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Surface Water Processes and Groundwater Flow Within a Hydrologically Complex Floodplain Wetland, Norfolk Broads, U.K.

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Abstract

Catfield Fen lies on the floodplain of the River Ant,—adjacent to Barton Broad, a flooded 13th century peat cutting in East Anglia, England. There are few studies of the hydrology of floodplain mires so this paper presents the results of a study of the surface and groundwater components of a fen system within the Norfolk Broads region. The study was undertaken as part of a larger study (Gilvear *et al.*, 1993; Gilvear *et al.*, 1994) to ascertain the sensitivity of East Anglian fen systems to groundwater abstraction and pollution.

Catfield Fen is a surface-water-dominated system maintained primarily by precipitation and flows to and from the river system. Upward groundwater flows from the Pleistocene Crag aquifer through a discontinuous clay layer to the fen and hillslope inputs also contribute nutrient rich waters to the wetland. Different areas of the marsh receive varying contributions of flow from these various sources so that spatial variations occur in surface water chemistry. The fen is hydrologically complex because a number of open drainage ditches, cut across its surface, act as preferential pathways for water movement. Part of the fen is effectively isolated from direct inundation from riverine flooding by a small embankment; thus defines an 'internal compartment' for which a tentative overall water balance is calculated. Both the drainage ditches and the embankment have modified surface and groundwater flows locally but have not altered the overall hydrological functioning or the water balance of the natural wetland system. The groundwater flow modelling demonstrates the sensitivity of the fen to groundwater abstraction. The results of the overall study suggest firstly that the site is complex and vulnerable to both surface and groundwater abstraction and pollution and secondly demonstrate the complexity and difficulty of investigations of the hydrology of floodplain mires.

Introduction

A knowledge of wetland hydrology and quantification of water inputs and outputs are a necessary prerequisite to understanding wetland environments and determining their vulnerability to hydrological and water quality changes resulting from man's activities. The hydrology and water balance of wetlands vary, however, according to the climatological, geological and topographic setting. For example, the water balance of upland blanket bogs is controlled by precipitation, evapotranspiration and surface water outputs while the water balance of fen systems are more complex because groundwater is also important: if the fen is on a floodplain, surface water inundation adds a further complicating factor. Within fens, the interaction between precipitation, evapotranspiration, groundwater flow and surface water flow determines not only the water balance of the wetland and its vulnerability to hydrological change but also affects its hydrochemistry (Grieve *et al.*, 1994); this in turn affects the surrounding vegetation (Wassen *et al.*, 1989). Relatively small inputs from any one source or any loss of water can therefore be critical to the hydrological and ecological functioning of a wetland.

Despite the importance of wetland water fluxes, very few studies have quantified the water balance of individual wetlands; even fewer studies couple wetland and groundwater hydrology. Notable exceptions are the work of Siegel and Glaser (1987) and Siegel (1983) in Alaska, the study by Roulet (1990) of a small headwater wetland in Ontario, Canada, and the study by Gehrels and

Mulamoottil (1990) of a Canadian headwater wetland. In many cases, groundwater inflow has either been omitted because of the difficulty of measurement, or simply been estimated as the residual term. Koerselmann (1989) illustrates the problem of determining wetland water balances accurately in a study of a small quaking fen in the Netherlands. Despite intensive monitoring, significant overall errors in the water budget occurred and the estimated groundwater component values varied considerably according to the method of calculation. There have also been very few studies of the detailed quantitative hydrology of floodplain wetlands. A notable exception is work on both a Dutch and Polish floodplain by Wassen *et al.*, (1990).

There are few examples of wetland water balances, particularly for floodplain mires, so this paper presents the results of a study of the surface and groundwater components of a fen system on the floodplain of the River Ant, East Anglia, England. The research was undertaken in an attempt to determine water inputs, quantify the water balance of the site, model groundwater flow and thus ascertain the hydrological sensitivity of the fen to the underlying groundwater system. The case study was part of a larger investigation examining the hydrodynamics of East Anglian wetlands and their vulnerability to groundwater abstraction (Gilvear *et al.*, 1993; Gilvear *et al.*, 1994). As part of this investigation, three sites were monitored; these were selected with reference to a hydrogeological classification of East Anglian wetlands, produced as part of the study (Lloyd *et al.*, 1993; Gilvear *et al.*, 1994). Catfield Fen was deemed to be representative of the surface water-dominated wetlands of the 'Norfolk Broads' region of East Anglia.

THE STUDY AREA

Catfield Fen is situated within the Norfolk Broads region of East Anglia, England. The Norfolk Broads region borders the North Sea and is almost flat, rarely rising more than a few metres above sea level. The major characteristic of the region is a number of slow flowing river systems, interconnected and interrupted by a number of 'broads'; the broads are shallow lakes formed by the flooding of 12th and 13th century peat cuttings (Lambert *et al.*, 1960).

Catfield Fen lies within a large expanse of fen adjacent to the River Ant and Barton Broad (Fig. 1). This floodplain environment is fringed by gently sloping sides rising to a height of less than 10 metres. The fen contains a wide variety of vegetation types and is botanically complex (Giller, 1982): herbaceous vegetation dominated by reed (*Phragmites australis*) and sedge (*Carex mariscus*) covers most of the site and some former mowing marshes have developed into birch (*Betula pendula*) scrub, and alder (*Alnus glutinosa*) woodland. Pockets of *Sphagnum* also occur. Small, partially infilled peat cuttings also exist on the site (Giller and Wheeler, 1986*b*). Because of its botanical and habitat value, the site is designated as a Site of Special Scientific Interest (SSSI). The SSSI designation is given to a site on the basis of high conservational value; it is aimed at protecting the site against damaging activities, principally via management agreements with landowners. Giller (1982) and Giller and Wheeler (1986*a*) provide more detailed botanical information about the site.

Catfield Fen is partitioned into two hydrologically distinct units (Fig. 1): an 'external' compartment close to the river and the broad which is in direct hydrological continuity with the river system; and an 'internal' compartment closer to the valley sides which is partially isolated from the river by a small embankment running parallel and adjacent to a drainage ditch (formed by compacted material excavated during construction of the drain). A small sluice, rectangular in cross-section, breaches the embankment at the north west corner of the fen adjacent to the upland and allows flow to and from Barton Broad/River Ant via a water course. Both the internal and external systems are cut by a number of drainage channels. Within the 'internal' compartment, the drainage ditches, typically 2 metres deep and 3 metres wide, run at right angles to each other and delimit a number of rectangular compartments. In the south west corner of the marsh, there is a hydrological connection between the internal fen system and the River Ant via a network of channels. Adjacent to the internal drainage ditches, small embankments consisting of ditch excavations also exist, but only one internal compartment is fully enclosed (Middle Marsh; Fig. 1). Between the valley sides and the fen, a 'ring' drainage ditch intercepts surface waters derived from adjacent hillslopes.

Methods

Quantification of the hydrological and hydrogeological processes at Catfield Fen necessitated four phases of investigation: data collection, hydrological conceptualisation, water balance quantification and groundwater flow modelling. Measurements required included meteorological inputs and outputs, surface water flows, surface water levels, groundwater levels, soil and rock permeability, ground surface contours and instrument elevations and subsurface stratigraphy. Measurements of most of the hydrological variables, on which this paper is based, were made weekly between April 1988 and September 1990. The location of the instrumentation is shown in Fig. 1.

A Didcot automatic weather station was installed on the site to measure precipitation and the climatological variables necessary to estimate potential evapotranspiration; the variables were monitored continuously and averaged to give hourly data. Because of uncertainty in the actual to potential evapotranspiration (AE/PE) relationship for wetland environments, and the uncertainties associated with the choice of aerodynamic and stomatal

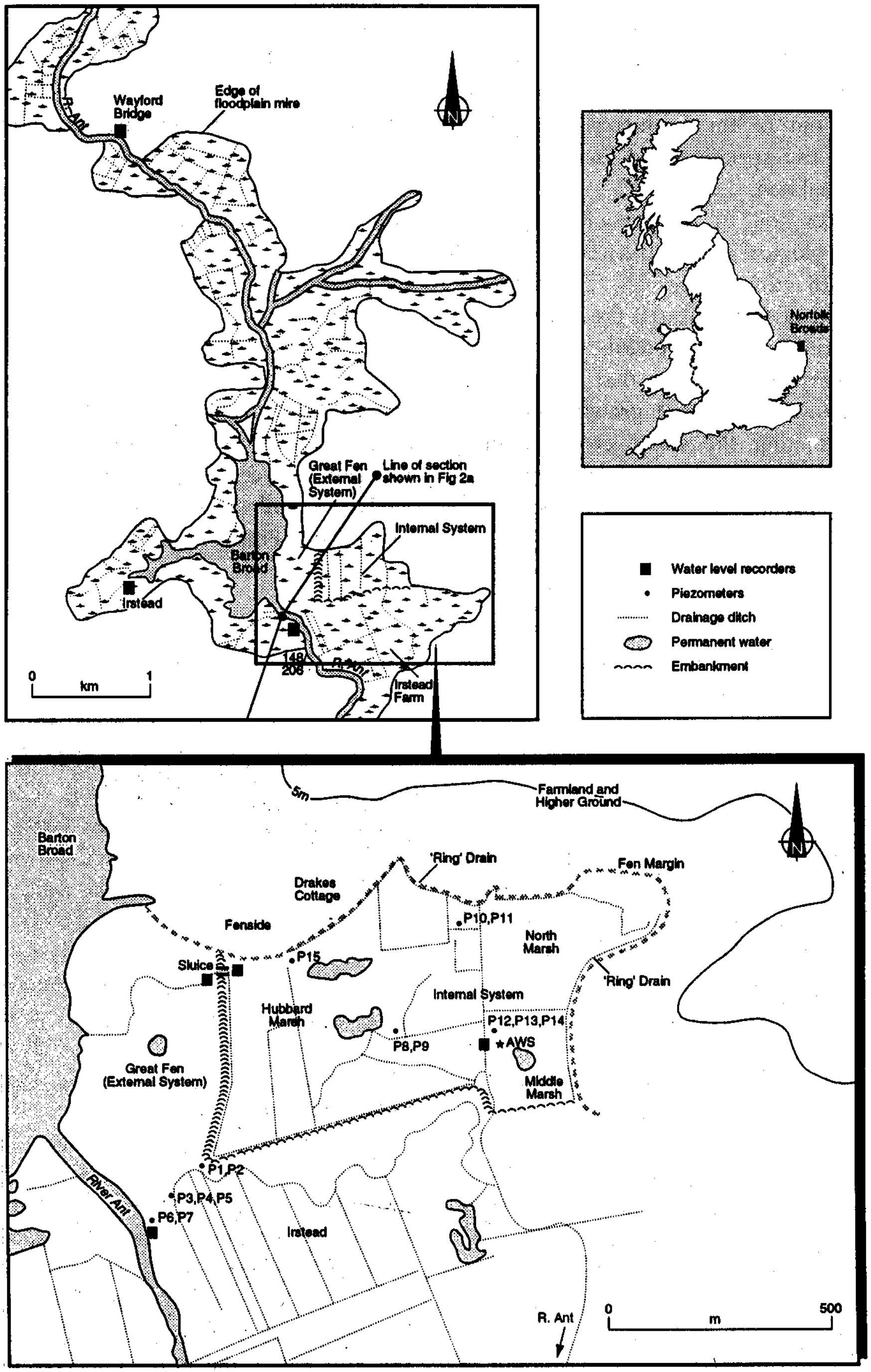

Fig. 1 *Location of Catfield Fen showing drainage and instrumentation locations.*

resistance terms in the Penman-Monteith equation, PE was calculated using the Penman method. Because automatic weather station data are not available for the whole period of the study, correlations between U.K. Meteorological Office data (MORECS) and the automatic weather station data have been used to provide a full data set based on the MORECS continuous record (Weather station PE = 1.092 × MORECS − 0.784; correlation coefficient = 0.97).

A short run of actual evapotranspiration data was obtained for the site using a wetland lysimeter (Gilman, 1994). A 1.43 m^2 area of land is enclosed using four sealed PVC sheets inserted to a depth of 75 cm (at which an impermeable clay horizon was met). Water table elevations are measured inside and outside the block to a resolution of 0.2mm and the measurements logged. Depending on the difference in water levels, pumps transfer water into or out of the lysimeter. Using the stage change data and the specific yield, actual evapotranspiration can be calculated.

Water levels on either side of the rectangular sluice separating the two hydrological compartments were measured automatically at 15 minute intervals. This allowed the direction and amount of flow through the sluice to be determined. The elevation of sluice boards was altered by the landowner occasionally to ensure that water levels on the wetland were suitable for reed growth and harvesting but without affecting the sluice cross-sectional shape. Flow through the sluice was estimated using the equation for rectangular partially constricted weirs:

$$Q_0 = 1.75bh^{1.5}$$

where Q = discharge in m^3s^{-1}, b = width of the weir crest in metres and h = head of water above the weir crest in metres. Under drowned conditions, the Villermont modification was applied:

$$Q = Q_0 \left(1 - (h_2/h_1)^{1.5}\right)^{0.385}$$

where h_2 is the lower head of water and h_1 is the higher head of water.

Water levels were also monitored on Barton Broad at a number of locations. At Wayford Bridge just upstream of Barton Broad, the National Rivers Authority (NRA) measured water levels continuously. Fortnightly maximum-minimum readings were also available for Barton Broad at Irstead (Fig. 1). An additional measurement of the water level of Barton Broad was taken during routine weekly monitoring. At all three locations, water levels responded almost identically and thus the continuous trace at Wayford Bridge was indicative of Barton Broad water level changes. Flows within the drainage ditches could not be measured because flow velocities were below the limit of detection of the current meters used; electromagnetic devices were not available.

Drive-in piezometers and mild steel or PVC tubing of 19mm i.d. were installed on the wetland to measure groundwater heads in each compartment and stratigraphical unit. Approximately weekly monitoring of 16 piezometers documented temporal changes in groundwater heads. The elevation of each piezometer was determined by a topographic survey of the site using a Electronic Distance Measurer (EDM). Because Giller and Wheeler (1986*a*) recorded a variation in the elevation of the peat surface with time at only one site out of eight monitored, it was assumed that the piezometers, all sunk to a depth of greater than 0.8 metres, would be unaffected by minor ground level variations. Rising and falling head tests were undertaken on the majority of piezometers to establish hydraulic conductivities and values were calculated using Hvorslev's (1951) equations. Other rising and falling head tests were undertaken on shallow temporary piezometers to examine spatial variability in peat permeability.

The detailed stratigraphical structure of Catfield Fen was ascertained using a number of resistivity and electromagnetic traverses (Metcalf, 1988), information provided by piezometer installation, and a detailed ground 'probing' survey using a steel rod.

A groundwater and surface water chemistry survey was undertaken to elucidate water sources, and to test the validity of the conceptual model. Calcium, magnesium, chloride, sulphate, total oxidised nitrogen, iron and manganese were analysed spectrophotometrically (autoanalyser), and sodium, potassium, silicon and strontium using flame emission atomic absorption spectrometry.

Geology

The regional geology, as determined by examination of available borehole logs, is typified by a three layer system: glacial North Sea Drift (5–10 metres) overlies Pleistocene Crag (20–40 m), which in turn overlies the Eocene London Clay (Fig. 2a). Locally, peat and alluvium overlies, the North Sea Drift in the river valleys. The Pleistocene North Sea drift consists of a complex suite of interbedded tills and associated meltwater sediments (Ehlers and Gibbard, 1991). The Crag consists of marine sands and gravels, shelly sands and interbedded lenticular clays (Fig. 2*b*). The London Clay, although not seen at Catfield, is typically a heavily overconsolidated clay of very low permeability (Tellam and Lloyd, 1981). At Catfield Fen the usual glacial sequence is replaced by peats and clays.

Detailed on-site geological surveys identified between 1 and 8 metres of peat resting on a thin (< 1 metre) and discontinuous layer of clay above the Crag (Sadler, 1989). The depth to the Crag surface shows that the wetland lies within a small buried tributary valley of the River Ant (Fig. 2*c*). The thickness of this clay was mapped using an auger, and by using a steel rod to 'feel' the clay below the peat. The clay layer is absent below some of the drainage ditches (Fig. 2*d*), having presumably been removal during their construction, and also in two small areas in the north east corner of the site (North Marsh; Fig. 2*d*). These clay 'windows' are important in that they allow hydraulic connection between the peat and the underlying Crag aquifer. Where present, the clay is between 0.3 and 1 m in thickness, generally thickening towards the south west (Fig. 2d).

The thickness of the peat sequence increases from less than 1m in the north to greater than 8 m in the south of the fen, and has been investigated in some detail by Giller and Wheeler (1986). They describe a thin (<0.5 m)

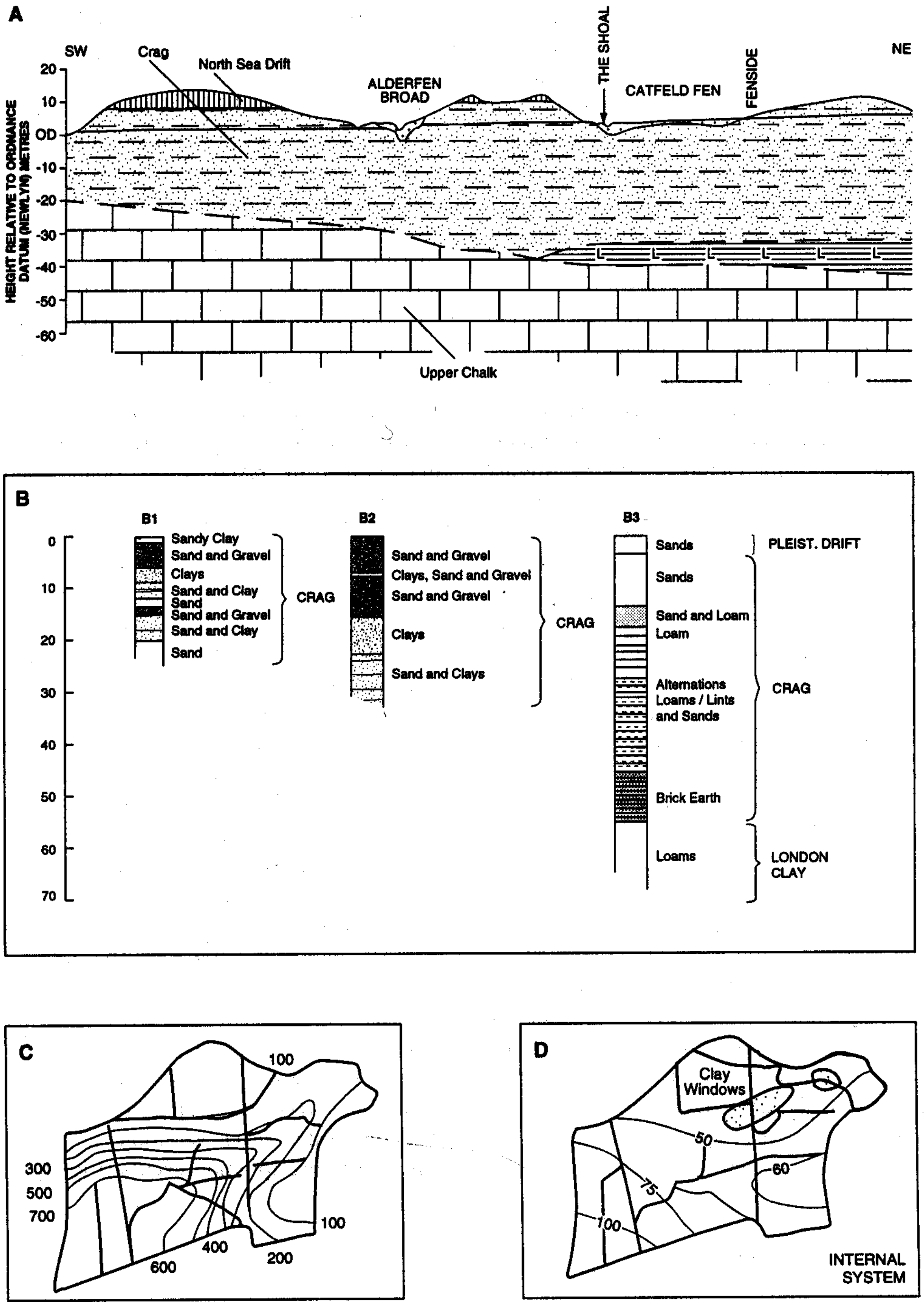

Fig. 2 *Regional and local geology. (A) regional Geology in the vicinity of Catfield Fen (B) borehole logs from nearby Catfield Fen available prior to the study: local lithological terms have been interpreted stratigraphically (C) Depth to Crag at Catfield Fen in centimetres, and (D) Clay thickness and areas devoid of clay at Catfield Fen. Thick drainage ditch lines indicate no clay beneath.*

clay within the peat which they interpret as arising from a transgression known locally as the Romano–British transgression: this clay occurs along the southern third of Catfield Fen, with a northern extension along the western margin of the external system (Fig. 1*b*). This layer influences vertical flows within the peat but its hydrological significance was not ascertained. Other fine grained but organic-rich material occurs at around the same depth of 2–3 m below ground level. Below this horizon are well humified brushwood peats; above are some 'solid humified peat' and 'loose fresh peat' (Giller and Wheeler, 1986). The loose peat corresponds to regions of

19th century peat cutting. A few 'turf' ponds remain in these areas, though most of the cuttings are now filled in by re-established peat growth. In the 1–2 m below the ground surface, therefore, there is a range from open water conditions to humified peat. The embankments between the fen compartments appear to consist of mixtures of compacted peat and clays.

Climate

Values of precipitation and potential evapotranspiration for the period are shown in Table 5. Average annual precipitation and potential evapotranspiration for the region are 660 mm and 640 mm respectively. Precipitation was high during the first 9 months of 1988 but an exceptionally dry period followed; from October 1988 to August 1989 only 390 mm of precipitation occurred, 65% of the annual average. A marked change from a wet period to a dry period allows a good understanding of the hydrological system to be ascertained under extreme conditions. The potential evapotranspiration data indicate the effects of the hot dry summer of 1989 compared to the summer of 1988. A short run of lysimeter data collected during the summers of 1989 and 1990, when water tables were between 5 and 40 cm below the surface, suggests an actual to potential evapotranspiration ratio of approximately 0.75. Fig. 3 shows results from one of the eleven runs, together with PE data from the automatic weather station. It is clear that the hourly lysimeter-measured AE is very similar to that of PE using the Penman method. Because the specific yield of the fen is poorly known, the absolute value of the lysimeter AE is difficult to determine. To match the PE data, the specific yield would need to be 0.6 in May 1990 and 0.05 in August 1990. The water levels at these times were 6–11 cm and 40–42 cm respectively, and it is possible that specific yield varies strongly with depth. Ingram (1983) presents data showing variation of specific yield from 0.6 at ground level to 0.2 at 30 cm depth in peats.

Outline Surface Water Hydrology

BARTON BROAD AND RIVER ANT LEVELS

Barton Broad and River Ant water levels in the vicinity of Catfield Fen vary seasonally and daily in response to seasonal flow fluctuations of the order of 0.3 m, flood flows and tidal influences (Fig. 4*a*). Diurnal fluctuations are typically of the order of a few cm and fortnightly variations of the order of 0.1 m. Analysis of the long-term water level record for Barton Broad shows little variation from year to year. Between 1980 and 1989 maximum annual recorded levels varied by only 8 cm and minimum annual levels by 5 cm. During the period April 1988 to September 1990, Barton Broad water levels varied between 0.83 m and 0.17 m above sea level fluctuations in response to tidal, flood and seasonal influences.

SURFACE FLOWS BETWEEN CATFIELD FEN AND BARTON BROAD/RIVER ANT

Fig. 4a compares the internal fen drainage ditch levels with the tidal Barton Broad levels. Overall, the fen levels are above the average broad levels, though during any particularly high tidal condition there is a potential for reversed flow, especially in summer. However, the short duration of high water levels, the limited connections between the broad and the fen, and the presence of the sluice, all limit such flows.

Fig. 4*c* shows the hydrographs for the internal and external sides of the sluice for the period January 1988 to September 1990; in general, water flows from the fen towards the River Ant and Broad and, only in late summer is there a tendency for the flow to reverse, confirming the findings of Giller and Wheeler (1986*a*). Continuous records of stage change at the sluice show that the water level variation can be quite flashy in response to precipitation events (Fig. 4*b*).

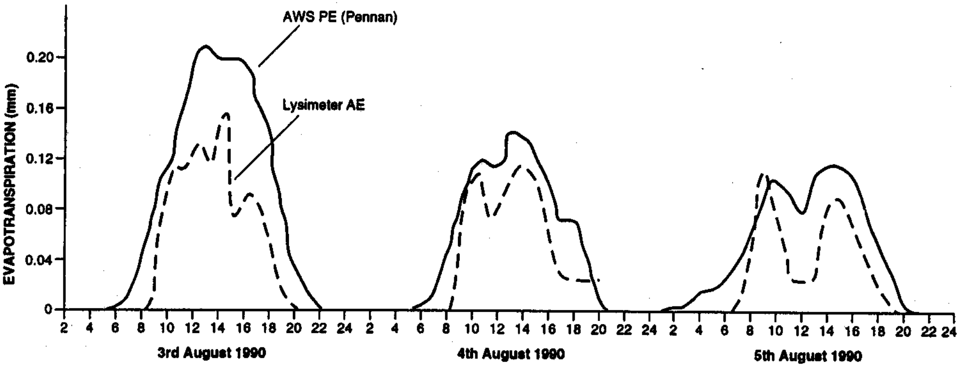

Fig. 3 *Comparison of PE values obtained from the AWS with actual evapotranspiration as obtained from the lysimeter for a a three day period. Lysimeter values based on a specific yield of 0.2. Where a negative value was calculated, a value of zero was assigned.*

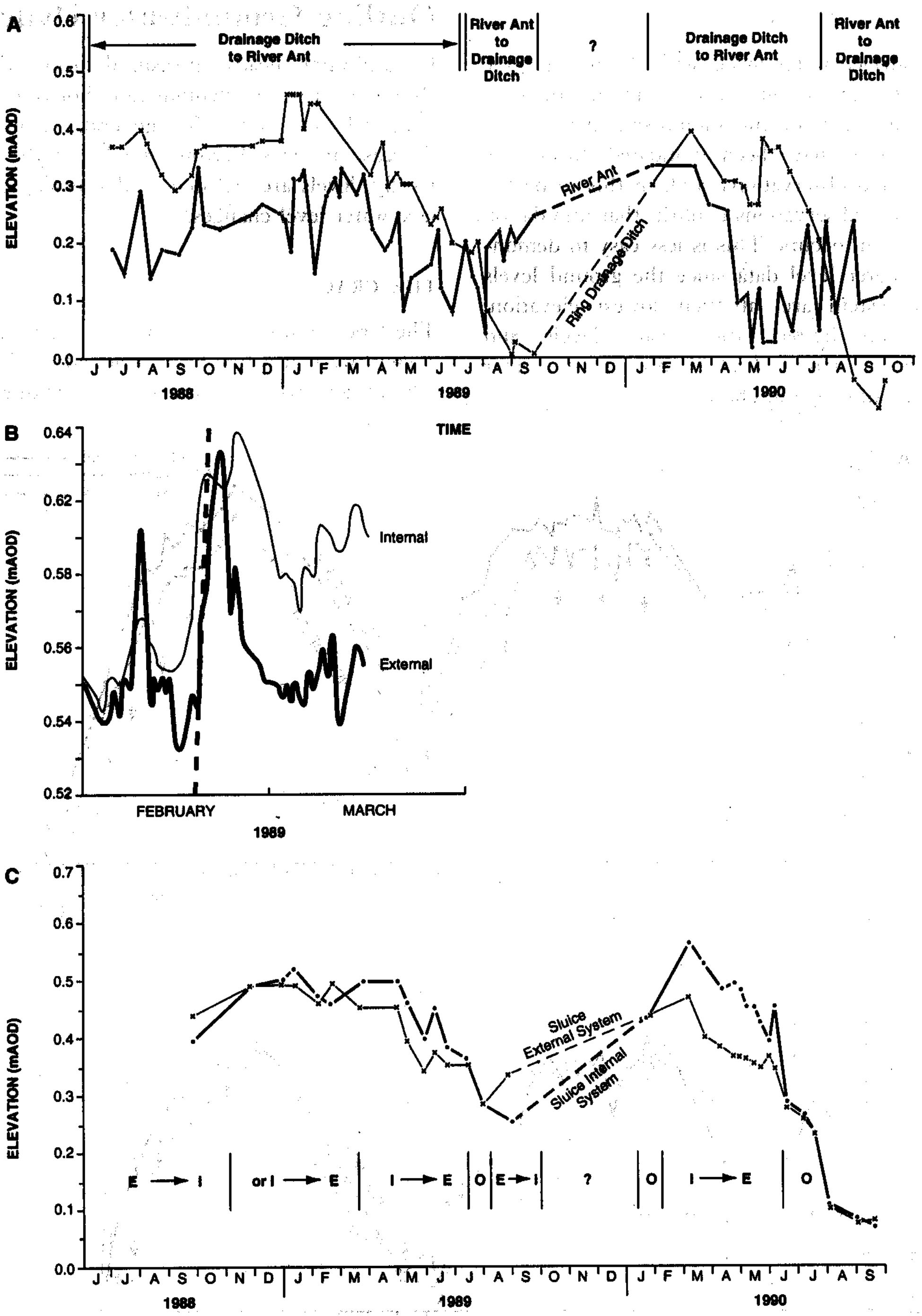

Fig. 4 *Comparison of Catfield Fen 'internal' and external water level fluctuations during the monitoring period (A) Barton Broad water level variations based on weekly data and internal drainage ditch water levels. Periods of potential inflow and outflow are shown. (B) Hourly data for February and March 1989 either side of the sluice indicating periods of inflow and outflow from the internal system (C) Weekly water levels either side of the sluice indicating periods of inflow and outflow from the internal system. I to E designates time when flow is from the internal to external, zero no flow and E to I external to internal flow.*

FLOODPLAIN INUNDATION

Comparison of surface water levels with the topographic survey of the site carried out in the summer of 1988 indicates that, for much of the monitoring period, the external system would have been inundated during the winter months. Field observations confirm this to be the case. Similarly, field observations confirm that inundation of the internal system occurs. This is less easy to demonstrate using the water level data since the ground levels in the internal system are, at their lowest elevation, closer to maximum drainage ditch water levels, and because 'lows' in the fen surface are present at greater distances from the drainage ditches.

Outline Groundwater Hydrology

Groundwater heads, measured using the piezometers shown in Fig. 1, demonstrate horizontal, vertical and temporal variation. In general, groundwater heads decrease towards Barton Broad and the River Ant but locally, levels are elevated or depressed according to surface water level changes.

THE CRAG

The Crag piezometers (numbers 2, 5, 14 and 15) indicate a southwest-directed head gradient of less than 0.001. The piezometric surface generally remained at or close to

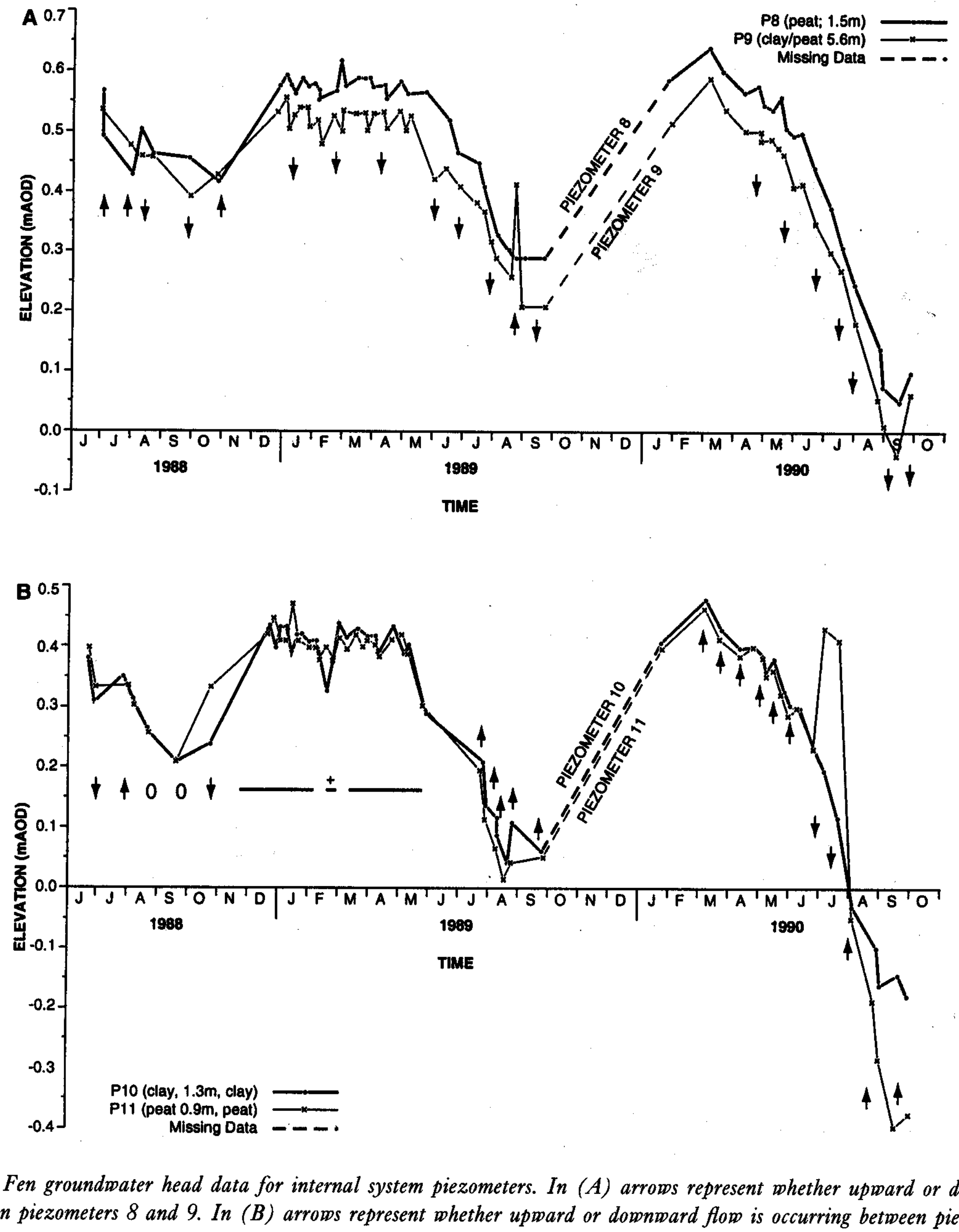

Fig. 5 *Catfield Fen groundwater head data for internal system piezometers. In (A) arrows represent whether upward or downward flow is occurring between piezometers 8 and 9. In (B) arrows represent whether upward or downward flow is occurring between piezometers 10 and 11. In (C) where two arrows exist the upper arrow relates to flow direction between piezometers 12 and 13 and the lower between 13 and 14. (D) No vertical head data differences are possible due to solely one piezometer In all diagrams a zero indicates no flow.*

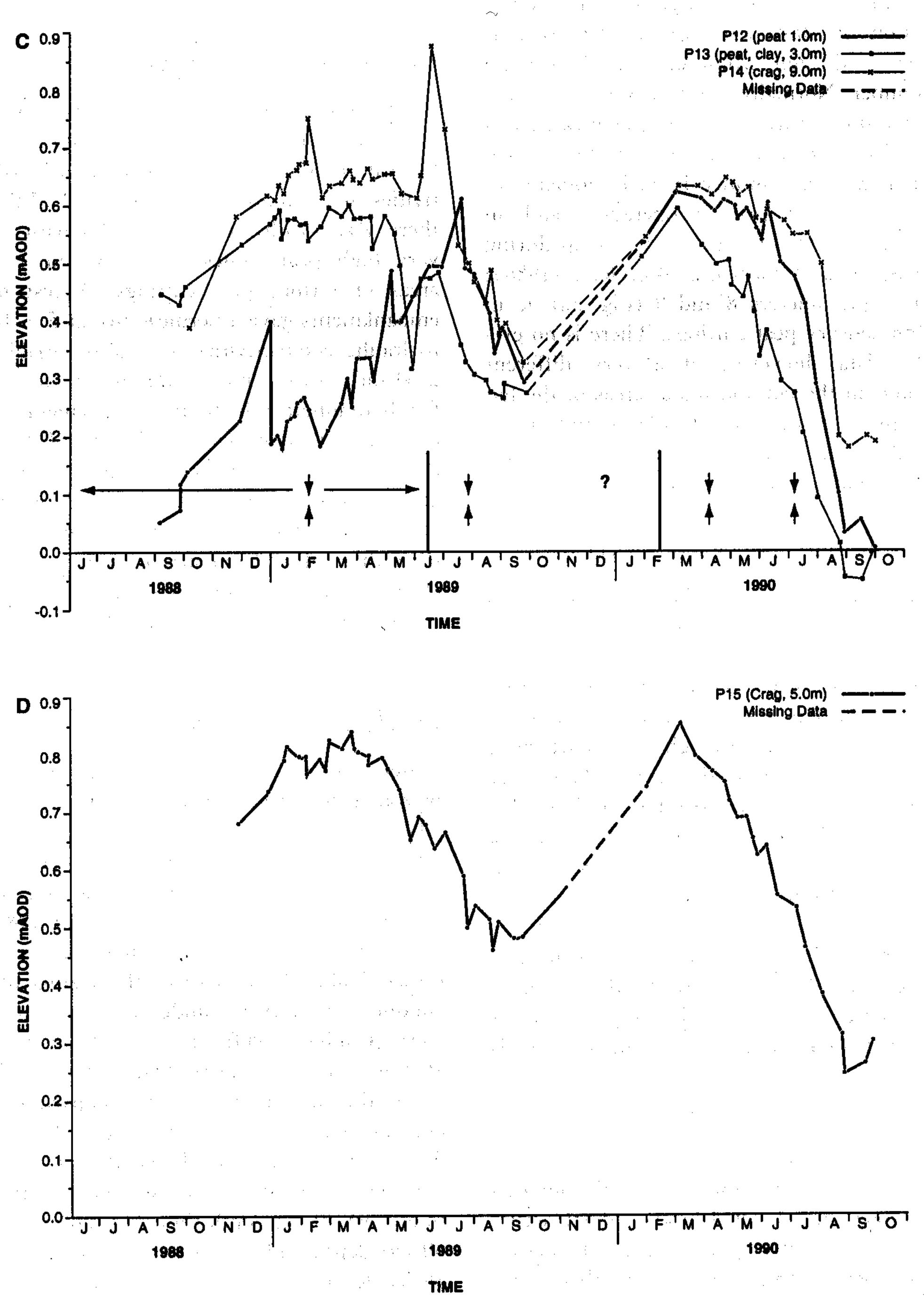

Fig. 5 *Cont.*

the peat surface elevation. All Crag piezometer hydrographs were similar. Piezometer 15 (Fig. 5d) had the highest recorded heads in the whole fen system. Piezometer 14 (Fig. 5c) heads were always above water levels in the peat and drainage ditches, except in late summer. Because peat groundwater heads are usually between 10 and 30 cms below the peat surface, there is an upward head gradient from the Crag to the Peat through most of the year. Upward groundwater head gradients were particularly pronounced in the summer months when the peat water table declined in elevation in response to high potential evapotranspiration (Figs. 5 a, b, c and d; Figs. 6 a, b and c): Thus, given hydraulic connection between the Crag and the Peat, a degree of self regulation is apparent..

THE INTERNAL SYSTEM PEAT

The peat hydrographs for the internal system show a seasonal fluctuation of 20–50 cm with similar patterns and elevations across the fen. Minimum water levels are in August/September. Normally the peat water levels are above the drainage ditch water levels but, at piezometers 10 and 11 (Fig. 5b), peat water levels were lower than the drainage ditch levels in summer 1989. Piezometer 12 behaved oddly in its first year of operation, and an increase in lag time caused by smearing of its tip during installation is suspected. Giller and Wheeler's (1986*a*) maps indicate that piezometers 8 and 9 (Fig. 5a) lie in the region of 19th century peat cuttings. There is no evidence from the data, however, of a very different hydraulic behaviour in the cut and uncut areas of the fen as a whole, though the permeability evidence and observations from Giller and Wheeler (1986*a*) indicate local pockets may be hydraulically distinctive.

VERTICAL FLOW IN THE INTERNAL SYSTEM

Piezometers 8 and 9 (Fig. 5a) lie in the centre of the fen and show a downward head gradient almost continuously throughout the year, both being located in the peat. The difference in depth between piezometers 10 and 11 (Fig. 5b) in the north of the fen is small; hence, water levels are similar throughout the year, though an upward head gradient in summer 1990 can be discerned. Piezometer 12 behaved oddly for its first year (see above). After this period the piezometers 12, 13, and 14 (Fig. 5c) show a downward head gradient from the peat surface and an upward head gradient from the Crag. Only during the late summer does the Crag water level fall to below the peat levels (Fig. 6b). The upper peat appears to discharge downwards and laterally towards the drainage ditches for most of the year and the lower peat receives water from the Crag. Only at the end of the summer is the pattern disturbed.

EXTERNAL SYSTEM

Examination of Fig. 6 indicates that nearest the internal system the usual downward directed head gradient occurs (piezometers 1 and 2). Water levels are nearly always above those of the River Ant. Close to the River Ant, piezometers 6 and 7 suggest a general upward-directed head gradient, presumably indicating discharge to the river: only in summer 1990 does the river head rise above the ground water levels. Piezometers 3 and 4, which lie half way between the internal system and the Ant, show a complex sequence of upward- and downward-directed head gradients. The Crag head at this piezometer nest (Piezometer 5) is generally always above the river water level: the river level is similar to the head in the peat.

The external system flows, at least in the southwest of the fen system, appear to be controlled by discharge from the fen to the river, though at the end of a dry summer some reverse flow is possible.

HYDRAULIC CONDUCTIVITIES

Rising and falling head tests, undertaken on piezometers, allow the estimation of the hydraulic conductivities of the various deposits. A wide range of hydraulic conductivities was found within the peat (Table 1) although there was no obvious relationship with depth. Latterly, very high peat values (above 50 md^{-1}) were found in areas of former peat cuttings. A test on one of the embankments gave a permeability of 5×10^{-5} md^{-1}. Crag hydraulic conductivities were also variable ranging from 2–41 md^{-1} with a mean value of 14 md^{-1} (Table 1). The few hydraulic conductivity measurements possible for the clay were of the order of 10^{-5} md^{-1} (Table 2). Because of clogging of piezometer tips and because the clay is known to be penetrated by roots in the northern part of the fen, the permeability of the clay is probably greater than this value. Comparison with values published for other normally consolidated high moisture content clays suggests that 10^{-5} md^{-1} is possible but rather low (Tellam and Lloyd, 1981).

Hydrochemistry

Water samples were taken from ponds, drains and piezometers across the site mainly during May–August 1988. The samples were analysed for major ions and a selection of minor determinands. In addition, surveys of electrical conductivity were carried out in January and July 1988 and in July and August of 1989 to see if the water chemistry indicated water sources and flow processes. Table 2 summarises the results of the electrical conductivity surveys undertaken in January and July 1988 (Collins, 1988); the surveys in July and August 1989 gave very similar results.

Middle Marsh is a fen compartment isolated by embankments such that surface inflows cannot occur. This compartment, and the centres of the other fen compartments, contain the lowest conductivity surface waters to at least 30 cm depth though a piezometer sample from 60 cm depth had a conductivity of 650 μScm^{-1} (Sadler, 1989). Rain water conductivities are around 60 μScm^{-1}. Low conductivities were also found on the western side of North Fen, the southern side of Hubbard Marsh, and just east of the sluice with the central parts of the compartments usually having waters with conductivities significantly lower than those within the drainage ditches. Towards the edge of each compartment, the conductivity of the water rises towards the figures given for the drainage ditches. The 'ring' drainage ditch in the north and east is of higher conductivity than the other parts of the drainage system with the exception of the polluted Fenside Drain. The external system water con-

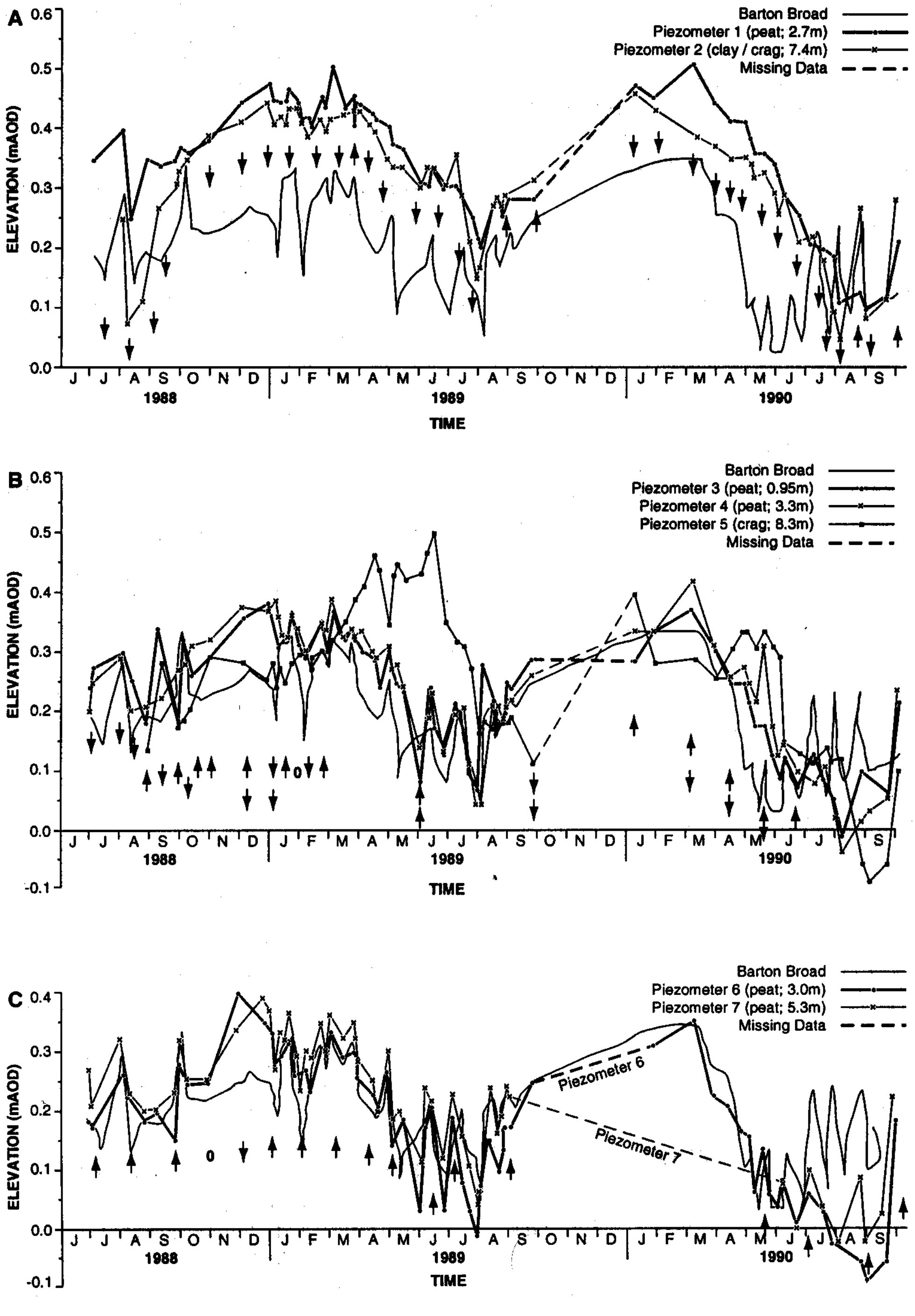

Fig. 6 *Catfield Fen groundwater head data for external system piezometers. In (A) arrows represent whether upward or downward flow is occurring between piezometers 1 and 2. In (B) arrows represent whether upward or downward flow is occurring. Where two arrows exist the upper arrow relates to flow direction between piezometers 3 and 4 and the lower between 4 and 5. In (C) arrows represent whether upward or downward flow is occurring between piezometers 6 and 7. In all diagrams a zero indicates no flow.*

ductivities show the same general pattern of lower conductivity in the centre and higher towards the margins. At the southern end of the external system, high conductivities were present in the July 1988 survey: evapotranspiration may have been the cause.

In summer, the water conductivities are higher, as might be expected as a result of greater evapotranspiration, less dilution by the low conductivity inner compartment waters, and possible influxes of surface water in response to low fen levels.

GENERAL DESCRIPTION OF WATER CHEMISTRY

The water samples from the fen have been grouped into four water 'types' based on their chemical characteristics (Table 3). The types are defined crudely and encompass

Table 1. Permeability estimates

Sequence	Depth (metres)	Water level mgbl[¶]	Piezo. Number	Location	Test type[†]	Reference	K (md^{-1})
Crag	2, 4, 4, 7, 9, 11, 14, 15, 16, 20, 22, 41 m/d						14[‡]
Clay above	—	—	—	Drakes Cottage	PT	Sadler (1989)	5×10^{-5}
Crag	—	—	—	Middle Marsh	PT	Sadler (1989)	3×10^{-5}
Peat	5.29	0.13	7		PT	Metcalf (1989)	0.85
	1.54	0.23	8	″	PT	Metcalf (1989)	1.5
	0.86	0.16	11		PT	Metcalf (1989)	0.03
	1.0	—	12		PT	Sadler (1989)	0.5
	'Deep'	—	—	Drakes Cottage*	TT	Sadler (1989)	2×10^{-3}
	'Shallow'	—	—	North Marsh	TT	Sadler (1989)	0.12
Tube tests in peat 'adjacent' to piezometers 8/9 (see text)							
	1.0	0.0	Northwest corner	*	TT	Metcalf (1988)	1670
	1.5	0.05	Northwest corner	*	TT	Metcalf (1988)	2800
	2.5	0.02	Northwest corner	*	TT	Metcalf (1988)	8340
	1.0	—	Northeast corner	*	TT	Metcalf (1988)	>>>[§]
	1.5	0.04	Northeast corner	*	TT	Metcalf (1988)	20
	1.0	0.05	Southwest corner	*	TT	Metcalf (1988)	25
	1.5	0.04	Southwest corner	*	TT	Metcalf (1988)	32
	1, 1.5	'Blocked'	Southwest corner	*	TT	Metcalf (1988)	'Blocked'
	2.5	0.04	Southwest corner	*	TT	Metcalf (1988)	670
Clay in	5.6	—	9	*	PT	Metcalf (1988)	2×10^{-3}
peat	0.55	—	10	*	PT	Metcalf (1988)	5×10^{-3}
Bund	—	—	—		PT	Sadler (1989)	5×10^{-5}

[†] PT = piezometer test; TT = Tube test
[‡] Average of values from region
[§] Too rapid to measure
[¶] mbgl signifies metres below ground level
* in peat cutting zone

Table 2. Summary of results of surveys of water electrical conductivities (Collins, 1988)

Location	Electrical Conductivity (µS/cm^{-1}) January 1988	July 1988
Middle Marsh	*c.*300	100–200
Central parts of fen compartments	320–550	200–500
Ring drain:		
west and south	500–520	620–700
north and east	580–800	800–970
Inner drains	400–500	560–700
Fenside drain	700–820	1000–1750
Crag	—	800
River Ant	—	Constant at *c.*800
Barton Broad	—	750
External system generally	—	580–770
External system southwest of fen	—	750–2500

a wide chemical range. Use has been made of the electrical conductivity surveys in interpreting the distributions of these water types.

Type 1: Type 1 waters have the lowest concentrations of determinands of any waters on the fen (Table 3; Fig. 8) and are grossly undersaturated with respect to calcite. They correspond to Giller and Wheeler's (1986b) poor-fen waters. Although electrical conductivity data suggest that they occur near the sluice, in the western part of North Marsh, and in the southern part of Hubbard's Marsh, the largest 'outcrop' of Type 1 waters is in Middle Marsh (Fig. 7). The enclosing embankment protects Middle Marsh from flooding by higher concentrations of drainage ditch waters, and the main source of water is therefore rainfall. The head gradient below Middle Marsh is downwards and, presumably, the outflows and plant uptake of dissolved constituents are sufficient to prevent salt build-up through evapotranspiration; as a result within this area the lowest concentrations are found and they have been deemed to be a sub-type (Type 1a) (See Fig. 7) Electrical conductivity data indi-

Table 3. Analyses from samples taken in May-August 1988. (Brackets indicate suspect colorimetric measurements in cases where ionic balance errors are outside ±15%. Ec = electrical conductivity Ppco2 = log10 (Partial pressure of CO2) SIC = saturation index for calcite = log10 (Ion activity product/solubility product): both calculated using WATEQF (Plummer et al., 1970)

Site	Ec $mS^{-1}cm$	C	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Sr mgl^{-1}	Fe	Mn	SiO_2	pH	$pPco_2$	SIC
Type 1																
P15	200	14	11	22	2.3	67	5.5	33	0.62	0.10	0.12	0.01	0.22	7.1	2.3	−1.5
P16	90	(6.3)	(5.3)	15	0.4	12	(4.9)	(22)	0.59	0.10	0.14	0.33	1.36	5.5	1.5	−4.4
Type 2																
P10	580	40	28	50	6.4	158	6.0	105	2.7	0.30	0.20	0.36	3.2	7.1	2.0	−1.0
P17	500	34	7.3	46	5.3	103	22	67	0.2	0.10	0.09	0.24	1.2	7.3	2.3	−0.8
Pz8	630	46	97?	44	2.9	49?	4.2	88	0.6	0.11	0.05	0.92	10.5	6.8	1.2	−0.6
Pz9	310	28	30	29	4.1	182	27	109	0.1	0.10	0.64	0.27	2.2	7.7	2.5	−0.5
S20	620	42	18	65	7.3	140	6.1	140	0.7	0.20	0.26	0.56	11.4	7.0	2.0	−2.6
S27	560	40	20	45	1.8	110	54	97	0.2	0.10	0.01	0.27	3.7	7.0	2.0	−1.8
S33	400	20	5.0	42	5.9	49	6.0	89	0.9	0.4	0.18	0.52	2.8	6.5	1.9	−4.7
S28	450	31	6.0	38	0.3	49	43	84	0.01	0.20	0.04	0.44	0.6	6.5	1.9	−5.0
D29	610	54	20	42	34	175	38	89	0.1	1.70	0.27	0.27	3.2	6.8	1.6	−1.8
D6	620	66	11	34	4.1	273	36	83	0.2	0.07	0.59	0.16	1.1	7.2	1.8	−0.2
D7	580	66	11	34	4.1	173	43	84	1.1	0.26	0.09	0.31	0.9	7.1	2.0	−0.7
D8	500	73	13	39	4.6	177	52	82	1.6	0.22	0.09	0.18	0.6	6.9	1.7	−0.7
D9	620	65	11	33	4.1	160	37	83	0.2	0.19	0.08	0.01	1.5	7.1	2.0	−0.7
D11	680	54	25	75	7.5	129	79	114	5.3	0.10	0.91	1.08	1.7	6.7	1.7	−1.2
D26	650	75	59	43	4.0	219	72	93	0.7	0.10	0.02	0.15	5.9	7.1	1.9	−0.6
Median	580	46	18	42	4.1	173	37	89	0.6	0.19	0.09	0.27	2.2	7.0	1.9	−0.8
Max	680	75	97?	75	7.3	439?	79	140	5.3	1.70	0.91	1.08	11.4	7.7	2.5	−0.2
Min	310	20	6	29	0.3	49	4.2	67	0.01	0.07	0.01	0.01	0.6	6.5	1.2	−5.0
Type 3																
D13	900	133	52	36	5.8	312	117	274	12	0.10	0.01	0.01	0.6	7.3	2.0	−0.5
D14	580	77	28	35	4.3	236	52	101	2.5	0.10	0.29	0.15	1.9	6.8	1.5	−1.4
D24	700	73	30	43	4.1	194	63	93	0.6	0.10	0.17	0.15	5.7	7.0	1.9	−1.9
D32	850	130	28	42	0.8	427	22	104	0.5	0.60	0.61	0.44	3.7	7.5	2.0	0.0
Type 4																
D30	1100	110	32	52	51	565	21	125	6.2	0.4	2.86	1.04	13.0	7.1	1.5	−0.6
External System																
Pz5	640	91	51	84	6.7	256	17	308	0.57	1.7	0.01	0.32	4.5	6.6	1.3	−0.8
S35	600	68	13	49	3.5	171	30	112	0.20	0.3	0.05	0.37	4.0	6.7	1.6	−1.1
S37	600	55	12	48	9.5	171	9.0	131	3.0	0.40	0.13	0.33	4.5	6.7	1.5	−0.9
S38	660	64	20	46	1.4	146	63	100	0.56	0.30	–	0.33	3.1	7.2	2.2	−0.7
D36	840	60	21	40	4.0	231	46	54	0.99	0.20	0.22	0.24	1.8	7.1	1.8	−0.4
Catfield Broad and Barton Broad																
8.6.88	690	88	29	36	4.5	235	76	95	0.25	0.20	0.05	0.09	4.8	7.7	2.5	+0.1
29.6.88	810	100	14	51	8.7	194	94	122	2.9	0.80	0.30	0.31	4.4	7.9	2.7	+0.5
Crag																
Drakes Cott.	800	68	2.7	17	12	121	80	40	10	0.10	0.02	0.05	8.3	7.2	2.2	−0.7
Ludham	480	76	9.4	34	3.4	258	33	46	0.56	0.30	0.07	–	8.5	6.8	1.5	−2.0
River Ant (seasonal data are given y Giller and Wheeler, 1986b)																
25.5.88	750	84	20	58	6.2	188	111	6.6	3.9	0.40	0.04	0.01	0.5	8.0	2.8	+0.4
19.6.88	780	102	15	36	3.0	188	97	89	9.2	0.10	0.13	0.09	3.6	7.1	1.9	−0.3

P = pond sample; S = water sample obtained by augering the peat; Pz = piezometer sample; D = ditch water sample

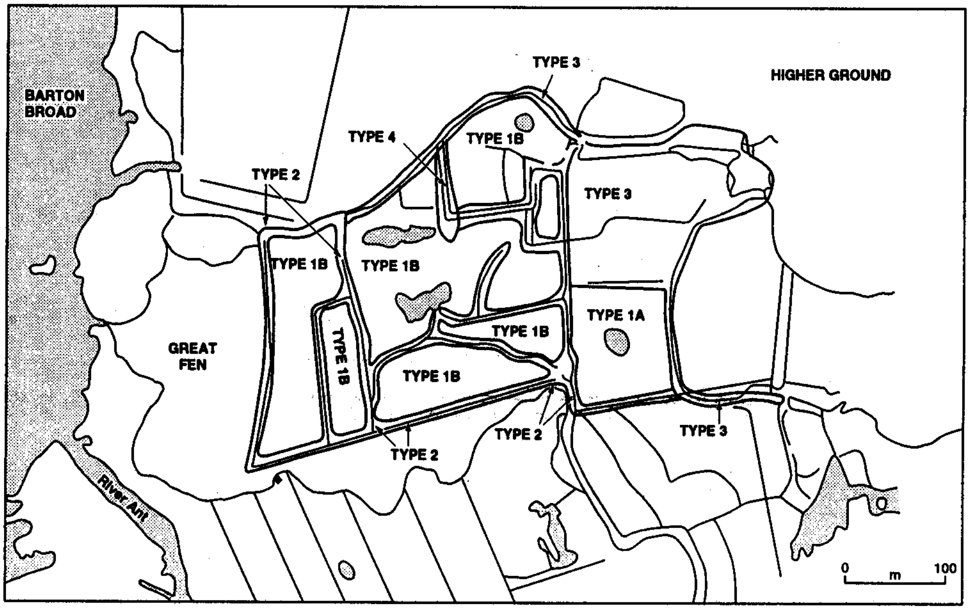

Fig. 7 *Distribution of type waters across the 'internal' compartments on Catfield Fen.*

cate that Type 1 waters are present only in the upper peat profile, a fact reported by Giller and Wheeler (1986b) who also noted Type 1 waters change little with season.

Type 2: The concentrations of almost all the determinands are greater in Type 2 waters than they are in Type 1 waters (Table 3; Fig. 8). Type 2 waters correspond to Giller and Wheeler's (1986b) rich-fen waters. They are undersaturated with respect to calcite, though less so than Type 1 waters. As in Type 1, NO_3 concentrations are generally low. As in almost all the peat waters, SiO_2 concentrations are low in comparison with substrates as expected. Type 2 waters occur throughout the western two thirds of the internal system (Fig. 7), and appear to be the 'normal' water of the near-surface fen, at least in early/mid summer; this may represent the water below Type 1 at depth in the peat as indicated by the electrical conductivity data, the piezometer samples, and observations given by Giller and Wheeler (1986*b*).

Type 3: Type 3 waters contain significantly greater amounts of Ca, HCO_3 and SO_4, on average, than Type 2 waters (Table 3; Fig. 8) and are approaching saturation with respect to calcite. Nitrate concentrations are often higher than in the other water types. Iron concentrations are highest in Type 3. The general chemistry of these waters is similar to that of the broad and River Ant waters (Table 3; Fig. 8). The distribution of Type 3 waters—on the northern and eastern margins of the fen (Fig. 7)—suggests influx from the surrounding fertilised and limed fields, with possibly some influx from the Crag aquifer, though Crag waters appear to contain lower Cl concentrations (Table 3). It is not suggested that the drainage ditch waters are derived from the river and broad water as the hydrograph data indicate flows should normally be away from the fen: the water chemistry is presumably similar because the main surface water courses are fed by runoff from agricultural areas. In combination, the chemical, conductivity and hydrograph data indicate that Type 2 waters may be the result of mixing between Type 1 water and Type 3 drainage ditch water during the periods of inundation. The external system water chemistry is most similar to Type 3 waters, which is consistent with the idea of mixing between Type 3 waters from the internal system, broad water and Type 1 water.

Type 4 waters are restricted in extent and indicative of local pollution probably relating to septic tank drainage from Drakes Cottage (Fig. 7 and 7; see Fig. 1 for location)

Identification of these various Catfield Fen water types and inferred sources not only provides valuable evidence for model conceptualisation but also can be used to assess the vulnerability of sites to water pollution above and beyond that possible by any desk study. A desk study of Catfield Fen (Lloyd *et al.*, 1993; Gilvear *et al.*, 1994) classified the site as vulnerable to surface water pollution but the hydrochemical data suggest groundwater pollution could also affect the wetland.

Conceptual Model of the Hydrology

Using geological, topographical, hydrological and water chemistry data collected during the first year of the

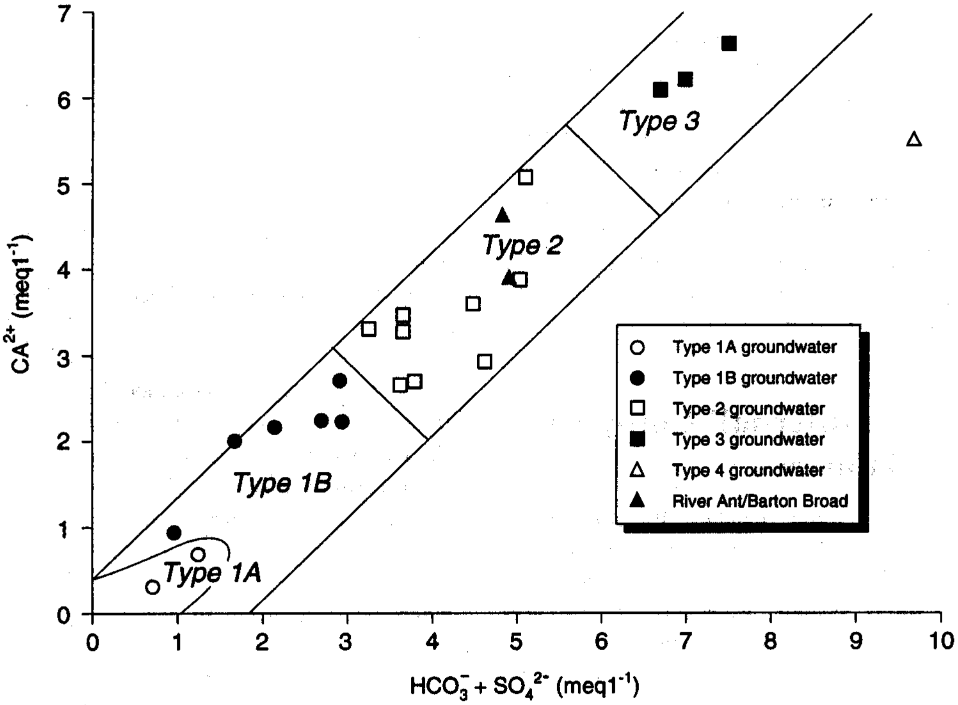

Fig. 8 *Type waters present on Catfield Fen as indicated by Calcium-bicarbonate levels.*

study, a conceptual hydrological model was formulated. The model (Fig. 9) accords with the surface water and groundwater outlines provided above; it provides a framework for wetland water balance quantification and groundwater flow model formulation. As illustrated in Fig. 9, the wetland results from a complex interaction between River Ant/Barton Broad water and fen water levels, the two systems being linked by the sluice. Below the wetland, the confined Crag aquifer, overlain by up to 8 metres of peat, is separated from the peat by a thin discontinuous clay layer; significant flow between the aquifer and the peat occurs only in areas where the clay is missing (Fig. 2d). Vertical groundwater flow, from the Crag aquifer to the peat, is induced by the upward head gradient.

The flow directions across the fen surface are determined by the relative levels of fen and river/broad water. Normally, flows occur from the fen towards the river but, during prolonged dry summer conditions, fen water levels fall relative to those in the river and broad and inflow along the drainage ditches will occur. Also, under intense rainfall conditions, Catfield Fen levels rise less

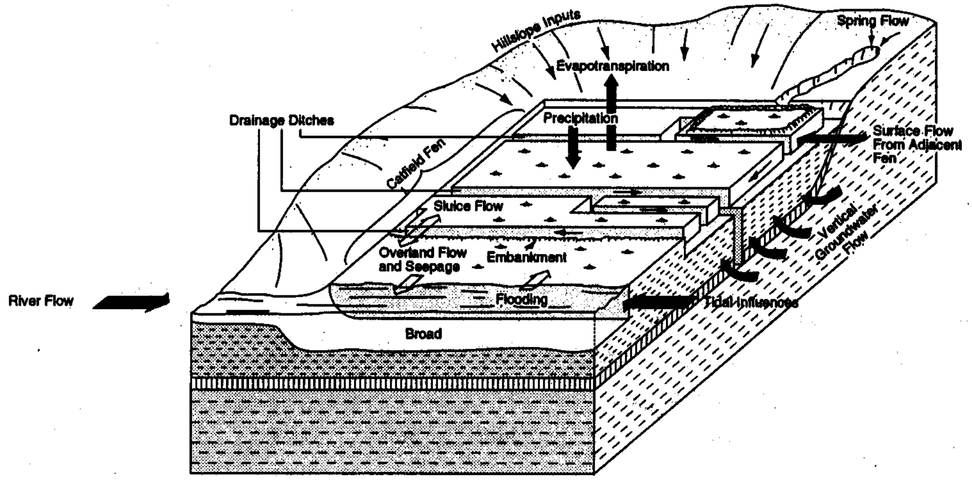

Fig. 9 *Conceptual Model of the hydrology of Catfield Fen.*

rapidly than those of the broad system so that inflow to the fen occurs.

Fen water levels, in the absence of flooding from the external system fluctuate in response to precipitation input, evapotranspiration and groundwater flow. The drainage ditches adjacent to the surrounding land collect and direct hillslope/lateral groundwater inflow to the fen drainage ditches. Flow from the fen compartments to the drainage ditches also contributes to flows through the sluice or to the River Ant via the drainage ditches.

Estimating the 'Internal' Compartment Water Balance

Obtaining an accurate water balance for the whole Catfield system has not been attempted, principally because of the difficulty of measuring the very low flow velocities in the ditch system, especially in the area where connection to the River Ant system is suspected. As a result, effort has been concentrated on obtaining a water balance for the peat groundwater system of the fen. For flows to and from the groundwater system, the following water balance equation holds.

$$P - ET + GWI - S - FTD = 0$$

where P = precipitation, ET = evapotranspiration, GWI = groundwater inflow, S = water gained to storage, and FTD groundwater flow to drainage ditches (negative values should include periods of inundation, but the storage term has not been modified to take this explicitly into account).

Monthly precipitation and evapotranspiration data for the period August 1988 to July 1989 inclusive were obtained for Catfield Fen by correlations between the incomplete automatic weather station data record and the MORECS data set. (Table 5).

Groundwater inflow to the fen occurs upwards from the Crag aquifer: inflow from the surrounding land is intercepted by the 'ring' drainage ditches and therefore does not affect the balance. Most of the fen (337,000 m^2) is underlain by clay, and hence the flows are estimated in Table 4 using Darcy's law with average head differences between the Crag and the peat, the thickness of the clay, and a clay hydraulic conductivity: allowance has been made for windows in the clay. The inflow rate is very sensitive to the vertical hydraulic conductivity at the windows in the clay: condition (c) probably overestimates the flows, as a hydraulic conductivity of 10^{-1} md^{-1} is relatively high for deep peat, and the hydraulic gradient in the clay window zones is certain to be less than that measured across the clay. Because of the great uncertainties in the calculation, the figures listed in (c) under Table 4 are used in the water balance of Table 5. Condition (C) measures a vertical hydraulic conductivity of 10^{-3} md^{-1} everywhere—a high value to account for the windows in the clay; the flows calculated are fairly consistent with the results obtained from the modelling work described below.

Water gained to storage in the fen can be estimated using the piezometer water level data and a specific yield value. The specific yield of peat is notoriously variable (Ingram, 1983) and the data from the lysimeter indicated a range of values from which a value of 0.2 was selected as a best estimate. Inundation has been ignored in terms of storage change estimation.

Table 5 shows the values of FTD calculated as the residual of the water balance equation: two values are given, one based on the assumption that actual and potential evaporation are equal, i.e. AE = PE, the other for AE = 0.75 PE. Also given are the estimates of flow from the internal system towards the external system (JWO) obtained by applying the sluice formula described in the methods section. The difference between the FTD and SWO values represents the groundwater and surface water inflows to the drainage ditch system from the Crag

Table 4. Estimates of groundflow inflow (mm per month) from the Crag to the peat assuming: clay thickness = 0.5m, total Fen area = 347,000 m^2, clay layer absent = 10,000 m^2, clay hydraulic conductivity = 10^4 md^{-1}, and hydraulic gradient everywhere is calculated as: (the average of all the Crag heads measured – average of the peat heads measured) / 0.5 m. Brackets indicate estimated head gradient.

Month											
A	S	O	N	D	J	F	M	A	M	J	J
		1988						1989			
(a)Vertical K in zones where clay absent = 10^{-2} md^{-1}											
(–4.2)	(0.5)	1.0	(3.7)	3.6	4.6	4.8	4.8	4.7	4.8	(7.0)	5.1
(b)Vertical K in zones where clay present = 10^{-2} md^{-1}											
(–33.1)	(3.6)	7.4	(28.7)	26.7	35.1	36.7	36.9	35.8	36.9	53.7	38.8
(c)Vertical K everywhere = 10^{-3} md^{-1} (ie windows not accounted for explicitly)											
(–11.2)	(1.2)	2.5	(9.6)	9.3	11.8	12.3	12.4	12.0	12.4	(18.0)	13.0

Table 5. The water balance of Catfield Fen; based on monitoring of climatological inputs and outputs and surface water outflows and estimation of groundwater fluxes using groundwater head and hydraulic conductivity data together with Darcy's Law.

Component						Months							Notes
	A	S	O	N	D	J	F	M	A	M	J	J	
			1988						1989				
P	30	67	62	47	31	34	53	65	66	20	62	45	MORECS/AWS[1] correlation
PE	69	63	28	13	12	9	19	33	42	93	98	91	MORECS/AWS[1] correlation
(0.75 pe	52	47	21	10	9	7	14	25	31	70	73	(68)	Assuming AE = 0.75 PE
GW1	(–11)	(1)	(3)	(10)	9	12	12	12	12	12	(18)	13	K clay = 10^{-3} m/d. Thickness = 0.5m
AS[2]	–6	–14	–8	14	12	0	–4	4	–2	–8	–14	–18	Sy = 0.2
FTD	–44	19	45	30	16	37	50	40	38	–53	–4	–15	Calc. using balance eq.
FTS[3]0.75 PE	–27	35	52	33	19	39	55	48	49	–30	21	8	Calc. using balance eq.
SWO[4]	–17	–16	–11	–23	4	(101)	35	70	–108*	4	0	0	Sluice equation
GW+SW[5]	27	–35	–56	–53	–12	–	–15	30	70	57	4	15	SWO – FTD
(GW+SW)[5]	10	–51	–63	–56	–15	–	–20	22	59	34	–21	–8	SWO – FTD $_{0.75\,\mathrm{PE}}$
P8/9–RD[6]	11	10	6	(2)	7	11	10	25	22	23	23	23	Field Data
P10/11–RD[6]	–5	–10	–8	(–11)	–5	–3	–6	11	8	9	(4)	2	Field Data
P8/9 [7]	47	42	43	(49)	55	56	55	56	55	51	46	38	Field Data
(P14+P15)/2–P5[8]	–18	2	4	16	15	19	22	20	20	20	(30)	21	Field Data

[1] AWS = Automatic Weather Station.

[2] Negative values indicate drop in water level.

[3] FTD calculated assuming AE = 0.75 PE.

[4] Outflow from sluice estimated using method outlined in Methods section.

[5] Groundwater and surface water inflow to ditches from outside Fen and Crag. Calculated using SWO–FTD (or SWO – FTD $_{0.75\,\mathrm{PE}}$).

[6] P8/9 = average head (cm) in piezometers 8 and 9 minus head in ring ditch: P10/11 = average head in piezometers 10 and 11 – RD.

[7] P8/9 = average head (on AOD) in piezometers 8 and 9.

[8] Head difference between Crag (piezometers 14 and 15) and peat (piezometers) (cm).

and from the region surrounding the fen. Table 5 also lists average heads for piezometers 8 and 9, and the average difference in head between the two piezometer pairs 8/9 (Fig. 5a) and 10/11 (Fig. 5b) and the peripheral 'ring' drainage ditch.

Although the water balance is crude, it is self-consistent, and several points of interest emerge:

- over the year in question, storage changes are small in comparison with other components of the water balance.
- the water balance is dominated by precipitation, evapotranspiration and outflow to the drainage ditches.
- given the uncertainties in other components, it is not possible to determine whether AE = PE or AE = 0.75PE is the better estimate.
- groundwater inflow from the Crag is relatively small and fairly constant, at least over most of the year examined.
- some flow from the drainage ditches to the fen can occur when water tables are low in the fen due to low rainfall and high evapotranspiration in the summer periods.
- in autumn 1988, net flow to the drainage ditches was occurring at the same time as net inflow at the sluice. This implies flow to the River Ant which agrees with the hydrograph data.

Modelling

AIMS

As an aid to investigating the sensitivity of the surface water-dominated wetland system to the local groundwater system, a vertical two dimensional (2D) steady state groundwater flow model was set-up using the finite difference code MODFLOW (McDonald and Harbaugh, 1988). The specific aims of the modelling were

i) To confirm that the conceptual model is self-consistent.
ii) To test the assumptions made in the water balance assessment.
iii) To determine the sensitivity of the system to variations in values of various variables.
iv) To investigate the vulnerability of the system to groundwater abstraction.

MODEL DESIGN

Model representation was based on the study and calibration data were provided by the hydrogeological and climatological monitoring. MODFLOW is a modular block-centred finite-difference groundwater flow model with 'packages' (groups of modules) for wells, recharge, drains and evapotranspiration. Only saturated flow is modelled. Aquifer layers may be simulated using MODFLOW as confined or unconfined.

The model 2D vertical cross-section (Fig. 10) is a schematic representation of a typical transect from the surrounding agricultural land (left-hand side) across the wetland to Barton Broad (right-hand side). Four geological layers are shown; the upper peat ('acrotelm'), the lower peat ('catotelm'), the clay and the Crag. The base of the model is the very low permeability London Clay. Flow in the Crag is maintained by fixed heads at the eastern and western edge of the model: the interaction with the fen is the only interest and the hydrogeology of the Crag has not been considered in detail. Drainage ditches and Barton Broad are represented by fixed head nodes. Embankments are represented in the model as 5 m wide low permeability cells.

'CALIBRATION' AND MODELLING AIMS (I)—(III)

Although field data were plentiful, several unknowns exist with regard to all the water balance components. The aim of the modelling was therefore to investigate the sensitivity of the system rather than to decide on one,

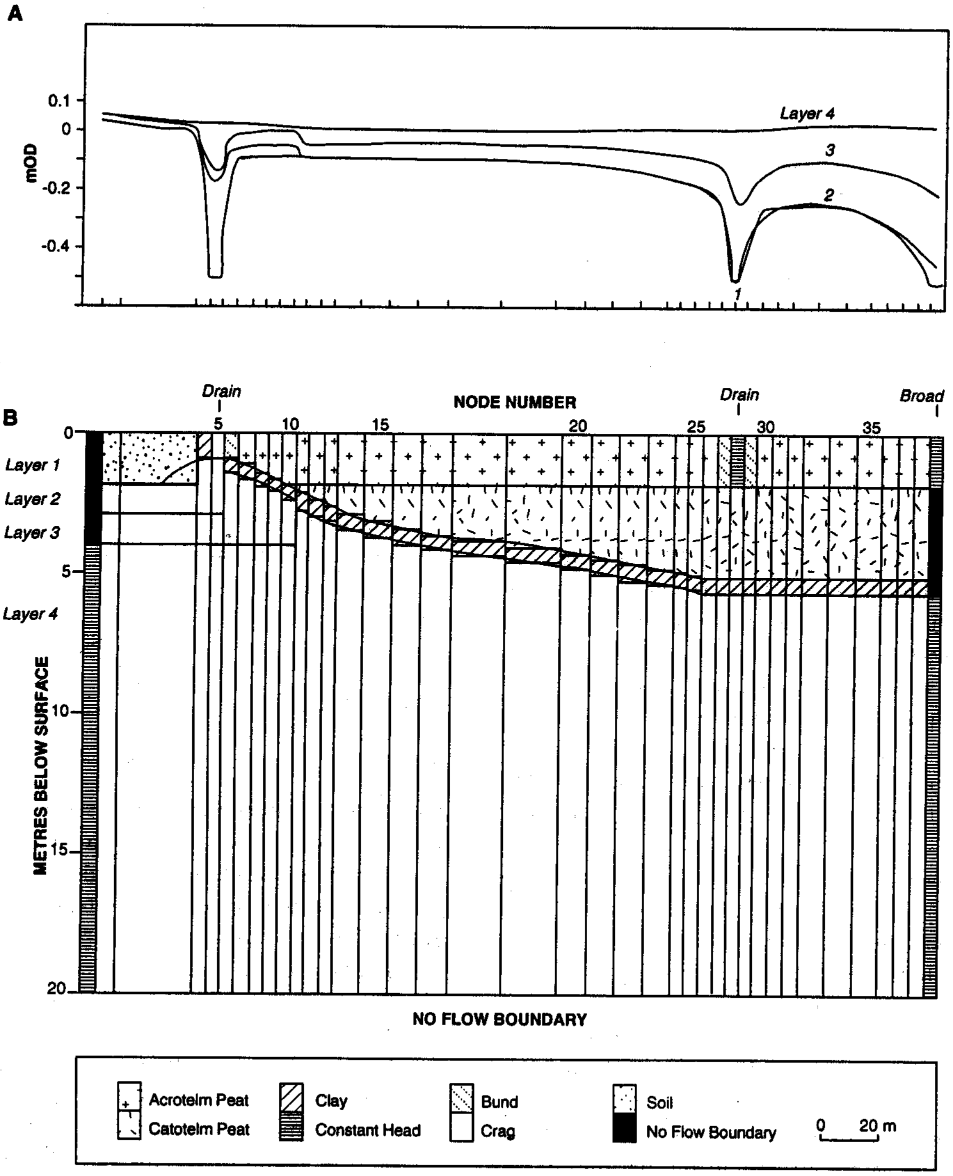

Fig. 10 *Catfield Fen model (A) groundwater head data for layers 1–4 in the calibrated model. (B) The model layout.*

possibly far from unique, solution. Nevertheless there needs to be one 'central model' around which the variations are based, and the physical constants are given in Table 6. This central model reproduces the main characteristics of the wetland hydrological system. Calibrated model results are shown in Fig. 10. The fit is acceptable in that it reflects the major features of the system: upward head gradients everywhere, heads in the Crag at around ground level everywhere, fen water levels close to the surface, drawdowns local to drainage ditches, and the external system head gradient is directed towards Barton Broad. The inputs and sensitivities are described in general terms below.

Table 6. Basic Model input physical constants

Permeabilities	
'Acrotelm' peat	1 mday^{-1}
'Catotelm' peat	0.1 mday^{-1}
Crag	14 mday^{-1}
Clay	1×10^{-3} mday^{-1}
Ronds	0.01 mday^{-1}
Thicknesses	
'Acrotelm' peat	1 metre
'Catotelm' peat	Average 2 metres
Clay	Average 0.5 metres
Crag	Average 18 metres
Climatological variables	
Precipitation	438 mmyear^{-1}
Actual evapotranspiration	511 mmyear^{-1}

The Crag permeabilities have been fixed at 14 md^{-1}, the value obtained from the local pumping tests. If the value is reduced to say 1 md^{-1}, the Crag heads are no longer uniformly at ground level and vary unrealistically across the site. Peat permeabilities are set at 1 md^{-1} in the upper layer and 0.1 md^{-1} in the lower layer. The most important effect of these permeabilities is on internal head gradients within the peat compartments. The peat is almost completely surrounded by much lower permeability deposits. The permeability of the embankments makes little difference to fen heads over the range 0.001 – 0.1 md^{-1}, and has been set at 0.01 md^{-1}. This is higher than the field-measured values of $10^{-5}\mathrm{md}^{-1}$, but a significant proportion of the drainage ditches lack embankments.

The permeability of the clay is critical to the system. If the clay permeability is set everywhere at the field-measured value of $10^{-5}\mathrm{md}^{-1}$, the fen becomes almost isolated and small imbalances in precipitation and evapotranspiration make large differences to water levels. Under such conditions, the real system would become a lake in winter and dry up almost completely in summer. This does not occur, because of the known occurrence of 'windows' in the clay (Fig. 2d) and thin clay is almost certain to be affected locally by, for example, root holes and thinning so that it is reasonable to assume a higher permeability in the model. After experimentation, a value of 10^{-3} md^{-1} was chosen. This value agrees with the water balance estimates based on calculated flows taking the clay windows explicitly into account. The experimentation also suggested that windows will have a strong influence on local fen groundwater heads.

Precipitation was fixed at the average for the year beginning 1st August 1988, as recorded by the automatic weather station. The evapotranspiration figure of 0.75 PE was used: removing water at the potential evapotranspiration rate leads to low heads, but there is the trade-off between clay permeability and the evapotranspiration rate. Attempts at steady state modelling of winter and summer conditions lead to unrealistic flooding and drying out, as might be expected: the system is never in steady-state at the seasonal time scale.

Although the model cannot prove the conceptual model to be correct, it does demonstrate that it is self-consistent—the first aim of the modelling.

The model has incorporated two of the fundamental water balance assumptions: evapotranspiration at 0.75PE and continuous outflow to drainage ditches. The inflow to the fen from the Crag predicted by the model is of the same order as in the water balance. The model is thus consistent with the water balance in (ii).

Experimentation with the model suggests that the most important variables are the permeability of the clay and the precipitation/evapotranspiration ratio. Although the model cannot distinguish the relative effects of varying these characteristics, a balance is essential for the existence of the wetland. Unless they are very closely spaced, the drainage ditches and embankments are of local importance only. The elevation of the Crag piezometric head controls the base level of the system.

MODELLING AIM (IV) VULNERABILITY TO GROUNDWATER ABSTRACTION

To assess the effect that groundwater abstraction from the Crag aquifer might have, the modelled head in the calibrated model was lowered from 1.05 m above sea level to 1 m below sea level. In general, modelled fen water levels fell to the Crag piezometric surface despite the drainage ditches being maintained at a fixed head. The drainage ditches are presumed to remain at their original level due to inflow from the river system. In the external system, flow is downwards with groundwater heads being kept higher by the broad. In the internal system, flow is downwards below the ditches, but upwards adjacent to them. The ditches therefore keep the fen wet. The effects of these flows are minimal, however, and the overwhelming control is the head in the Crag which still causes upward flow to the fen. It is clear that, even though groundwater constitutes only a minor component of the water balance of the fen, dropping the Crag groundwater heads by abstraction would lower the base level to such a degree that the system could not compensate and the wetland would dry out.

Conclusion

The Catfield Fen case study illustrates the complexity of surface and groundwater flow processes within floodplain fens as was found by other investigations on floodplain wetlands (eg. Wassen *et al.*, 1990; Grieve *et al.*, 1994). Local geology and local surface water and groundwater regimes are important in determining wetland water sources, water balances and hydrochemistry .

Catfield Fen is maintained by precipitation, surface water and groundwater inputs. Giller and Wheeler (1986b) came to a similar conclusion, based upon vegetation and peat water chemistry investigations and stated that the 'River Ant may have less pervasive influence on the chemical budget of the Fens than is suggested by the designation "floodplain mire"' (p112). Differences in the relative importance of the water sources across the fen are reflected in spatial variability in fen hydrochemistry; no doubt this, together with variable depths to the water table and frequency and duration of flooding, controls the vegetation. Catfield Fen contains herbaceous vegetation dominated by reed (*Phragmites australis*), and sedge (*Carex maricus*) with pockets of *Sphagnum* and birch (*Betula pendula*) scrub and alder (*Alnus glutinosa*) woodland (Giller and Wheeler, 1986a).

Despite the hydrological and hydrogeological complexity of Catfield Fen, an approach based on hydrological monitoring, geological investigations, hydrochemical surveys and groundwater flow modelling quantified a tentative fen water balance and contributed to an understanding of the hydrological processes within the vicinity of this fen environment. Moreover, such an approach allowed the sensitivity of the fen to groundwater abstraction to be assessed and its vulnerability to surface and groundwater pollution to be deduced. Thus, detailed hydrological and hydrogeological investigations of wetlands can provide findings, not readily revealed by wetland classification procedures and other rapid assessment techniques, but critical to determining the hydrological robustness of the site and its vulnerability to man's activities.

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