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Hydrogeology of a restored coastal dune system in northeastern Scotland

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Abstract. This paper reports the results of 12 years of hydrological monitoring at the St. Fergus dune system in northeastern Scotland. The site is adjacent to the UK's largest gas terminal and the dunes are crossed in five places by North Sea gas pipelines which were constructed between 1976 and 1990. These are buried beneath the dune system which was restored after pipeline installation. The dunes include a substantial freshwater wetland which is seasonally flooded and provides an important habitat for waterfowl. The hydrogeology of the site is characterized and the hydrogeological processes that sustain this wetland feature are considered including recent climatic fluctuations.

Keywords: Dune slack; Groundwater; Restoration; Sand dune; Water table; Waterfowl.

Nomenclature: Names of vascular plants follow Clapham et al. (1962).

Abbreviations: AE = Actual evaporation; ASMD = Actual soil moisture deficit; PE = Potential evaporation; PSMD = Potential soil moisture deficit.

Introduction

Sand dunes border 7.4 % of the coastline of the United Kingdom and they are important resources in terms of conservation interest, recreational use and natural coastal defence (Doody 1989a). It is, therefore, a matter of concern that they are subject to increasing pressure from a number of sources, including land reclamation, rising sea-levels, visitor pressure and pollution (Green 1986; Pye 1989). Hydrological processes are fundamental to the ecological structure and function of dune systems (Nordstrom et al. 1990); their high biodiversity is partly explained by the marked hydrological gradients that occur, with xerophytic species dominating the arid dune ridges whilst organisms tolerant of waterlogging are found in low-lying slacks (Doody 1989b). It has also been shown that the geomorphological stability of sand dunes is dependent on moisture availability, with dune systems being more prone to the development of blowouts when dry (van der Meulen & Jungerius 1989). Although extensive hydrological research in dune environments has recently been undertaken in other parts of Europe, such as The Netherlands (e.g. Grootjans et al. 1991; van Dijk & Grootjans 1993; Stuyfzand 1993) and Spain (Lamas 1990), published work on the hydrology of dune systems in the UK is older and more prosaic (e.g. Ranwell 1959; Willis et al 1959; Clarke 1980). Consequently the main hydrological characteristics of dune systems are often poorly understood and this can hinder the development of sustainable management strategies, particularly where dunes are subject to development pressures.

Dune systems dominate much of the northeast coast of Scotland between Aberdeen and Fraserburgh (Fig. 1a-d). The exploitation of North Sea oil and gas resources has involved heavy utilization of this coastline for a variety of purposes, including the siting of landfalls for offshore pipelines. North Sea gas pipelines, constructed in 1976, 1987 and 1990, cross a major dune system at St. Fergus, Rattray Bay, in five places (Fig. 1c). The St. Fergus dune system includes a large low-lying slack which floods during the winter between October and May. The area is close to the Loch of Strathbeg, an internationally important ornithological site, and is extensively used by waterfowl. Because of the ornithological value of St. Fergus, Environmental Impact Assessments (EIA) prior to the construction of pipe landfalls stressed the need to maintain, amongst other things, the site's hydrological processes. Dune restoration procedures were developed and a hydrological monitoring programme commenced in 1981 to detect adverse effects (Ritchie & Kingham 1990). This paper discusses the preliminary findings from the data collected at St. Fergus with the specific aims of (1) characterizing the hydrology of the site and (2) identifying the factors regulating the spatial and temporal patterns of flooding in dune slacks.

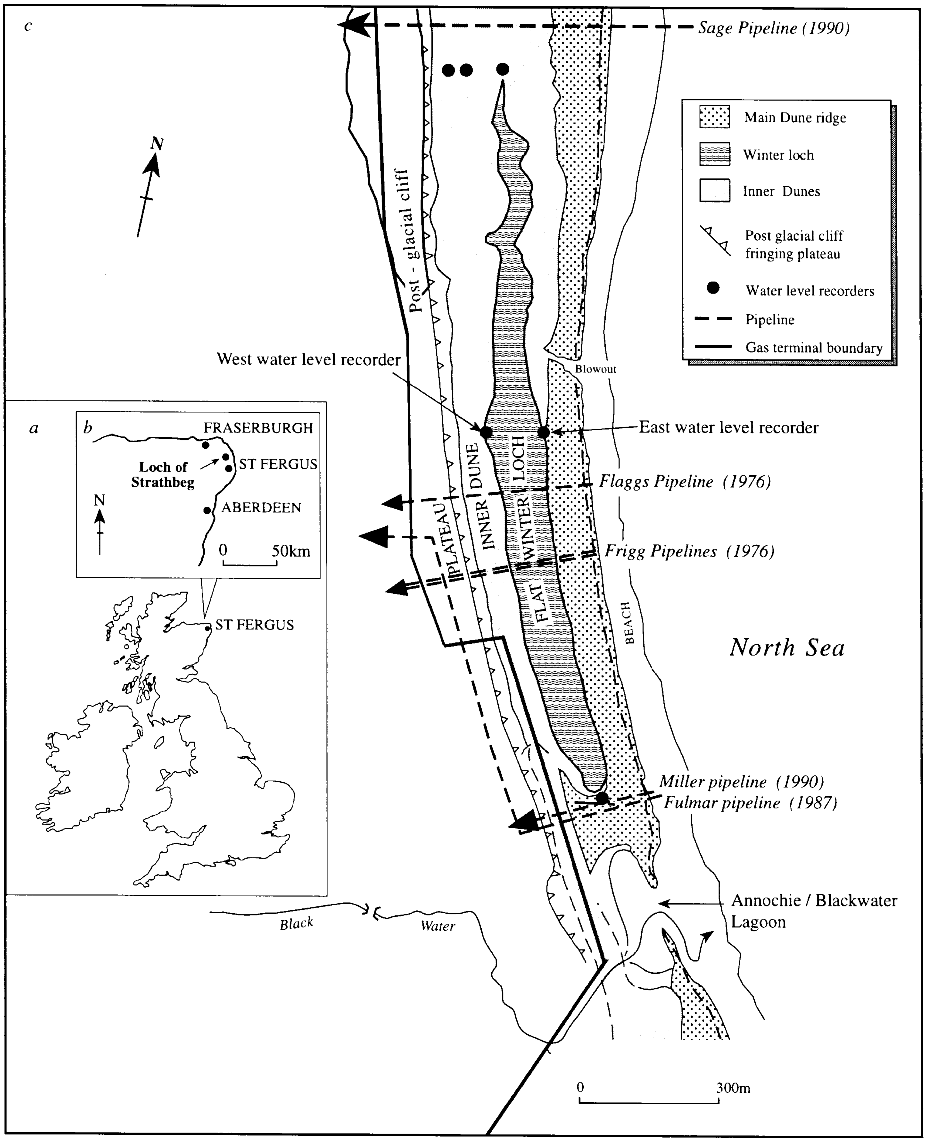

Fig. 1. a. Location of the study area; **b.** St. Fergus site; **c.** main features, instrumentation and pipeline location (with year of construction) at the St. Fergus dune system. **d.** Air photograph of the St. Fergus dunes with gas terminal behind the dunes.

Site description

Topography and vegetation

The St. Fergus dunes are part of a more extensive geomorphological assemblage that includes the Loch of Strathbeg; the largest paramaritime freshwater lake in the United Kingdom and an internationally important conservation site (Ritchie 1990). The primary conservation value is the large number of waterfowl that use the site for winter roosting and whilst resting on migratory routes (Ratcliffe 1977). The dune slacks at St. Fergus are also extensively used by waterfowl with over 6 000 roosting birds occupying the site during the migration season (Patterson pers. comm.). Four main topographic units can be identified at St. Fergus (Fig. 1c).

Dune ridge

The dunes form an eastward facing ridge which is generally 11 m above sea-level. The backslope ranges from 12 - 16 ° in gradient. The dunes are mature and retreating with frequent sand cliffs on the seaward side showing signs of undercutting and retreat. Marram grass (*Ammophila arenaria*) dominates the vegetation, though other species such as *Festuca rubra*, *Galium verum* and the lichen *Cladonia arbuscula* provide extensive cover that indicates a stable, mature dune ridge.

Fig. 1. d.

Winter Loch

This is an almost flat area between the dune ridge and the western inner dunes. The height of the ground surface ranges from 1.5 to 2 m above sea-level; it is 2 km long and up to 120 m wide. Nine artificially constructed ditches, up to 4 m wide and 0.4 m deep, lie at right angles to the orientation of the dune slack. These were dug to prevent gliders landing during the second world war. In addition, the installation of the Frigg and Flaggs gas pipelines in the centre of the Loch in 1976, and the creation of wildfowl shooting butts at the southern end have produced embankments that, in places, rise to 1 m above the original surface.

The vegetation of the loch reflects the topography and the duration of flooding. The northern and southern ends are characterized by a rich grass turf community dominated by *Agrostis stolonifera*, *Carex nigra*, *Hydrocotyle vulgaris* and *Potentilla anserina*. A transitional turf community fringing the eastern edge of the loch includes the above species and other taxa that are also present on the main dune ridge. The western fringe of the Loch is characterized by a sedge community dominated by *Carex arenaria*. Elsewhere, the surface is covered by poorly vegetated sandy areas. The anti-glider ditches, however, have a distinctive flora dominated by *Myosotis scorpioides*.

Inner dunes

The area west of the loch is characterized by mature and stable inner dunes which range from 3 - 7 m above sea-level. Grasses such as *Festuca rubra* are important components of the vegetation as are *Trifolium repens* and *Plantago lanceolata*. Extensive rabbit burrowing is a feature of this area, though the near-complete ground cover and organic-rich soils contribute to its stability.

Escarpment and plateau

West of the inner dunes the former cliff line delimits an inner escarpment, 12 - 16 m above sea-level, which slopes gently west. The cliff, which was originally cut into glacio-lacustrine clays and silts, is now covered by blown sand as post-glacial uplift has raised the original beach above sea-level (Gemmell 1990). The Winter Loch and dunes have therefore developed on a raised beach at the foot of the former cliff. The St. Fergus gas terminal is situated on the plateau to the west.

Surficial geology

The logs of numerous boreholes drilled during construction work at the gas terminal provide a comprehensive view of the geology of the site (Fig. 2). Pink schistose granite forms the bedrock, the surface of which remains entirely below sea-level (Gemmell 1990). Above this, glacial till (2 - 4 m thick) and glacio-lacustrine silts and clays (up to 10 m) form effectively impermeable layers (Robins 1990). In the area immediately east of the former cliff line, these are overlain by former beach deposits of gravel and coarse sand. Aeolian sand covers most of these deposits; the Winter Loch and plateau have a sand cover up to 2 m thick and much thicker deposits occur on the coastal and inner dune ridges. In contrast to the underlying glacial and glacio-lacustrine sediments, the blown sands and gravels have a high hydraulic conductivity in the range 1 - 100 m/day (MacMillan & Aitken 1981).

Soils

The soils of the St. Fergus dunes are dominated by calcareous regosols of the Fraserburgh and Links Association (Walker et al. 1982). These are characterized by a thin, weakly developed organic-rich A-horizon which rests on unconsolidated sand. On the Winter Loch surface, organic enrichment of the A-horizon is evident in places as a result of guano from waterfowl.

Dune restoration

The St. Fergus dune system is crossed by gas pipelines in five places constructed in 1976, 1987 and 1990 (Fig. 1c). These are buried in trenches which were excavated following detailed topographic surveys. The dunes and Winter Loch were, as far as possible, restored to their original profile by carefully replacing the sand and topsoil. The back-filled trenches were revegetated with a mix of local species to accelerate the re-establishment of plant communities and facilitate stability (Ritchie & Gimingham 1989).

Field monitoring

Hydrometeorological data have been collected at the St. Fergus site since September 1981; precipitation and air temperatures were measured along with other climatic parameters at 09.00 (Greenwich Mean Time) each day. These data were used to calculate monthly Potential Evapotranspiration (PE) using the empirical method of Thornthwaite (Shaw 1993). The freely draining dune soils often limit moisture availability during the dry summer months; Actual Evapotranspiration (AE) rates were therefore estimated by modelling potential soil moisture deficits (PSMD) from PE estimates. A monthly soil moisture budget was constructed for the Winter Loch and its adjacent recharge area based on the assumption that a deficit of 75 mm represented the root constant for permanent grass (characteristic of most of the dune vegetation) and the permanent wilting point was 100 mm. The PSMD is the deficit that which would result if PE was fulfilled; in contrast the actual soil moisture deficit (SMD) is the same as the PSMD until it reaches 100 mm. Thereafter the actual SMD < PSMD, and declines as soil water becomes less readily available. Given the complexity of the evaporation process and the variation in vegetation cover in the dune system the estimates can only be considered as tentative first approximations (Lamas 1990).

Two Munro recorders have provided continuous data on groundwater levels from boreholes in the Winter Loch area since 1981. The two recorders were located 180 m apart in a west-east transect approximately half way along the length of the loch (Fig. 1c). The west recorder has an elevation of 2.97 m (above ordnance datum) whilst the east recorder is at 2.88 m (above ordnance datum). Further water level recorders were installed in new boreholes located at the northern and southern ends of the Winter Loch during 1990.

Results and Discussion

Precipitation

Precipitation (predominantly rainfall) is well distributed throughout the year, though the winter months tend to be wettest (Table 1). October has the highest mean monthly precipitation (79 mm) and February the lowest (36 mm). Annual precipitation totals show limited variability during the 12-yr period (Table 2). However, 1984/1985 was an anomalously wet year with 1412 mm, and 1988/1989 was exceptionally dry with 436 mm. The high total for 1984/1985 was primarily the result of 63 % of the annual amount falling in an exceptionally wet period between November and

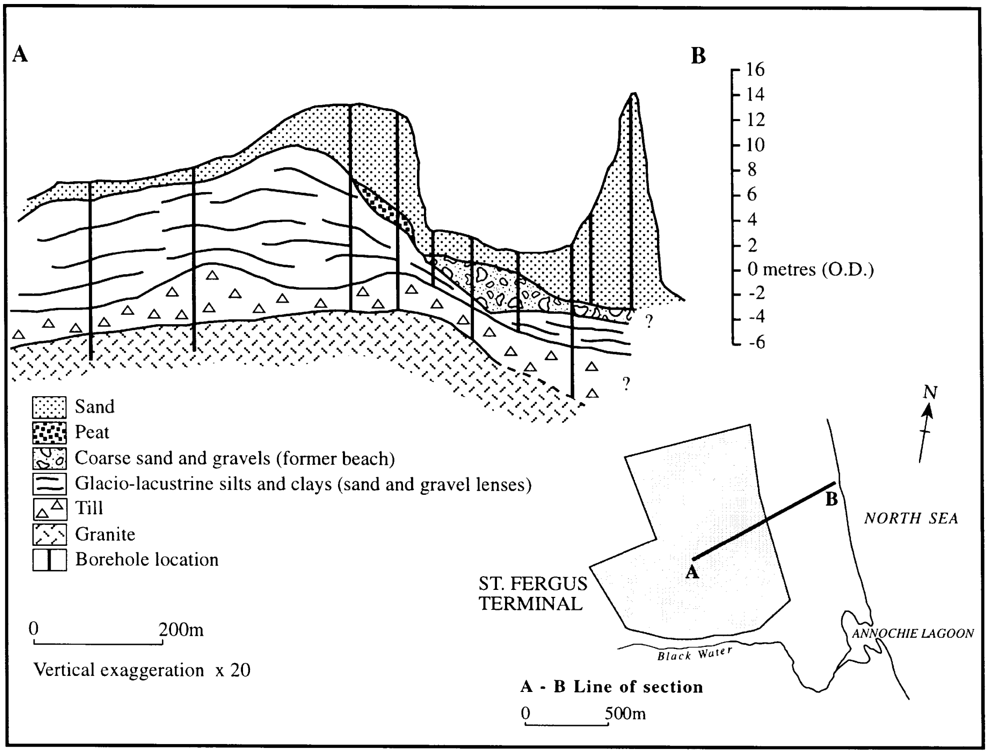

Fig. 2. Surficial geology at St. Fergus along section A - B (approximate location of the Frigg pipeline). (O.D. = ordnance datum.)

January. In contrast, three months during 1988/89 received less than 10 mm of rainfall. The last five years have been the driest; this corresponds to a recent regional decline in annual rainfall totals along the east coast of Scotland (Smith & Bennett 1994).

Temperature

Temperatures exhibit a clear annual cycle, with mean monthly values being highest during July and August and lowest between December and February (Table 1). The three warmest summers occurred in succession in 1989-1991, with 1990 producing the highest daily and mean monthly temperatures of the study period. This formed part of a series of increasing summer temperatures between 1987 and 1990 which corresponded to a period of higher than average temperatures over much of eastern Britain (Marsh & MacRuari 1993). This was further reflected in the winter temperatures which also increased between 1985 and 1989, before declining in 1989/1990 and 1990/1991. The winters of 1988/1989 and 1991/1992 were exceptionally mild, with 0900 Greenwich Mean Time temperatures falling to or below 0 °C only on one and two days, respectively, compared to an average of 15 days over the study period.

Evaporation and soil moisture deficits

Maximum monthly evaporation rates occur between June and August, with minima occurring between December and February (Table 1 and Fig. 3a). Annual AE totals vary between 548 mm and 632 mm (Table 2). The highest annual total occurred during 1989/1990, a year characterized by a mild winter and a hot summer. Lower annual totals such as that of 1985/86 generally reflect cold winters and cool summers. June is generally the first month of the year when soil moisture deficits occur.

Monthly ASMD values during the drier summers are lower than those of PSMD due to the model's assumptions about reduced moisture availability. The drying phase of the soil appears to continue until August or September, thereafter recharge usually returns the soil to field capacity by December. During the prolonged spell of high temperatures and low rainfall in 1989, the most marked and sustained period of soil moisture deficits occurred (Fig. 3a). This was exacerbated by the dry preceding year which dictated that deficits were maintained throughout the winter. This situation contrasts strongly with the wet winter period of 1984/1985 where short-lived deficits occurred

Table 1. Mean monthly temperature, precipitation, potential (PE) and actual evaporation (AE), potential soil moisture (PSMD) and actual soil moisture deficit (ASMD), and water table levels in the west and east recorders in the St. Fergus dunes over the period 1981-1993.

Month	Temp. (°C)	Precip. (mm)	PE (mm)	AE (mm)	PSMD (mm)	ASMD (mm)	Watertable E (m)	Watertable W (m)
January	3.6	74.3	12.6	12.6	0	0	1.635	1.805
February	3.4	35.6	16.8	16.8	0	0	1.629	1.827
March	4.9	54.8	29.8	29.8	0	0	1.493	1.745
April	6.9	44.2	45.7	45.7	0	0	1.454	1.673
May	9.5	49.5	71.2	71.2	0	0	1.333	1.523
June	11.7	48.9	93.4	93.4	52.8	51.1	1.174	1.366
July	14.2	49.6	108.1	100.6	112.7	94.4	1.098	1.261
August	13.9	50.7	94.3	83.9	156.3	107.9	1.108	1.229
September	11.3	53.2	65.9	65.9	156.0	98.6	1.153	1.213
October	9.3	78.7	44.6	44.6	121.9	85.4	1.288	1.383
November	6.2	68.9	24.2	24.2	77.2	51.5	1.448	1.621
December	4.4	73.7	14.0	14.0	17.5	1.6	1.538	1.731
Overall mean	8.3	682.3	620.6	602.8			1.362	1.531

during the following summer. Annual water balance estimates from the precipitation and tentative AE calculations suggest that on average around 80 mm of precipitation is available for groundwater recharge. This is close to the annual recharge of < 100 mm which was cited by Robins (1990) as typical for northeastern Scotland.

Annual patterns of groundwater behaviour

Water table fluctuations in the unconfined aquifer at St. Fergus exhibit a distinct annual cycle in response to the meteorological conditions (Table 1 and Fig. 3b). Peak monthly levels (around 1.8 m above sea-level in the west and 1.6 m a.s.l. in the east) usually occur during the November-January period. Thereafter the water table declines to its lowest level in July/August, generally dropping below 1.2 m in the west and 1.1 m in the east. Levels usually begin to rise by late September as soil moisture deficits decline, to bring about complete recovery by midwinter. Water levels are consistently higher on the western side of the Winter Loch with an average difference of 0.169 m between the two recorders. The gradient varies throughout the year being highest (up to 0.25 m) when water table levels are maximum and lowest (< 0.10 m) during the summer dry period.

Table 2. Mean temperature, precipitation, PE and AE, water table levels and number of days flooding for each hydrological year (October-September) at St. Fergus.

Year	Temp. (°C)	Precip. (mm)	PE (mm)	AE (mm)	Watertable E (m)	Watertable W (m)	Days flooded
1981/1982	7.9	682.0	629.0	602.6	1.369	1.520	193
1982/1983	8.3	625.3	625.4	625.4	1.415	1.565	294
1983/1984	8.2	640.5	625.2	591.9	1.258	1.564	245
1984/1985	8.3	1411.8	636.3	636.3	1.482	1.833	329
1985/1986	7.8	620.8	611.1	575.9	1.342	1.539	209
1986/1987	7.9	745.5	618.3	618.3	1.376	1.537	198
1987/1988	8.3	730.0	626.1	611.5	1.332	1.561	235
1988/1989	9.2	435.9	620.5	620.5	1.277	1.463	193
1989/1990	8.9	517.7	661.6	632.2	1.224	1.387	145
1990/1991	8.3	615.6	604.9	547.6	1.303	1.498	198
1991/1992	8.8	571.8	603.2	603.2	1.254	1.374	216
1992/1993	8.4	589.1	605.1	580.1	1.317	1.483	180
Overall mean	8.4	682.2	622.2	603.8	1.329	1.527	223

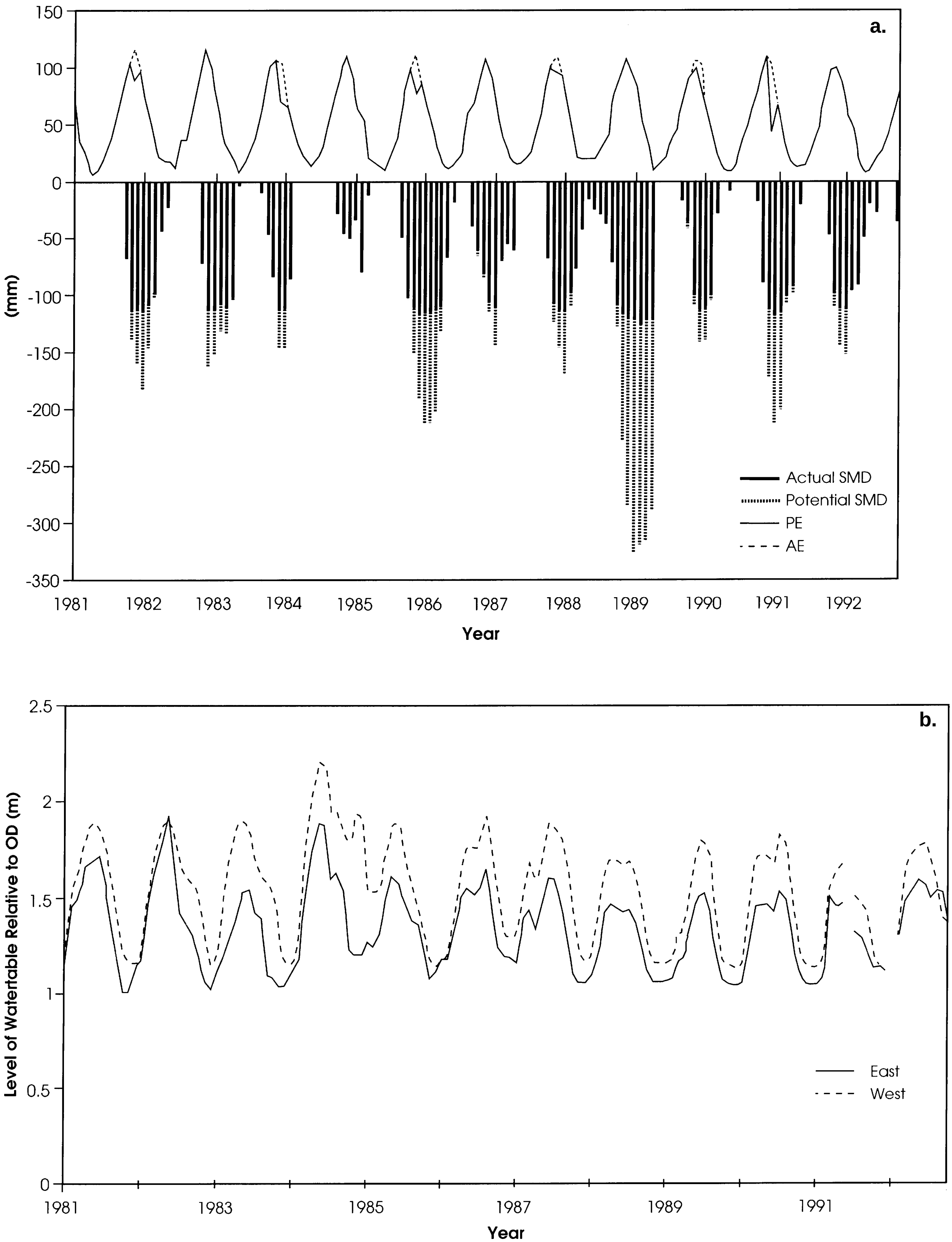

Fig. 3. a. Modelled evaporation and soil moisture deficits at St. Fergus; **b.** Levels of water table relative to O.D. (ordnance datum) at the east and west water level recorders (1981-1993). SMD = soil moisture deficit; PE = potential evapotranspiration; AE = actual evapotranspiration.

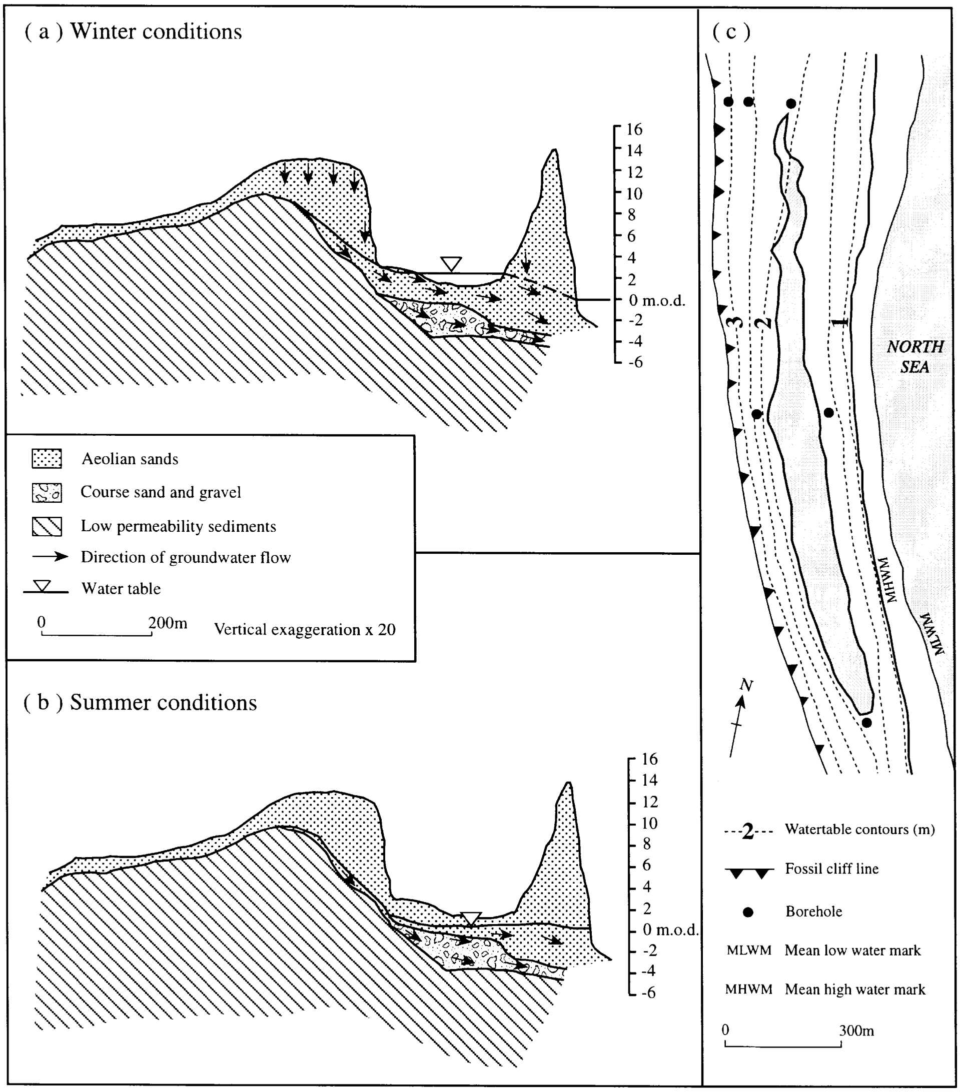

Fig. 4. Conceptual model of (**a**) winter and (**b**) summer levels of water table relative to ordnance datum at the east and west water level recorders; **(c)** winter water table contour map showing seaward hydraulic gradient.

Groundwater flow paths

These annual patterns can be explained by a simple conceptual model of groundwater behaviour which is based on the observed distribution of heads within the dune system. The water table contours (Fig. 4c) were calculated by drawing equipotentials on a map of the mean annual water tables from the six recording points. Flow lines could then be inferred to demonstrate the direction of groundwater flow. The Winter Loch flooding essentially results from the recharge of the unconfined aquifer in the aeolian sands. The groundwater recharge catchment is ca. 0.85 km^2 and includes the Loch itself, the western inner dunes and the eastern edge of the plateau and former cliffline (Fig. 4a). Vertical drainage during the autumn and winter is impeded by the impermeable glacio-lacustrine sediments underlying the dunes and the subsequent water-table rise into the overlying sands and floods the low-lying Winter Loch. The seaward hydraulic gradient, which appears greatest in the west, facilitates lateral water movement beneath the dune system and groundwater discharges as seepage along the beach (Fig. 4c). Given their north-south alignment, the St. Fergus dunes and Winter Loch act as an integrated groundwater system driven primarily by the west-east movement of subsurface water from the former cliffline. It is probable that the lateral flow velocities vary between the sands and former beach deposits, though both units are highly permeable. In addition, the Winter Loch itself possibly encourages rapid lateral movement with water exfiltrating on the western side of the loch and infiltrating on the eastern side (van Dijk & Grootjans 1993). The lower rainfall in spring and summer, coupled with increasing evaporation rates, reduces re-

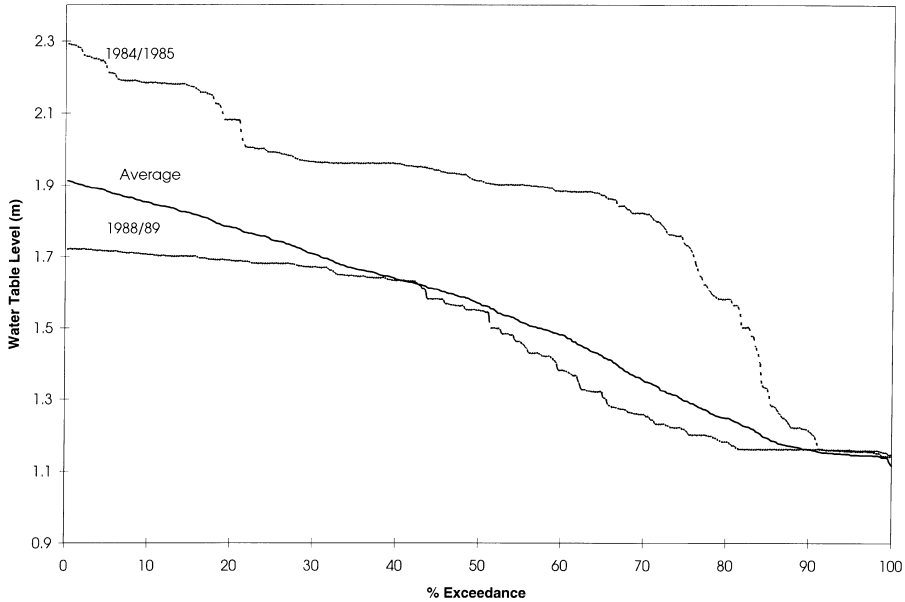

Fig. 5. Water level recorded by the west recorder during average, wet (1984/1985) and dry (1988/1989) conditions.

charge and water-table levels fall as groundwater discharge continues, albeit at a reduced rate under a falling hydraulic gradient (Fig. 4b). During dry years the rates of groundwater discharge during the summer are probably very low.

Long-term groundwater fluctuations

Over the 12-yr period from 1981 to 1993 groundwater levels have shown a tendency to become lower (Table 2 and Fig. 3b). Although pipelines were constructed at the southern and northern end of the site in 1987 and 1990, climatic factors are the dominant control on interannual variation and there is little evidence to suggest that the pipelines have had a major influence on the hydrology of the dunes. The extremes of the exceptionally wet year of 1984/1985 and the hot, dry years of 1988/1989 and 1991/1992 clearly stand out. Peak mean monthly water levels have ranged between 1.8 and 1.9 m in the west recorder for all years except 1984/1985 and the dry years of 1988/1989 1989/1990 and 1991/1992 where the winter peaks were between 1.4 and 1.7 m. Summer minima are relatively constant with lower levels close to the base of the sand above the former cobble beach and are therefore probably only reached when seaward discharge of groundwater has almost ceased. Exceptions to the normal seasonal cycle are apparent in wet years such as 1984/1985 when water levels remained high throughout the summer and autumn. Dry years, in turn, are reflected by the length of minimum water table levels, which last three to four months compared with only one or two months in wetter years.

Flooding of the Winter Loch

The duration of flooding in Winter Loch varies: average conditions are shown by a mean exceedance curve for the west recorder (Fig. 5). On average, ca. 50 % of the Loch is flooded for 15 % of the year and 75 % of the area is flooded for 10 % of the year. The most prolonged flooding occurs in the shallow basin immediately to the north of the two water level recorders where water is present on average for 200 days per year. However, marked contrasts occur between years, such as the average exceedance curve for the west recorder in 1984/1985 and 1988/1989. In the former year the Winter Loch was at least partially flooded for 90 % of the year compared with 60 % on average and < 50 % for 1988/1989 (Table 2).

Maps showing the spatial and temporal extent of flooding within the Winter Loch have been constructed from the average groundwater exceedance curves and topographic maps (Fig. 6). Reduced periods of flooding occur in the immediate vicinity of the Frigg and Flaggs pipelines. The restoration of the pipeline tracks resulted in small areas remaining at slightly higher elevations than the original Winter Loch surface, so that areas either no longer flood or flood for a reduced period of time. Elevations are also naturally higher in the southern part of the Loch, thus extensive flooding usually only

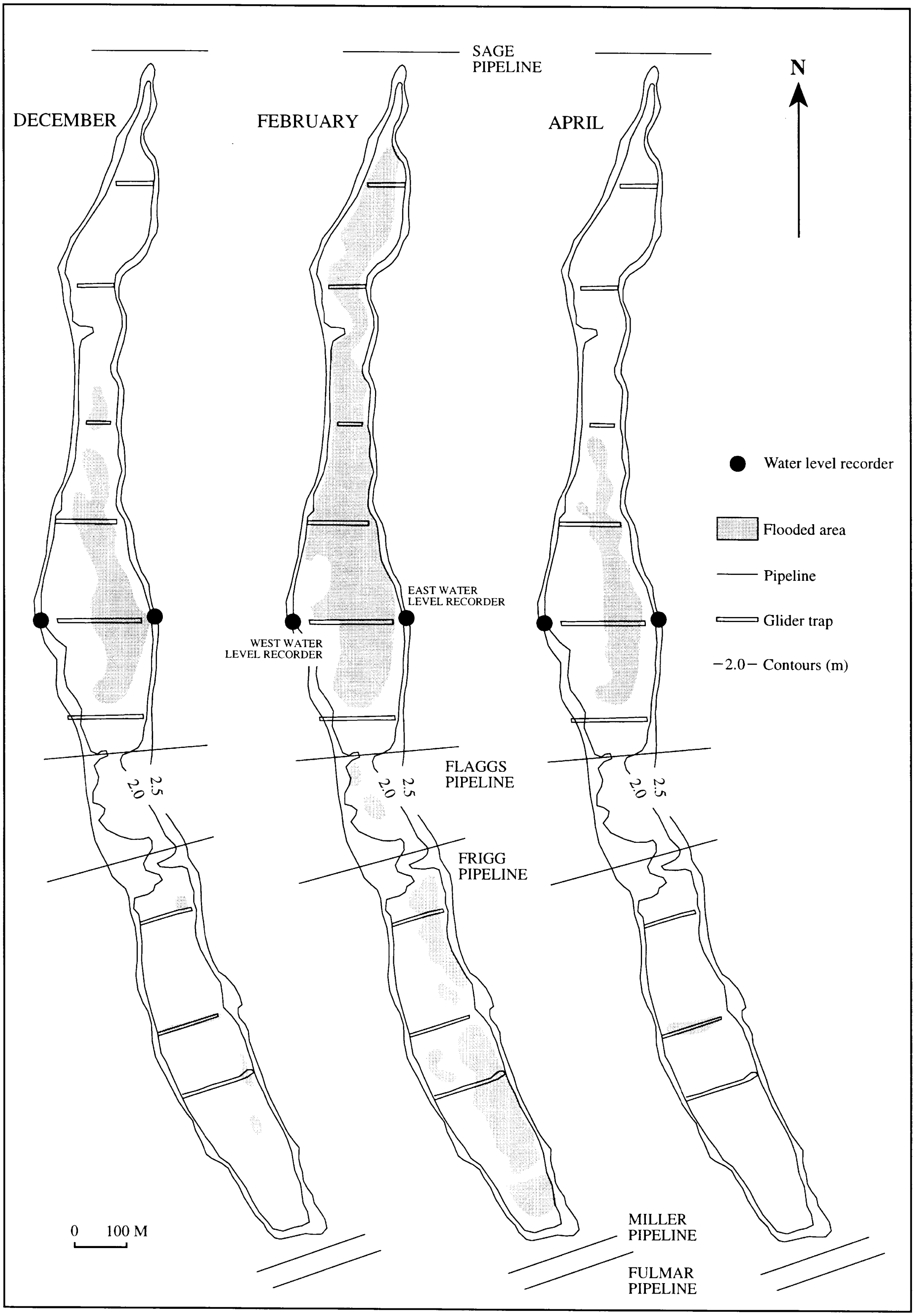

Fig. 6. Average extent of flooding of the Winter Loch in December, February and April (1981-1993).

lasts until February and has normally receded significantly by March.

Implications for management

Monitoring at St. Fergus has provided the first long-term hydrological data for a Scottish dune system. Groundwater behaviour at the St. Fergus dunes contrasts to many other European sites where similar hydrological studies have been carried out. In particular, the aquifer at St. Fergus is relatively shallow and the dune system is narrow compared with the Ainsdale dunes in northwestern England (Clarke 1980; Boorman 1993), Dutch dunes, both those fringing the Wadden Sea (van Dijk & Grootjans 1993) and along the mainland coast (van der Meulen & van der Maarel 1993), or larger sites such as Doñana (Spain) (Lamas 1990; García Novo & Merino 1993). Moreover, the fossil cliffline at St. Fergus creates a high hinterland which drives a seaward hydraulic gradient and a relatively simple groundwater flow system compared with other hindshore dunes which often have a low-lying hinterland which results in complex landward drainage patterns from the inner dunes (Clarke 1980; Bakker 1990). Nevertheless, the dunes at St. Fergus are typical of many others on the Scottish coast in terms of their topography, vegetation and ornithological importance (Boorman 1993).

Development and reclamation of dune environments are major threats to the conservation of the hydrological regime. The hydrogeological data at St. Fergus exhibits no obvious trends over the last 12 years that are not consistent with climatic conditions. From analysis of the water table fluctuations both pre and post-construction of the pipeline landfalls in 1987 (Fulmar) and 1990 (Miller and Sage) there appears to have been no major effect on groundwater levels or regional groundwater flows in the dune system. This reflects the permeable nature of the aquifer and the perceived limited differences in hydraulic conductivity of the natural substrate and the re-packed pipeline trenches. The fact that the areas affected by the pipelines and gas terminal itself are a relatively small part (0.05 km^2) of the recharge catchment of the Winter Loch (0.85 km^2) is also significant. This finding is important as a lowering of the water table would reduce the spatial and temporal extent of flooding in the Winter Loch and result in a loss of wetland habitat in one of the UK's most important locations for waterfowl conservation (Ratcliffe 1977). Davidson & Stroud (1996) have recently summarized the importance of networks of coastal wet habitats for migrant waterfowl.

The preliminary results reported in this paper have given a general insight into the hydrogeology of the restored dune system at St. Fergus. Current work to be reported in future papers will involve intensive hydrometric and hydrogeochemical monitoring at the site. A numerical model of the groundwater system will be produced (Stuyfzand 1993) to identify the extent of the recharge catchment and examine more fully the pipeline impact on local hydrology. Furthermore, mechanisms of recharge through the unsaturated zone will be examined (Ritsema et al. 1993) and the effects of different vegetation cover on evaporation rates will be assessed (Grootjans et al. 1991) to determine what variation, if any, occurs throughout the dune system and examine how this influences soil moisture movement.

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