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Possible effects of proposed drainage improvements at Walmore Common SSSI Gloucestershire

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1 Background

Walmore Common SSSI (SO 745150) is an expanse of wet grassland occupying a flat-floored valley to the west of the River Severn downstream of Gloucester. Flooding during winter is a regular feature of the SSSI, which provides feeding and roosting grounds for Bewick swans. During the summer, ditch levels are kept high to supply water for cattle and for irrigation. Although Walmore Common is drained by a network of open ditches, some of impressive width, the length of the flooding period is determined by the rather restricted drainage outlet through an old culvert under the A48 trunk road, and into the river through a tidal flap.

The Internal Drainage Board has put forward a proposal to make a simple modification to the drainage pattern, which would allow water to escape through another culvert, taking advantage of this culvert's excess capacity. The intention is to reduce the period of flooding of land adjacent to the SSSI, where prolonged inundation in the winter of 1989-90 caused damage to the grass sward.

The Institute of Hydrology was approached by NCC to provide advice on the probable consequences of this drainage improvement on the water regime of the SSSI.

2 Geology and soils

The Keuper Marl of the area around Walmore Common has an undulating topography, with higher ground such as Chaxhill (SO 741146) and Lewis Hill (SO 745164) capped by the Tea Green Marl, the Rhaetic marls and the clays of the Lower Lias. The Walmore valley appears to have been an ancient channel of the River Severn, and there are extensive tracts of gravel of the Worcester Terrace of the Severn. An expanse of gravel, mantled by stagnogley soils, extends eastwards from Westbury-on-Severn, and appears in the Walmore valley as a salient of slightly higher ground dividing the two main peaty areas of the Common.

The soils of the Common are mapped at 1:250000 as Midelney Series. The Midelney is an alluvial soil that has developed by outwash of clay over peat, and it is certain that the upper horizons of much of the Common are clayey, suggesting a long history of seasonal inundation. However, there are areas of pure fen peat, notably the field immediately southwest of the barns at SO 740159, and it is possible that the peat is of considerable depth. The bowl-shaped form of the ground surface of Walmore Common, and the deep ditch that is necessary to carry the outflow, imply a degree of wastage and ground surface lowering, probably as a result of drainage operations in the 19th century. The soils of the Walmore catchment are slowly permeable pelosols and stagnogleys.

3 The drainage network

There are two main components to the drainage network at Walmore, high-level and low-level systems which may owe their inspiration to the drainage of the Fens, and were intended to handle the problem of flooding by dealing separately with flows from higher ground and from the Common itself (Figure 1). The greatest area of the Common drains towards a low-level ditch which enters a 1.2 m wide brick-lined culvert at SO 75321534, with an invert level at this point of 4.75 mOD. The culvert is about 160 m in length, and water emerges into the river through a modern tidal flap about 1 m in diameter, at an invert level of 4.864 mOD. It has been suggested that this culvert falls towards a sump which was part of a 19th century pumped drainage scheme: if so, siltation in the culvert would explain in part the present inefficient performance of the outlet.

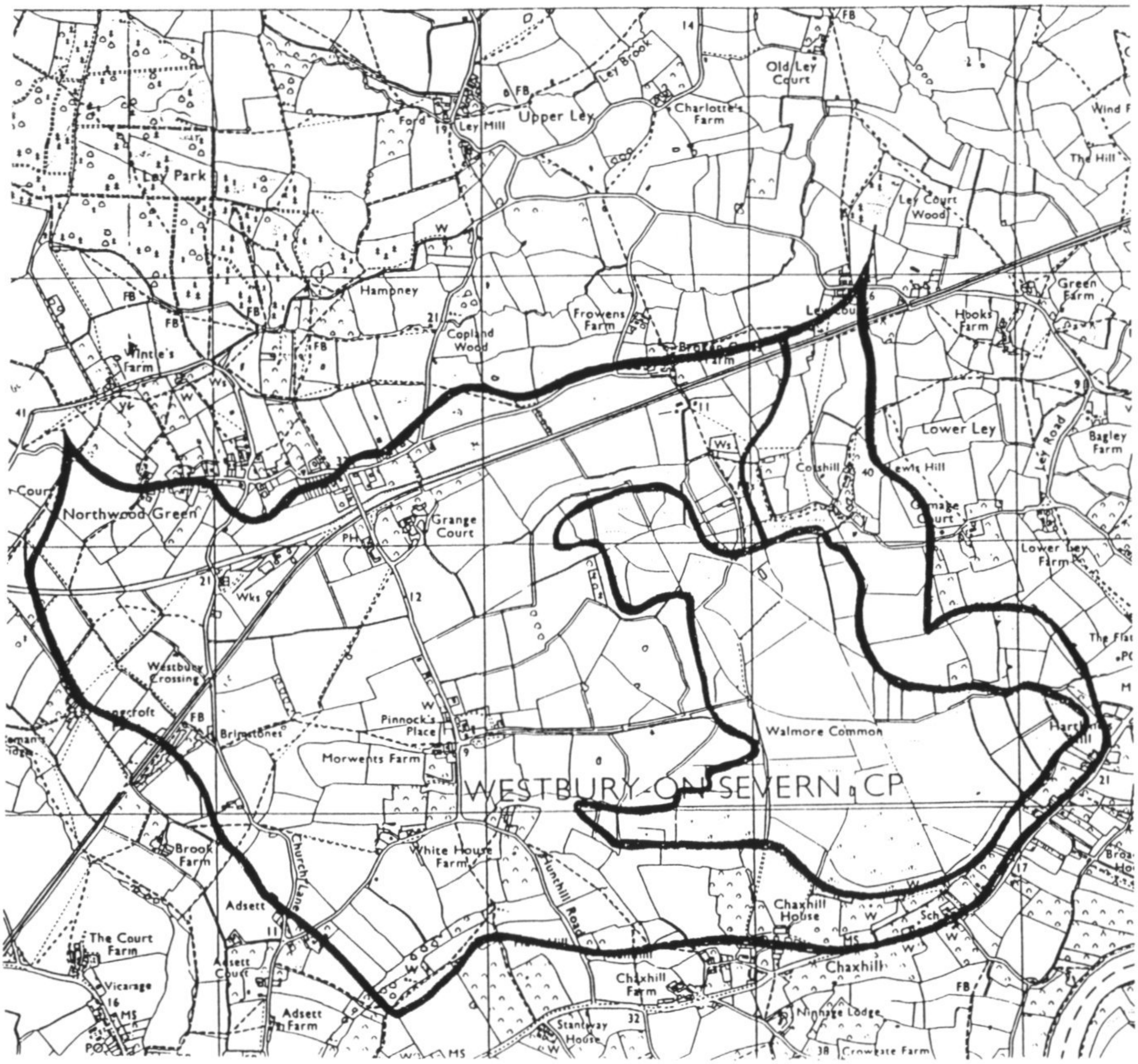


Figure 1 Location map of Walmore Common, showing catchment boundary and high- and low-level drainage systems. The 7.5 mOD contour is taken as a physiographic outline for the Common.

Upstream of the culvert, the drainage system appears to have grown organically by stages, and contains elements from several periods of activity. There are traces of an old, semi-natural and meandering channel, which was bypassed and cut off by newer works. The principal channel is now a straight, well-maintained east-west ditch extending right across the Common along grid line 150. This is crossed by another straight ditch running NNW-SSE. Laterals extend westwards as far as the higher ground forming the catchment boundary, and most field boundaries are associated with ditches. Although the system is well-maintained, the gradients are very low, and culverts under farm tracks and field entrances, mostly of 1 m or 1.2 m diameter compared with a ditch cross-sectional area of up to 5 m^2, must present obstacles to flow at the onset and end of flood conditions, when standing water is shallow and the ditch channels are the main means of evacuation. The sluice controlling summer water levels, which is fully open in winter, would offer little additional resistance to flow.

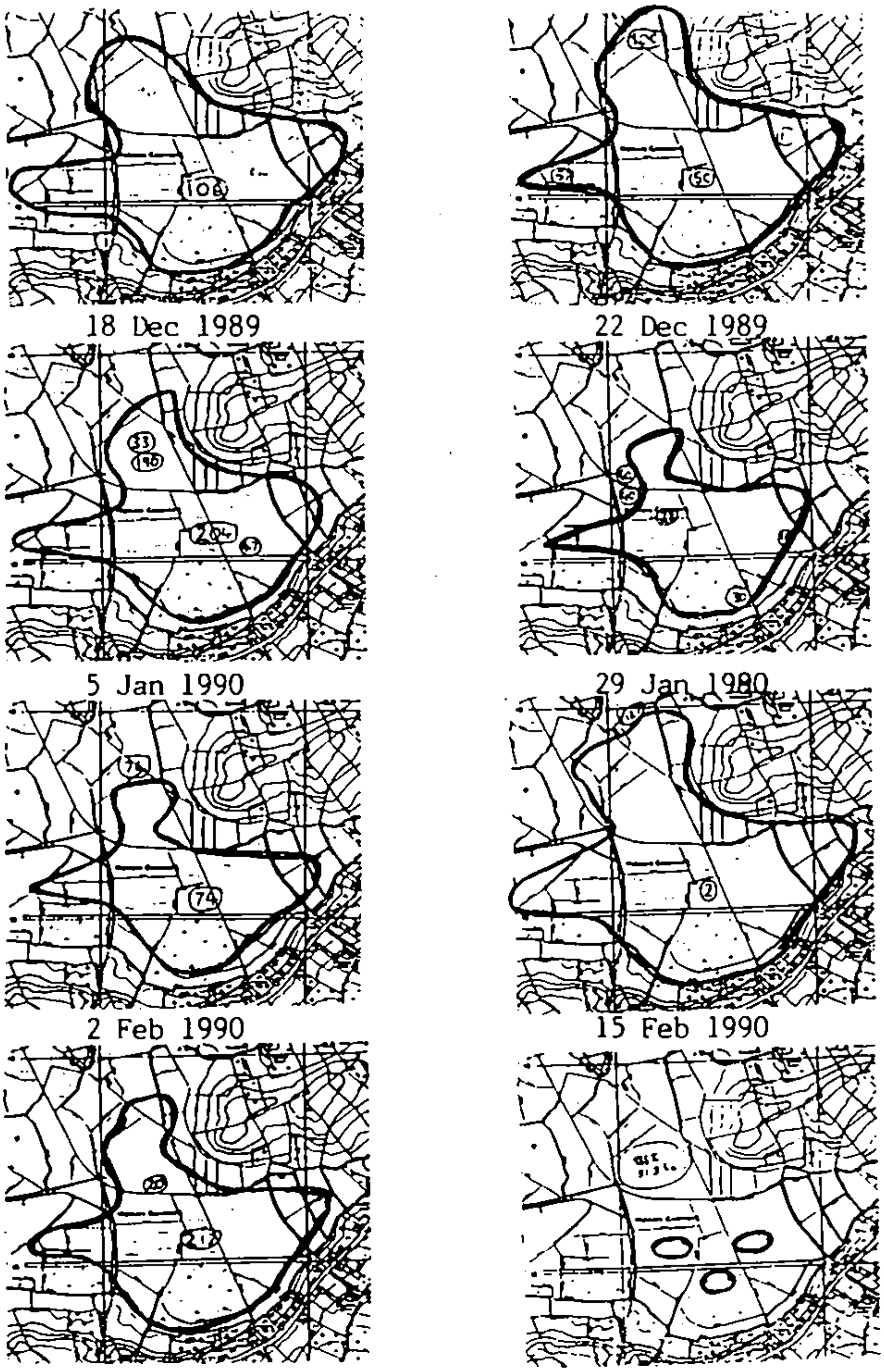
The high-level system skirts the northern edge of the Common, picking up runoff from fields on the Keuper Marl and the alluvium of the Severn First Terrace, and delivering it to a second culvert under the A48 road and the floodbank. The high-level drain was embanked well above the level of the land to the south, to prevent overspill adding to the problems of the Common, but the bank, generally between 8.5 and 9 mOD, has been allowed to subside in places, and is breached by field access tracks, for example at SO 744158, where spillage on to the Common would occur at 7.8 mOD.

The culvert carrying the high-level drain under the trunk road is shorter than that for the low-level drain, and consists of two segments 23 m and 43 m long. Its cross-sectional area is similar: where it is clearly in view in the garden of The Cottage (SO 75441534) it appears to be 1.2 m wide and about 2.4 m high, with a trapezoidal invert. At its upper end (SO 75421536) the invert level is 5.96 mOD, and the downstream segment emerges into the river through a modern tidal flap at 5.234 mOD.

The proposal by the West Gloucestershire IDB is to link the two systems by a short culvert with a flap valve, so as to take advantage of the spare capacity of the high-level drain when its short-term high flow has declined but the Common is still flooded. In this way evacuation from the Common would be less delayed. This is a simpler and less expensive, perhaps less hazardous, option than the reinstatement of the low-level culvert, which may well be in need of repair in addition to silt removal. The purpose of this report is to examine the effects that this linking drain might have on flooding on the SSSI, and for this purpose the only available quantitative records of flooding at Walmore, observations of flood extent in the winter of 1989-90, have been examined in depth.

4 Modelling the floods of 1989-90

In spite of the importance of the water regime of Walmore Common for wildlife, and of the number of livelihoods in the agricultural community affected by long periods of flooding, there is little or no available information on the frequency or extent of flood events. On visits to the Common between 1980 and 1990, staff of the Wildfowl & Wetlands Trust at Slimbridge have recorded flooding, sometimes extensive, each winter, but for analysis of the evacuation rates from the Common, we are dependent on a series of maps of the extent of flooding during the winter of 1989-90, reproduced as Figure 2. These maps were drawn by a Slimbridge observer from ground surface viewpoints, and may not indicate the precise limits of standing water, but the general shape of the water body does reflect the landform, as revealed by spot heights taken from aerial photographs by the National Rivers Authority (NRA), the basis for much of the interpretation that follows. Using the flood maps as an indicator of flood stage, and the NRA spot heights to compute the volume, it is possible to estimate the outflow from the Common, as one of the elements of a mathematical model, which simulates flood runoff from the catchment, storage on the Common, and outflow through the culverts.


18 Dec 1989

22 Dec 1989

5 Jan 1990

29 Jan 1990

2 Feb 1990

15 Feb 1990

22 Feb 1990

28 Feb 1990

Figure 2 Extent of flooding at Walmore in the winter of 1989-90

The inputs to Walmore Common in wet weather comprise direct rainfall on to the low-lying area, and flood runoff generated by rainfall on the higher ground around. Both high- and low-level drains receive runoff from the catchment, and in extreme conditions there will be spillage from the high-level system, but it is difficult if not impossible to simulate the interaction between the two systems with such a small resource of data. Outflow to the river depends on the relative levels of the ditches and the river, and of course on the resistance to flow offered by the culverts and flaps. Again, it is impossible to estimate this flow for a given hydraulic gradient without a great deal more information about the culverts, but it is possible to derive an estimate from the observed change in storage on the Common as the flood rises and recedes.

The prediction of the effects of changes in the drainage network depends on an accurate characterisation of conditions as they stand: if the flood response of the Common can be shown to depend in a simple way on known inputs of rainfall and on the river level, it may be possible to extend this model to cope with changes in the distribution of outflow from the Common. The water regime of hydrological systems is best characterised by mathematical models, which are a means of formalising the relationships between the various components of the water balance, and investigating the consequences of varying the parameters of the system.

The model requires estimates of the principal water balance components, either measured or determined from simple equations. Unknown parameters in the equations can be determined by the process of optimisation, in which the fit of the model to observed facts is improved by selection of parameter values.

4.1 Rainfall

Daily rainfall records were provided by the NRA for the period from January 1989 to October 1990, from a raingauge at Netheridge water reclamation works at SO 811157. Comparison with the long-term average monthly rainfalls shows that December 1989 and January and February 1990 were well above the average (Table 1).

Table 1 Monthly rainfall at Netheridge water reclamation works

Month	Long-term average	1989	1990
Jan	59.0	30.3	114.7
Feb	44.0	59.2	112.6
Mar	43.0	63.2	13.9
Apr	44.0	62.3	
May	57.0	25.6	
Jun	50.0	30.4	
Jul	51.0	41.5	
Aug	71.0	71.0	
Sep	59.0	57.0	
Oct	53.0	80.6	
Nov	69.0	48.8	
Dec	65.0	113.7	
Total	665.0	683.6	

The area of low-lying land was calculated by digitising the 7.5 mOD contour obtained from the NRA photographic survey (see Figure 1). This area (157 ha) was subtracted from the total catchment area of the low-level drain (596.2 ha) to give the area of the upper catchment responsible for flood runoff on to the Common. Daily figures for direct rainfall on to the Common were calculated using the 157 ha area.

4.2 Runoff from higher ground

The daily rainfalls were used to predict flows in the high- and low-level drainage networks, using methods set out in the UK Flood Studies Report (IH 1975)[1]. The Flood Studies Report (FSR) presents equations for the percentage runoff generated by a given rainfall, and for the time to peak of the flood hydrograph, given simple data about the catchment and a number of simplifying assumptions. The percentage runoff is given by equation 6.40 on page I-420 of the FSR:

$$\left(\frac{Q}{P}\right)\% = 0.22(\mathrm{CWI} - 125) + 0.10(P - 10) + 95.5\mathrm{SOIL} + 0.12\mathrm{URB}$$

where P is the total precipitation for a storm event

CWI is the catchment wetness index in mm, which is calculated from the soil moisture deficit. In the case of Walmore, the soil moisture deficit was effectively zero in winter 1989-90, and the catchment wetness index evaluates as 125 mm

SOIL is a quantity depending on the soil type in the catchment. For Walmore, **SOIL** is 0.45

URB is the percentage urban area in the catchment. Urban development is effectively zero in the Walmore catchment.

The equation simplifies to

$$\left(\frac{Q}{P}\right)\% = 0.1(P - 10) + 95.5 \times 0.45$$

When this equation was applied to eleven periods of rain between 11 December 1989 and 28 February 1990, the percentage runoff was predicted as an average of 45.4%, with a range from 42.1% to 53.3%.

Each of the eleven wet periods lasted several days, and the runoff was distributed in time according to unit hydrograph theory. The Flood Studies Report gives a method for deriving the response to an instantaneous rainfall input in the form of a unit hydrograph of triangular form, with a peak at a time T_p after the rainfall pulse, and a total length of 2.52 x T_p. The time to peak (FSR equation 6.18, page I-407) is estimated from the catchment characteristics, including mapped climatic factors, and for both high- and low-level catchments the result of the calculation is a time to peak of 22 hours. Taken on a daily basis, and regarding the daily rainfall (measured at 0900 GMT on the following day) as a pulse between 1900 and 2300 GMT, this is equivalent to assigning 16% of the runoff to the day of the rainfall, 68% to the second day, and 16% to the third day. If this rule is

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[1] IH (1975) Flood Studies Report, 5 vols, NERC (London).

applied to all the daily rainfalls and the calculated runoff estimates summed, the result is a daily estimate of runoff from the catchments into the Common ditch systems.

The Flood Studies Report, whose main objective was the prediction of flood peaks, did not concern itself with the slower percolation processes that maintain low flows in streams. The later Low Flow Studies report, concerned with drought flows sustained by deeper groundwater sources, also devoted limited attention to seepage under wet conditions. If 54.6% of rainfall does not run off directly, it must be lost to evaporation, add to the soil moisture store, or reach stream channels by throughflow in the soil. For the Walmore model, assuming that the soil moisture store was fully satisfied between December 1989 and February 1990, the rainfall that did not contribute to runoff, after subtraction of evaporation at the estimated potential rate, was added to the catchment runoff at a rate proportional to the 30-day moving average of rainfall. In this way the slow drainage through soils in the catchment was simulated. The choice of the 30-day period is somewhat arbitrary, but it is thought to give a reasonable estimate of winter baseflows in the ditches. For example, the total daily flow for day *i* into the low-level ditch system from higher ground within the catchment is

$$q_2(t_i) = 10A_2\left(\left(\frac{45.4}{100}\right)(0.16P(t_{i-2}) + 0.68P(t_{i-1}) + 0.16P(t_i)) + \left(\frac{54.6}{100}\right)\left(\frac{\sum_{j=0}^{29} P(t_{i-j})}{30} - E(t_i)\right)\right)$$

where A_2 is the catchment area

$P(t_i)$ is the rainfall for day t_i

and $E(t_i)$ is the potential evaporation rate.

The factor of 10 is for the conversion from mm x ha to cubic metres.

4.3 Storage of floodwaters

4.3.1 High-level drain

The level of water in the high-level ditch is controlled by the quantities of water flowing in and out: as the level rises, the rate of flow out to the river increases until inflow and outflow are equal, at the peak of the ditch stage hydrograph. At very high stages, above about 7.8 mOD, there may be overspill on to the Common.

The high-level ditch has little flood capacity, when compared with the area of the Common served by the low-level drain, and it is difficult to construct a stable model which will simulate flow and storage within the high-level system. For this reason, it has not been possible to make predictions of overspill, or of the water level in the high-level drain. The possible role of the high-level drain in evacuating the Common after construction of a link between the two systems will be considered in a later section of this report. For the purposes of the model, the two ditch systems were assumed to be distinct.

4.3.2 The Common and the low-level drain

The quantity of floodwater on the Common may be characterised in three ways: as a water level h_2, as an area covered A_2, and as a volume V_2. It is assumed, fo lack of better information, that the flood stage h_2 is uniform across the Common. The information available is in the form of maps of the open water area on eight occasions in the winter of 1989-90. These maps were digitised to give a sequence of areas in hectares (Table 2).

Table 2 Approximate areas of flooding, winter 1989-90

Date	Area flooded, ha
18 Dec 89	95.6
22 Dec 89	96.6
5 Jan 90	77.5
29 Jan 90	54.7
2 Feb 90	57.9
15 Feb 90	112.2
22 Feb 90	77.1
28 Feb 90	3.0

The mathematical model generates values of the total volume of floodwater. For comparison of the model with observations, it is necessary to have a relationship between area and volume, while for the model to compute the outflow through the culvert, there must be a relationship between volume and stage. These relationships have been established in polynomial form using a linear regression method.

The NRA maps, six in all at a scale of 1:2500, contained contours and spot heights, determined to an accuracy of 0.1 to 0.2 m. For each hectare (100 x 100 m) square of the Common, an average ground elevation was estimated from both contours and spot heights. For stage values ranging from 6.2 mOD to 10 mOD in intervals of 0.1 m, the number of hectare squares with average elevations below the given stage was tabulated. For each stage, the volume of water contained in a body of standing water at that stage was calculated by simple summation, e.g. for a stage of 6.4 mOD, the volume in Ml (1 Ml = 1000 cu.m) would be

$$V_2 = \frac{1}{100}\sum(6.4 - h_g)$$

where the summation is over all squares for which the ground level h_g is less than 6.4

Polynomial relationships were calculated for volume V_2 as a function of area A_2 (correlation coefficient $r^2 = 99.67\%$), and for stage h_2 as a function of V_2. For the latter, a better fit ($r^2 = 99.96\%$) was obtained for h_2 as a function of $\ln(V_2 + 1)$. The equations are

$$V_2 = 4.855A_2 - 0.0325A_2^2 + 0.000273A_2^3$$

and

$$h_2 = 6.212 - 0.1435\ln(V_2 + 1) + 0.1396(\ln(V_2 + 1))^2 - 0.0300(\ln(V_2 + 1))^3 + 0.00241(\ln(V_2 + 1))^4$$

Figures 3 and 4 show the relationships in graphical form.

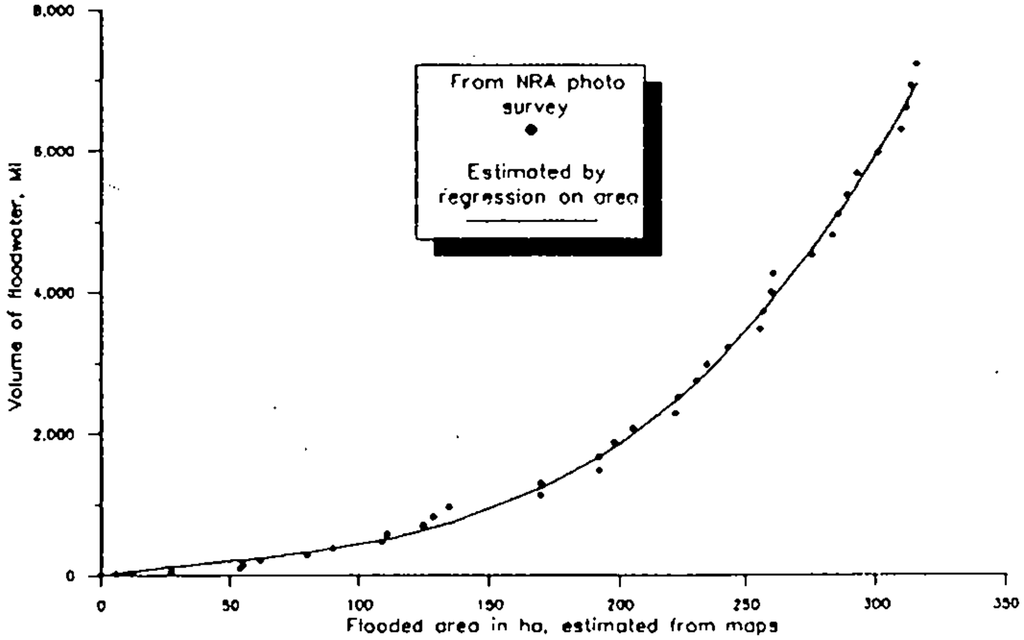

Figure 3 Relationship between flooded area and volume

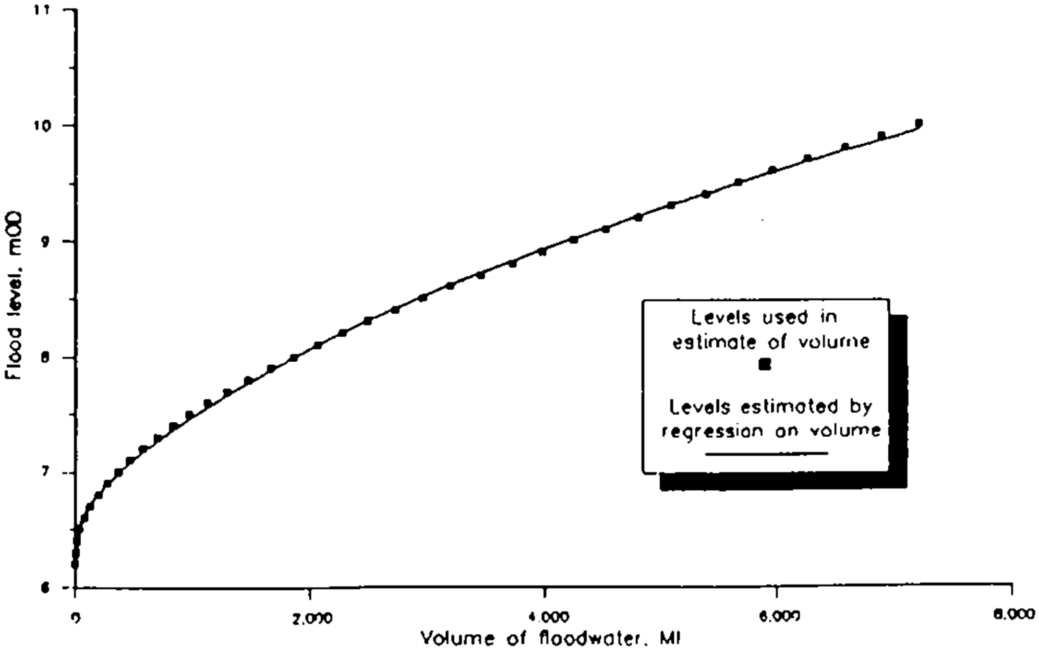

Figure 4 Relationship between volume and stage

Table 3 shows the values of total volume of floodwaters computed from the area of open water, using the cubic polynomial above.

Table 3 Volume of floodwaters, winter 1989-90

Date	Area of flood ha	Volume of floodwater Ml
18 Dec 89	95.6	406.4
22 Dec 89	96.6	412.6
5 Jan 90	77.5	308.6
29 Jan 90	54.7	213.2
2 Feb 90	57.9	225.3
15 Feb 90	112.2	522.3
22 Feb 90	77.1	306.7
28 Feb 90	3.0	14.3

4.4 Outflow to the river

The outflow from the low-level culvert is computed as the product of a multiplying factor α and the square root of the difference in water levels between the ditch network and the river.

River level is measured continuously by a bubbler gauge at Minsterworth, upstream of Walmore, and the records from this gauge, between 8 December 1989 and 28 February 1990, were digitised at one-hour intervals for the purpose of this report. Records for a gap of one week in early February 1990 were synthesised by linear interpolation. The river level varies widely in response to flood events and tides: the mean daily stage varied between 4.82 mOD and 8.01 mOD over this period, with a daily range of up to 3.15 m. The choice of a suitable river level for the computation of the outflow was difficult, but a compromise solution was adopted, in which an effective level midway between the daily mean and the daily minimum was selected. This choice takes account of the fact that the steep rise towards high tide, which in extreme conditions leads to the Severn Bore, is followed by a slightly less steep fall, and low stage values dominate each tidal cycle.

The river level at Walmore is slightly lower than that at Minsterworth. No information on the gradient of the river was available, so the fall between Minsterworth and Walmore, denoted by Δ was included as the second parameter for optimisation in the mathematical model.

The outflow was calculated for each day as

$$q_4 = \alpha\sqrt{h_2 - (h_{river} - \Delta)}$$

where h_2 is the level in the low-level drainage system
and h_{river} is the effective river level as defined above.

4.5 Simulation of flooding at Walmore

For each day, the model calculates the volume of floodwater in Ml from values of inflows, storage and outflows for the previous day

$$V_2(t_i) = V_2(t_{i-1}) + 0.001(157 \times 10(P(t_{i-1}) - E(t_{i-1})) + q_2(t_{i-1}) - q_4(t_{i-1}))$$

where q_2 is the flow from the low-level catchment
and q_4 is the outflow through the low-level culvert

The parameters α and Δ, implicit in the value of $\dot{q}_4$, must be optimised: the model was run with selected values of these two parameters, to minimise the objective function, the sum of squares of differences between observed and simulated flood volumes.

The optimised values of α and Δ, with 95% confidence limits, are:

$$\alpha = 52000 \pm 14000$$
$$\Delta = 0.38 \pm 0.08$$

With these values of the parameters, the maximum evacuation rate is 61000 cu.m/d, and the maximum flood volume matches closely the extent of flooding observed on 15 February 1990 (Figure 5). The model predicts complete drainage of the floodwaters during January 1990: although this is unsupported by flood extent data for this period, it is plausible in view of the comment by the Slimbridge observer that flood levels were dropping on 5 January 1990.

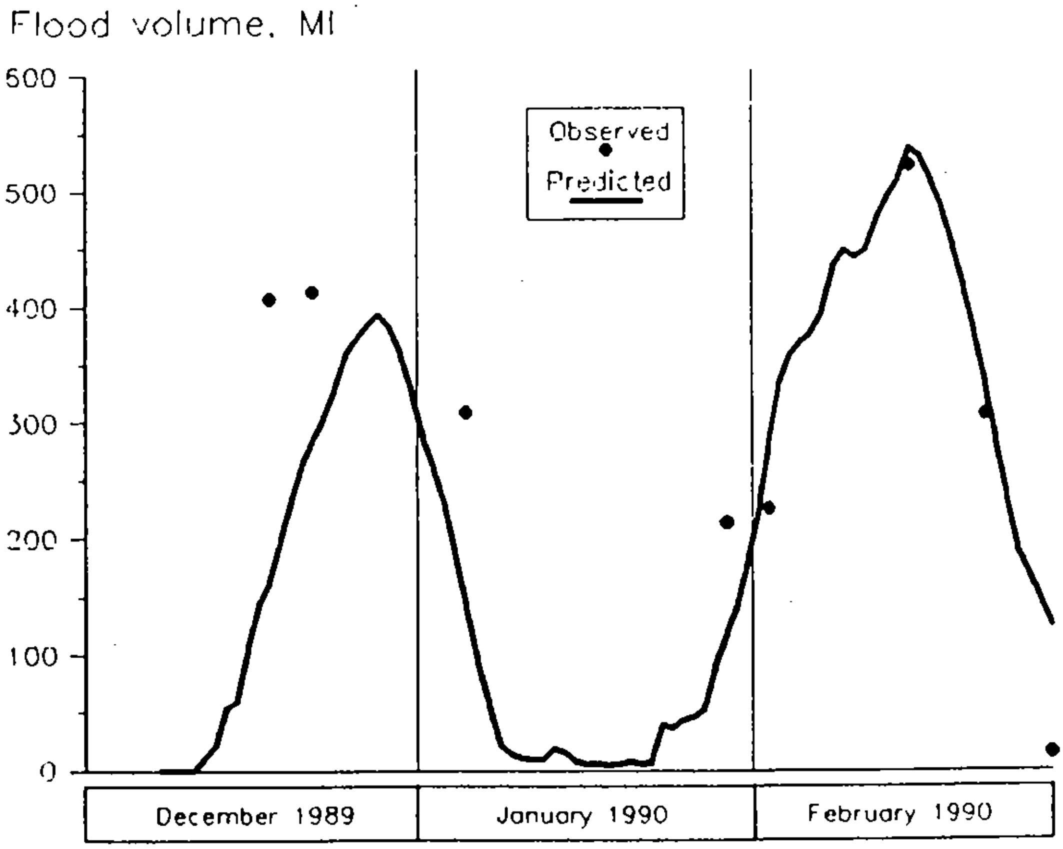

Figure 5 Predicted flood volumes, Dec 89 - Feb 90

It became clear from the results of using other parameter values that flood volumes, and the rate of rise of floodwaters, are chiefly controlled by the quantity of rainfall, but the recession of the flood is sensitive to the choice of the parameters. In particular the length of the two main flooding episodes during winter 1989-90 depends on the parameter α, which controls the evacuation rate. Figure 6 shows the results of taking values of α of 25000 and 100000.

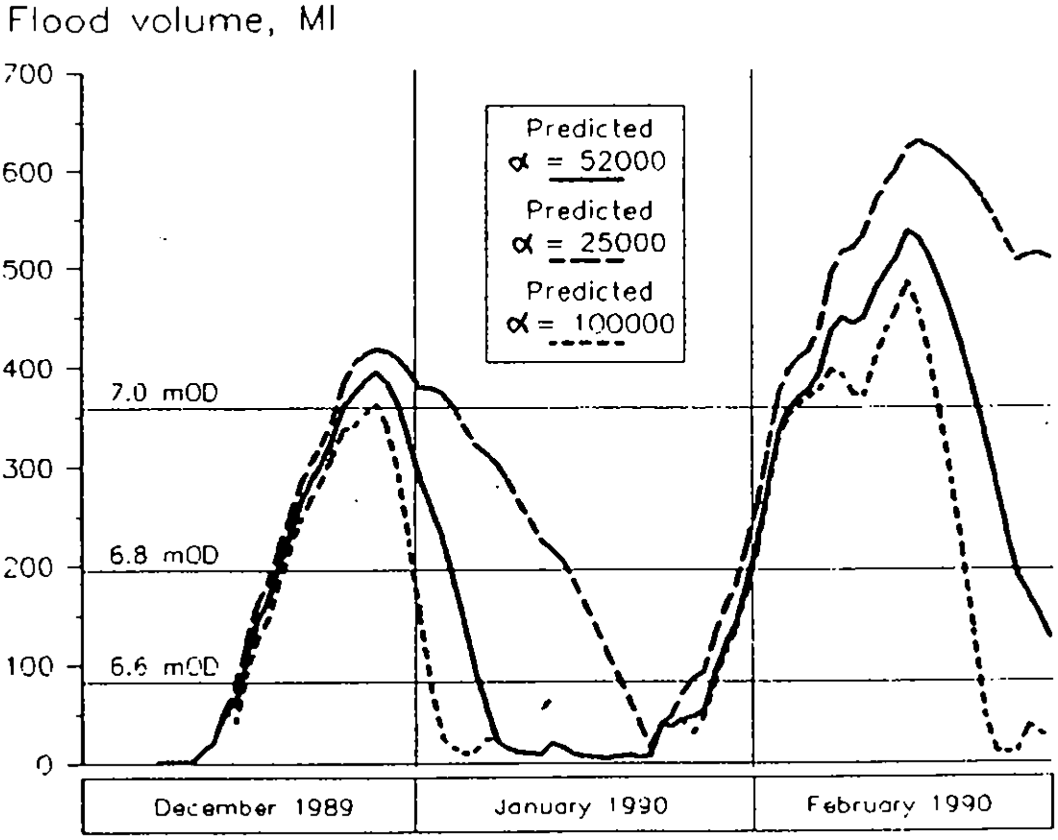

Figure 6 Flood volumes predicted for other values of α

5 Probable effects of modifications to the drainage

The model has been calibrated to give predictions of the flood volumes during three months of the winter of 1989-90, without linkage between the high-level and low-level systems. The installation of a linking drain between the high- and low-level drains would increase the rate of evacuation under the following conditions:

(i) flood level on the Common above 6.5 mOD. The link would be controlled by a tidal flap which would prevent flow from the high-level system.

(ii) water level in the high-level drain below that on the Common. This condition may be satisfied on the recession limb of the hydrograph, owing to the more efficient culvert of the high-level drain, and to the small capacity of the system.

(iii) the effective water level in the River Severn below that on the Common. The 1989-90 floods demonstrated that river level is an important factor in retaining water on the Common. Figure 6 demonstrates that a much more efficient culvert on the low-level system would have little effect on maximum flood levels, but would shorten the period of flooding by hastening the recession, provided that river levels were sufficiently low for gravity drainage.

Figure 7 shows the significance of water levels in the high-level drain and the river. Although the high-level stage could not be predicted, it is possible to conclude from the calculated inputs to the high-level system that its stage would be high on the onset of flooding, but would reduce after the rainfall period. The high correlation between River Severn levels and flood runoff on to the Common shows up well, adding emphasis to the conclusion that improvements to the gravity drainage of Walmore would have a limited effect on flooding.

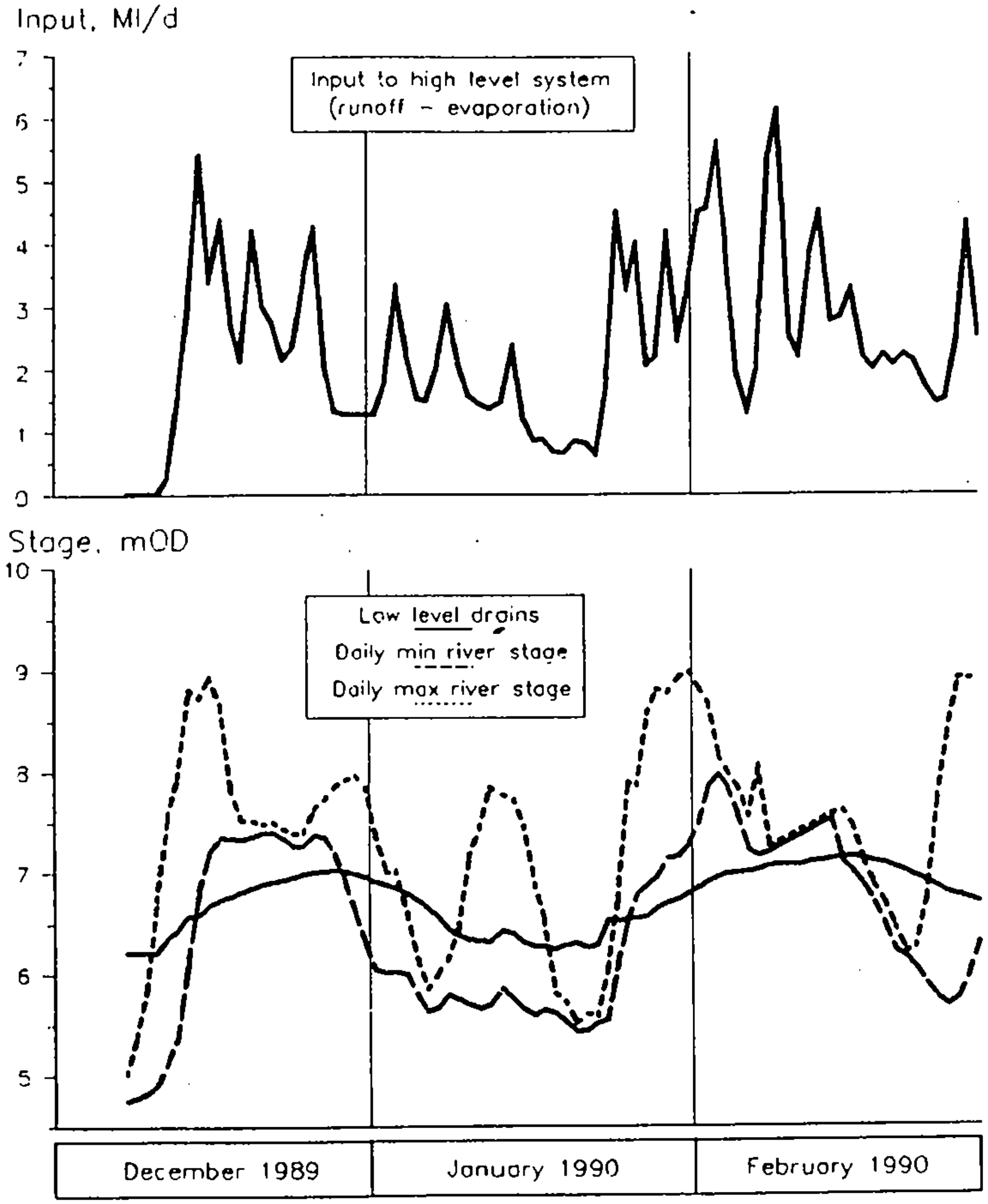

Figure 7 Comparison of predicted flood stage, river level and the input to the high-level system.

The effects of a link were simulated by incorporating an additional outflow into the model. This additional outflow was assumed to be proportional to the root of the difference between flood level and the sill level of 6.5 mOD, or between flood level and effective river level when this was higher than 6.5 mOD. The constant of proportionality was given values of α (Case 1) and 2 α (Case 2), corresponding roughly to a doubling and tripling respectively of the evacuation rate from the Common under the favourable conditions outlined above. The predicted flood levels are shown in Figure 8.

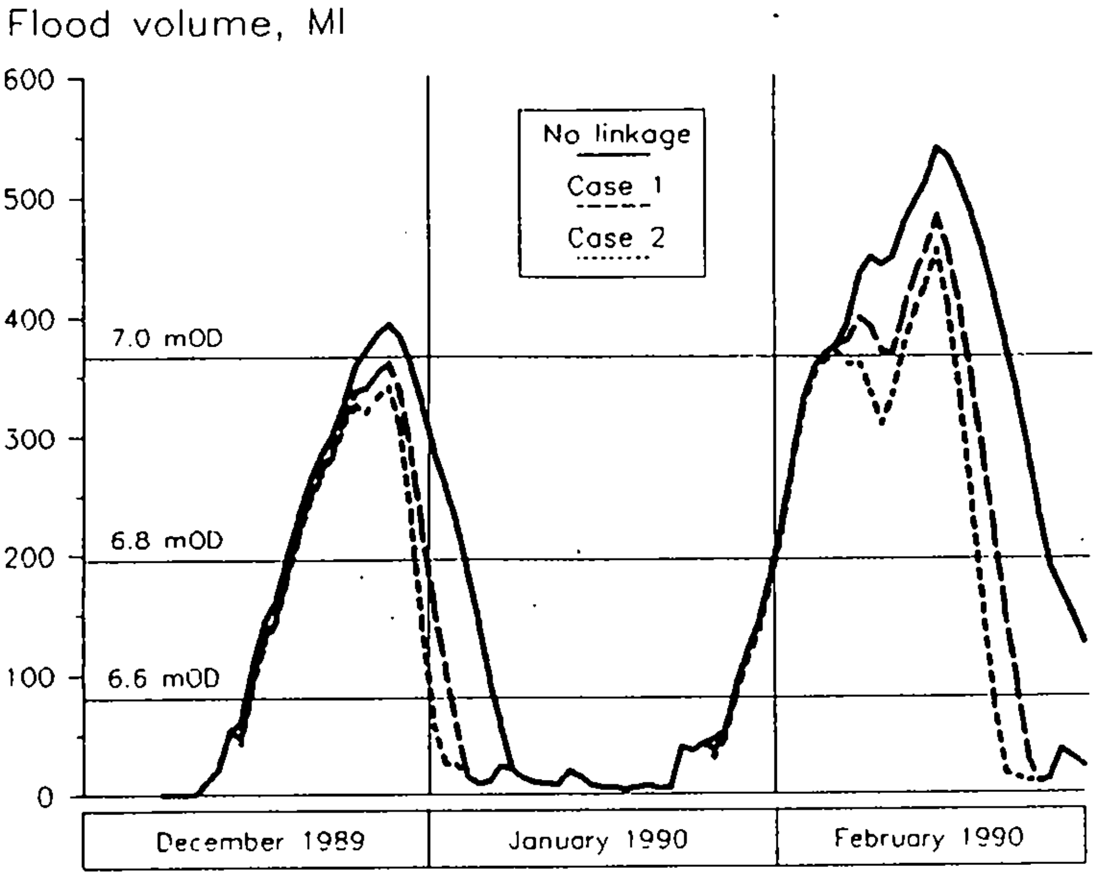

Figure 8 Predicted flood levels with linkage of high- and low-level systems.

6 Conclusions and recommendations

The observed extent of floodwaters on Walmore Common during the winter of 1989-90 has been used to determine the flood evacuation rate from the Common with the present drainage outlet. It has been demonstrated that, while the length of the recession would be altered if the evacuation rate were improved, the river level exerts a strong controlling influence on the rate of outflow from the Common during rising and peak flood levels, and hence that there is a limited return to be expected from improvement to the gravity drainage of the site.

Flooding on the Common may be quantified by considering the duration of levels above 6.6 mOD, 6.8 mOD etc. Table 4 shows the lengths of flooding periods for a range of values of the parameter α , and should be examined in conjunction with Figure 7. The effect of a twofold increase in α from its optimised value would be a 22% decrease in the period of flooding over 6.6 mOD, when more than 54 ha would be covered, and a 57% decrease in the period of flooding over 7.0 mOD (90 ha). This gives some indication of the change in the flooding regime to be expected if the low-level culvert were restored to full capacity.

Table 4 Effect on flooding period of varying evacuation rate

Stage	α = 52000 (optimised)	α = 25000	α = 100000
> 6.6 mOD	54 days	68 days	42 days
> 6.8 mOD	40	56	32
> 7.0 mOD	21	36	12

The installation of a link between the two drainage systems, to take advantage of the spare capacity of the high-level culvert, would have a similar effect, as indicated by Table 5 and Figure 8. The rather scant reduction in flooding periods at low to moderate levels that would reward a doubling in the capacity of the linking culvert should be noted.

Table 5 Effect on flooding period of linking drainage systems

Stage	No linkage	Case 1	Case 2
> 6.6 mOD	54 days	43 days	39 days
> 6.8 mOD	40	32	29
> 7.0 mOD	21	13	6

It should be noted that the amount of improvement ultimately possible is limited: Case 2 offers a substantial increase in the evacuation rate, but the reduction in flooding time at low to moderate levels is entirely as a result of the steepening of the recession limb of the stage hydrograph. It is unlikely, given that river stage is the ultimate control on the evacuation rate, that the 6.8 mOD flooding period in 1989-90 could have been reduced much below 28 days.

While it has been possible to draw conclusions from the rather scarce data available, the confidence that could be placed in predictions of flooding at Walmore would have been increased greatly by more hard quantitative information. In particular, it is essential for the proper supervision of the SSSI that flood levels are recorded over future flooding episodes, and a database should built up to characterise the flooding regime as it now exists, as a background against which possible future changes could be assessed. As a bare minimum, a staff gauge extending at least to 7.5 mOD should be installed at an accessible place in the southern part of the Common, to be read weekly during flood events.

It is possible that flooding problems in the north of the Common, outside the SSSI, are being exacerbated by spillage from the high-level drain. The embankment south of the drain should be examined, particularly where it is crossed by field access tracks, and the condition of the drain and its culverts should be subjected to scrutiny, with a view to minor works which could both improve the carrying capacity of the drain and limit its interaction with the low-level system.