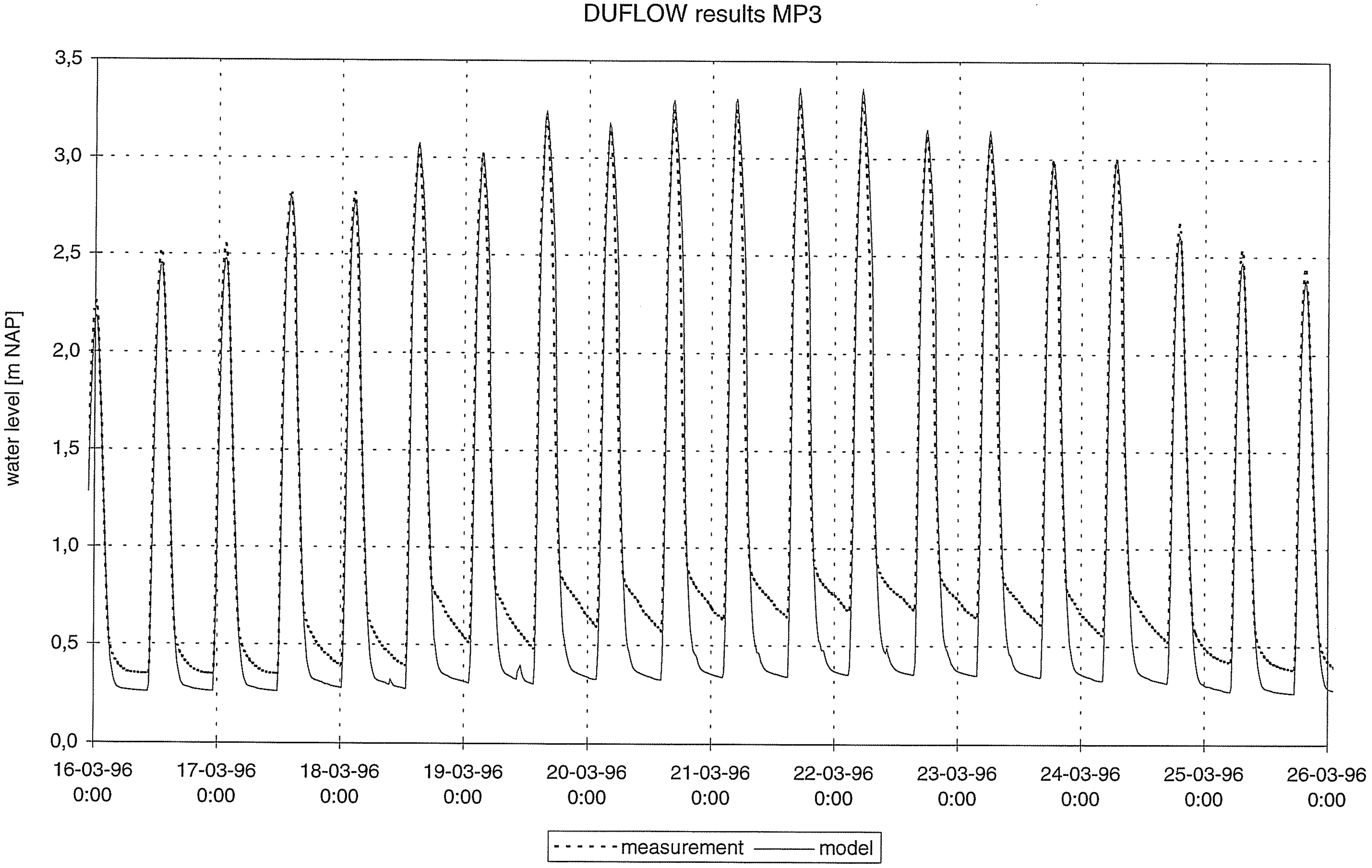

Figure 5.11 Calculated and observed waterlevels at MP3 for March 16 until March 26, 1996

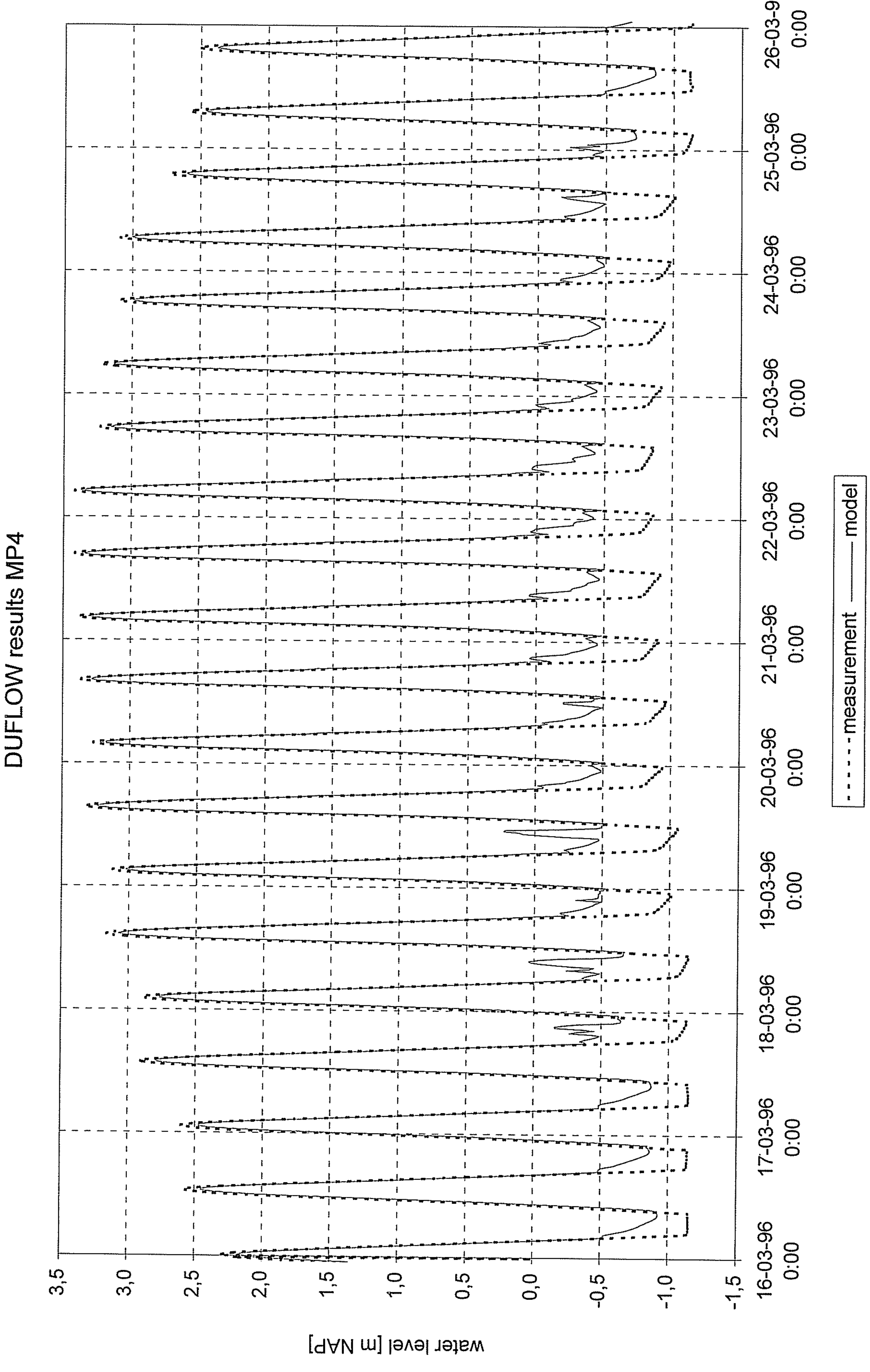

Figure 5.12 Calculated and observed waterlevels at MP4 for March 16 until March 26, 1996

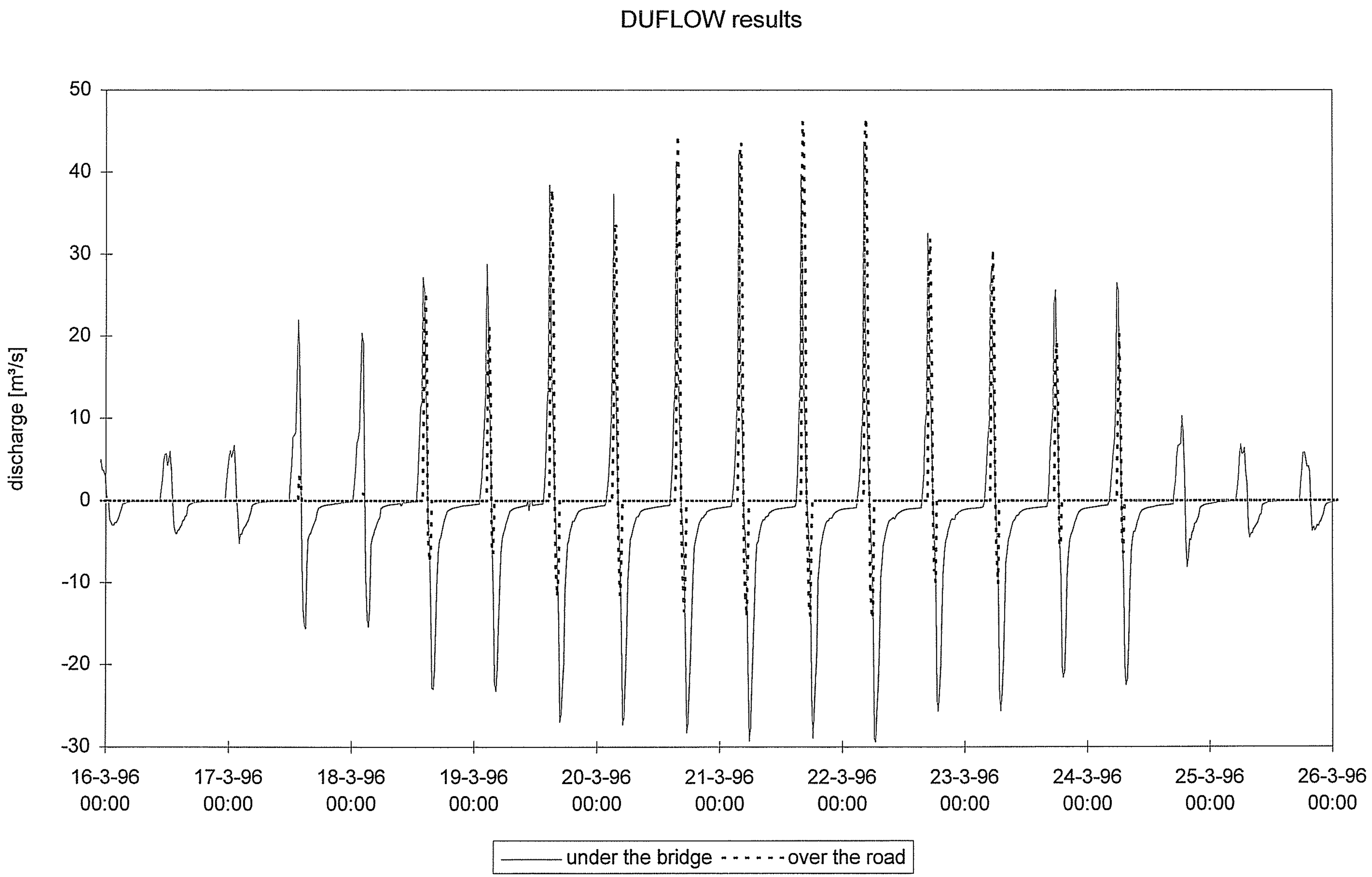

Figure 5.13 Calculated discharge under the bridge and over the road over a spring tide period, March 1996

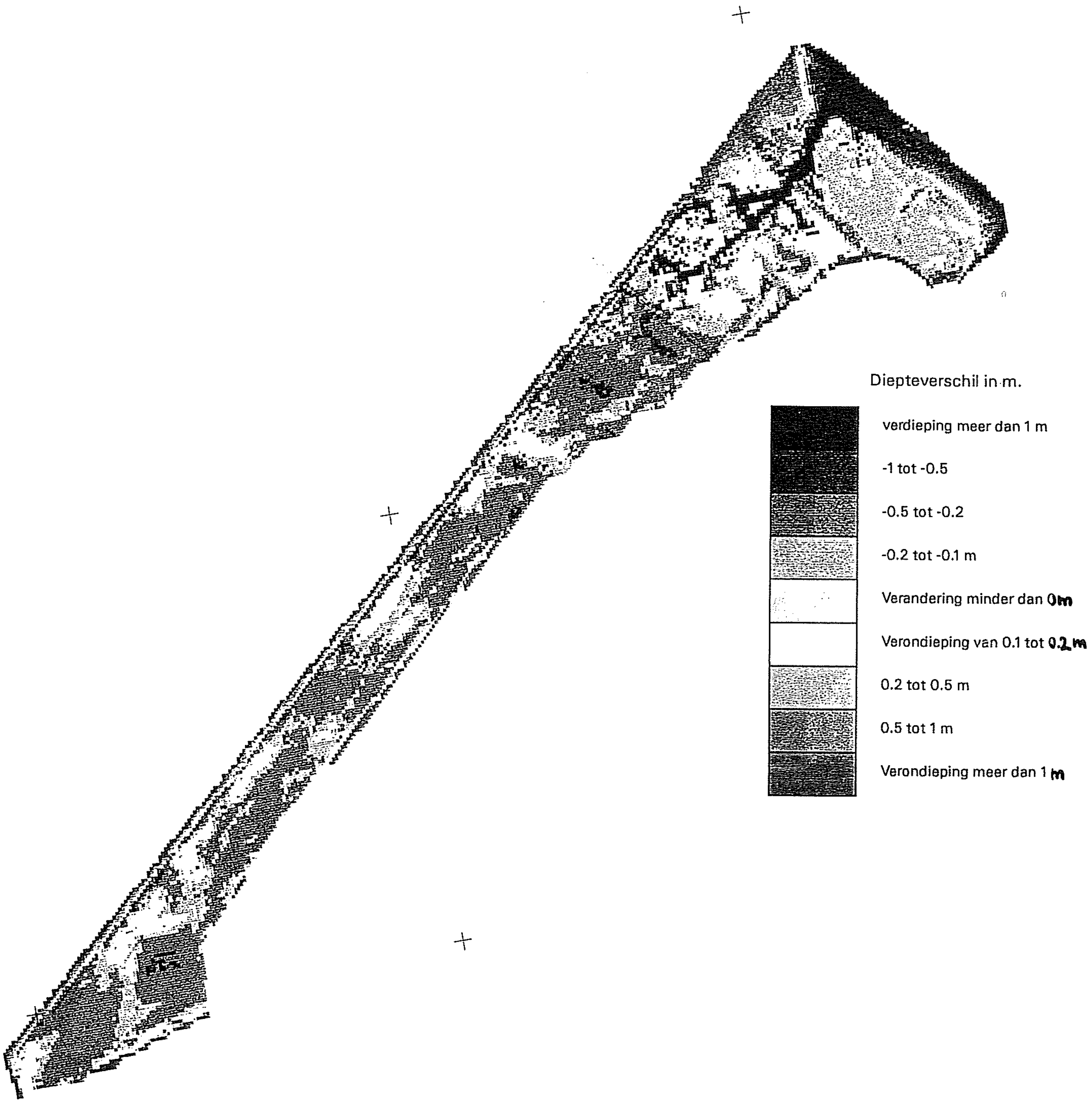

Figure 6.1 Height differences between 1963 and 1994 in the Sieperdaschor.

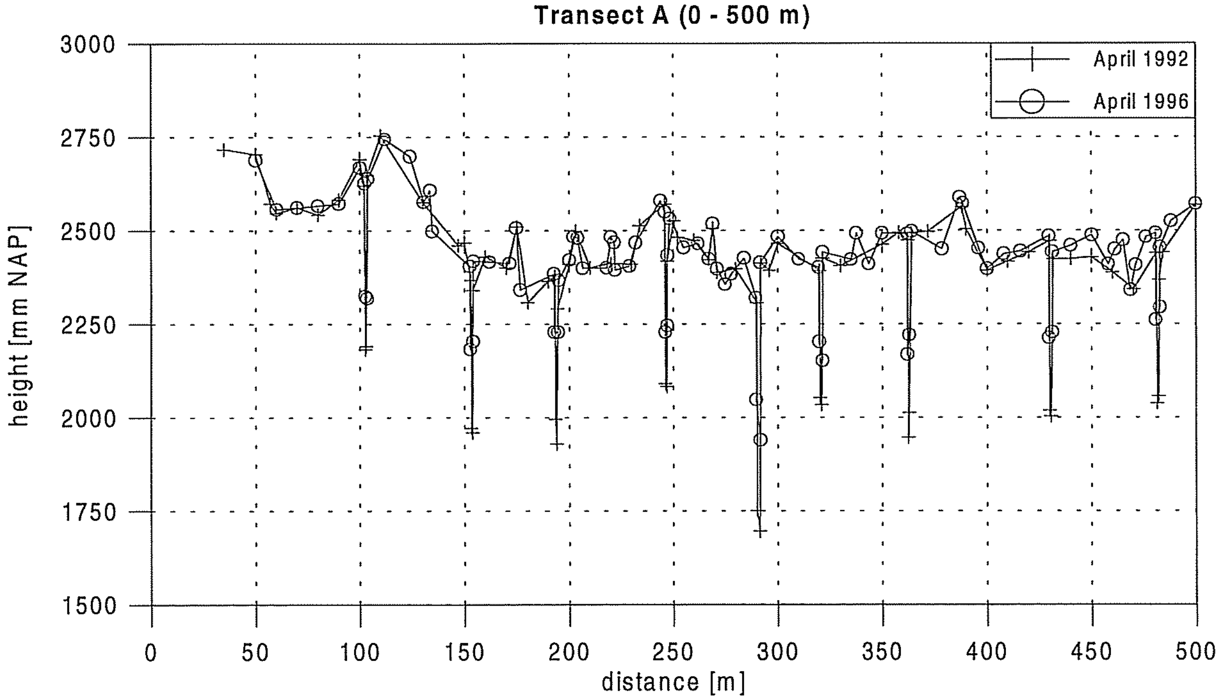

Figure 6.2a Marsh and creek bed topography Transect A (0-500 m) for April 1992 and April 1996.

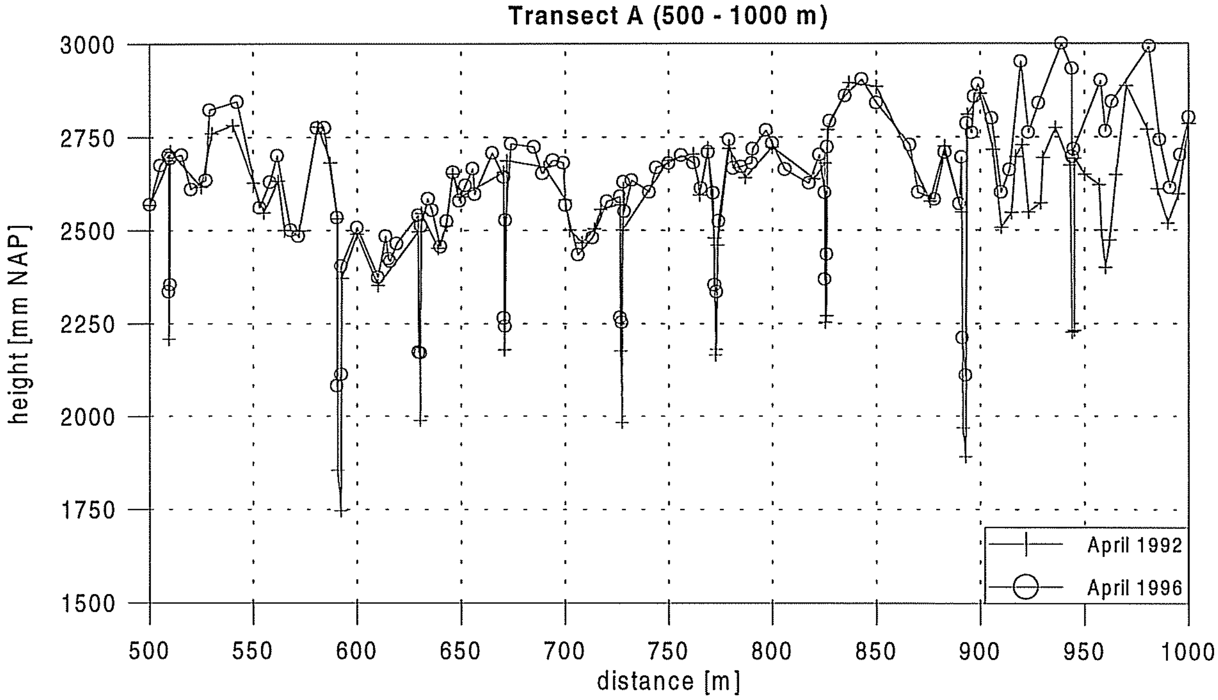

Figure 6.2b Marsh and creek bed topography on Transect A (500-1000 m) for April 1992 and April 1996.

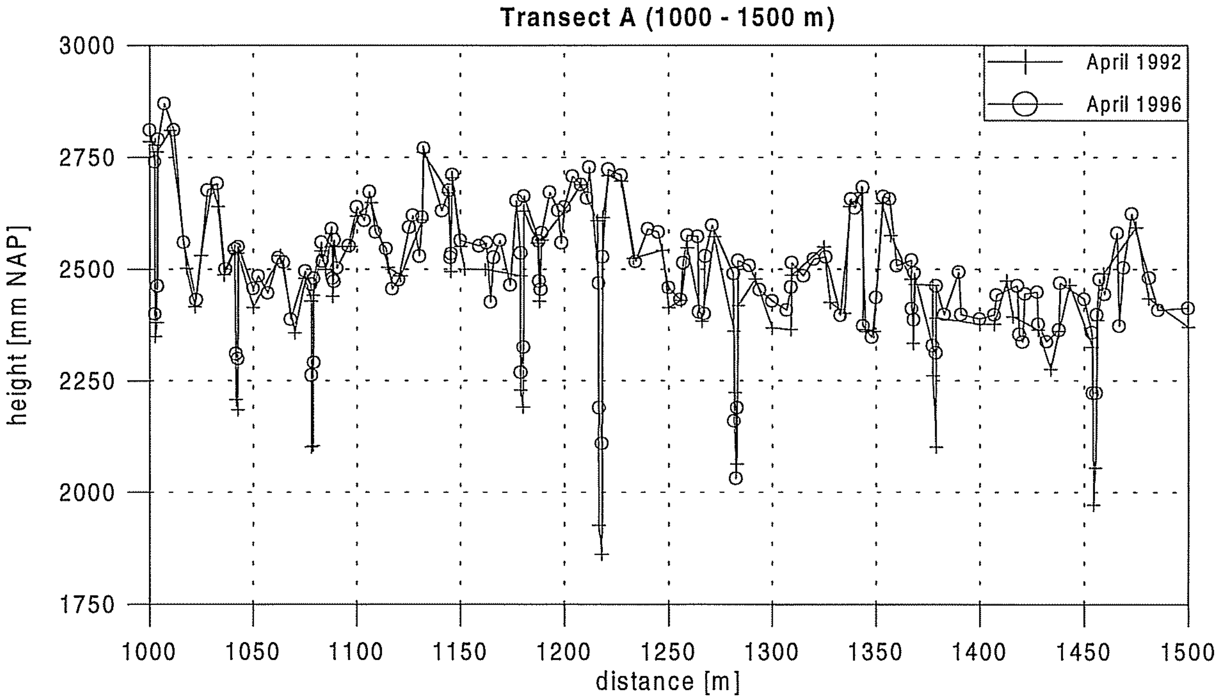

Figure 6.2c Marsh and creek bed topography on Transect A (1000-1500 m) for April 1992 and April 1996.

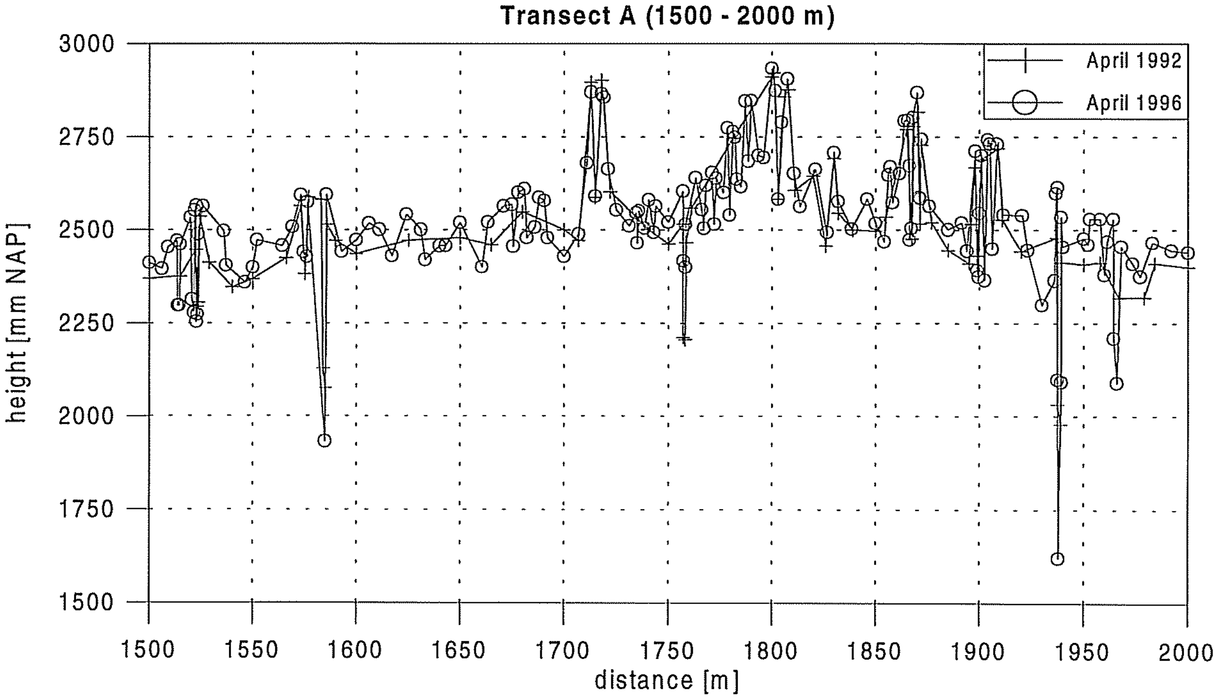

Figure 6.2d Marsh and creek bed topography on Transect A (1500-2000 m) for April 1992 and April 1996.

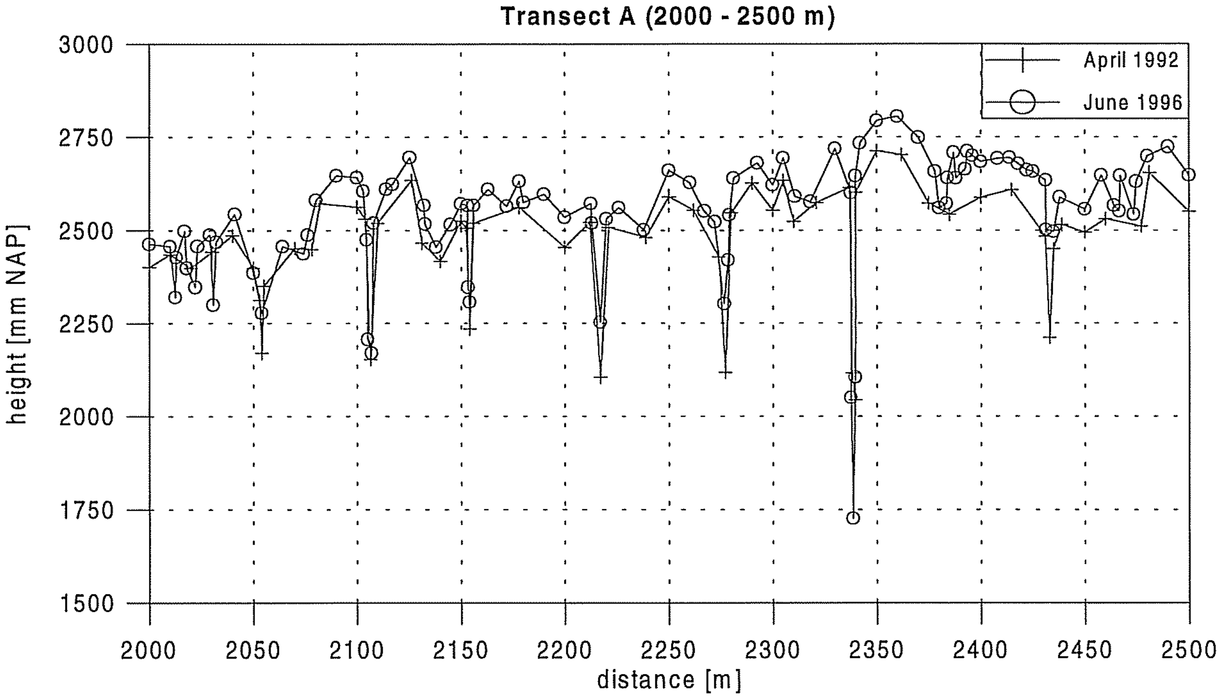

Figure 6.2e Marsh and creek bed topography on Transect A (2000-2500 m) for April 1992 and June 1996.

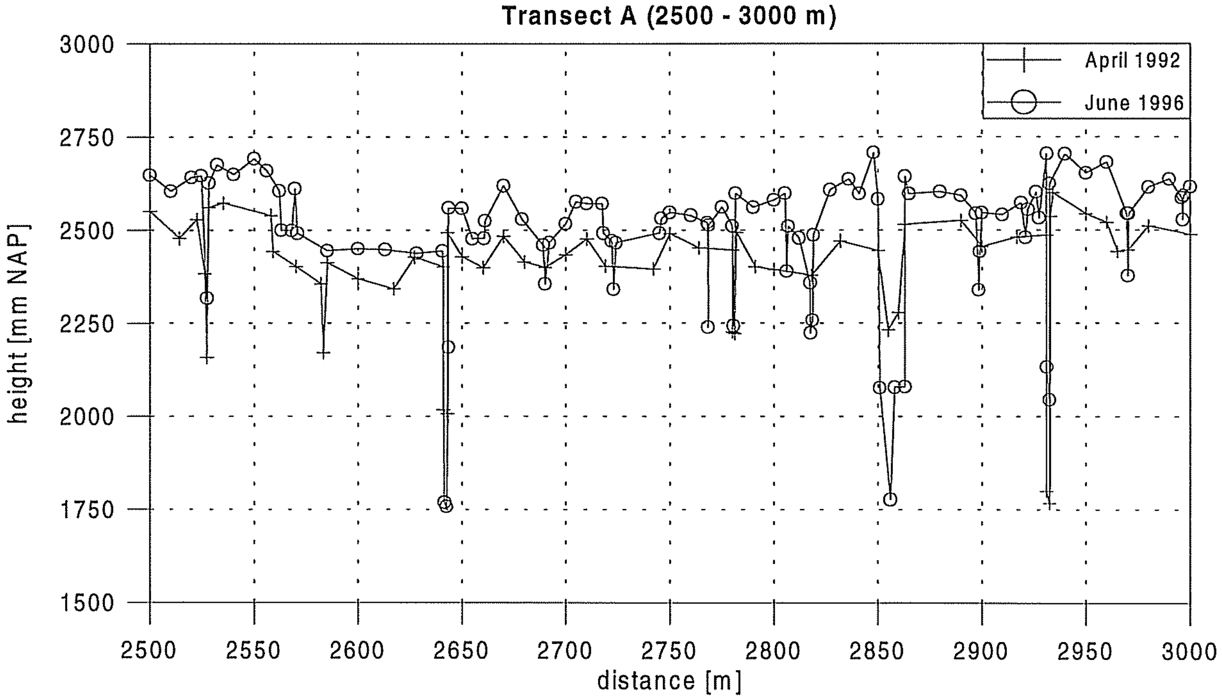

Figure 6.2f Marsh and creek bed topography on Transect A (2500-3000 m) for April 1992 and June 1996.

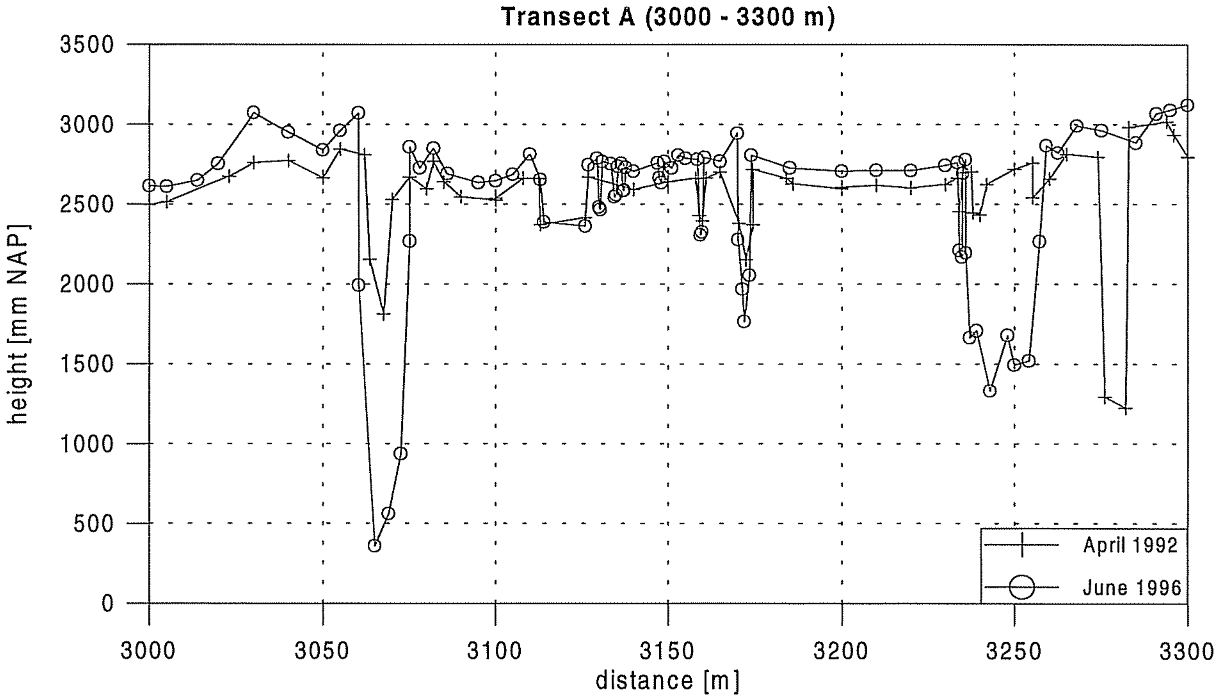

Figure 6.2g Marsh and creek bed topography on Transect A (3000-3700 m) for May 1992 and June 1996.

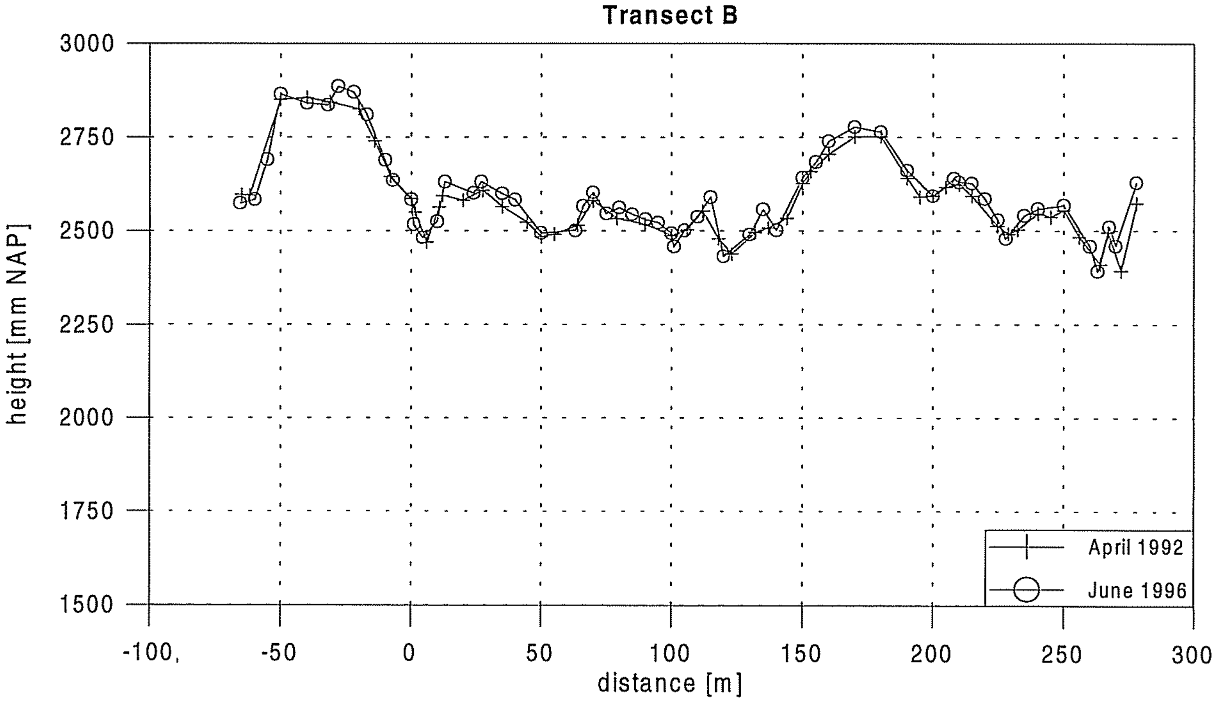

Figure 6.3 Marsh and creek bed topography on Transect B for April 1992 and June 1996.

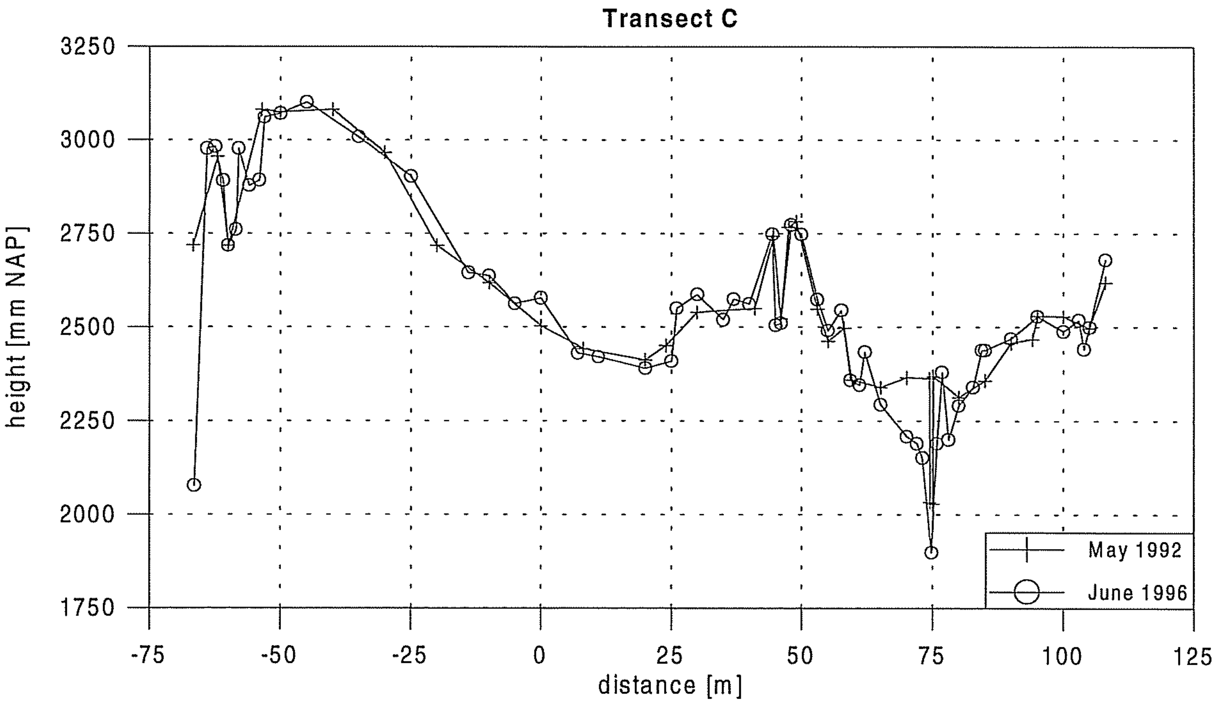

Figure 6.4 Marsh and creek bed topography on Transect C for May 1992 and June 1996.

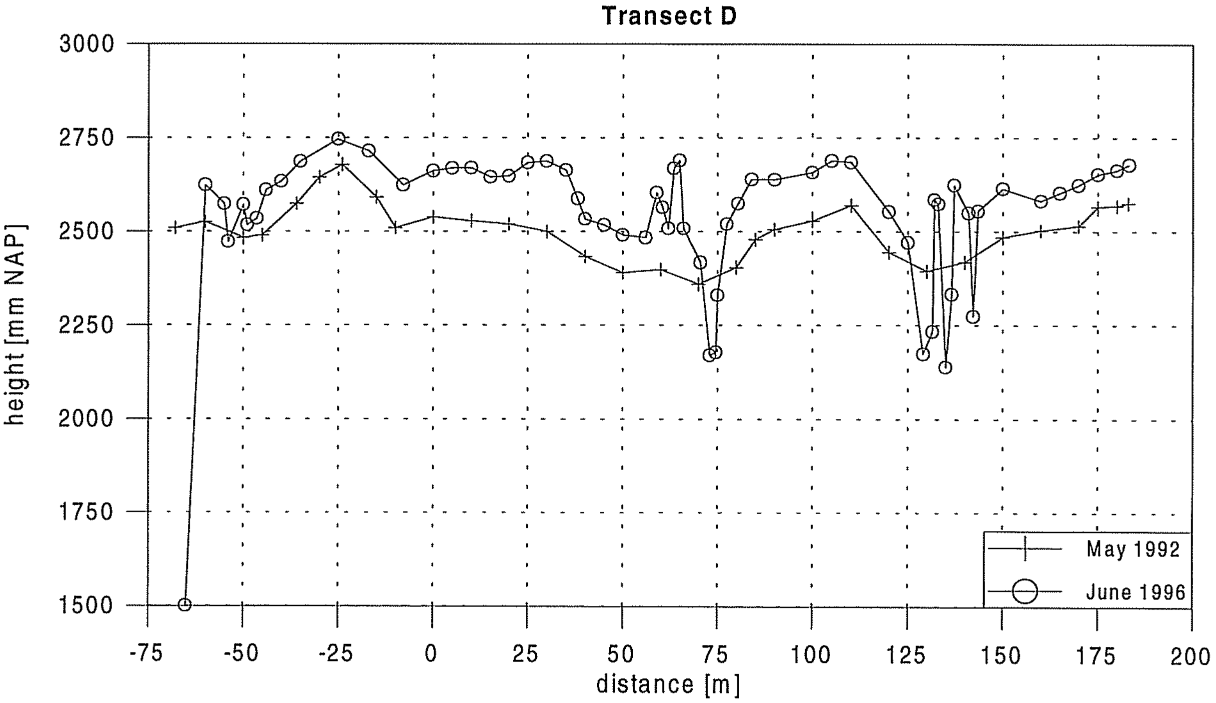

Figure 6.5 Marsh and creek bed topography on Transect D for May 1992 and June 1996.

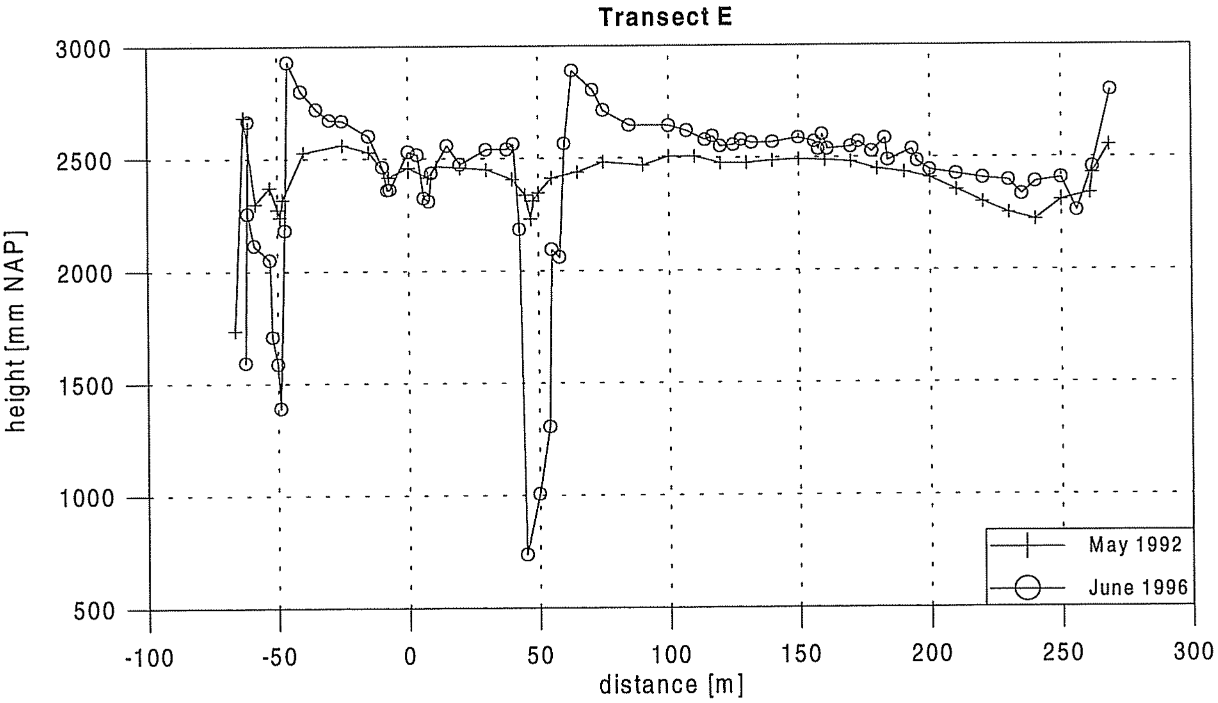

Figure 6.6 Marsh and creek bed topography on Transect E for May 1992 and June 1996.

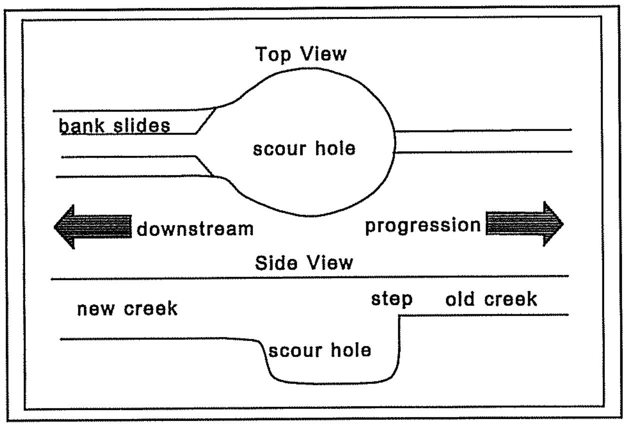

Figure 6.7 Top and side view of the backward erosion process in the creeks in the Sieperdaschor.

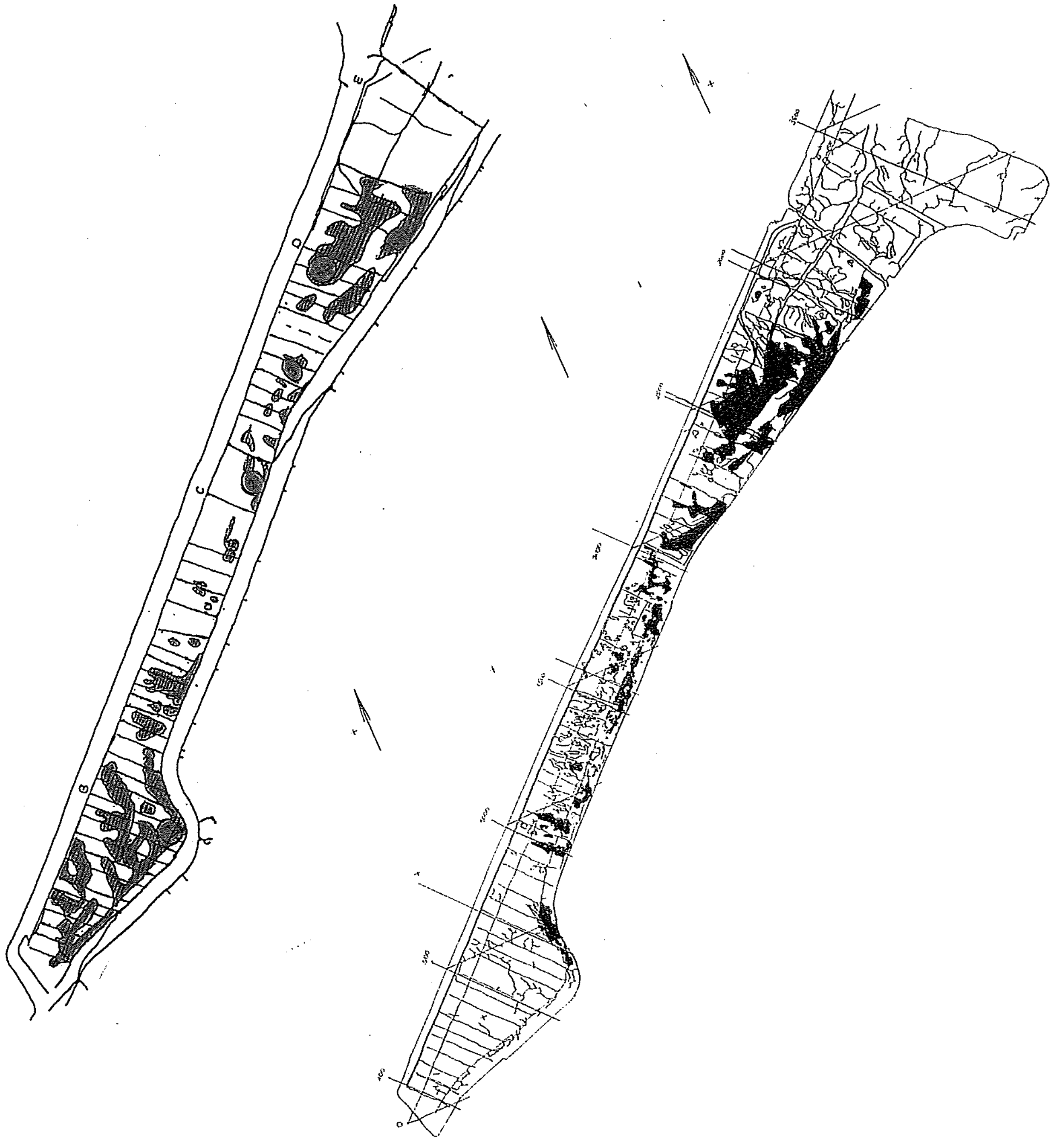

Figure 6.8 A) The mud flat areas in the Sieperdaschor in 1994 (from Moermond, 1994); B) The mud flat areas in the Sieperdaschor in 1996 (both constructed with aerial photographs)

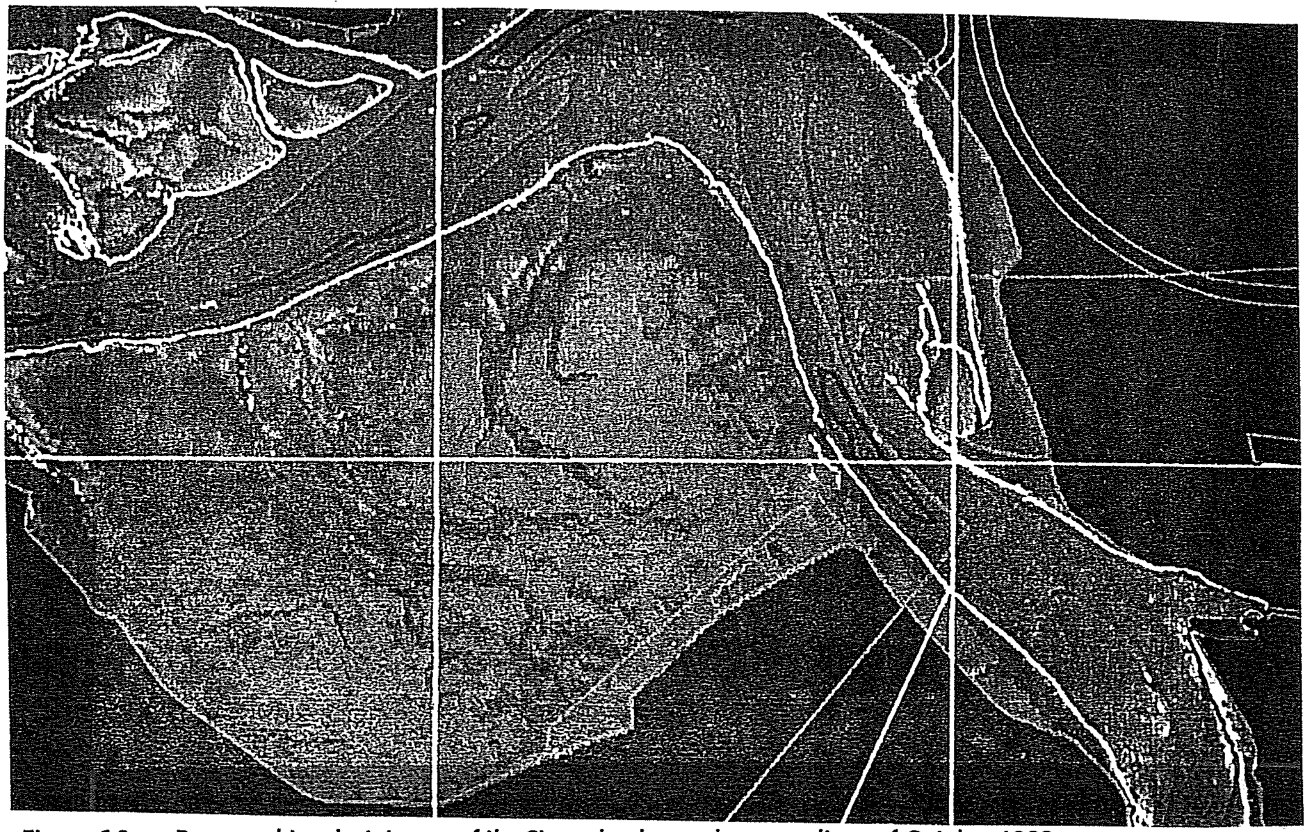

Figure 6.9 Processed Landsat image of the Sieperdaschor and surroundings of October 1989.

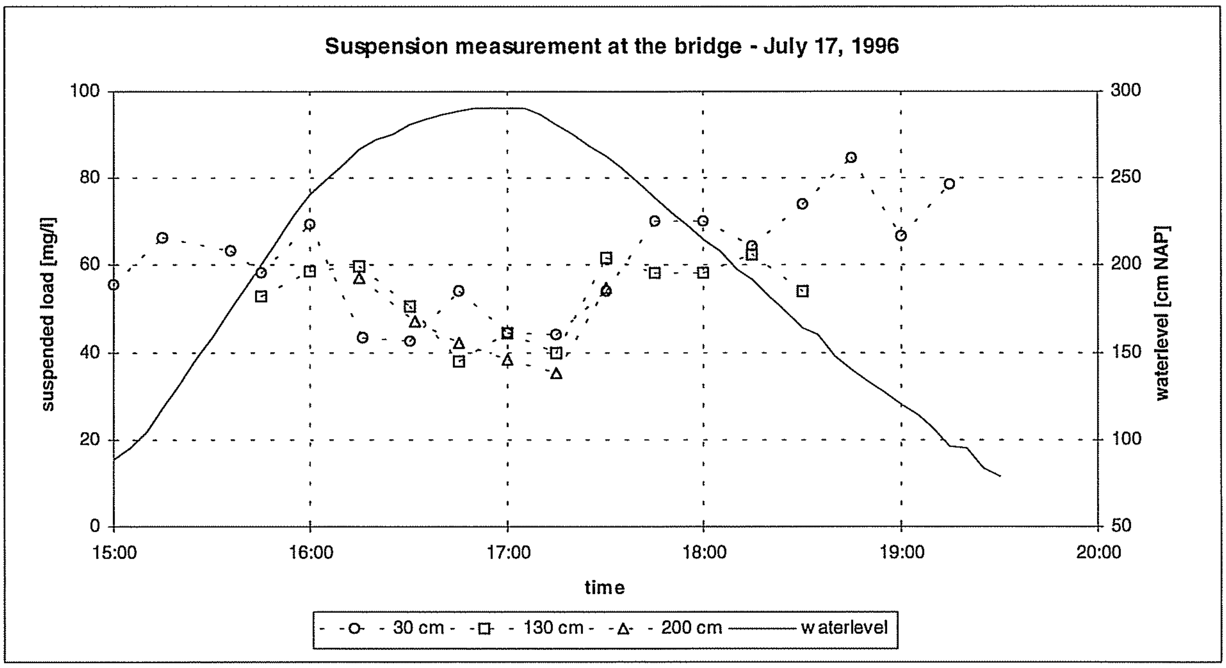

Figure 7.1 Water levels (pressure gauge) and suspended load (mg/l) on at 3 different heights relative to the creek bed for the bridge location; normal spring tide 17/7/96.

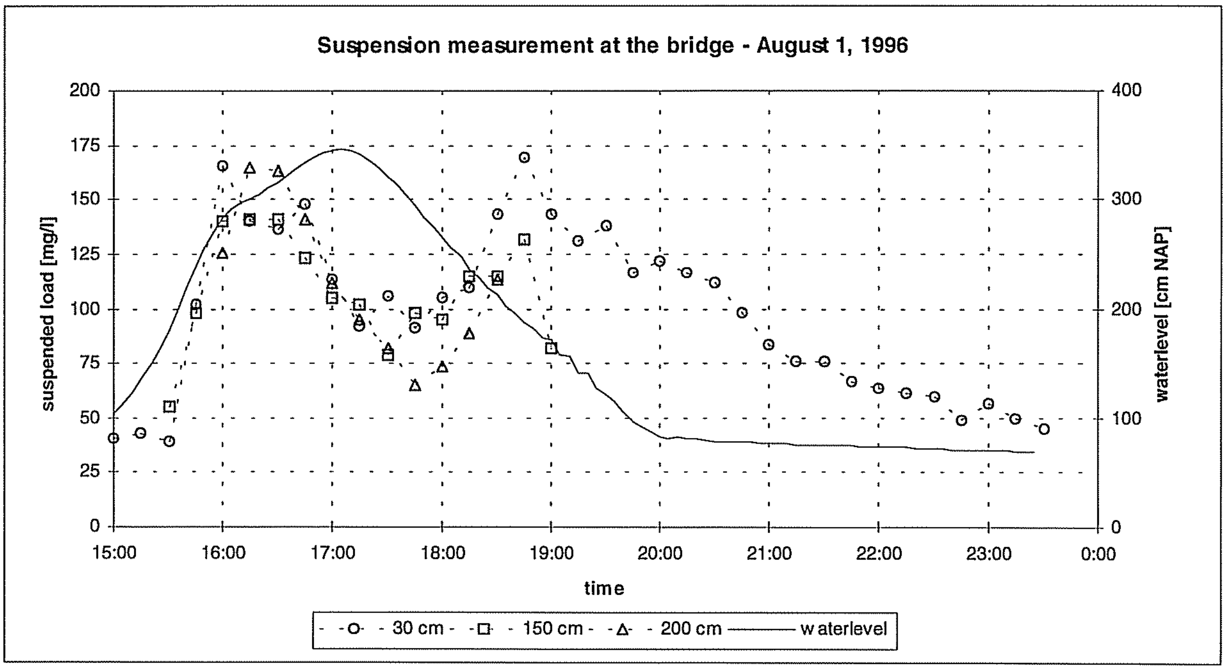

Figure 7.2 Water levels (pressure gauge) and suspended load (mg/l) on at 3 different heights relative to the creek bed for the bridge location; high spring tide 1/8/96.

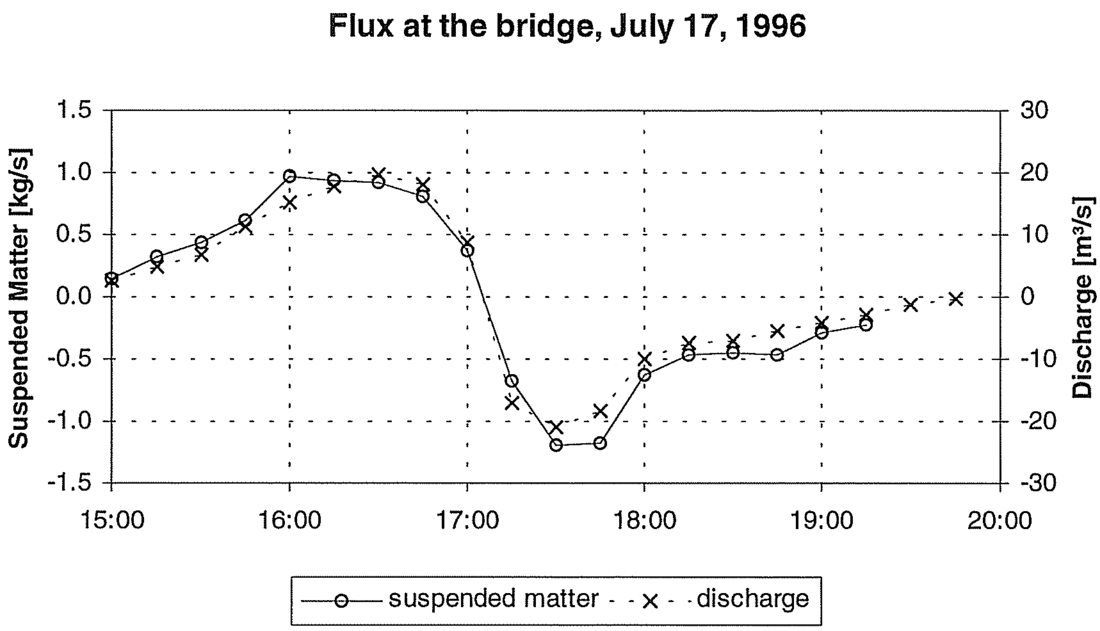

Figure 7.3 Suspended flux and discharge at the bridge location; normal spring tide 17/7/96.

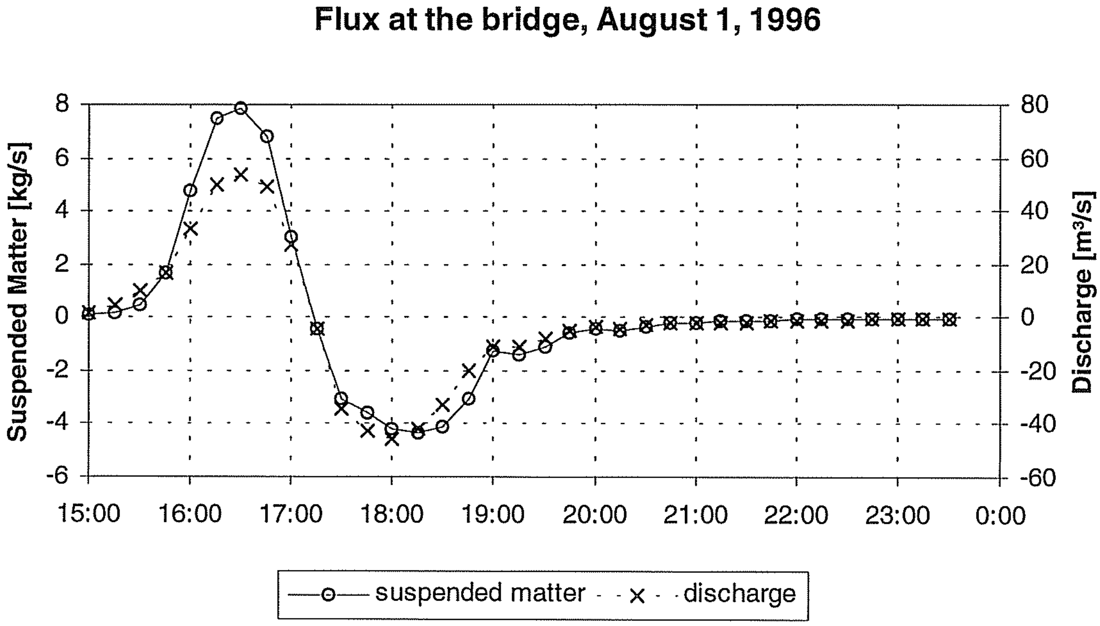

Figure 7.6 Suspended flux and discharge at the bridge location; high spring tide 1/8/96.

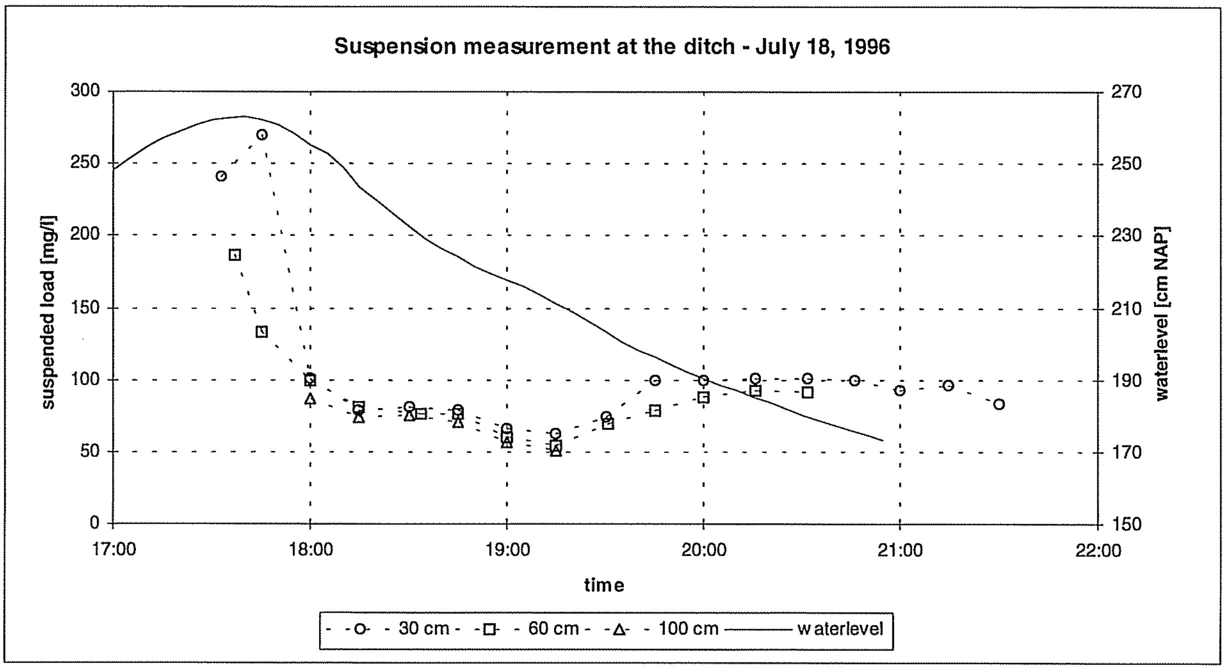

Figure 7.5 Water level (pressure gauge) and suspended load (mg/l) at 3 different heights relative to the creek bed; for the ditch location; normal spring tide 18/7/96.

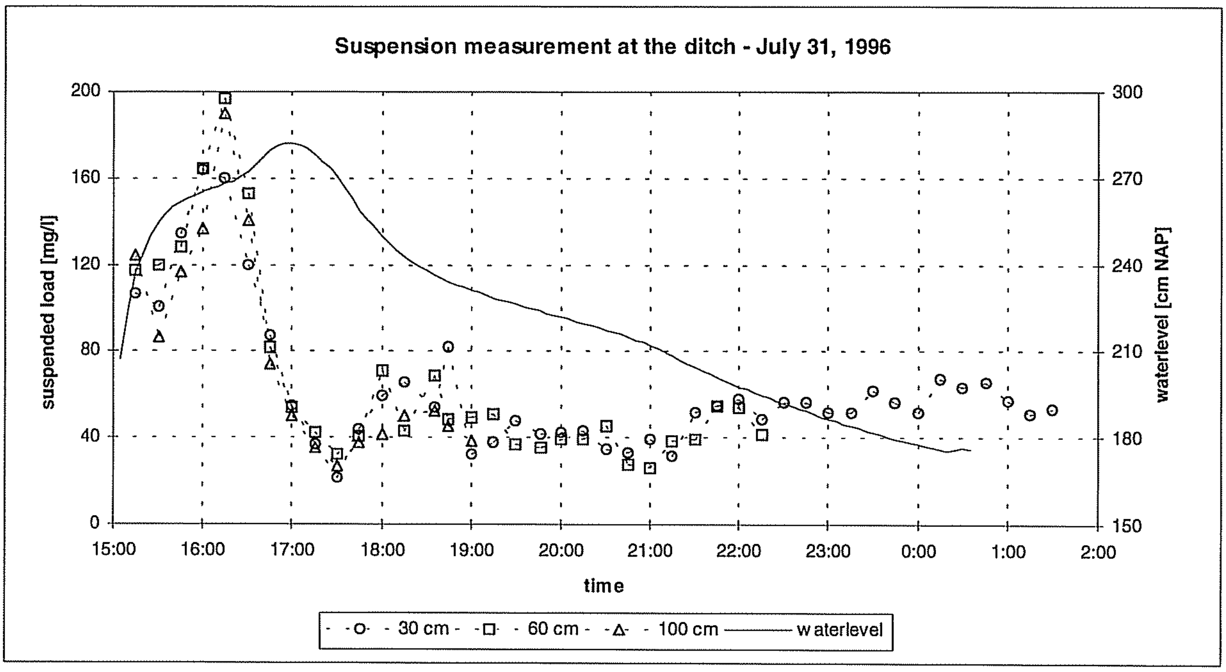

Figure 7.6 Water level (pressure gauge) and suspended load (mg/l) at 3 different heights relative to the creek bed for the ditch location; high spring tide 1/8/96.

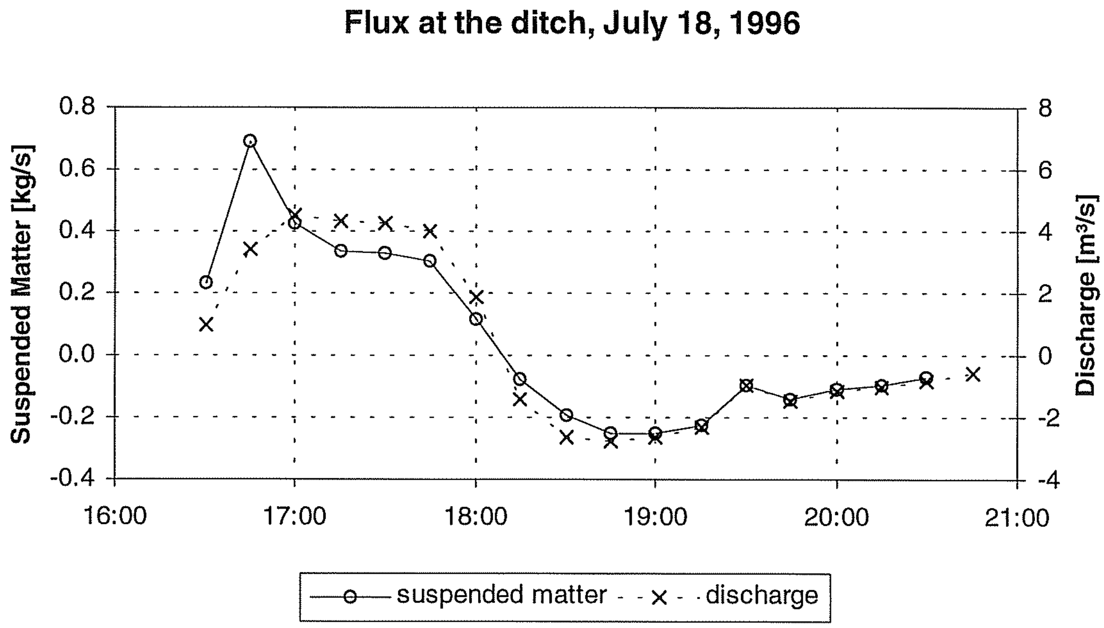

Figure 7.7 Suspended flux and discharge at ditch location; normal spring tide 18/7/96.

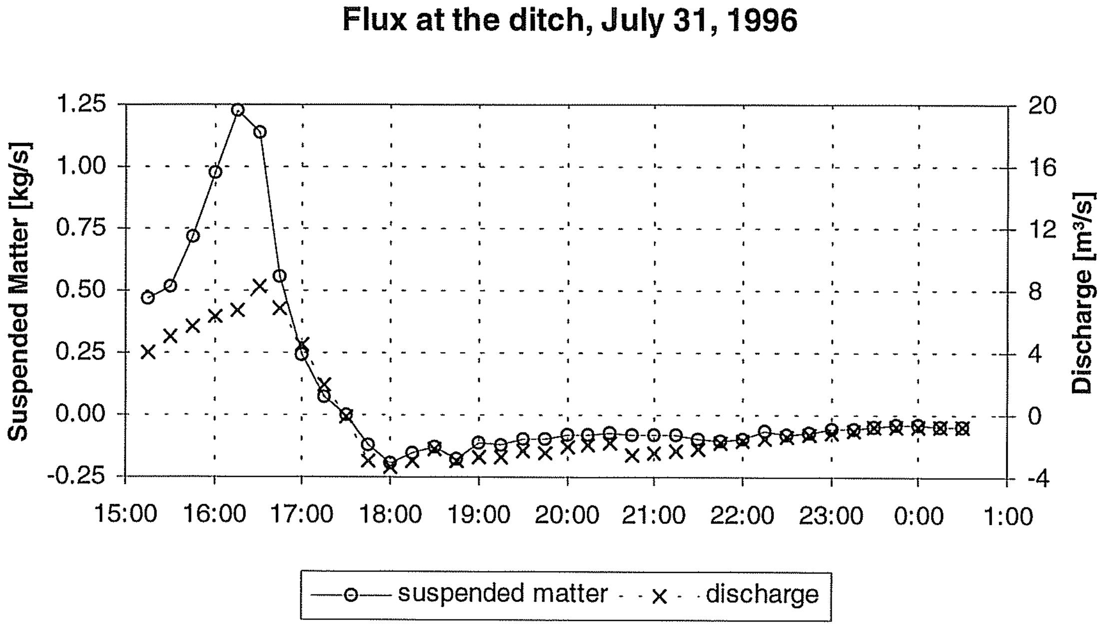

Figure 7.8 Suspended flux and discharge at ditch location; high spring tide 31/7/96.

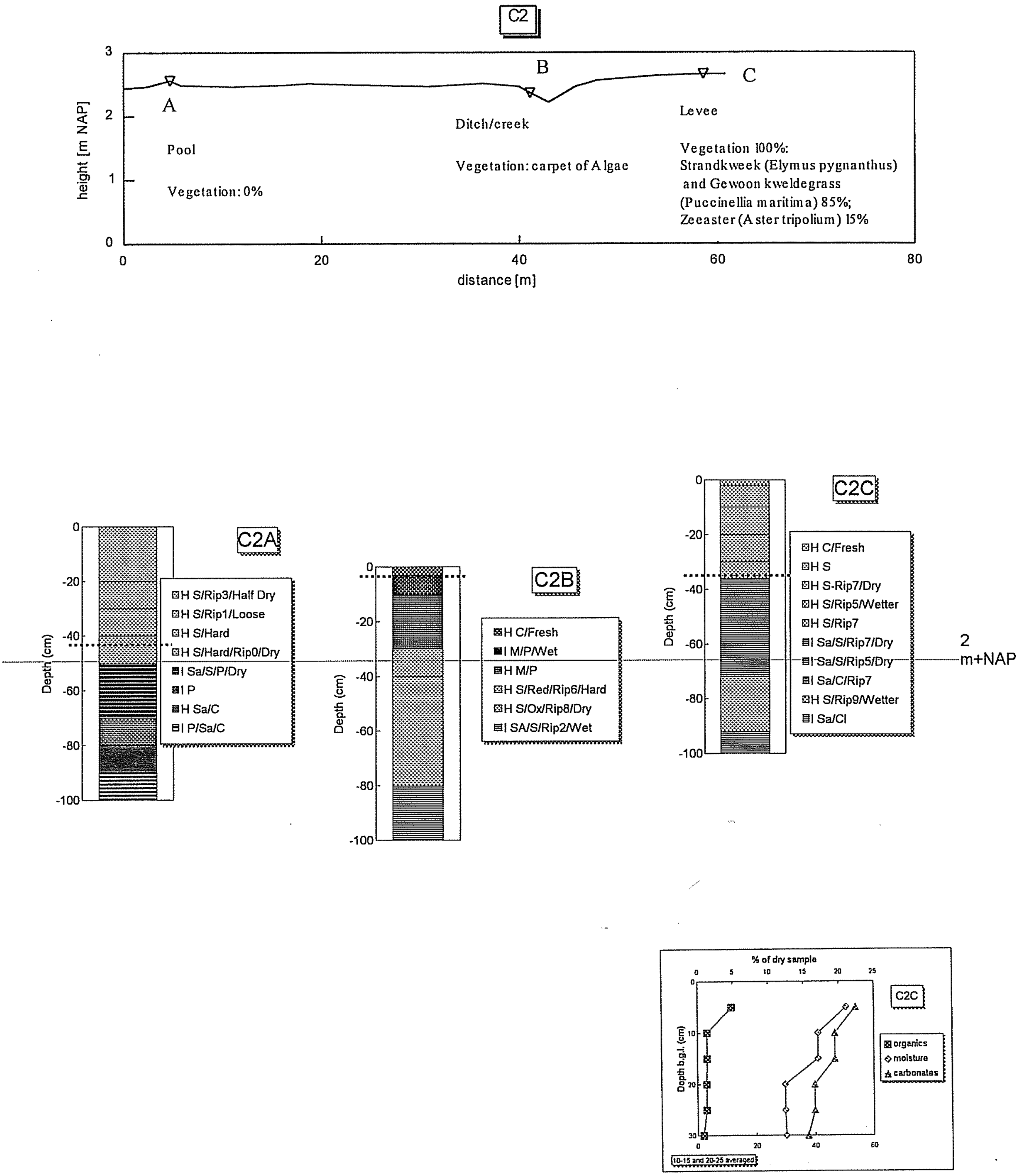

Figure 8.1 Transect C2: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

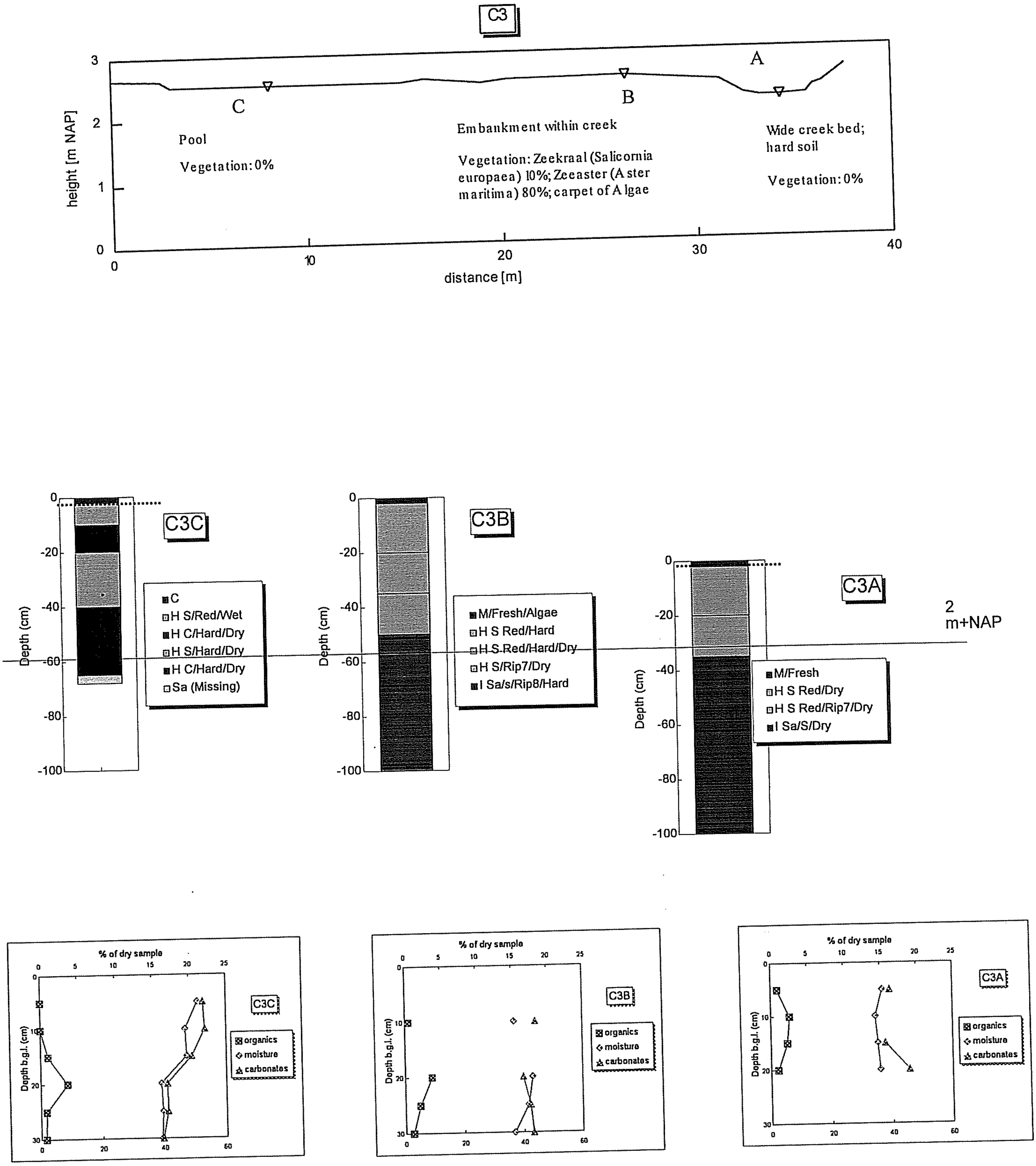

Figure 8.2 Transect C3: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

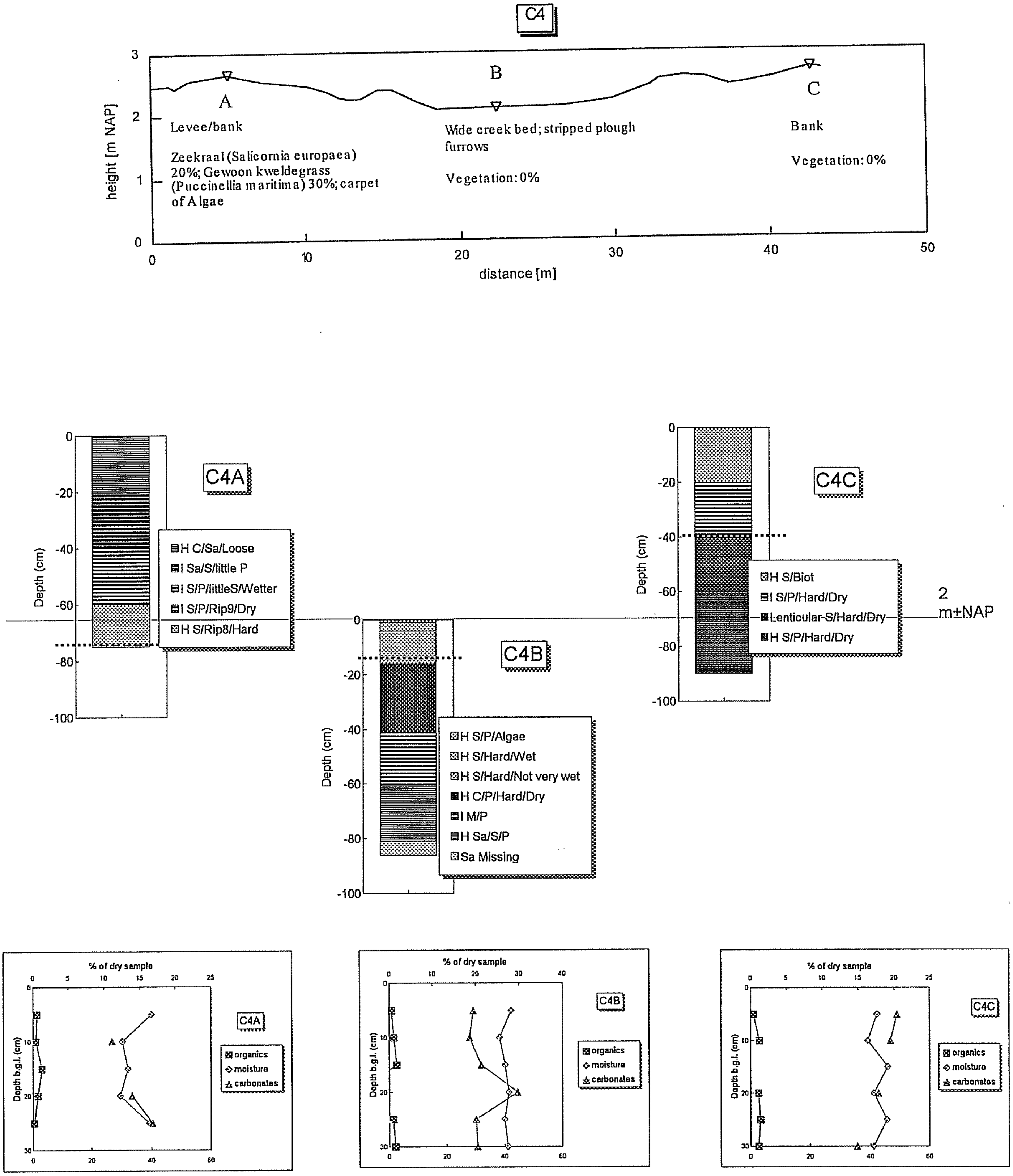

Figure 8.3 Transect C4: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

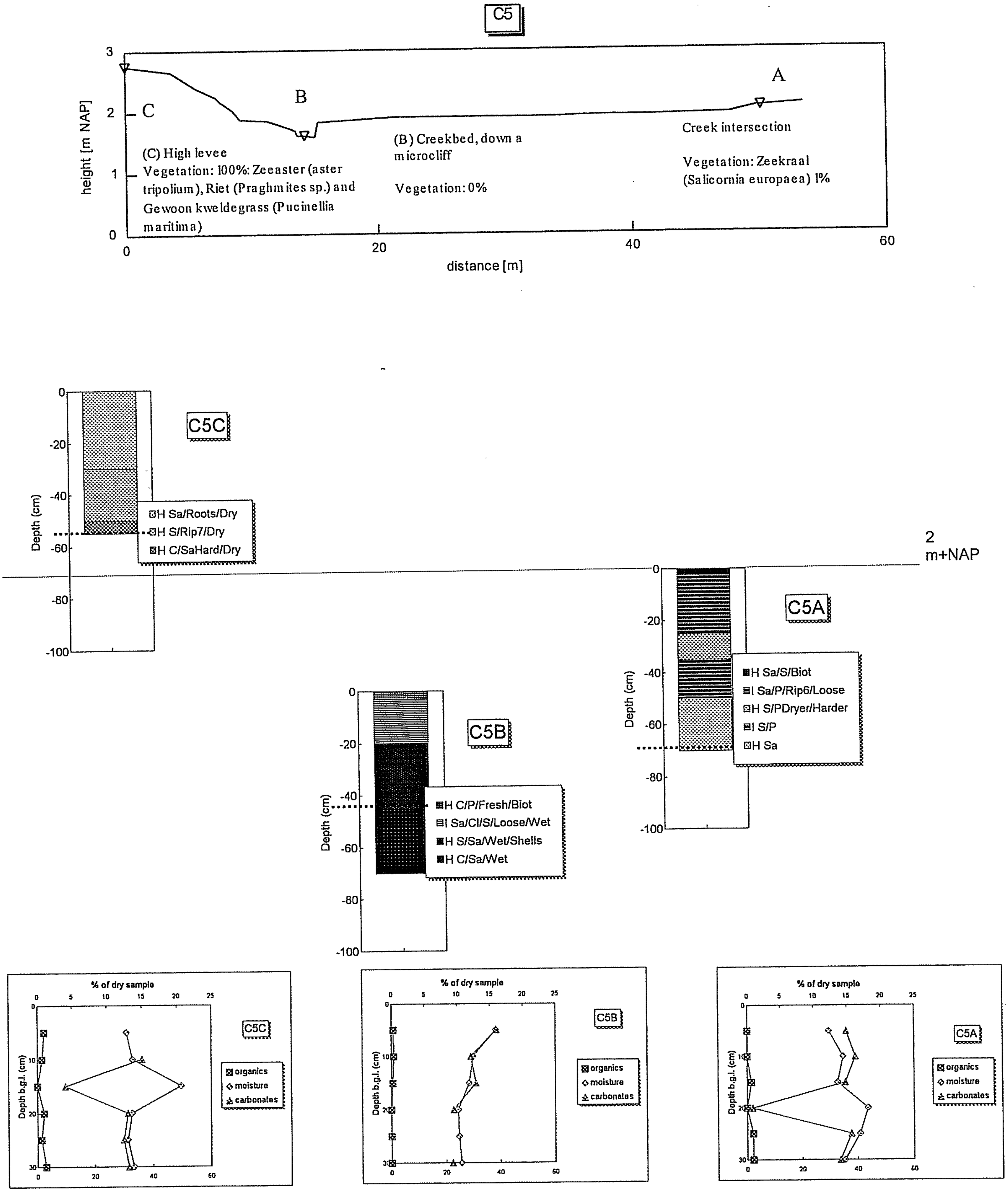

Figure 8.4 Transect C5: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

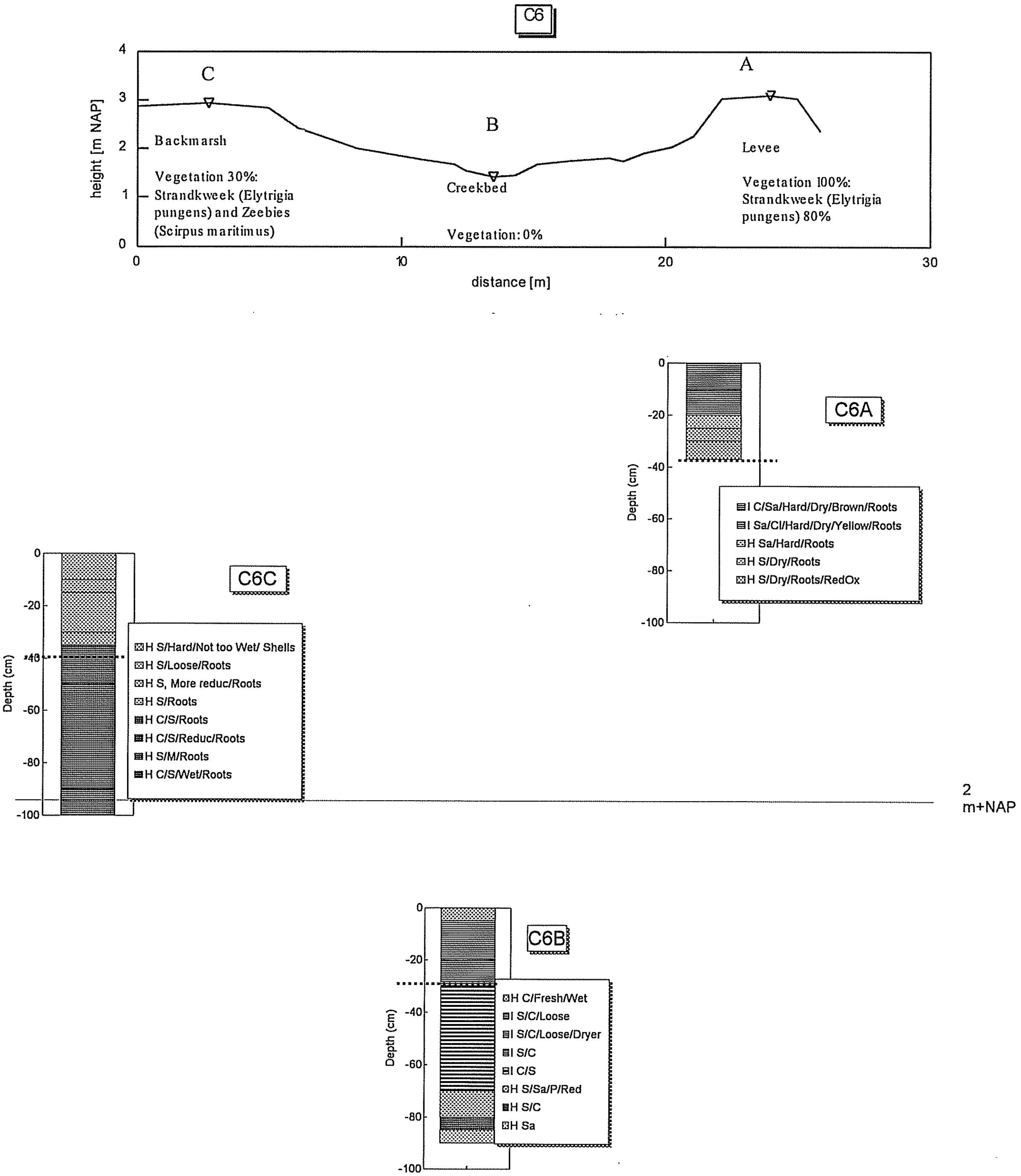

Figure 8.5 Transect C6: A) profile with information on morphology and vegetation; B) sediment profiles (cores).

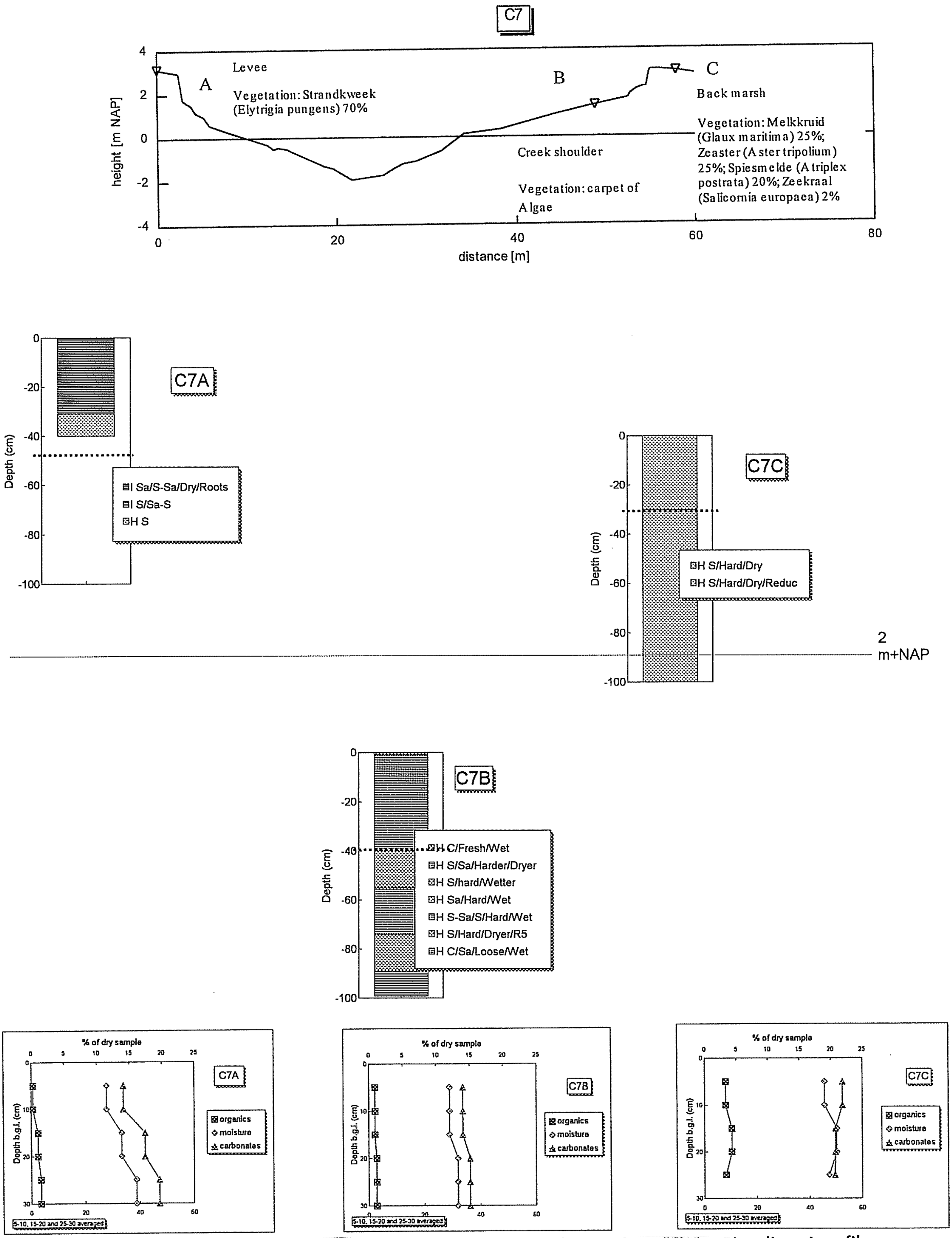

Figure 8.6 Transect C7: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

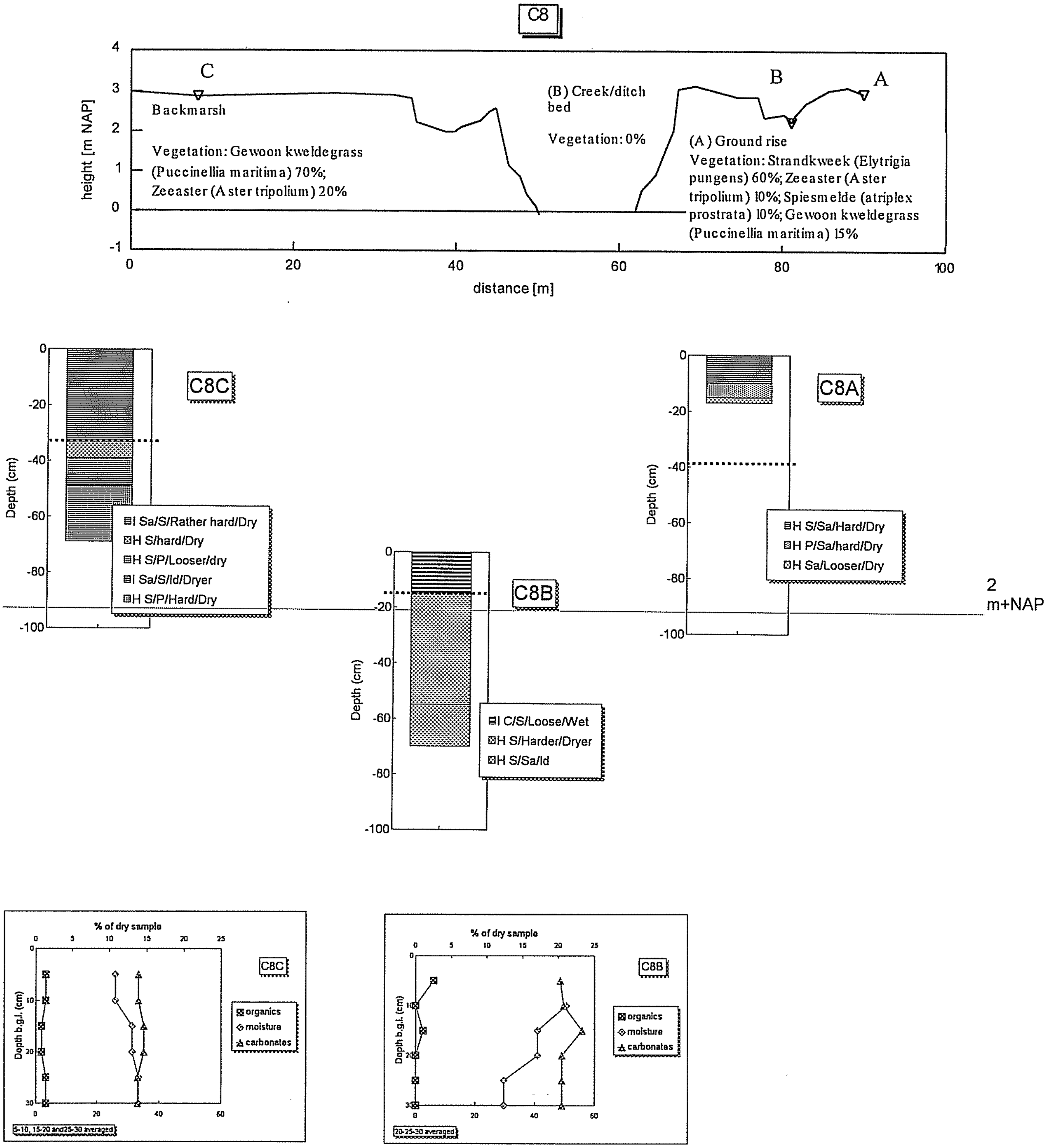

Figure 8.7 Transect C8: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

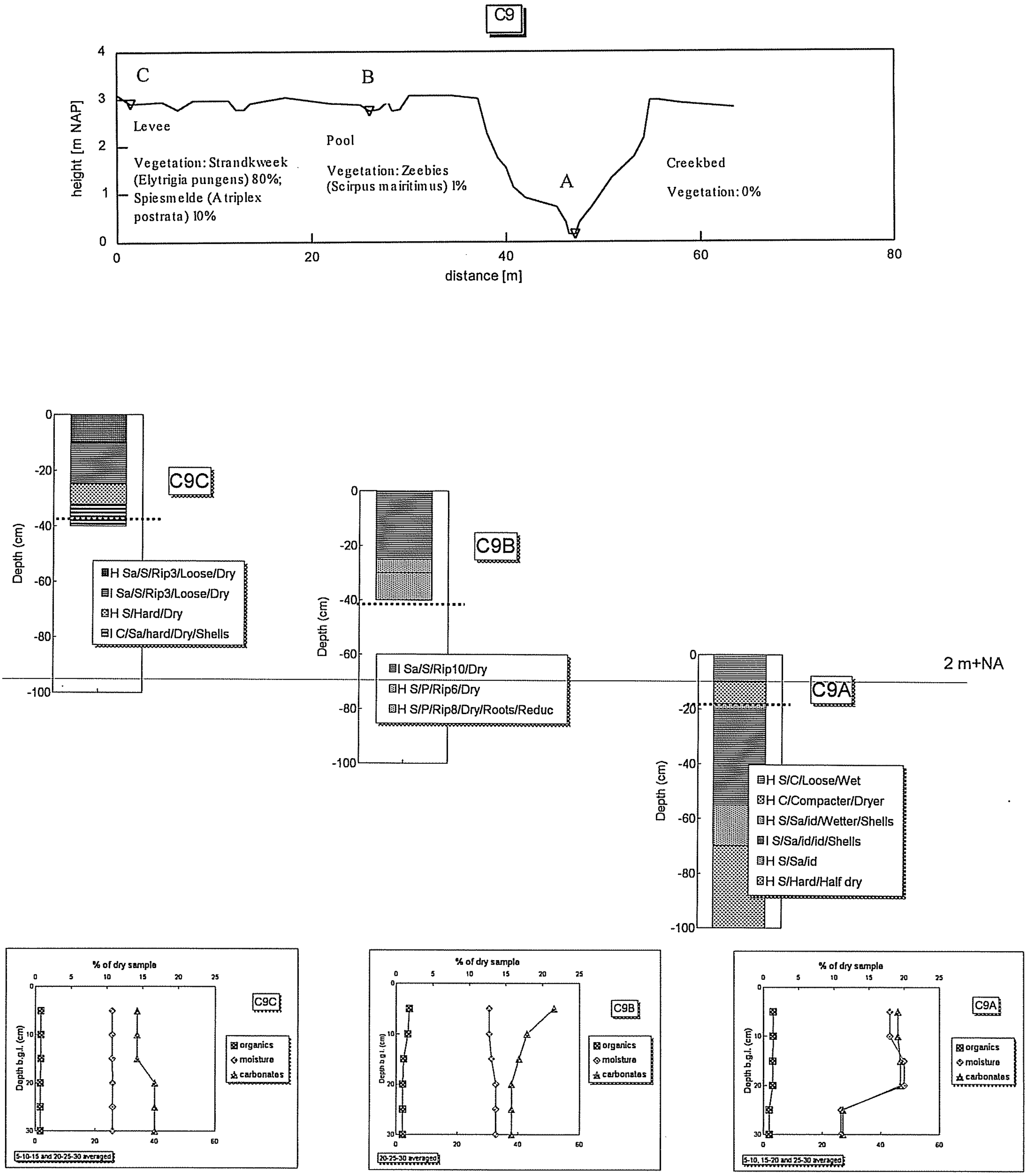

Figure 8.8 Transect C9: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

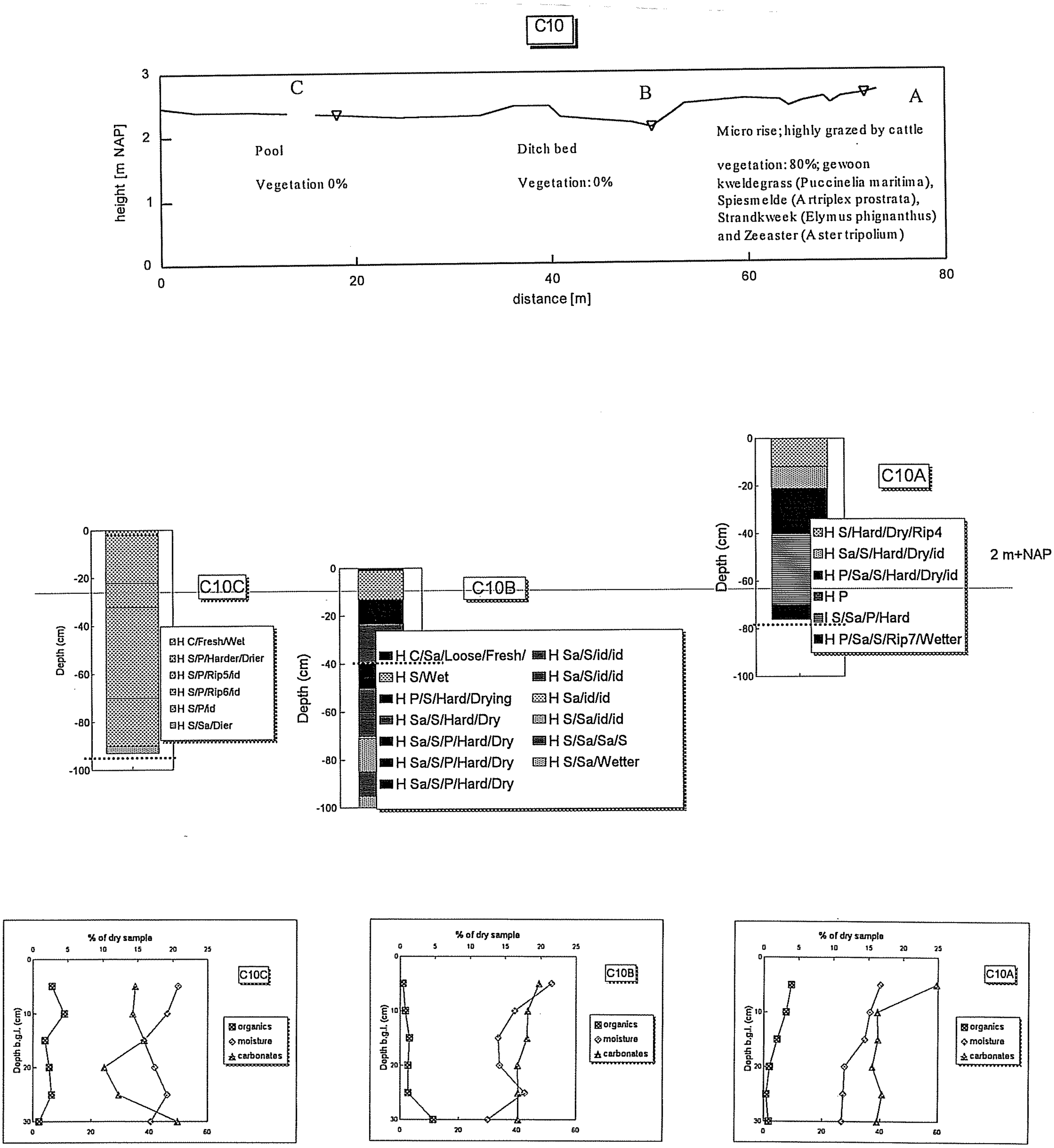

Figure 8.9 Transect C10: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

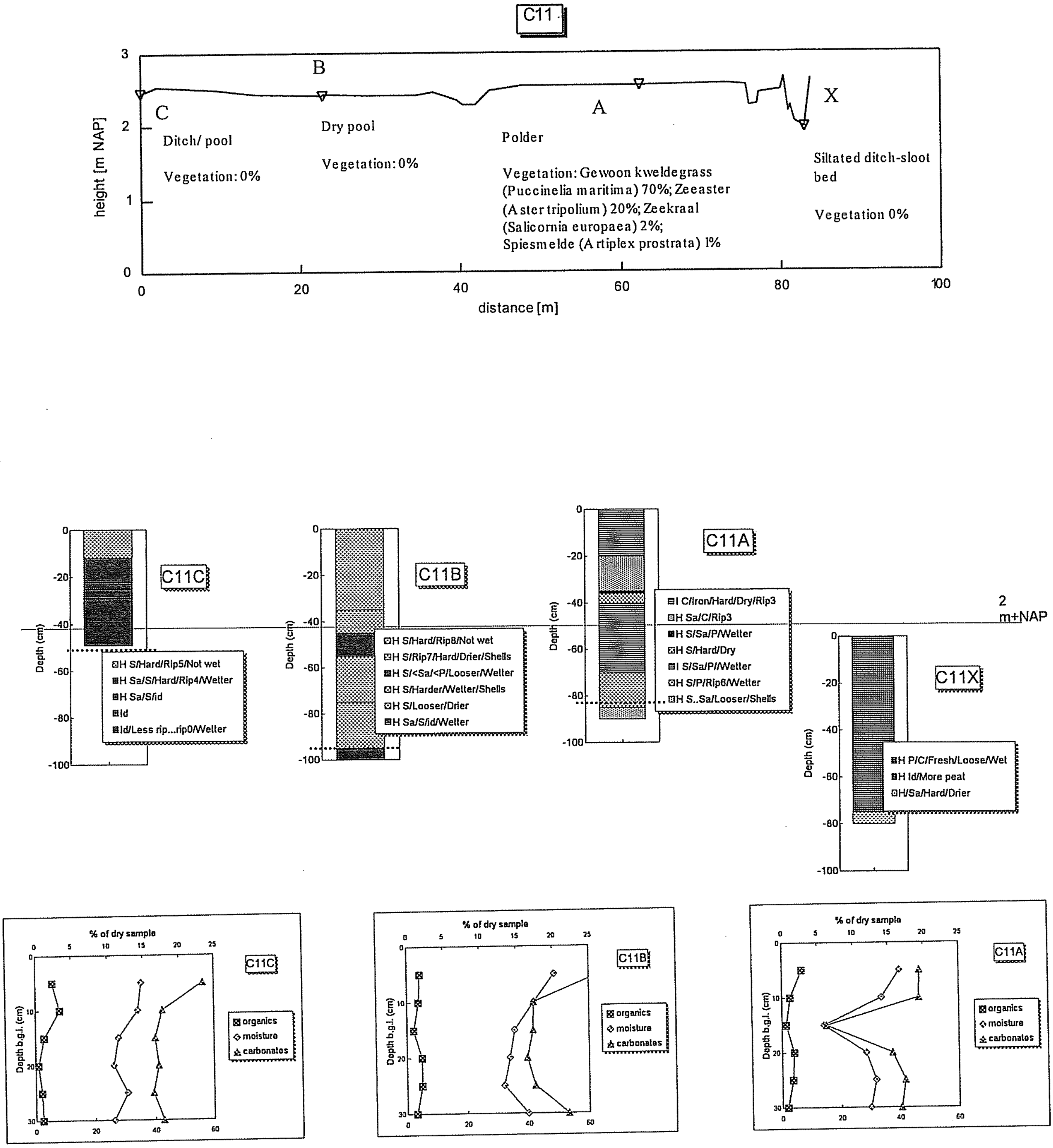

Figure 8.10 Transect C11: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

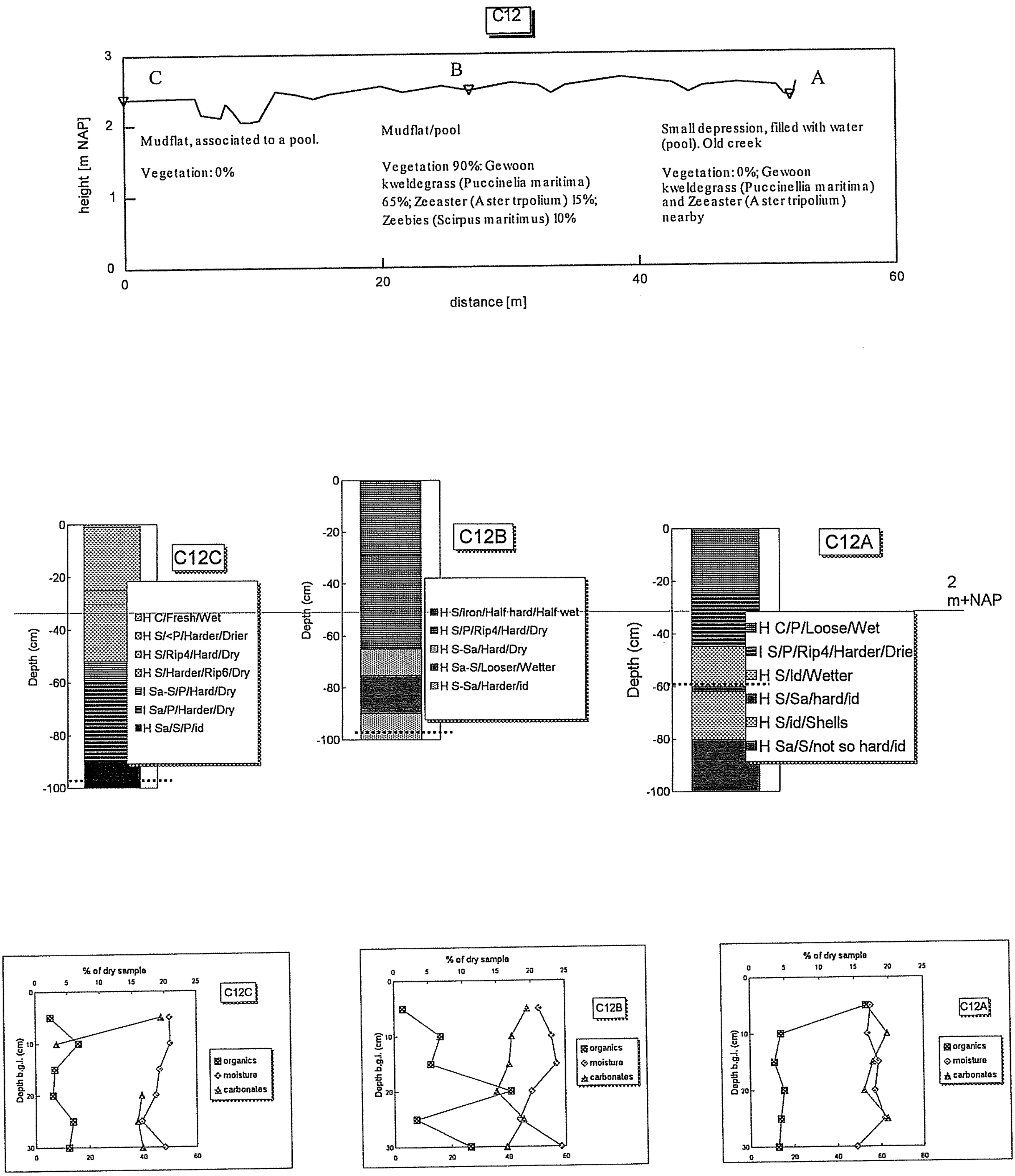

Figure 8.11 Transect C12: A) profile with information on morphology and vegetation; B) sediment profiles (cores); C) depth profile of organic, moisture and carbonate content.

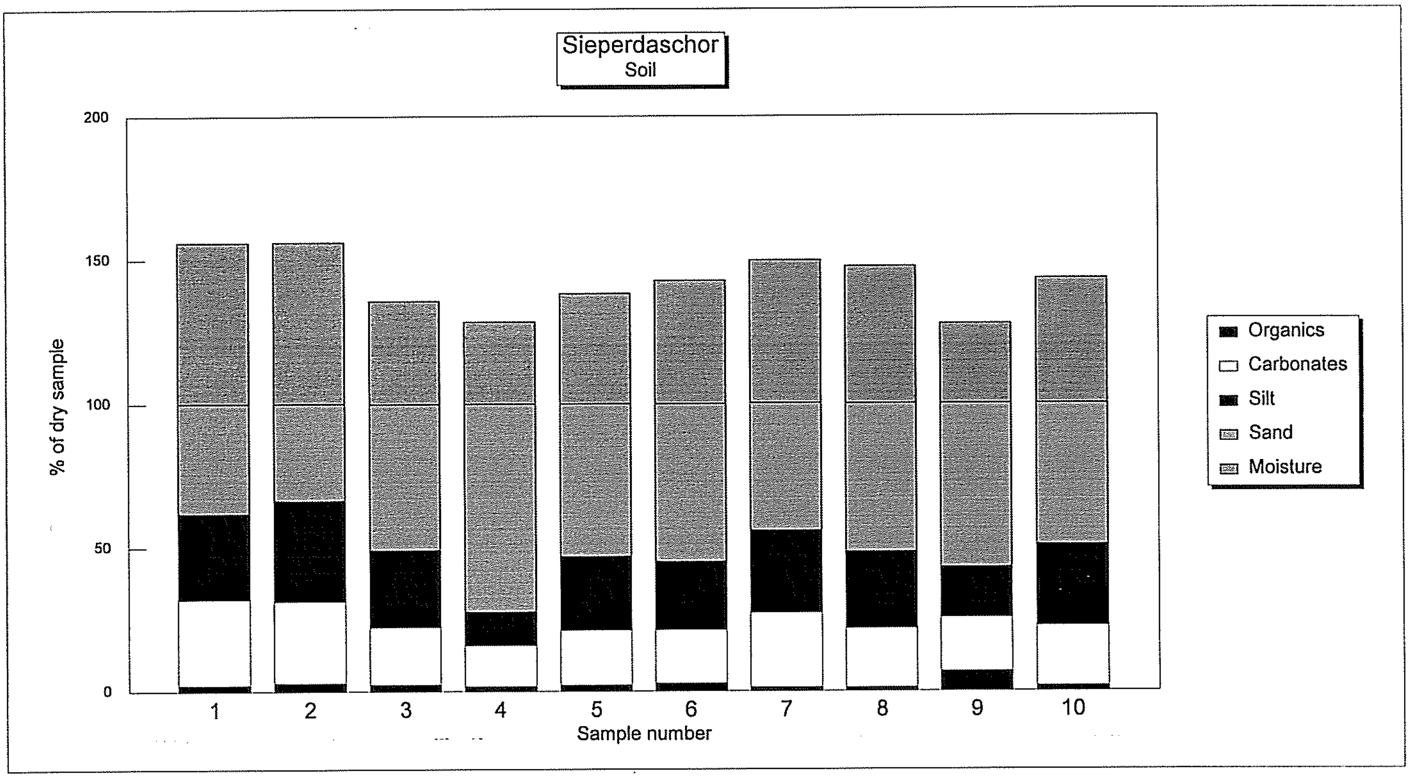

Figure 8.12 Sand, Silt, Organic, Moisture and Carbonate contents of 10 samples distributed over the Sieperdaschor.