Hydrobiologia **265**: 281–304, 1993.
E. P. H. Best & J. P. Bakker (eds), Netherlands-Wetlands.

Wet dune slacks: decline and new opportunities

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Key words: dune slacks, eutrophication, hydrology, infiltration, nitrate, phosphate, public water supply, vegetation, water table

Abstract

For a number of infiltrated coastal dune areas it is discussed to what extent artificial infiltration for the public water supply affects the quality of soil, groundwater and vegetation around pools and ponds, and what its effect is on the vegetation. Further, the results of investigations into the quality of vegetation, soil and water of a number of non-infiltrated, less affected dune areas are presented. The emphasis is on changes in groundwater flow pattern and on changes in the chemical composition of groundwater on the vegetation of wet dune slacks. Finally, recommendations for the management of wet dune slacks are presented.

It can be concluded that the introduction of nutrients through infiltration causes an abundance of nitrophilous herbaceous vegetation along the banks of all infiltration ponds and most dune pools. Of the three investigated macro-nutrients, nitrate, potassium and phosphate, the latter shows the most significant correlation with the composition, cover and biomass of the vegetation.

The moist biotopes of non-infiltrated dunes have largely disappeared because of desiccation, mainly as a consequence of water withdrawal, afforestation and coastal erosion. Relatively unaffected dune slacks can be found in the dunes on the Dutch Wadden Sea islands and a small number of dune areas on the mainland. In most areas, however, a serious decline in many rare species has been observed during the past twenty years because of eutrophic and acid precipitation, often in combination with disturbances of the groundwater regime.

Introduction

The coastal dunes are among the relatively least damaged and unaffected ecosystems in The Netherlands (Westhoff, 1989). The dry ecosystems in particular are unspoilt, although they have undergone changes due to such influences as dune reclamation, acidification and eutrophication through precipitation, and locally intensive recreation (Van Dorp *et al.*, 1985; Van der Meulen, 1982; Van der Zande, 1989). As for the present vegetation of wet dune slacks, only the dunes of the Wadden Sea Islands, the Zwanenwater dunes near Callantsoog and Voorne's dune still bear comparison with the natural abundance of the vegetation as found by Holkema (1870), Van Eeden (1886) and Vuyck (1898). Ninety years ago Vuyck described the first signs of deterioration of the wet dune slacks. Nowadays the character of almost all dune slacks has changed dramatically, especially on the mainland.

The origin and natural development of the dune

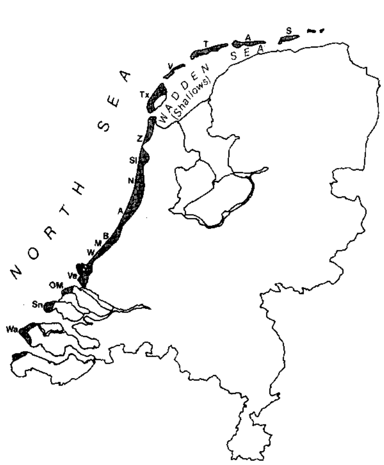

Fig. 1. Coastal dunes (hatched) in The Netherlands and location of areas mentioned in this paper. Wadden islands: S = Schiermonnikoog; A = Ameland; T = Terschelling; V = Vlieland; Tx = Texel. Mainland dunes: Z = Zwanenwater; Sl = Schoorl dunes; N = North-Holland Dune Reserve; A = Amsterdam Municipal Waterworks Dunes (Luchter-dunes); B = Berkheide dunes; M = Meijendel dunes; W = Westland dunes; Ve = Voorne's dunes; OM = Oost dunes and Midden dunes; Sn = Schouwen dunes; Wa = Walcheren dunes.

area are characterized by natural and dynamic processes, more so than most other landscapes in the Netherlands. Whereas elsewhere, both before and during the Middle Ages, there was embankment, reclamation, development, canalization, etc., in the dune areas wind, water, sand, and vegetation were untampered with until a few centuries ago (Klijn, 1990). Human interference was then essentially limited to the gathering of wood, hunting and pasturing. The first major changes concerned the safeguarding of the inner dune belt from sand drift through afforestation and prohibition of pasturing. This introduced an era of landscape rigidity. Many parts of the inner dunes were afforested and/or levelled. During the past century, many of the middle dunes were planted with vast pine forests to be used in coal mines. Halfway through the 19th century in many dune areas rather extensive agriculture was attempted locally, as well as management for drinking water supply. The farming had to end soon but the use of dune areas for water catchment has been successful until now. Nowadays, the major functions of the dune areas are sea defence, water catchment, outdoor recreation and nature conservation. In most cases the above-mentioned sequence was the order of priority with the dune planning policy.

Apart from origin and use, the wet dune systems are different from other Dutch wetlands in other ways as well. For example, the substrate consists of fine sand, which is chemically rather inert and highly permeable. This feature allows for relatively high groundwater velocities. Hydrologically, the dunes do not just differ from other systems by the good permeability of the dune sand: the water in the dunes is quite isolated from surrounding water systems (the sea, polder water in the hinterlands, possible brackish water systems). This isolation can be explained as follows: over many centuries a large freshwater lens has developed in the entire dune area. This freshwater supply has a dynamic equilibrium with the underlying saline water and can be compared to an iceberg floating in the sea (Bakker, 1990). The development of the freshwater lens is closely related to the precipitation residue (about 300 mm year^{-1}) and the elevation of the dunes, up to tens of metres above the flat polder landscape behind it. The (potential) volume of freshwater stock is determined by the extent of the dune areas and the average height of the dunes. The shape of the freshwater lens is determined by the shape of the dunes as well as by the underlying, less permeable (semipervious) layers. The flow of precipitation residue occurs both towards the sea and towards the hinterland. However, despite the hydrological isolation and the rather inert dune sand the distinct origins of the groundwater in the Dutch dune areas can cause extremely complex hydrochemical situations in many places (Stuyfzand, 1990).

In coastal dunes of average size the freshwater lens reaches up to six or seven metres above the average sea level (in the central dune area) and it may reach down to a hundred metres below sea level. Theoretically, based on specific gravity and dynamic hydrological equilibrium only, the maximum distance from the depth of the freshwater lens to sea level would be forty times the distance measured from the top to sea level. Because of impervious peat and clay layers in the subsoil, in practice this factor is less, about fifteen to twenty-five (Bakker, 1981, 1990). From the top of the freshwater lens, i.e. the natural infiltration area, groundwater movements occur towards the sides. Where the freshwater lens intersects with low-lying areas, wet dune slacks are present. These slacks may contain marshes and in some cases also small pools.

Wet dune slacks originate from very dynamic processes in which the impact of wind and water on the sand movement is predominant. Two types of dune slacks can be distinguished based on their origin:

- Primary dune slacks; originated by separation from beach plains. In augmented dune areas this slack type is mainly restricted to the Wadden Islands and may develop in the near future at the southwest coast of The Netherlands.
- Secondary dune slacks; originated by blowing-out in the older dune areas.

The life expectancy of many of the *primary slacks* is not high: situated in the dynamic outer dune environment they are subject to strong blowing in of sand, which causes them to dry out. Apart from that, local abrasion of the dune area may also cause desiccation.

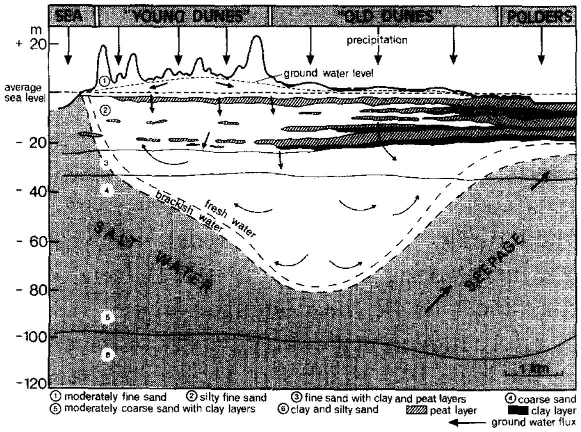

Fig. 2. Cross-section of a natural dune area (Berkheide dunes before artificial infiltration) showing the original water table and the freshwater front.

Essentially, recently formed primary slacks contain brackish water. High chloride concentrations may remain long after separation due to the salt spray as the location is close to the sea (Van Dijck & Meltzer, 1981). This sea-spray is greater when the surf is closer to the foot of the dune. Apart from an increased salt concentration, pools near the sea tend to have higher concentrations of nutrients, because the wind carries much organic material from the shore, which mineralizes rapidly in an alkaline environment. In addition seabird colonies near these pools may provide an extra input of nutrients. In the vicinity of the beach, the water and the soil contains so much calcium that the system will be sufficiently buffered against acidification for several decades.

If local circumstances allow complete blowing out of *secondary slacks*, the erosion will carry on till the capillary zone of the (summer) water table has been reached. In unaffected dune areas the local climate introduces seasonal fluctuations of the water table as a result of the alternation of high evaporation during summer and little during winter, which results in negative effective precipitation during summer and a large precipitation surplus in winter. The water level is lowest in August or September and rises in winter to a maximum in January or February. The annual fluctuation of the water table is 0.3–0.7 (exceptionally even 1.1) m; the pattern of fluctuation is mainly determined by the extent of open water and by the size of the surrounding water system. The result of the seasonal fluctuation pattern is that in summer there are vast, recently-drained sites, whereas in winter, pools with a depth of half a metre appear. Should there be accretion of the coastal area then locally the water level can increase strongly and these pools can achieve a more permanent lake-like character.

Secondary slacks may contain precipitation- and groundwater-type pools. The first type is characterized by a relatively low calcium concentration, and is generally found in the central dune areas, near the top of the freshwater lens, where infiltration predominates. Precipitation water-type pools are sometimes found near the borders of the dune area. In this case superficial impervious layers occur, which cause an apparent water table and stop the groundwater from entering the pool. Most water of the second (groundwater-) type has been in the soil for a long time (Van Dijk & Meltzer, 1981). In general precipitation water-type pools are characterized by lower nutrient concentrations than the groundwater pools and they are usually more sensitive to acidification and desiccation.

Originally, the moist to wet dune slacks in the Dutch coastal dunes took up one-third of the total surface area (Londo, 1971). In these slacks the surface water used to be oligotrophic to mesotrophic because of low nutrient loads from the substrate, the sparseness of forest and brushwood, and hydrological isolation (Leentvaar, 1963, 1967, 1981). In its natural state the phreatic groundwater has low nutrient concentrations as well (Bakker, 1981,1990). Depending on the content of calcium in the dune sand the grounwater may contain much or little calcium. The dune district south of Bergen is characterized by high lime contents of the dune sand, and therefore by higher concentrations of calcium in groundwater and surface water than the dunes in the Wadden Sea area, which are either moderately rich in lime or even completely leached and acid in the top layers.

In the moist to wet dune slacks, the original vegetation is very diverse. Many environmental gradients are reflected in it (Vuyck, 1898; Bijhouwer, 1926; Londo, 1971; Van Zadelhoff, 1981; Westhoff, 1989). The constancy of the annual water table fluctuation, the relative shortage of nutrients in the soil and in the groundwater, the gradients of wet and dry in the slacks, and the scant development of brushwood and forest under the influence of seawind and grazing, contributed to this diversity of the 'Young Dunes'.

The next sections provide a description of the changes which have occurred in the Dutch dune area during the past century as well as the ecological processes involved. The water cycle and the nutrient cycle in the past and at present are treated.

Water cycle: natural and affected geohydrology

Original situation (until ca. 1850)

After the formation of the present Young Dunes during the Middle Ages, several centuries passed before the freshwater lens reached its maximum size. Roughly speaking, the width of the dune area is directly proportional to the period required to build up the freshwater table. This process takes approximately 50 years for a dune area with a width of 0.5 km, approximately 200 years for a width of 2 km, and 300 to 400 years for the maximum width of 4 km (Bakker, 1981, 1990). From that moment on, a dynamic balance sets in with the total surplus precipitation (300 to 350 mm $year^{-1}$) draining off sideways. About half the surplus precipitation goes to the adjacent polders while the remainder flows seawards because of this sideways drainage. The groundwater flows horizontally at a speed of 0.05 to 0.15 m day^{-1} in the first few meters below the surface.

Water extraction and/or drainage result in a new balance. Accelerated drainage or the extraction of the total surplus precipitation will eventually cause the total salination of the groundwater. The extraction of smaller quantities causes the freshwater lens to shrink and the groundwater level will subside till a new dynamic balance sets in.

Interference with the hydrology

As for the disturbances of the natural water cycle in the dune area in The Netherlands we see a mosaic of effects: great differences between local situations may occur. In some parts, water extraction may have a strong impact, while in others, the planting of woods or the shifting of the coastline may be the dominant factor. We will therefore only indicate the intensity of the effects on the basis of a number of Dutch case studies.

Taking 1850 as their reference year, Bakker *et al.* (1979) trace the disturbances of the natural hydrological system to the following main factors: the afforestation and the formation of brushwood and reduced grazing, the shifting of the coastline, sand excavations in the inner dune edge, the lowering of the polder water level, surface drainage of dune water through excavated in the dune area and, finally, water extraction. For each disturbance factor Bakker (1981, 1990) indicates a mathematical approach to analyse the effect quantitatively. This section is based on the practical values which Bakker (1981) gives for the reduction in groundwater levels and for the disturbance of the groundwater flow in the dune area.

Changes in the vegetation

With the changes in the vegetation a distinction has to be made between the afforestation (mostly pine woods, occasionally larch or oak woods) and the more or less spontaneous formation of brushwood and natural forests.

A good example of the effects of planted pine woods are the Schoorl dunes. Here water levels in the central dune area, near the seabord dunes and in the north have dropped by approximately 1 m, and consequently all formerly humid-to-wet dune slacks have completely dried up. Bakker (1981) regards the planted pine woods as the main cause of the drop in the groundwater level in the central area. Near the seaboard dunes, however, coastal abrasion has also played an important role. Pine woods were planted here from the end of the 19th century onwards. As it can take approximately a century for a new hydrological balance to set in, this means that the total effects of desiccation due to the increase of the evaporation of these woods have only been realized for about 50 percent. The sharpest reductions in the water level are recorded at the actual sites of the woods. Some examples of hydrological data on the effects of planted woods are presented here:

- In the Bergen dunes the planted pine woods are causing a drop in water levels ranging from 0.1–0.2 m (inner dune edge) to 0.2–0.5 m (central, seaboard) (Bakker, 1981).
- For the dunes south of Zandvoort Bakker (1981) estimates that the groundwater levels have fallen by 0.1–0.2 m as a result of the newly planted woods.
- On the Wadden Sea island of Terschelling the pine woods planted between West-aan-Zee and Hoorn have led to a decrease in groundwater levels averaging 0.4–0.7 m in the central dune area (Bakker, 1981).
- The dunes at Schouwen have seen groundwater levels fall by 1 to 2 m at actual (pine) wood sites (Van Dijk, 1984b).

The spontaneous development of a vegetation of shrubs and deciduous trees may in due course result in the complete disappearance of the open character of the dune vegetation, particularly in the (moist) dune slacks. This development is not entirely part of a natural transition towards the final stage of the vegetation succession. Often human influences have stimulated the process. Such influences include the planting of beach grass and sea buckthorn to promote local binding, excavations that stimulated the buckthorn and the depletion of grazing levels due to hunting, and bans against cattle grazing. It is plausible that after the rabbit disease myxomatosis – which was introduced by man and decimated the rabbit population (the most important grazers in the dunes) in the Dutch dune area during the 1950s – the formation of dune scrubs accelerated. In the case of Voorne's dune, another contributory factor is the coastal works that reduced the amount of salt blown in from the sea (Van Dorp *et al.*, 1985). In addition, the planted pine woods (for instance on the Frisian islands) reduce the sea spray and subsequently encourage the growth of shrubs and trees.

Deciduous trees and shrubs have a lower evaporation rate than the pines, which remain green through the winter (coniferous wood: additional annual evaporation of approximately 25 m yr^{-1}). However, due to the more or less spontaneous encroachment of high and dense brushwood, water levels may still drop by 0.1–0.2 m (example: Terschelling to the east of Hoorn (Bakker, 1981).

Coastal abrasion or coastal formation

Local coastal formation and abrasion have caused proportional increases or reductions in groundwater levels. Some well known cases (Bakker, 1981) are presented:

- Since 1850 the coastal abrasion near Bergen aan Zee has varied between 50 to 100 metres. As a result, the water level behind the seaboard dunes has dropped by 0.5–1 m, in the central area by 0.2–0.5 m, and in the inner dune zone by 0.1–0.2 m.
- In West Terschelling coastal formation has occurred since 1859 with an average of 1 km (maximum 1.5 km). As a result, water levels have risen by 3 m at the original foot of the dune by approximately 1 m in the centre of the original area, and by 0.2 to 0.5 m at the inner dune zone.
- On the same island approximately 150 m of the originally 1.9 km wide dune corridor between Midsland and Oosterend has been eroded since 1850. In this context, Bakker (1981) mentions reduced water levels of 0.5–1 m (seaboard dunes), 0.25–0.5 m (central dune area) and 0.1–0.2 m (inner dune edge).

Excavation of the inner dune edge

Excavations have taken place in the inner dune edge to extract sand (e.g. for the sand-lime industry and for roads, as well as for residential and industrial estates). These do not have any noticeable effect on the hydrological system unless the excavation cuts into the freshwater lens. Near the Schoorl dunes, only the Hagergat quarrying has had a small and local effect on the groundwater level (Bakker, 1981). The reduction in groundwater levels caused by larger quarries (e.g. the Oosterduin lake near the dunes south of Zandvoort) has not been quantified so far.

Lowering of the polder level

Another factor mentioned by Bakker (1981) is the lowering of the water levels in polders located directly behind the dunes and the reclamation of land further away from the dunes. Examples of reduced polder water levels near the dune area include:

- The island of Terschelling: a reduction in the polder water level of 0.25–0.5 m caused a reduction in groundwater level in the dune area by a value decreasing almost linearly from 0.25–0.5 m at the inner dune edge to 0 at the seaboard dunes.
- Schoorl dunes: a reduction in the polder water level of 0.2 m (winter level) caused a reduction in groundwater levels in the dune area decreasing almost linearly from 0.1 m at the inner dune edge to 0 at the seaboard dunes.
- The effect of land reclamation further away from the inner dune edge can be seen in the Haarlemmermeer (reclaimed ca. 1850); the resulting reduction in water levels was 0.3 m at maximum in the central part of the Kennemer dunes while the effect at the inner dune edge and seaboard dunes was zero.
- In the dunes of Zandvoort which are further from the Haarlemmermeer and have more impervious and semipervious layers in the subsoil, reclamation caused the water level in the central area to drop by about 0.1 m.

Drainage ditches in the dune slacks

In the first half of the 19th century, extensive systems of drainage ditches were constructed with the intention of cultivating dune slacks in North and South Holland. At the turn of the century, similar systems were excavated in the dune slacks of the present North-Holland Dune Reserve, Terschelling, Vlieland, Texel and Schouwen, sometimes in combination with extensive forestry schemes. In some dune areas these ditches still exist causing a significant drop (in the order of decimetres) in water tables over extensive areas (Bakker, 1981). Bakker (1981) mentions that ditches excavated in West Terschelling around 1910 reduce water levels by an average of 0.3–0.5 m. In most dune areas (e.g. Central and East Terschelling, Luchter dunes), however, the old drainage systems have fallen into disuse and are of negligible importance.

Extraction of dune water and dune infiltration

Since the mid-19th century, the larger cities in the west of The Netherlands (excluding Rotterdam) have collected dune water on behalf of the public water supply. Today, virtually all mainland dunes are being used as water extraction areas. Parts of the dunes in Zeeland and the islands of South Holland and Friesland also serve as water extraction areas. In total, approximately 40 million m^3 of natural dune water is pumped up annually for the production of drinking water (Udo de Haes, 1982). The dunes in The Netherlands (40 000 hectares) have an overall annual precipitation water surplus of approximately 120 million m^3 per year. Water collection, therefore, accounts for a third of the surplus. At the actual extraction sites, a much larger proportion of the surplus precipitation is extracted, but it is subsequently recharged from other parts of the dune area. In many cases the extraction of dune water has caused the slacks to dry up entirely. The highest (winter) water levels dropped more than 1.5 m below the surface of the slacks. A clear example is the reduction in the water level in the dunes north of Noordwijk (1 to 2 m between 1850 and 1978) which is almost completely attributable to water extraction (Bakker, 1981).

Water extraction not only reduces the average water level, but it also affects the seasonal fluctuations of water tables. In most cases these fluctuations have increased because more water is extracted in periods of drought than in the winter season, and because a larger portion of the water remains underground (the so-called open water effect). The increased dynamics impoverish the richness and diversity of the vegetation, partly because desiccation combined with increased and accelerated fluctuations speed up the mineralization process, thereby increasing the availability of nutrients (Van der Laan, 1979; Grootjans, 1985).

The extraction of natural dune water from deep and surface layers is one of the major causes of the strong decline of Dutch slacks over the past century (Bakker *et al.*, 1979). It is worth mentioning that not all of the extracted dune water is used as drinking water; over half a million m^3 of dune water is pumped up annually to sprinkle the golf courses located in the dunes – and most of this water evaporates in the process.

Since the mid-50s, many dune areas in the west of The Netherlands have been infiltrated with river water or reservoir water from adjacent polders. Hydrologists saw the replenishment of the dune water with surface water from elsewhere as a logical and welcome step after the continually increasing dune water extraction had made great inroads into the freshwater lens (Carrière, 1929; Huisman & Oltshoorn, 1983). The fresh-saline water boundary had, for instance, risen tens of metres in many places while the groundwater level had dropped sharply. The depletion of the supply of pure groundwater in the dune area posed a direct threat to the future extraction of dune water and also threatened to increase salt seepage in the hinterland.

In the past nature conservationists, too, applauded the advent of dune infiltration. The reason for that is that between the 1930s and 1950s it was generally assumed that if, following the introduction of dune infiltration for water supply purposes, the dune valleys were made wet again, all phreatic plant species (e.g. *Parnassia palustris*, *Schoenus nigricans* and diverse species of *Orchideae*), which had almost disappeared because of desiccation, would regenerate themselves. At the same time, the fauna characteristic of moist places and surface waters was expected to recover.

Most infiltration ponds and accompanying extraction installations were constructed between 1955 and 1960. The technical background of this method of producing drinking water – virtually unique in the world – is described by Huisman & Oltshoorn (1983). Broadly speaking, two methods of dune infiltration can be distinguished. The first method is extensive infiltration whereby natural slacks in hilly dune territory are flooded; the natural contours of the dunes are only adapted to water extraction purposes on the side where the extraction installations – consisting of drain

Table 1. Quantification of the dune infiltration in The Netherlands (ca. 1985).

Dune area	Infiltrated water	
	Million m^3 $year^{-1}$	% in relation to natural surplus precipitation
North-Holland Dune Reserve (Castricum/Egmond)	48	460
Kennemer dunes (Bloemendaal)	10	210
Amsterdam Waterworks Dunes (south of Zandvoort)	70	640
Berkheide (Katwijk)	17	610
Meijendel (north of The Hague)	50	860
Solleveld (south of The Hague)	3.2	490
Middle and East dunes (Goeree)	2.2	100
Westerban dunes (Schouwen)	1.9	70

pipes or rows of wells – are located. The second method – intensive infiltration – is found in dune areas that have been levelled by natural causes or by large-scale excavations; the infiltration ponds are parallel, more or less straight channels and the extraction installations are situated between the channels.

With both methods of infiltration, the distances between infiltration ponds and extraction installations have been chosen to ensure that the infiltrated water takes two to three months to flow through the dune from the pond to the well or drain. However, particularly in extensively infiltrated areas, the water may remain in the dune soil much longer if it is free to flow from the infiltration ponds in the direction of the sea, e.g. due to the absence of extraction installations. In this case, water may resurface locally in the slacks resulting in seepage on the side of the infiltration pond and infiltration on the other side. If this process gives rise to permanent open water in these naturally depressed areas, we speak of seepage pools; these can be up to 2 metres deep. Many of the presented research results relate to these seepage pools. There are two reasons for the focusing of research on seepage pools. First, seepage pools were expected to have comparatively high natural values; and second, they appeared very convenient for performing hydrological and hydrochemical measurements.

In the past 10 years, the supply of infiltration water amounted to over 200 million m^3 per year. Table 1 indicates the maximum amounts of water which is filtered into various dune areas via the constructed infrastructure.

It appears that in the larger dune areas the quantity of infiltrated water is 5 to 9 times greater than the amount reaching the dune naturally, i.e. via surplus precipitation.

Infiltration has caused a marked change in the

Table 2. Maximum local change of the groundwater table by various factors.

Factor	Maximum change (m) in the total dune area	Maximum change (m) in the central dune area
1. Vegetation		
– Planted pine woods	– 0.7 (– 2)	– 0.7 (– 2)
– Natural forests of deciduous trees	– 0.2	– 0.2
2. Coastal abrasion/formation	– 3/ + 1	– 0.5/ + 0.5
3. Excavation of inner dune edge	– 0.1	> – 0.1
4. Lowering of polder level	– 0.5	– 0.25
5. Surface drainage	– 0.5	– 0.3 (?)
6. Water works		
– Extraction of dune water	– 3	– 3
– Infiltration	– 4/ + 3	– 4/ + 3

Table 3. Quantification of landscape and hydrological changes in dune areas between 1850 and 1980.

Type of change	Cause	Surface-area (% of current dune area)	
Disappearance	Coastal erosion	5	
Complete loss of original character	Industrial development	3	
	Closed construction	4	
	Quarrying of inner dune zone	1	
Loss of total dune area (% of current total)		**13**	
Severe negative impact on original character	Infiltration area	6	
	Open construction	4	
Severe negative impact, total		**10**	**10**
Moderate negative impact on original character	Afforestation	15	
	Total dessication	33	
Moderate negative impact, total		**48**	**58**
Disappearance of dune flows	Fall in groundwater	p.m.	
Small negative impact on original character*		34	
Small negative impact, total		**34**	**92**
New formation	Dry	1	
	With wet slacks	7	
Total new formation		**8**	
Total current dune area, approximately 40,000 ha			**100**

* 'Small' means there may well have been a moderate fall in the water table (as much as 3 dm), considerable scrub growth in the valleys or thick wooding.

original, gradually bulging shape of the groundwater level between the beach and the polders in the hinterland. With infiltration, the groundwater level is in some places many metres higher than its original level – i.e. near infiltration ponds on high ground – while in others – i.e. near wells or drains – the actual water level is metres lower than the situation prior to the water extraction activities. As a result, the gradient of the groundwater level is much steeper than it has ever been causing the groundwater to flow much faster than in the original situation. in the natural situation groundwater never flows than 0.1 to, at maximum, 0.2 m day^{-1}, while through infiltration the velocity can run up to 1.5 m day^{-1} (Van Dijk 1984a, 1985a; Van Dijk & De Groot, 1987).

Summary of the disturbances of the water cycle

The maximum local impact of the factors mentioned in the preceding sections is presented in Table 2.

The consequences since 1850 of the factors discussed above and of their cumulative local effects have been estimated and are presented in Table 3 (from: Bakker *et al.*, 1979):

Only one third of the Dutch dune area can be characterized by a 'small negative impact' which still may include a drop in the water table of as much as 0.3 m as well as the effects of acid rain. During the last century over 10% of the total dune area was lost because of coastal erosion, industrial development, closed construction and excavation of the inner dune zone.

Cycle of dissolved substances: abiotic effects of interferences

Original situation (until ca. 1950)

In the original situation, the availability of nutrients in the dune area was the result of dissolved minerals from the dune sand, from precipitation water and from what was blown in from the sea. In the past, the latter two sources were minor suppliers of macro-nutrients (nitrogen and phosphate), while the mineral yield from the dune sand (particularly calcium) varied widely from one dune area to another being strongly dependent on the local age of the dunes within a particular dune area. The older the substratum in other words the farther from the sea and the lower the calcium content, the more organic material and accompanying nitrogen and accumulated in the upper soil layers (Ranwell, 1972; Gerlach, 1990).

Interference by air pollution

As in the rest of The Netherlands, the deposition of acid components has risen considerably in the dunes due to the effects of industry, domestic heating and traffic. In 1983, the highest average concentrations in the air of hydrogen fluoride, sulphur dioxide and nitrogen dioxide were measured in, respectively, southwest Zeeland, near Rotterdam, and near Leiden. To the north, total acid deposits are decreasing from more than 2,200 acidity equivalents to less than 1,800 ha^{-1} $year^{-1}$. In the Wadden Sea area, the sulphur dioxide concentration increases to the east, due to the effects of industrial plants in Delfzijl and in Germany (Van Dijk, 1985c).

The effects on the dune pools and lakes which are fed directly by precipitation are evident: particularly in the leached sand soil (Wadden Sea district and inner dune area of the calcium-rich mainland dunes) ecological processes and the changes recorded are rather similar to those observed in oligo- to mesotrophic fens (Arts, 1990; Van Dam, 1987). In naturally calcium-deficient dune areas even pools fed by groundwater are affected severely. The reason is that the surrounding soil loses its buffering capacity to a considerable depth within a few decades (Manual *et al.*, 1984), particularly when (semi)pervious layers are lacking and the groundwater contains oxygen. The pH of the groundwater then decreases dramatically and the mineral composition changes radically. Significant changes in the quality of the groundwater due to the effects of precipitation have been observed even in calcium-rich dune soils, for example a doubling of the nitrate content of the drainage water from the top 2.5 m of dune soil in the course of 20 years (in the same period local NOx emissions also doubled) (Stuyfzand & Moberts, 1987b). In addition, the surface water in the (non-infiltrated) dunes not only becomes more acidic but also richer in nutrients. Dune lakes that were still oligotrophic to mesotrophic around 1960 have become eutrophic almost without exception (Van Dijk & Meltzer, 1981). This could very well be attributed to polluted precipitation.

Interference by scrub growth and afforestation

Apart from changes in the quality of precipitation, the more rapid growth of scrub and woodland in dry dune areas possibly cause the eutrophication of originally mesotrophic dune lakes (Van Dijk & Meltzer, 1981). It has been observed that a dune area that was open fifty years ago, such as Voorne's dune, is now transformed completely into scrub and woodland (Van Dorp *et al.*, 1985). The tendency is the same in most other dune areas. In the event of abundant scrub growth, a large accumulation of organic substances occurs in the top soil layers; mineralization and leaching increase the nutrient content of the shallow groundwater and neighbouring surface water. Abundance of the nitrogen-fixating sea buckhorn, in particular, may result in considerably increased concentrations of nitrates in the ground and surface water (Van Dijk, 1985a; Van Dijk & De Groot, 1987).

Eutrophication by avifauna

Between the 1930s and the 1970s many (herring) gull colonies have increased rapidly in size since they are no longer controlled (Van Ommering & Verstrael, 1987; Van Ommering & Van der Salm, 1990; Texeira, 1979; Van Dijk & Meltzer, 1981). Colonies of cormorants have also established themselves in some places. Van Dijk & Meltzer (1981) consider these developments to have contributed to the eutrophication of larger dune lakes.

Dune infiltration

Artificially infiltrated water has been pre-purified to a greater extent in recent years but due to its scale and use, dune infiltration affects the cycle of dissolved substances more than any of the factors referred to above.

From the end of the 1960s until far into the 1970s, infiltration water contained large quantities of macro-nutrients. This caused problems in the production of drinking water. Algal blooms blocked the bottoms and banks of infiltration ponds increasingly so that the penetration of the water into the soil stagnated. Another problem was the seepage of substances into the dune soil and into the drinking water. For these reasons, most dune water companies switched to more stringent pre-purification of inflow water. This strongly reduced the ammonia and phosphate contents. Thanks mainly to phosphate stripping the original clarity of the water and a natural richness of water plants was restored in many infiltration ponds (Van Dijk, 1989a).

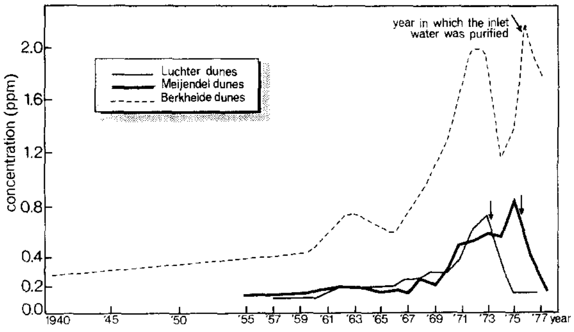

Fig. 3. Changes in the orthophosphate concentration in the inlet water of infiltrated dune areas during 37 years (after: Van Dijk, 1989).

The investigations presented here largely relate to situations encountered before or immediately after these phosphate strippings. Figure 3 shows the concentrations of orthophosphate in the infiltration water, which, between 1973 and 1978, increased to 0.9 (river water) and even to over 2 mg PO_4 l^{-1} (source of inlet water: reservoir water of polder). For reference: in natural dune pools the average annual orthophosphate content is between 0.01 and 0.1, with incidental peaks <0.5 mg PO^4 l^{-1} (Van Dijk & Meltzer, 1981; Van Dijk & Bakker, 1984; Van Dijk & De Groot, 1987). The nitrogen and potassium contents of the infiltration water were, and still are, much higher than the natural concentrations (Van Dijk, 1982, 1984a).

The water quality in the infiltration ponds strongly reflects the quality of the inlet water because it only stays there for a short time (a few days to weeks). Local improvements in the water quality can be observed at points situated far from the inlet. This is due to the longer residence time and therefore the extraction of nutrients by water plants and dying and sinking algae (Hoekstra, 1974; Van Dijk, 1989a).

As for the increase of the actual nutrient load caused by infiltration in dune areas Van Dijk & Bakker (1984) record some estimations for a number of larger infiltrated dune areas. For example the potassium loads have increased by a factor 12 to 200 and the orthophosphate loads up to a factor of 200. These estimated values depend strongly on the calculation method used.

Before infiltration started it was expected that the ecosystems of wet dune slacks which had disappeared by desiccation would return in general. This recovery would occur in the seepage pools and marshes which would develop in the infiltrated dunes. The original assumption about seepage pools was that valleys situated several hunderd metres away from the infiltration ponds would be safeguarded from infiltration water and related increases of nutrient load. This was based on the hypothesis that there should be a precipitation water lens on top of the flowing infiltration water. If, for example, the underlying infiltration water had travelled for three years since penetrating the dune soil, the assumption was that three years' effective precipitation would be present above this infiltration water. After having made corrections for the pore volume of dune sand, this would mean a 3 m thick precipitation water lens. Figure 4 shows this hypothesis diagrammatically. In practice, however, it was observed (Van der Werf, 1974; Londo, 1975) that seepage pools also displayed vegetation development – albeit later and less extreme than observed on the borders of the infiltration ponds – towards nitrophilous phreatophytes. This indicates that the infiltration water forces its way to the upper groundwater even in the case of seepage pools located far away from the infiltration ponds. A three-year investigation of flow lines in seepage pools in Meijendel gives the definite answer (Van Dijk, 1984a; Stuyfzand & Moberts, 1987a, 1987b).

In the Meijendel research project the origin of the groundwater and seepage pool water was determined with the aid of tracer substances (chloride, potassium, fluoride), which are, in principle, conservative substances with higher concentrations in the infiltration water than in the precipitation water and the original dune water. The concentrations of nitrogen and phosphate were also measured. Investigation of the top 2.5 m of groundwater near seepage pools revealed that, in the case of rapid flow (around 3 m day^{-1}), 50% of this groundwater still consisted of original infiltration water even 200 m from the infiltration pools (Fig. 5).

The conclusions of the investigations are:

- residence time is a main factor in the proportion of infiltration water in the upper groundwater and seepage pool water (Fig. 6); therefore the impact of the nearby infiltration pond decreases faster at an increasing distance from the infiltration pond in the case of slower groundwater flow;
- the size and depth of the pools are a second important factor.

The second conclusion indicates that the explanation for the occurrence of infiltration water in seepage pools should not be sought in hydrodynamic (macro) dispersion (De Groot, 1984), but in characteristics unique to the seepage pool (Stuyfzand & Moberts, 1987; Van Dijk & De Groot, 1987). The somewhat deeper seepage pools attracted groundwater from several metres down, while this water – after being mixed in the pool by the wind – infiltrated again across a broad front in the bottom and the banks. As a result of this hydrological mechanism less than 20 of some

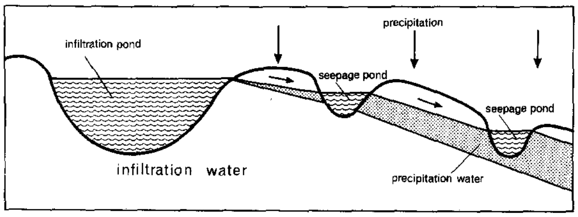

Fig. 4. Model of the 'precipitation water lens' hypothesis.

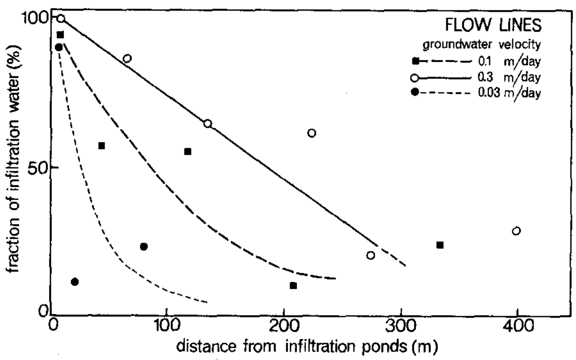

Fig. 5. The contribution of infiltration water in the top 2.5 m of groundwater in relation to the distance from the infiltration ponds (after: Van Dijk, 1984a).

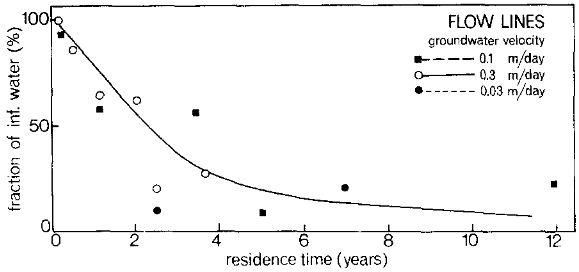

Fig. 6. The contribution of infiltration water in the top 2.5 m of groundwater in relation to the residence time (after: Van Dijk, 1984a).

300 seepage pools in the Meijendel and Berkheide infiltration areas appear to be safeguarded from mixture with infiltration water (Van Dijk, 1986, 1989b).

The relation between the hydrological mechanism described above and the nutrient contents in groundwater and seepage pool water was studied. In the case of the flow lines presented in Fig. 6, hypothetical concentrations of nitrate and phosphate were calculated on the basis of the concentration of the substances used as tracers. The projected value was based on the assumption that only dilution with precipitation water determines the concentration. The results of these calculations, together with the concentrations measured, are presented in Figs 7 and 8. Nitrate, representing 90% of the nitrogen in the groundwater, proved to have natural sources in the dune which overruled the effect of infiltration (Fig. 7). Obvious sources are eutrophication from gull colonies and nitrogen-fixing sea buckthorn. In addition, the effect of atmospheric deposits cannot be excluded.

Generally speaking phosphate (Fig. 8), unlike nitrate, behaves as a conservative substance in groundwater; in other words, the groundwater concentration is in equilibrium with the dune soil, i.e. the dune sand is more or less saturated with phosphate. The results are, however, obscured by the dephosphatization of the infiltration water carried out by some waterworks companies shortly before the observations presented here.

Far higher phosphate concentrations than in Meijendel were revealed in the seepage pool water

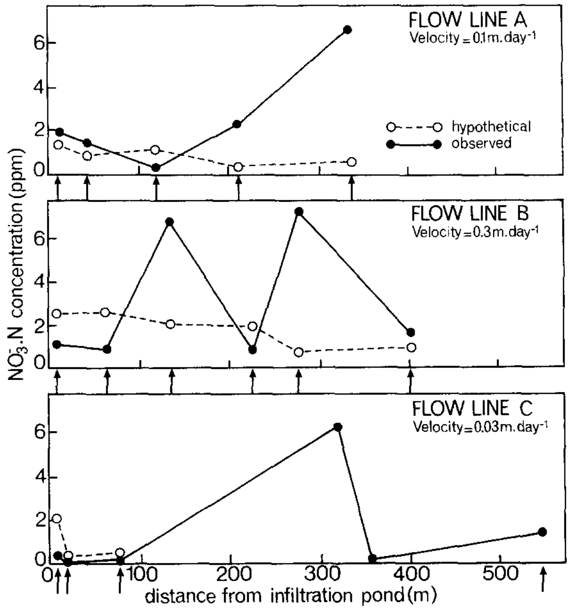

Fig. 7. The nitrate concentration in the top 2.5 m of groundwater in relation to the distance from infiltration ponds (West Meijendel) (Van Dijk, 1984a; Van Dijk & De Groot, 1987).

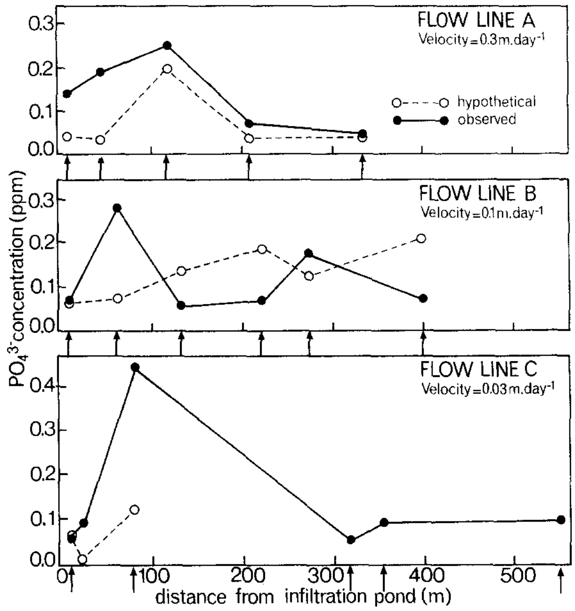

Fig. 8. The orthophosphate concentration in the top 2.5 m of groundwater in relation to the distance from infiltration ponds (West Meijendel) (Van Dijk, 1984a; Van Dijk & De Groot, 1987).

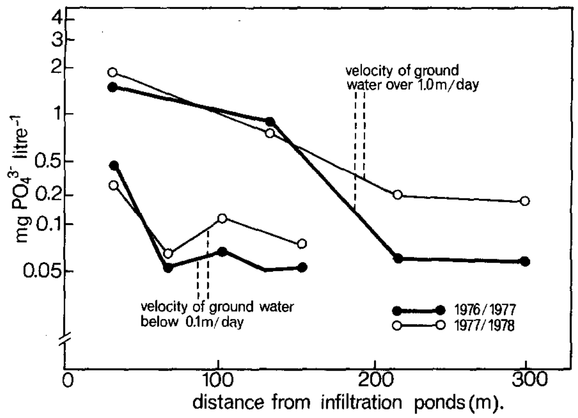

Fig. 9. The orthophosphate concentration in seepage pool water in relation to the distance from infiltration ponds (Berkheide) (Van Dijk, 1984a and 1985).

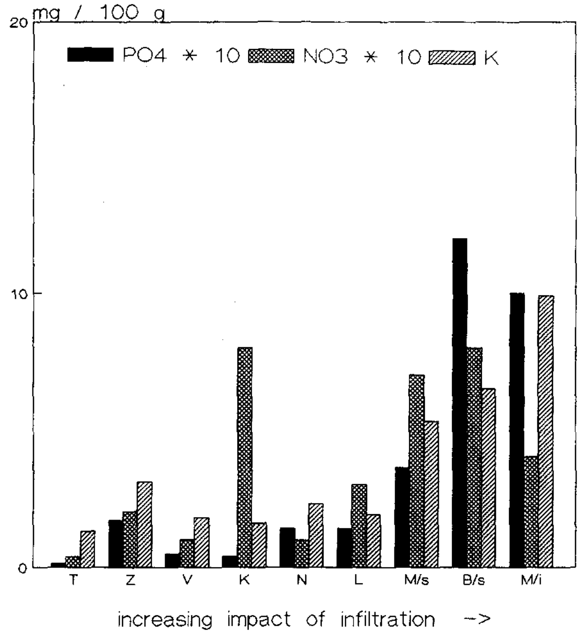

Fig. 10. Nutrient amounts (grams m^{-2}) of the upper 30 cm subsoil of the banks of pools and ponds (average values; sampling August–September/after: Van Dijk, 1985b). T = Terschelling; Z = Zwanenwater; V = Voorne's dunes; K = Kennemer dunes; N = North-Holland Dune Reserve; L = Amsterdam Municipal Waterworks Dunes (Luchter dunes); B = Berkheide dunes; M = Meijendel dunes;/ s = seepage pools; /i = infiltration ponds. (*left (T,Z,V)*: non-infiltrated areas; *middle (K,N,L)*: areas very recently infiltrated or infiltrated with good prepurification of inlet water; *right (M,B)*: areas infiltrated during about twenty years).

in the Berkheide dune area, were phosphate concentrations in the infiltration water were some three times higher than in Meijendel (Fig. 9). An originally clear gradient of concentration decreasing with distance to infiltration levelled out markedly within one year, which points to strong signs of saturation of the subsoil. In addition, it was found that the highest phosphate concentrations occurred where the groundwater velocities were highest.

The nutrient contents in the dune soil appear to reflect the observed gradations of the nutrient concentrations of the groundwater between infiltrated and non-infiltrated areas as well as within the infiltrated areas.

Obvious differences occurred in the soil nutrient contents of banks in infiltrated and non-infiltrated dune areas (Fig. 10). In Fig. 10 Terschelling (T), Zwanenwater (Z), Voorne (V) are non-infiltrated areas. Kennemer dunes (K), North-Holland Dune reserve/southern infiltration area (N) and Luchterdunes (L) represent infiltrated dune areas where the infiltration started very recently (K, N) or where infiltration occurred with strongly dephosphatized inlet water. Infiltration with very phosphate-rich inlet water has been going on for 20 years in Meijendel (M, s = seepage pools; i = infiltration ponds) and in Berkheide (B, only seepage pools). In Fig. 10 the infiltration influence increases from left to right. As can be seen, large differences between the infiltrated and non-infiltrated areas occurred in the potassium and orthophosphate contents of the soil. As far as phosphates are concerned, the seepage pools in Berkheide were much more polluted than the infiltration ponds in Meijendel.

The gradient in the concentration of phosphate in the Berkheide pool water (Fig. 9) recurs in the phosphate concentrations in the soil of the pool banks (Fig. 11). The phosphate concentrations in the soil, however, showed much more variance compared to the concentrations recorded for the pool water. The highest soil concentrations per pool or pond were found in the places with the strongest seepage and infiltration – in other words, in the places with the highest temporary and cumulative phosphate load.

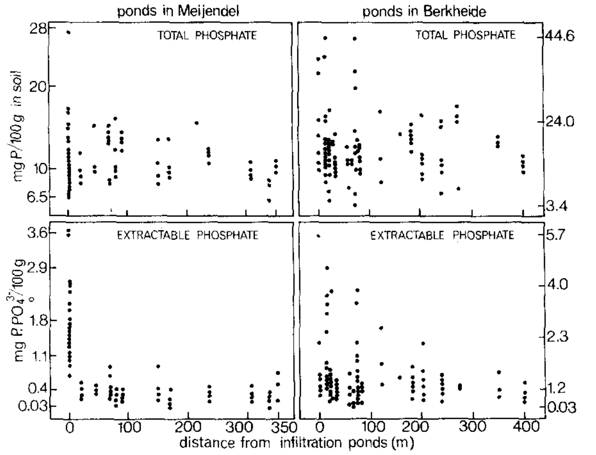

Fig. 11. Phosphate levels of the top 3 dm in the banks of seepage pools in relation to the distance from infiltration ponds (after: Van Dijk, 1985b).

Ecological consequences of interfering with water, calcium and nutrient cycles

A great deal is known about the consequences of affecting natural cycles for higher plants. Causal ecological chains are less known for the bird world, and even lesser for mammals, amphibians and reptiles (Croin Michielsen, 1974). Ecological knowledge about the lower animals in the dune area is hardly adequate. The ensuing text is restricted to the consequences of interfering with the water and nutrient cycle for the phreatophytic dune vegetation.

Decline in the average water level and changes in water table fluctuation

Even before the turn of the century, Vuyck (1898) pointed to a strong deterioration in phreatophytic plant species which he attributed to extracting water from the dunes. Local research such as done in the Verbrande Pan near Bergen (N.H.) by Bijhouwer (1926) and Hoffman & Westhoff (1951) confirmed that many wet plant species and vegetation types shifted to lower places or ultimately disappeared.

Examples of phreatophytic plant species that have substantially declined since 1850, especially between The Hague and Den Helder, include *Epipactis palustris*, *Parnassia palustris*, *Equisetum variegatum*, *Orchis morio*, *Carex pulicaris*, *Gentianella amarella* and *Echinodorus ranunculoides* (Londo, 1971; Van Zadelhoff, 1981). Eight phreatophytes, including two *Rhynchospora* species, *Eleocharis acicularis* and *Narthecium ossifragum*, completely vanished from the dune area during this period (Van Zadelhoff, 1981). Strangely enough, these eight species mainly occurred to the north of Petten and on the Wadden Sea Islands which are the hydrologically least affected dune areas (Van Zadelhoff, 1981). The largest decline in phreatophyte species was assessed among the moisture-loving species tied to the less dynamic, relatively nutrient poor and vulnerable biotopes. The aquatic macrophytes have also dwindled and often disappeared completely (Van Dijk, 1989a).

Changes in the water table fluctuation pattern can lead to eutrophication due to accelerated mineralization, especially in lime- and humus-rich situations. The vegetation, therefore, acquires a bushier and more nitrophilous character. The very large water fluctuations that sometimes occur in infiltration areas severely affect the vegetation. Only a few plant species such as *Agrostis stolonifera* can survive whereas a few pioneering species such as the *Chenopodium rubrum*, *Limosella aquatica* and *Cirsium arvense* can germinate in such situations.

Changes in groundwater flows, without artificial infiltration

Intensive extraction of groundwater sometimes leads to serious disturbances in the direction and volume of groundwater flows. Bakker (1981) reports that near the extraction installations on Texel, the groundwater velocity has increased fivefold from 0.1–0.2 to 0.5–1 m day^{-1}. According to Bakker *et al.* (1979), the concurrent increase in the supply of (nutritional) substances per time unit is less clear than the drop in water tables. By contrast, other authors (Grootjans *et al.*, 1988, 1990) claim that the consequences of the disturbance of the groundwater flow – with the ground-

Table 4. Decline of nine plant species measured as a percentage of the number present in 1964 in permanent plots (10 m × 10 m) in the Kapenglop (Grootjans *et al.*, 1990).

Species	Occurrence in number of plots (1964)	Decline (% of permanent plots)	
		1964–77	1964–87
Antennaria dioica	171	75	>90
Liparis loeselii	8	100	100
Pedicularis palustris	151	68	97
Epipactis palustris	143	29	95
Dactylorhiza incarnata	39	7	97
Schoenus nigricans	64	?	>80
Parnassia palustris	68	55	91
Pyrola rotundifolia	14	7	100
Gentianella amarella	13	?	100

water level remaining largely unaffected – can be extremely serious.

The detailed studies cited here were carried out in three dune valleys on the Wadden Sea island Schiermonnikoog: the Arnica marsh, the Grïenglop and the Kapenglop. The Grïenglop has for years consisted exclusively of heavily acidified and impoverished vegetation, while the lower parts of the Arnica marsh still have many rare plants, such as *Pedicularis palustris*, *Carex pulicaris* and various species of orchids, that more or less point to calcium-rich groundwater. The Kapenglop, which comprised some of the best developed dune valley vegetation in the 1950s with lots of *Schoenus nigricans*, *Pedicularis palustris* and *Litorella uniflora*, had been monitored in 1964, 1977, 1983 and 1987; now it is strongly acidified and tall bushy hemicrytophytes and shrubs dominate locally. More than 90% of the following rare plant species of vulnerable gradient situations have disappeared within a detailed and frequently investigated 0.6 ha area (Table 4).

Grootjans *et al.* (1988, 1990) show that differences in the development of the valleys are not primarily attributable to desiccation. The water level is such that all three examples can still be categorized as moist to wet valleys. The influence of water extraction is not so large that drying out occurs in the strict sense, but groundwater flows have been shifted. The groundwater begins to flow in new directions because the groundwater level elsewhere has experienced a significant drop, which diminishes hydrostatic pressure. The seepage and run-off are weakened, while the direction in which the groundwater flows may change. The low-lying wet-to-dry gradient situations in the Arnica marsh with extremely high numbers of species, appear to be coupled to a stable hydrological situation in which calcium-rich groundwater can reach the surface of the lower lying seepage areas throughout the entire growing season and thereby pushes the acidifying precipitation aside (Fig. 12).

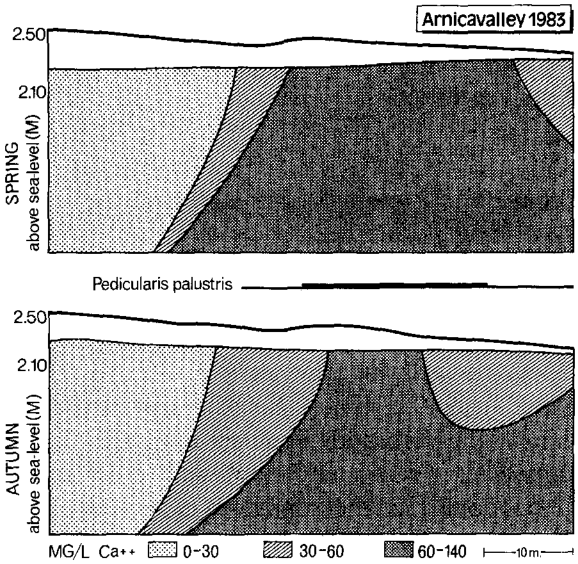

Fig. 12. Cross sections of the Arnica marsh, showing the calcium content of the groundwater in relation to the occurrence of *Pedicularis palustris*.

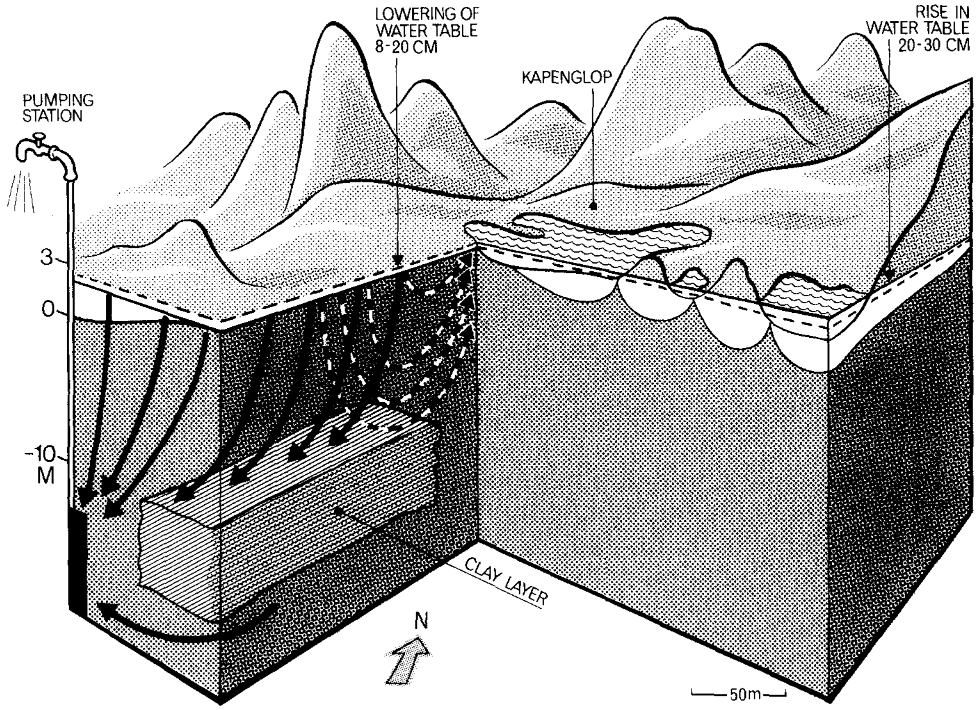

Fig. 13. Hypothesis if the hydrological situation around the Kapenglop valley; solid lines indicate the present flow lines and dotted lines indicate former flow lines.

Small decalcified sand hills function as local infiltration areas and the presence of less impervious layers of peat enables the calcium-deficient infiltration water to run off to more calcium-rich seepage situations. The zone where calcium-poor groundwater meets the calcium-rich seepage water is characterized, among other things, by the frequent occurrence of *Carex pulicaris*. This species is still found in the same zone as it was over 25 years ago, illustrating the stability of the hydrological gradient.

This situation contrasts with the nearby Grïenglop, where the whole structure of local hydrological systems has collapsed and the vegetation has acidified. This has been caused by hydrological measures in the polder and probably also by the excavation of a sand extraction hole in the Grïenglop itself.

The acidification in the Kapenglop was attributed by Grootjans *et al.* (1990) to changes in the local hydrological system that provided the Kapenglop with calcium-rich groundwater (see Figs 13 and 14). The local acidification is assumed *NOT* to originate from a natural de-calcification process because the top soil layers had already been totally decalcified for many decades. The underlying causes here are the increasing influence of water extraction in the nearby Hertenbos valley from about 1960 and the growing evaporation through the dune vegetation.

Some measures taken in the dry years of the 1970s, to save the valley from drying out, have had an adverse effect on the natural values during the wet 1980s. Specifically, the measures taken to retain precipitation water in the valley seem in retrospect to have put an *EXTRA* brake on the inflow of calcium-rich groundwater, which has led to reinforcement of the acidification phenomenon.

The data described show that the dune valleys in the centre of the dune system are very vulnerable systems for several reasons: infiltration is very prevalent in these valleys; they are situated in the midst of leached-out dunes; they rely on

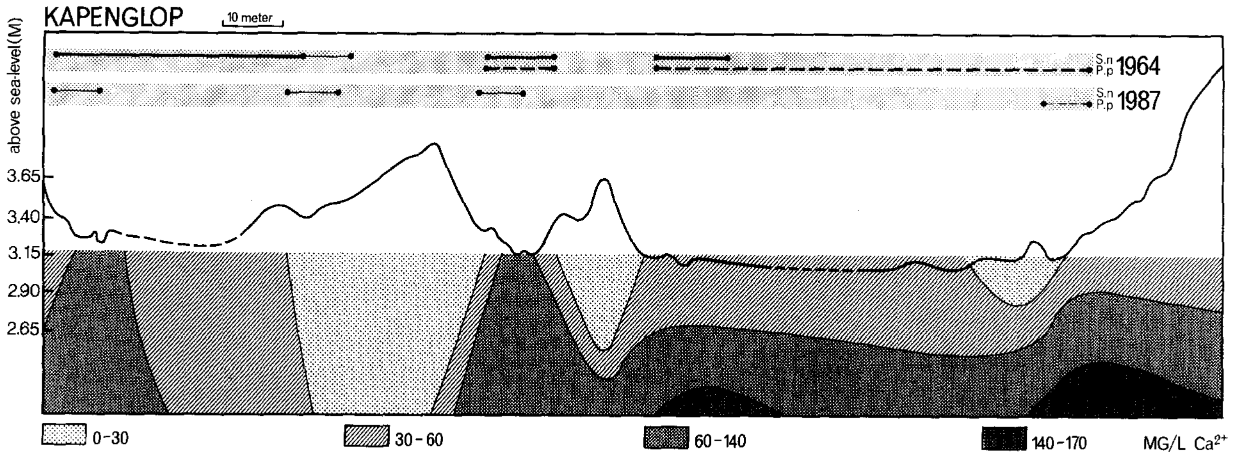

Fig. 14. Cross section of the Kapenglop valley, showing the calcium content of the groundwater in relation to the occurrence of two plant species (*Schoenus nigricans* (S.n.) and *Pedicularis palustris* (P.p.) in 1964 and 1987. The tickness of the lines indicates the relative abundance of the species.

local hydrological systems which provide calcium-rich groundwater. These small hydrological systems can thus be adversely affected by very minor influences, such as a slight increase in water extraction, the digging of run-off ditches in source areas, or increasing evaporation from woods. All these influences lead to shifts in groundwater flows, after which the acidified precipitation can begin to dominate the local surface water (Grootjans *et al.*, 1990).

Outside Schiermonnikoog the occurrence of endangered calciphilous plant species (among others, those mentioned in Table 4) has declined sharply (Table 5). This decline does not necessarily always point to a disturbance in the hydrological systems, due to which calcium-rich seepage has declined or disappeared. A species such as *Pedicularis palustris*, for example, has declined mainly because currently fewer primary dune valleys are being formed than was previously the case. The optimal environment for this species is the boundary zone of this kind of valley, where the influence of the sea, rather than seepage, takes care of hydrological 'buffering'.

From Table 5 it also becomes clear that the decline of endangered dune slack species in the Wadden Sea Islands is much less pronounced than elsewhere in The Netherlands.

Table 5. Percentage decline since 1950 in the occurrence of calcium and moisture-loving plant species in squares of 5 x 5 km (Grootjans *et al.*, 1988).

Species	Wadden Sea dune area	Dune district	Elsewhere in The Netherlands
Pedicularis palustris	17	53	58
Dactylorhiza incarnata	0	11	70
Liparis loeseli	20	71	61
Parnassia palustris	33	46	74
Anagallis tenella	38	71	83

Dune infiltration

Occurrence of nitrophilous tall forbs in the bank vegetation

To get a rough impression of the effects of artificial infiltration, the species composition of four infiltrated and thirteen non-infiltrated dune areas were compared (Van Dijk, 1989a). Fifty plants species, indicative of oligotrophic and mesotrophic habitats, have declined as a result of infiltration. Nineteen species have increased, all of which demand a high nutrient availability. The development of the vegetation of the banks of infiltration ponds and seepage pools since the start of the infiltration to the present situation has been described by Van der Werf (1974) and Londo (1975). In a period of ever increasing nutrient concentration in the infiltration water they observe a shift in vegetation towards dominance of only a few species, which succeed each other in the following sequence: *Calamagrostis epigejos*, *Mentha aquatica*, *Lycopus europaeus*, *Epilobium hirsutum*, *Eupatorium cannabinum*, and finally *Urtica dioica*.

At the present the herbaceous bank vegetation along most of the infiltration ponds is strongly dominated by these tall forbs, which are fast-growing, have large leaves and are very productive. When fully grown they intercept much of the light from the small, slowly growing, indigenous dune valley plants. Figure 15 shows the average cover of two ecological groups of herbaceous plant species occurring along the pond banks of various dune areas. The first group is formed by the tall forbs *Epilobium hirsutum*, *Eupatorium canabinum*, *Cirsium arvense* (grey in Fig. 15) and *Urtica dioica* (dark grey), which are extremely

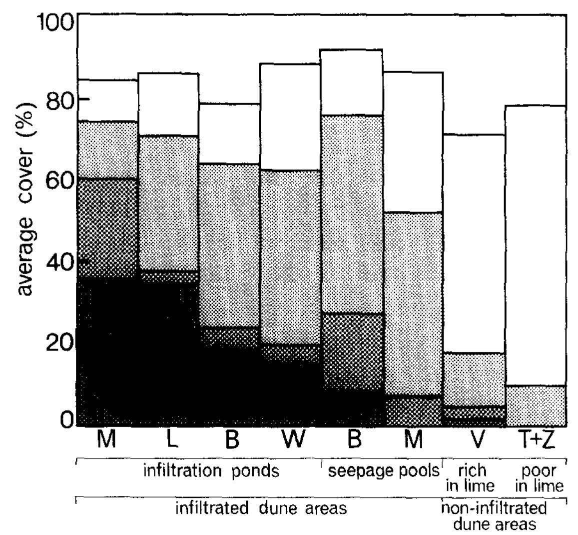

Fig. 15. The average of nitrophilous tall forbs in the bank vegetation of pools and ponds in heavily to non-infiltrated dune areas (after: Van Dijk, 1989). The most extremely 'nitrophilous' species are marked grey (*Epilobium hirsutum*, *Eupatorium canabinum*, *Cirsium arvense*) and dark grey (*Urtica dioica*). The three less nitrophilous species *Calamagrostis epigejos*, *Mentha aquatica* and *Lycopus europeus* are marked light grey. (M = Meijendel dunes; L = Amsterdam Municipal Waterworks Dunes (Luchter dunes); B = Berkheide dunes; W = Westland dunes; V = Voorne's dunes; T = Terschelling; Z = Zwanenwater).

'nitrophilous' according to Ellenberg (1979). The second group consists of three species (light grey): *Calamagrostis epigejos*, *Mentha aquatica* and *Lycopus europeus*. The species of the second group are less nitrophilous and much smaller, but may dominate the vegetation too when the nutrient availability is increased by infiltration.

Figure 15 clearly shows that species of both ecological groups hardly occur among the bank vegetation in non-infiltrated dune areas. In the areas with recent infiltration or with infiltration with pre-purified inlet water the cover of the seven 'nitrophilous' species is also relatively low, but in areas that have been infiltrated with very eutrophic water for about 20 years (Berkheide and Meijendel dunes), the four most nitrophilous tall forbs have left little room for the original vegetation. Not only the banks of the infiltration ponds are covered with tall forbs, but also the banks of seepage pools situated up to 100 metres further down.

To investigate the ecological mechanisms involved in this eutrophication process, the vegetation of the pond banks was related to nutrient concentrations in soil and groundwater, and finally to nutrient supply in the rooting zone, where nutrient concentrations and flow velocities are combined.

Biomass and nutrient concentration in soil and groundwater

The relationship between vegetation characteristics and nutrient concentration in the soil and incoming groundwater was studied in eight infiltrated and eight non-infiltrated areas. The dry biomass values of the bank vegetation were averaged per area and related to the annual average nutrient concentrations of surface water, soil and vegetation (Fig. 16).

The phosphate concentrations – of surface water and soil as well as above-ground dry weight – clearly show the most positive relationship with regard to biomass. The potassium and phosphate concentrations have a strong mutual correlation (Meltzer & Van Dijk, 1986), but potassium only

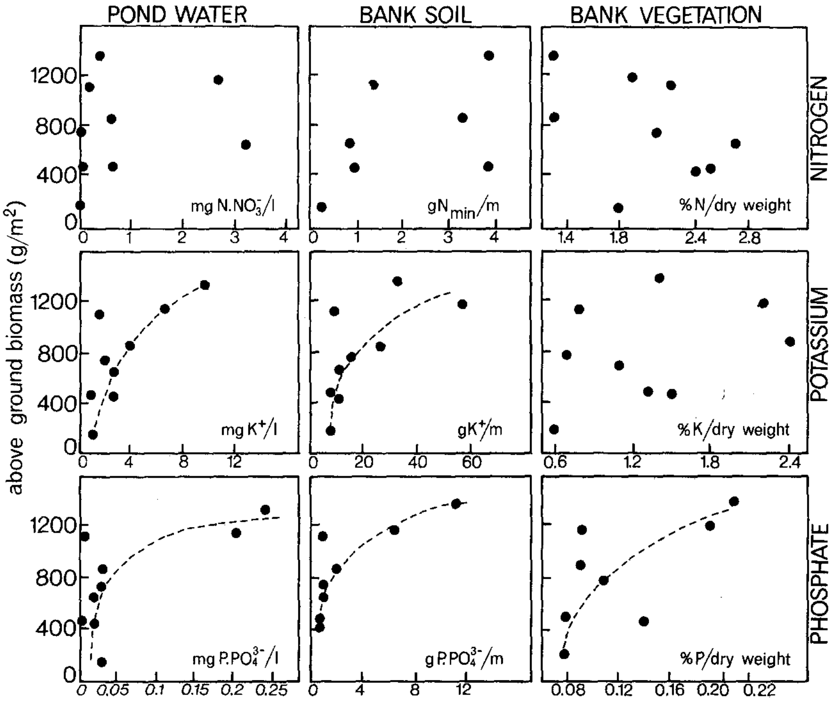

Fig. 16. Relationship between dry biomass of herbaceous bank vegetation and nutrient contents in surface water, soil and surface vegetation sections (average values of eight areas / after: Van Dijk, 1985b).

showed a clear relation with regard to surface water and bank soil. The nitrogen concentrations demonstrated no clear relations with the biomass. The right-hand graphs of Fig. 16 (bank vegetation) show strong indications that changes of the phosphate supply have the greatest influence on the occurrence of nitrophilous macrophytes along the banks of dune ponds and pools. The other graphs of Fig. 16 (surface water and bank soil) appear to indicate that the nitrogen level has a smaller influence than the potassium level.

Nutrient loading via groundwater flow

Great differences were often encountered in the cover of tall nitrophilous plant species along the banks of one seepage or infiltration pond. In general the water quality was the same here. Since large differences in flow velocity may occur in such situations, the nutrient load via the groundwater might play a key role here; extremely nitrophilous species reached the highest cover on those parts of the bank where the seepage or infiltration was greatest (Van Dijk, 1984a).

The nutrient loading via flowing groundwater was estimated from the product of groundwater flow rate and nutrient concentration. Annual average nutrient concentrations of the surface water were determined per pond or pool from monthly concentration measurements. In addition the velocity of the groundwater flow was measured (method: see Van Dijk, 1984a).

When the maximum covers of the seven 'nitrophilous' species of ecological species group R7 were related to the momentary phosphate load, a sequence in response curves was obtained (Fig. 17). *Mentha aquatica*, for instance, increases at a relatively low loading, while *Urtica dioica* increases significantly at a high loading. It is striking that the same succession in species was described by Londo (1975) and Van der Werf (1974) in a sequence of species gaining dominance during the time that the nutrient concentrations in the infiltration water increased strongly.

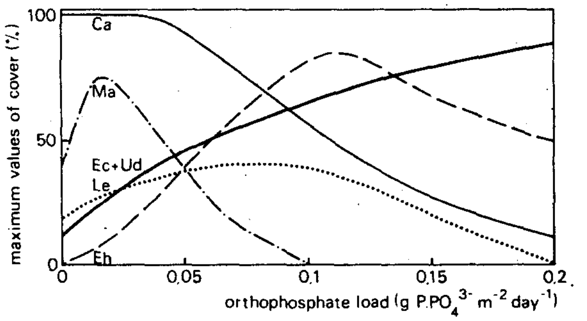

Fig. 17. The relationship between the maximum covers of six nitrophilous species and the annual average orthophosphate loading via infiltration pond water (after: Van Dijk, 1984a) (Ca = Calamagrostis epigejos; Ma = Mentha aquatica; Le = Lycopus europaeus; Eh = Epilobium hirsutum; Ec = Eupatorium cannabinum; Ud = Urtica dioica).

Conclusions

As for artificial dune infiltration, it must be concluded that the strongly increased velocity of the groundwater results in unnaturally high nutrient loads, even after thorough pre-treatment of the infiltration water. In addition, the small-scale hydrological gradients that determine the quality of the groundwater in wet dune slacks have become greatly affected.

Further it must be concluded that all ecological observations in infiltrated and non-infiltrated dune areas indicate that the supply of phosphate via the groundwater plays a key role in the occurrence of 'nitrophilous' tall herbaceous plant species in dune valleys under the influence of artificial dune infiltration. This is in accordance with earlier eco-physiological work on *Urtica dioica* (Pigott & Taylor, 1964) which showed that this 'nitrophilous' species requires a high local concentration of phosphate.

The last conclusion is supported by the observation that in the Meijendel area the cover of most 'nitrophilous' species has substantially decreased since 1976 when the intake water was de-phosphated. This decrease in cover was not followed, however, by an increase in the number of species nor by the re-establishment of original dune valley species.

Both conclusions are supported by data on nutrient loading via mineralization in both non-infiltrated and infiltrated dune areas (Van Dijk, Noordervliet & De Groot, 1985). It appears that within the non-infiltrated areas the cover of the nitrophilous species of the bank vegetation primarily corresponds with nitrogen mineralization; but the infiltration areas, however, phosphate loading via the groundwater flow dominates over mineralization and over potassium and nitrogen loading via flowing groundwater.

Recommendations

Revised starting points for drinking water extraction.

Surface infiltration must ultimately be stopped. Thorough pre-treatment of the infiltration waters offers no guarantee whatsoever for the return of the complete ecosystem of the wet dune slacks with this type of infiltration. Under certain circumstances, depth infiltration with intensively pre-treated water may offer a better alternative from an environmental point of view (Van Dijk, 1989a). The freshwater lens above the impervious soil layers can restore itself, and the dune area still retains the function of a safe repository for drinking water. Other alternatives for surface infiltration are also at hand (Udo de Haes *et al.*, 1980; Anonymous, 1982).

Both the regional authorities of North and South Holland and the central Dutch government have made political statements to the effects that surface infiltration is to be reduced in due course. Nevertheless, the infiltration and extraction installations at the Berkheide infiltration area have recently been greatly expanded and there are also plans to expand the infiltration capacity of the Amsterdam Waterboard Dunes.

For the Wadden Sea islands alternatives for dune-water catchment must be more intensively initiated. The still increasing influx of recreational visitors and the greater disturbance of the hydrology related to this, is taking an ever-increasing toll on the relatively unaffected ecosystem – at least in comparison with the mainland dunes – of the wet dune slacks.

Renewed out-blowing of dune slacks

Many factors such as coastal erosion, afforestation, water extraction, lowering of the water level in polders and drainage systems cause strong reductions of the water table, with the result that more than half of the dune area suffers severely from desiccation. At the same time, the dune area is strongly immobilized by the measures against sand-drifts which have been carried out intensively for many centuries. If the causes of the desiccation can only partially be dealt with, then stimulation of blow outs in the valleys will often allow the groundwater to reach the surface again.

While choosing locations for sand-drift experiments, very close account must be taken of the chemical and hydrological factors of the soil that control the external conditions for a return of the rich variety of the natural vegetation of the dune slacks.

Revision of forestry management

It has been shown that in many places the non-indigenous planted woodlands may exert a dominant local influence on the hydrology. Possibilities to reduce the negative effects of the woodlands are the reduction of the woodland area or – a less good solution – wettening of the present woodland by means of removing the drainage ditches that were excavated when the woodland was planted. In any case it is not recommanded to consider new pine-tree planting for the dune area and in more cases, and more quickly, the existing pinewood should be cut and contingently replaced with deciduous trees. In addition, drainage systems in or near the woods should be eliminated.

Choice for a withdrawing or an accreting coast

The renewed interest in scenarios for coastline management, partly prompted by discussions over a possible rise in the sea level, has important implications for wet dune slacks. The choice for extensive sand supplementation is the choice for wettening of and decreasing sea influence in existing dune slacks and possibly for beaches and primary dune formation. The choice for the local withdrawal of the primary sea barrier can mean the new creation of sea inlets ('slufters'), an almost extinct type of natural landscape. In the first case the development of marsh vegetation in the secondary dune slacks will be stimulated; in the second case the secondary dune slacks will be further dried up, but new salt and brackish vegetation may start the succession anew.

Acknowledgements

The authors are indebted to Dr T. W. M. Bakker and Drs W. Hurkmans for critically reviewing the manuscript, and J. Seebus and Drs A. B. Kaal for taking care of the translation. E. Leeuwinga and D. Visser drew the figures.

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