DITCH: a model to simulate field conditions in response to ditch levels managed for environmental aims

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Abstract

Wetland areas are frequently managed by manipulating the water levels in the surrounding ditches, with the aim of restoring or enhancing the wetness of the site, especially for the ecological requirements of some bird populations. The extent to which water tables in the centre of fields can be controlled by this action can be simulated through the use of a model, Drain Interaction with Channel Hydrology (DITCH), based on drainage theory. DITCH successfully predicted the pattern of water table behaviour on two wetlands sites, in the Norfolk Broads and Somerset Levels areas in the UK. The model can also be used to predict the strength of the soil surface and the extent of surface flooding. When used to examine the effects of alternative ditch management regimes within the two test areas, the model shows that the effects of ditch management options are not easily converted into impacts in the centre of the fields. If the effects are not sufficient, then hydrological manipulation of sites to achieve or improve wetland status may require more active intervention. ©2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Public awareness and concern for the maintenance and preservation of wetlands (Maltby, 1986), has lead to positive action to manage wetland resources. In the past, many wetland areas have been drained, with the aim of increasing agricultural productivity. In an attempt to restore wetland status, or to improve the wetness of those wetlands that have survived, the same structures that were used to drain the land are now being used to control the wetness, primarily through the control of ditch water levels. These manipulations are intended to improve the ecological status of the area, as to improve the landscape value. Populations of birds, which are often taken as critical environmental indicator, require soft, wet soils, for feeding; and partially flooded areas for breeding. (Tickner and Evans, 1991).

Consequently, governments have introduced agri-environment schemes, in which they encourage (often through payments) the management of agricultural areas in environmentally sensitive ways. One such scheme in the UK is the Environmentally Sensitive Areas (ESA) scheme, in which the Ministry of Agriculture Fisheries and Food enters into agreements with farmers to adopt practices which seek to conserve and enhance areas of high landscape or historic value which are vulnerable to changes in agricultural practices. Where the ESAs encompass wetland areas, the agreements may prescribe the water levels in

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the ditches, and the land owners have to meet these targets in order to qualify for the relevant payments.

Within such schemes, the practical issue of determining the correct management options (as defined in the terms of the ESA agreements), particularly the ditch water levels that are appropriate, may be subject to debate. As a tool for understanding some of the possible outcomes of adopting specific ditch management regimes within wetlands ESAs, a model, called DITCH (Drain Intraction with Channel Hydrology) has been developed to examine the consequences of various ditch management regimes (Armstrong, 1993; Armstrong et al., 1993). This paper describes the model, its development and its validation against data sets collected from two sites in the UK, in the Broads ESA and in the Somerset Levels and Moors ESA. The results have been used to indicate the effectiveness of the ESA prescriptions in meeting their ecological and landscape objectives.

2. Model development

To simulate the soil water regime within a field, a model is required to calculate the sequence of water levels in the field in response to the meteorological inputs and the imposed boundary (ditch) conditions. The theory of water movement to drains, derived from an understanding of the physics of soil water flow processes, is based on Darcy’s Law for saturated flow, leading to the development of a theory of drainage systems that can be used for this study (e.g., Van Schilfgaarde, 1974; Smedema and Rycroft, 1983; Ritzema, 1994).

The DITCH model is based on the calculation of the water balance in the field, using the fluxes of water moving through the soil to the peripheral ditches, to estimate the changing position of the water table in the field. The water elevation in the field on day \( t \) is

\[
M_t = M_{t-1} + \left( R - ET - Q_d \right) / f
\]

(1)

where \( R \) is the rainfall, \( ET \) is evapotranspiration, \( Q_d \) is the discharge through the drainage systems and \( f \) is the relevant porosity. For geometrically regular situations such as a uniform soil drained by parallel ditches, the drainage can be calculated from one of the well-known drainage equations. For example, for soils of hydraulic conductivity, \( K \), drained by parallel ditches penetrating to an impermeable layer at the base of the soil profile at spacing \( L \), a simple equation such as the Donnan drainage equation (Ritzema, 1994) can be used to calculate the drainage fluxes:

\[
Q_d = \frac{4K(M_t^2 - D_t^2)}{L^2}
\]

(2)

where \( D_t \) is the level in the ditches at time \( t \). The Donnan equation considers horizontal flow only, but can be used if the impermeable layer is a small distance between below the drains or the ditch bottom. Where the ditches do not penetrate to the base of the soil (as is usually the case), then vertical flow components can no longer be ignored, and the Hooghoudt drainage equation (described for example by Ritzema, 1994) should be used to replace the simple drainage Eq. (2). The flux between ditch and field, \( Q_d \) can be in either direction, and therefore includes both drainage (\( Q_d \) is positive) and recharge (\( Q_d \) is negative), so representing both the winter and summer phases of operation. If the level in the ditches is input into the model as an externally constrained set of values, then the water balance can then be solved directly.

Although drainage theory gives, strictly, only steady-state solutions to the fluxes, the fluxes calculated by the drainage equations can be considered to be correct if considered over a succession of steady states during which the position of the boundaries can be considered to be fixed. This is achieved by use of a small model time step, which in DITCH is 1 hour.

The DITCH model, thus, parallels the model described by Youngs et al. (1989), although differing in its choice of drainage equations, and being simpler in that it considers only the mid-field water table. A first approximation to the two-dimensional form of the water table can be made by scaling the potential function \( E(x, y) \) for rectangular fields described by Youngs et al. (1989 equation 10), between the two fixed points of the ditch level and the field centre water table. Other models such as DRAINMOD (Skaggs, 1982) or SWATRE (Belmans et al., 1983) could potentially be adapted for the same function. However, the flexibility afforded by a purpose-built computer code is preferred, as it requires only data relevant to the issue in hand. In particular, the DITCH model does not consider the unsaturated zone above the water table,
which is acknowledged to be a simplification, justified by the difficulty of acquiring suitable data for the characterisation of the soil hydraulic functions required for a full consideration of the unsaturated phase.

Initially, the DITCH model was described as a theoretical model (Armstrong, 1993) to demonstrate that the degree to which the ditch and field systems were interlinked depended both on the frequency of the ditches, and the hydraulic conductivity of the soil. In highly permeable soils, the soil water table in the centre of the field could be tied quite closely to the ditch level, but in low permeability clay soils the degree to which water could be moved from the ditch to the field centre was extremely limited, and the field could dry out in response to summer evapotranspiration despite there being high levels in the surrounding ditches.

2.1. Non uniform soil parameters: hydraulic conductivity decreasing with depth

The assumption of a vertically homogenous soil in Eq. (2) is not always realistic, as it is frequently observed that the hydraulic conductivity of soil decreases with depth. Solutions for the flux through drains in soils in which the hydraulic conductivity varies continuously as a function of depth (or height above the drain) are given by Youngs (1965). If the variation of hydraulic conductivity with height above the profile base, \( K(z) \) shows an exponential increase from the base (equivalent to an exponential decrease from the surface), written as:

\[
K(z) = K_0 e^{-\beta z}
\]

where \( K_0 \) is the hydraulic conductivity at the base of the saturated soil (i.e., at \( z = 0 \), with \( z \) increasing upwards), and \( \beta \) is a constant. For non-empty ditches the analysis of Youngs then gives the drainage equation:

\[
q = \frac{2K_0 [e^{\beta H_m} - e^{\beta H_w} - \beta H_m + \beta H_w]}{\beta^2 D^2}
\]

where \( H_w \) is the height of water in the ditches, and \( H_m \) is the maximum water table height at mid-drain spacing, which gives estimates of the drainage flux which can then be easily included in Eq. (1).

2.2. Layered soils

A second situation that requires to be modelled is the situation where a soil consists of two layers, for which the analysis of drainage fluxes is given by in (Wesseling, 1973 p. 19–31, and Ritzema, 1994, p. 272–277). For a two-layered soil with the drain or ditch in the lower layer, the drainage flux is given by:

\[
\frac{H_d}{q} = \frac{D_1}{K_1} + \frac{L^2}{8(K_1D_1 + K_2D_2)} + \frac{L}{\pi K_1} \ln \frac{a D_0}{u}
\]

in which the depth of the layers are \( D \) and have conductivity \( K \), with subscripts 1 and 2 for the upper and lower layers, respectively, \( a \) is a shape factor, and \( H_d \) is the head difference between the water table and the ditch, the force driving the water movement. Again, the direction of the overall flux, which is determined by the sign of the head difference driving the flow, \( H_d \), can be either positive or negative, depending on the circumstances, so predicting both drainage and recharge.

3. Field study sites

The model has been used to study the effects of ditch management regimes in two of the ESA in UK: the Broads ESA and the Somerset Levels and Moors ESA (MAFF, 1989). In these areas, selected sites have been monitored, and the results used to validate the results of the model. Once validated, the model has then been used to examine the issues raised by varying the ditch regimes within these areas.

3.1. Halvergate, the Broads ESA

The Halvergate marshes are part of a wide expanse of flood plain, traditionally summer grazing pasture, lying in the centre of the Broads ESA, a series of low-lying river valleys, marshes and fens, in Norfolk and North Suffolk in Eastern England was chosen as the site for detailed monitoring studies. Since 1989, water levels in six fields and the adjacent ditches have been monitored (Armstrong and Rose, 1998b). Four fields were subject to a water management scheme for the retention of spring and summer water levels (ESA Tier 2) and of these two were subject to the
additional raised water levels in the ditches (ESA Tier 3) from January 1994. Reference fields (Fields 5 and 6) outside this area, had the normal managed water levels (ESA Tier 1) which were kept low in winter for drainage although allowed to rise in summer for stock watering. In all fields, water tables and ditch levels were monitored by continuous recording water level meters (Talman, 1980; 1983) supplemented by a open auger holes, ‘dipwells’ (Armstrong, 1983) read on a 3–4 week cycle. Monitoring of fields 2, 3 and 5, was discontinued in the summer of 1992, but maintained on the remaining three fields.

The soils of the area are Gleysols, alluvial clays of the Newchurch series (Clayden and Hollis, 1984). They are well structured in the topsoil, where they are rich in organic matter, but rapidly become structureless with depth, and at 2 m depth are ‘buttery’ and anaerobic. Measured hydraulic conductivity of the soil (measured in situ using the single auger hole technique) reflects this structural development, and varies between values in excess of 100 m/day close to the surface, to values less than 0.01 m/day at depths below 1 m, and becoming effectively impermeable at 2 m. The data were fitted to the exponential function Eq. (3) using linear regression techniques.

3.2. Southlake Moor, the Somerset Levels and Moors ESA

The Somerset Levels and Moors ESA forms the largest remaining lowland wet grassland or grazing marsh system in England and is consequently of outstanding environmental interest (MAFF, 1991a, b). Within it, Southlake Moor is a self-contained unit controlled by an inlet and an outlet sluice. Here, water levels have been monitored in four fields within Southlake Moor and one reference field outside the moor since June 1989 using similar instrumentation as for Halvergate. Until summer 1991 the dipwells were shallow (no more than 0.50 m deep), but were replaced by deep (1.50 m) auger holes from then on. Gauge boards, recording the water levels in the ditches, at both the inlet and the outlet were also recorded.

The soils are Histosols of the Midelney series (Avary, 1955), having a shallow clay cap (approximately 0.40 m deep on Southlake Moor) of river alluvium, overlying a peat substrate at least 2 m deep. The clay cap arises from practice of ‘warping’, which involves letting the area flood with the waters from the adjacent river.

Prior to the establishment of the ESA, the ditch levels for Southlake Moor were maintained at 3.50 m above ordnance datum (AOD) – mean sea level) from mid-November to the end of March, and at 3.65 m AOD from April to mid-November. Land levels are between 3.7 and 4.0 m AOD. On this site, a raised water level regime was initiated at the beginning of December 1988. The water levels were maintained at 3.65 m at outlet sluice throughout the year, except for March, when the levels were 3.50 m to facilitate ditch cleaning operations.

4. Hydrological modelling

The DITCH model was implemented for both sites, using the observed values of the soil parameters and field data on land and water levels. For each, the model was validated by a comparison with the observed water tables in the centre of the field.

4.1. Halvergate

The DITCH model was applied to the conditions in the Broads area using the depth-dependent drainage Eq. (4). The meteorological data and the observed daily ditch levels for the relevant fields were used to model the water tables in the centre of each of the six monitored fields (Fig. 1). Visually, the results show excellent agreement between the model and the observations. A statistical evaluation of the whole set of model results, which thus included the ability of the model to represent the variation both between fields and within fields, gave a correlation coefficient between the modelled and observed water tables of 0.69, which was considered to be an excellent confirmation of the model. The model efficiency criterion (Loague and Green, 1991), for the same data set was 0.44, which again was considered to indicate an acceptable level of model performance.

4.2. Southlake

Application of the model to Southlake required the use of the two layer drainage equation 5, even though
the dipwell data had suggested a continuity between the two layers in the profile. Direct measurement of the hydraulic conductivity of the peat subsoil, using the single auger hole technique indicated a subsoil conductivity of the order of 1–2 m/day.

The observed gauge board heights at the outlet sluice were used to define the input boundary conditions. The modelled water tables were compared to the observed data (Fig. 2) for the recording period. Visual inspection of the model results showed that they were in general very close to observations. In particular, the model simulated the lowest depth to which the water table fell in the middle of the summer in the last three years of the study. The same comparison was not possible for the first three years, during which the field data did not record deeper water tables because of the shallow nature of the recording locations. The biggest divergence was that the model did not accurately reproduce the depths of flooding caused by the very high ditch levels.

The statistical comparison of the results was made using the same criterion as for the Halvergate site, namely the simple correlation coefficient (0.63) and the model efficiency (0.38). Although not quite as good as the results for Halvergate, these were still considered to indicate an adequate model performance.
5. Estimation of soil surface strength

As the ability of birds to probe the soil for food is a major factor in the choice of sites for breeding, the estimation of soil surface strength is required to identify site suitability for bird feeding needs (Tickner and Evans, 1991). For many soils, there is a relatively well defined relationship between soil strength and water content. As a first approximation, soil water content at the surface is also correlated with the water table depth from the surface, so a relationship between soil strength and water table offers the possibility of modelling the suitability of the soil for feeding by birds. This relationship cannot, however, be established from a priori principles, and must be calibrated from field observation.

The penetration resistance of the soil is a measure of the difficulty that a bird might be expected to have in feeding. For work specifically related to bird beak penetration, a special penetrometer has been devised (Green, 1986) which records the force required to push a narrow cylinder into the soil a distance of 100 mm, and so mimics the behaviour of a bird beak. At both sites, the soil surface strength was recorded whenever the auger holes were read using this penetrometer. On each occasion eight replicate measurements of soil strength were taken at three locations within each field.

The field data showed very different behaviours for the two sites. At Halvergate, the soil strength measurements (Fig. 3), showed no significant correlation between water table depth and soil strength for any of the six fields. Nearly all the observations are for values greater than a 6 kg force required to penetrate the surface, and this value was maintained even when the soil was flooded. This value is greater than the estimated maximum force of 3 kg required for penetration of the soil by Snipe (Gallinago Gallinago) (Green, 1988). It is considered that this high surface penetration resistance is the consequence of the grazing management regime of the marshes, which are subject to short periods of high intensity stocking. The consequence is the formation of a hard surface mat of vegetation and compacted soil. It is suggested that this capping behaviour is one of the characteristics of clay marshes, such as the Halvergate marshes, compared to peat marshes.
The results also serve to emphasise the impact of and agricultural management practice affecting the value of land for ecological purposes.

These results contrast with those obtained at Southlake Moor, (Fig. 4) where a clear correlation between water table depth and soil surface strength has been observed, for all the fields in the study area. The overall correlation of 0.69 was considered to be remarkably good, especially when the other (often short term) factors that can affect soil penetrability are considered. For Southlake it was, thus, possible to estimate soil surface strength from the water table position. Linear regression was used to estimate the relationship between the two variables, and the estimated pattern of soil surface strength was shown to follow the observed pattern (Fig. 5). These data show the pattern of behaviour that is expected, being harder in the late summer, coming to their softest in the winter, and gradually hardening again during the summer, this pattern of behaviour being repeated for all the fields.

6. Estimation of surface flooding

The ecological requirements of some bird populations (which are often taken as critical indicators) requires the deliberate maintenance of partially flooded areas (Tickner and Evans, 1991). Although it is possible to calculate the form of the water table, either in two dimensions or in three (Youngs et al., 1989) and
so estimate the soil water regime at all locations within the field, a simpler alternative is to assume that the water table is approximately flat, and that the area of the field that is flooded is defined by the intersection of this modelled water table height and the cumulative distribution of heights. Data presented by Armstrong and Rose (1998a) demonstrate the essentially flat nature of the water table. The DITCH model, thus, simply takes the predicted water table height in the centre of the field, and then identifies the intersection of that height value with the cumulative frequency curve, to give an estimate of the extent of surface flooding in the field at any one time.

To implement this approach, it is essential to have some measure of the microtopographic roughness of the area modelled, ideally, as a cumulative frequency curve. Collection of these data requires measurement not only of the gross topographic features of the site, but also measurement of the microtopography. It was found that this information is best given by a series of closely measured transects, which give sample estimates for the whole field, rather than systematic surveys which tend to define only the macrotopographic features. Fig. 6 shows the cumulative distributions of surface heights for the six monitored fields in the Broads ESA. These are roughly Gaussian in their form, and so it is suggested that for more general application of the DITCH model, and in order to move away from the need to collect a large amount of topographic data, the cumulative frequency distribution could be replaced by its mean and standard.

The DITCH model, thus, includes a prediction of the area flooded by considering the intersection of the water table and the cumulative distribution of height. Unfortunately, it has not been possible to implement a scientific verification of the estimation of the extent of flooding, as there is no direct observation of this phenomenon. Nevertheless, the results do correspond with the subjective assessments of the site operators at both sites.
7. Use of the model to evaluate management options

The DITCH model thus produces information about soil water regime, soil surface strength, and flooded area. The model was then used to evaluate a number of alternative management options in these two areas.

7.1. Halvergate

The model was used to examine the effectiveness of the various tiers of management on the water regimes of the Halvergate soils. In the implementation of the DITCH model the predicted water tables and surface flooding conditions were plotted on one graph (Fig. 7). In addition, to aid interpretation, the basic hydrological variables of rainfall, evapotranspiration were plotted, and also the drainage fluxes which immediately identified periods of recharge and drainage.

The model was run for a 16 year period, from 1979 to 1994, using the observed values for the hydraulic conductivity from the Halvergate area. and adopting three different ditch water level regimes representative of the three tiers of management relating to the ESA prescriptions:

- Tier 1. Ditch levels at 1.5 m below ground level from 1 January to 30 March, at 1.0 m below ground level 1 April to 30 October, and at 1.5 m below ground level 1 November to 31 December.
- Tier 2. Ditch levels at 1.2 m below ground level from 1 January to 1 March (i.e., with 30 cm more water in the ditches than the comparable Tier 1 levels), rising to 45 cm below field level by 1 April, remaining
at 45 cm below ground level until 30 October, and thereafter at 1.2 m below field level.

- Tier 3: Water levels are held at mean field level from 1 January to 30 April; at 45 cm below field level from 1 May to 30 October, then rising to mean field level by 1 December, and remaining at that level until the end of the year.

The mean in-field water tables simulated by the model over the 16 year run of rainfall data whilst subject to the 3 different levels of management are shown in Fig. 8, for each water management option. These results show the dramatic effect on in-field water regimes that are created by the different tiers of management. In particular, the adoption of high water levels in the Tier 3 levels results in the water table fluctuating only in the upper, conductive, layers of the soil, so that the field and ditch levels are closely tied together. By contrast, where the ditch levels fall in summer, the zone of water movement becomes concentrated in the lower impermeable layers, and the field and ditch water levels become effective disconnected, as the soil is then unable to transmit sufficient water to maintain the water levels in the face of continuing evaporative demand.

7.2. Southlake

Lastly, the model was used to examine some of the effects of the water management prescriptions in the Somerset Levels and Moors ESA (Fig. 9). It was considered that the model had fitted the data sufficiently well to be used to identify the impacts of these various regimes on the water levels within the field. The model was thus used to simulate the water table under both Tier 3 and under ‘normal conditions’, i.e., unmodified by the current ESA agreements, and under the current Tier 2 levels. The model was then run to represent a 10 year period, to produce a sequence of water tables for the three conditions. The mean results for all three water regimes are shown in Fig. 10, and as soil strengths in Fig. 11.

For Southlake Moor, the model simulates a small but consistent raising of the water table under the Tier 3 regime, compared to either the Tier 2 or the ‘un-
altered’ regime, with the effect being greatest in the
spring and early summer. In the later part of the sum-
mer the effects of evapotranspiration become domi-
nant, reducing the effect the ditch levels have on the
field water table. Although the three tiers represent
three very different ways of managing the ditches,
the effects on the mean in-field water tables are thus
quite small. The dominant signal in the soil moisture
Fig. 9. Example application of the DITCH model to the Southlake area: ditch levels (---) and predicted water tables (solid line). To aid interpretation, rainfall, evapotranspiration and drainage fluxes are also shown.

Fig. 10. Mean water predicted for each of the three ditch management options.
regime is always the winter saturation and the summer period of drying out. However, the effect in the centre of the field in terms of changing from the ‘old regime’ (Regime 2 in Figs. 10 and 11) to the new Tier 3 regimes with raised water levels in the ditches, is to delay the start of the spring drying out phase by an average of 20 days.

8. Conclusions

This paper has shown that a hydrological budget model can be used effectively to estimate the soil water and ditch regimes where those ditch levels are being manipulated. The validation tests of the models using the two data sets suggest that the model offers a good representation of the system.

However, the results also show that the effects of ditch management options are not easily converted into impacts in the centre of the fields. The small impacts identified in Figs. 10 and 11 indicate that although the ditch regimes may alter, the effects in the centre of the fields are very much more subtle. Although these effects may seem small, they are concentrated at the critical time of the year both for plants and for bird life. Whether this effect is sufficient to achieve the required ecological objectives is the subject of on-going research. If the effects are not sufficient, then hydrological manipulation of sites to achieve or maintain wetland status may require more active intervention on the within-field regimes.

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