

An assessment of the impact of floodplain woodland on flood flows

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Abstract

This paper examines the potential role of floodplain woodland in flood alleviation. In theory, the presence of trees and associated woody debris on the floodplain increases the hydraulic roughness, thus slowing down flood flows and enhancing flood storage. One and two-dimensional models were used to simulate a 2.2 km reach of river in south-west England to test this theory for a 1 in 100 year flood using appropriate roughness parameters. Both models predicted a reduction in water velocity within the woodland, increasing water level by up to 270 mm and creating a backwater effect that extended nearly 400 m upstream. Flood storage increased by 15 and 71%, while flood peak travel time was increased by 30 and 140 min for the two scenarios simulated. The results suggest that there is considerable scope for using strategically placed floodplain woodland to alleviate downstream flooding. In particular, it offers a means of tackling the increased flood risk associated with climate change.

Introduction

Recent flooding events imply that storm-generated river flow peaks are increasing in magnitude and frequency. This is in line with the climate change prediction for an increase in the quantity of winter rainfall across much of the British Isles. Consequently, there are major concerns about existing levels of flood defence and the management of future flood risk.

The increasing cost of providing adequate hard-engineered defences, combined with their low ecological and aesthetic value, has led to greater attention being given to the use of alternative, softer engineering techniques. These are based on the principle of impeding run-off from the land and river flows following an extreme rainfall event by providing areas of semi-permanent or permanent wetland to store floodwater and delay the downstream passage of the flood peak. A range of options are currently being considered including the creation of washlands, river corridor widening and river restoration (Defra 2004).

The use of floodplain woodland as a soft-engineered aid to flood control has been discussed for a number of years (Kerr & Nisbet 1996). Some flood defence engineers have argued that floodplain woodland would only be able to exert a small effect on flood flows, while others have

expressed concern that any backing-up of floodwaters could adversely affect local properties. The high degree of uncertainty associated with these and other potential impacts has precluded any significant floodplain woodland planting to date.

In addition to the potential advantages for flood control, floodplain woodland offers a wide range of other benefits including improvements to water quality, nature conservation, fisheries, recreation and landscape (Kerr & Nisbet 1996). Natural floodplain woodland represents a very valuable, essentially lost habitat in the United Kingdom (Peterken & Hughes 1995).

The main mechanism whereby floodplain woodland could aid flood defence is by slowing the downstream passage of a flood peak, resulting in a lower but longer-duration event (Fig. 1). Floodplain woodland is thought to have naturally carried out this role in the past, and its historic removal may have contributed to an increase in flooding severity. The delaying effect on flood flows is mainly due to the contribution of vegetation roughness. The nature of the vegetation is important because of the type of frictional effects it has. Thus, trees create more of a physical barrier than bushes because the latter can flatten during high flows whereas trees do not. The spacing and layout of trees, smoothness of trunks, presence of lower

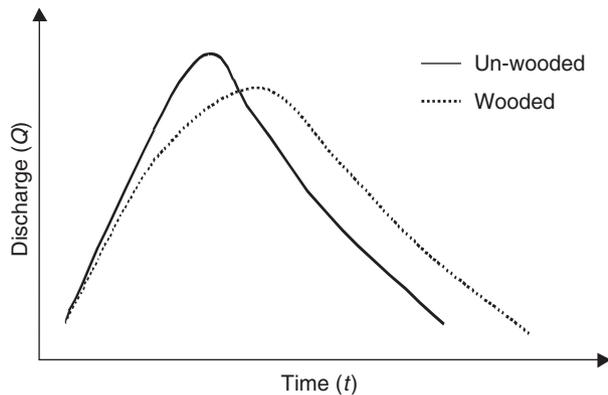


Fig. 1. Theoretical time discharge hydrograph showing the possible effect of floodplain woodland on flood flows (Q , discharge; t , time).

branches, level of undergrowth and amount of dead wood on the woodland floor all have an effect. By varying these factors, woodland management and design can exert a strong influence on woodland roughness and thus on the capacity of floodplain woodland to impede flood flows.

As there will be a long time lag between the planting of floodplain woodland and any significant effect on flood flows, there is an urgent need for research to quantify the effectiveness of floodplain woodland as a mechanism of flood defence. In particular, information is required about the actual flood storage potential of floodplain woodland, the extent to which woodland could retard different-sized flood peaks, and how any flood attenuation effect could be maximised through woodland design, including location, shape, size, stocking density, age structure and species choice. The rarity of floodplain woodland in the United Kingdom and the lack of hydrological data means that research must first focus on hydraulic modelling. This paper describes the results of initial work aimed at quantifying the hydraulic effects of establishing a floodplain woodland at a test site in south-west England.

Channel and floodplain modelling

Models of river flooding are primarily based on hydraulics, representing water flow both within the channel and on the floodplain. Most hydraulic models require the parameterisation of separate roughness factors for each of these pathways. A storm hydrograph is usually taken as the input and routed downstream through the modelled reach. The hydrograph may be derived through direct flow measurement or generated by catchment rainfall-runoff models.

Traditional one-dimensional (1D) models have been used to investigate river flooding by performing a series of 1D hydraulic calculations for steady or unsteady flow

conditions for a range of channels. These use a 1D resistance formula, which is usually calibrated by adjusting the roughness coefficient until the model output reproduces the observed hydraulic behaviour of the reach as accurately as possible. However, this process of calibration lumps together several resistance effects such as skin friction and form roughness, turbulence and multidimensional flows into a single term. Consequently, they are less suitable for dealing with floodplains where there is complex surface topography and variation in vegetation structure.

Two-dimensional (2D) hydraulic models were first developed and applied to flows in estuaries (Beffa & Connell 2001) and are currently at the forefront of research into river flood modelling. They represent a significant advancement on 1D models in being able to predict certain aspects of out-of-bank flows. The fundamental physics of all 2D models is more or less common. They solve the basic mass conservation equation and two components of momentum conservation. The main model outputs are two water velocity components and a vertical water depth for each point or node. Water velocity is assumed to be uniform with depth, while water pressure is hydrostatic.

The main factor limiting the application of 2D models until recently has been a lack of detailed spatially distributed data. However, such data are becoming increasingly available from satellite imagery and airborne remote-sensing techniques such as synthetic aperture radar (SAR) and airborne scanning laser altimetry (LIDAR). Apart from providing spatial topographical data for the channel and floodplain, LIDAR can be used to obtain vegetation height data for the parameterisation of model friction.

A number of studies have shown that 2D models are capable of accurately predicting both flood extent and flood wave travel times using independent calibration data from hydrometric and satellite sources (Bates *et al.* 1992, 1997; Bates & Roo 2000; Horritt & Bates 2002). These models are thought to offer considerable scope for investigating the effects of vegetation roughness on floodplain flows.

Channel and floodplain roughness

The principal effect of floodplain vegetation is to increase surface roughness. Modelling techniques in the past have treated vegetation in open channels and on floodplains as an additional flow resistance to be added to the bed roughness. The presence of submerged or non-submerged vegetation along riverbanks and/or across floodplains has often been found to be the largest source of resistance.

A roughness coefficient is used to represent the energy lost from flowing water due to channel roughness. One of the most commonly applied uniform-flow formulae for open-channel computations is Manning's formula, owing to its simplicity and the satisfactory results that have been achieved in practical applications. The selection of an appropriate value for the Manning's roughness coefficient (n) is crucial to the accuracy of the computed hydraulic parameters. The value of Manning's n is highly variable and depends on several factors including surface roughness, vegetation, channel irregularities, channel alignment, scour and deposition, obstructions, size and shape of the channel, stage and discharge, seasonal changes, water temperature, and suspended material and bedload.

Details of 1D and 2D hydraulic modelling software

The 1D Hydraulic Engineering Centre-River Analysis System (HEC-RAS) and the River2D hydraulic models were selected to explore the potential effects of floodplain woodland on flood flows. This was based on their capabilities to model flood flows and the fact that they are commonly applied in flood flow simulation studies.

Problems in floodplain hydraulics require the prediction of flows over complicated topography. 1D models using a network of channels are suitable in some respects, but do not allow a consideration of changes in the direction of water flow at a point. 2D models calculate changes in the direction of flow as part of the solution. Evaluation of 1D and 2D models for predicting river flood inundation has shown that both 1D and 2D models are capable of predicting flood extent and travel times to similar levels of accuracy at optimum calibration (Horritt & Bates 2002).

HEC-RAS

The US Army Corps of Engineers developed HEC-RAS, which is an integrated system of software containing three 1D hydraulic analysis components designed for steady flow, water surface profile computations, unsteady flow simulation, and moveable boundary, sedimentary transport computations (www.hec.usace.army.mil). It is able to perform 1D hydraulic calculations for a single river reach, a dendritic system, or a full network of natural and constructed channels. The steady flow, water surface profile component accommodates the effects of gradually varied flows and is capable of modelling subcritical, supercritical and mixed flow conditions.

The underlying computational procedure is based on the solution of the 1D energy equation. Energy losses are evaluated by friction (Manning's equation) and contrac-

tion/expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilised in situations where the water surface profile is rapidly varied. Allowance can also be made for the effects of various obstructions such as bridges, culverts, weirs, spillways and other channel and floodplain structures. The model is widely used by flood defence engineers in the United Kingdom.

River2D model

The River2D model is a 2D, depth-averaged finite element model developed by the University of Alberta, USA. It is based on a conservative Petrov–Galerkin upwinding formulation and intended for use on natural streams and rivers, with special features for accommodating supercritical and subcritical flow transitions and a variable wetted area. Although it is basically a transient model, it provides an accelerated convergence to steady-state conditions. The model has been verified through a number of comparisons with theoretical and field results (Ghanem *et al.* 1995; Waddle *et al.* 1996).

The River2D model uses an equivalent roughness parameter ' k_s ' to represent frictional energy losses. Equivalent roughness, sometimes referred to as 'roughness height', is a measure of the linear dimension of the roughness elements, but is not necessarily equal to, or even the average of, the actual height of these elements. For example, two roughness elements with different linear dimensions may have the same value of k due to differences in shape and orientation (Chow 1959).

The advantage of using the equivalent roughness k_s instead of Manning's n is that k_s better reflects changes in the friction factor due to stage. The equivalent roughness can be converted to Manning's n and vice versa (Steffler & Blackburn 2002).

Case study – Parrett Catchment

Background

The River Parrett is 59 km long and its main tributaries include the Rivers Tone, Isle, Yeo and Cary. It drains an area of over 1690 km², comprising around 50% of the land area of Somerset (Fig. 2). Land use is predominantly agricultural. The River Parrett is one of a number of major river systems in the country facing a serious and recurrent flooding problem. It is the location of a major study, the Parrett Catchment Project, to formulate a strategy and integrated catchment plan for improving flood management. A key objective of the strategy is to explore how new woodland could help to alleviate downstream flooding in towns and villages, including Bridgwater.

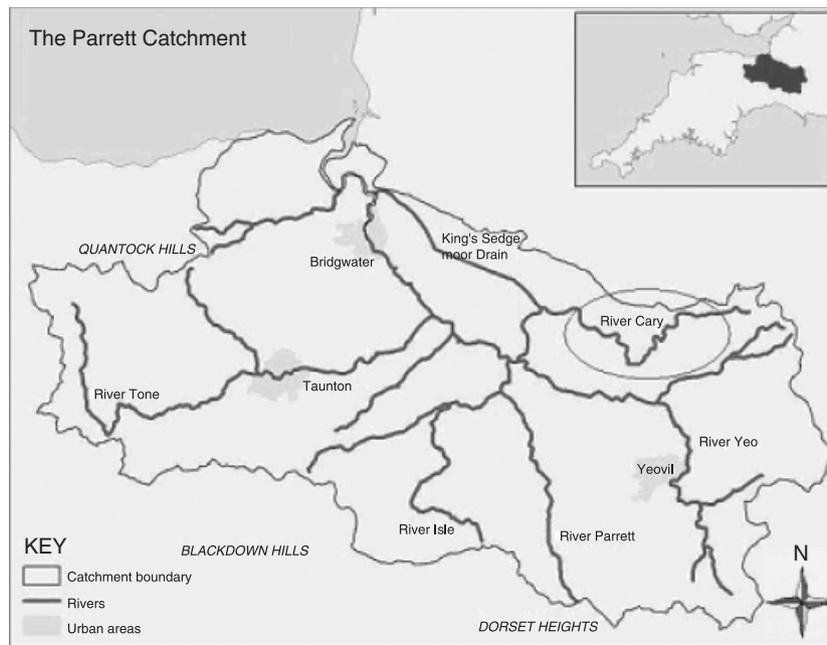


Fig. 2. Location of the River Parrett Catchment and location of River Cary.

Study reach

A reach on the River Cary, 300 m upstream of the Environment Agency's gauging station at Somerton (NGR ST 498 291), was chosen as the study site. This was one of a number of areas in the Parrett Catchment identified as being potentially suitable for floodplain woodland restoration (Nisbet & Broadmeadow 2003). The modelled river reach extends for approximately 2.2 km and has the potential to be completely wooded.

The catchment area to the gauging station is 82.4 km² and the highest recorded flow since the gauging station opened in 1965 is 13.65 m³/s. The estimated 1 in 100 year flood or 1% annual probability event (a.p.e.) is 15.2 m³/s, which defined the inflow boundary condition for the model simulations. Topographic data for the study reach were obtained from the Environment Agency in the form of 2 m resolution LIDAR data and 10 surveyed cross sections of the channel. The channel is approximately 16 m wide and 2 m deep. The potential flooded area extends mostly over the northern bank of the river, reaching a maximum width of approximately 400 m.

Model simulations

Three contrasting scenarios were considered for the 1 in 100 year flood model simulations:

Scenario 1

This scenario represents the existing situation, with the floodplain covered by pasture. A Manning's n of 0.04 was



Fig. 3. Typical woodland type that would give a Manning's n roughness of 0.15 during a flood with a water depth of 1.25 m.

used for the channel, representing the average roughness for a clean, winding channel with some pools and shoals. A floodplain Manning's n of 0.035 was used to represent pasture with high grass and/or cultivated areas with row crops.

Scenario 2

The vegetation on the wider northern bank of the floodplain was changed in this scenario to a complete cover of thick broadleaved woodland. A Manning's n of 0.15 (and a k_s of approximately 3 m) was selected for this type of woodland (Acement & Schneider 1990), a typical example of which is shown in Fig. 3.

Scenario 3

For this scenario, a 500 m length section in the centre of the floodplain was covered by a 50 ha block of woodland of the same nature as in Scenario 2 (Manning’s n of 0.15, k_s of approximately 3 m). This scenario allowed both the upstream and downstream impact of the woodland to be evaluated.

For all model scenarios, the 1D HEC-RAS used the channel geometry obtained from the surveyed channel cross sections, while the floodplain topographic transects were interpolated from the LIDAR data using a geographic information system (GIS) loaded with the HEC-RAS GIS extension, HEC-GeoRAS. The interpolated cross sections were spaced at approximately 10 m intervals along the reach and were aligned perpendicular to the expected flow direction. The model was run using the HEC-RAS steady flow simulation.

The topographic data required by the River2D model were obtained from the 2 m resolution LIDAR survey. The surveyed cross sections were used for the channel and interpolated at 5 m intervals. Outflow boundary conditions were set at a water level of 10.41 m. The outflow condition was determined using the results of the 1D simulated flood elevations for the downstream limit of the model for the 1 in 100 year flood.

Results

1D HEC-RAS model

The model simulated the impact of floodplain woodland on flood level, flow velocity, flood storage volume and flood peak travel time.

Flood level

Figure 4 shows that the roughness associated with the presence of a complete cover of woodland on the north side of the floodplain increased the flood level by around 190 mm along most of the reach, with a maximum of 270 mm. The water level also rose within the smaller 50 ha woodland block, reaching a maximum of 180 mm at the upstream edge. This created a backwater effect that extended a distance of nearly 400 m upstream of the woodland.

Storage volume

Figure 5 demonstrates that both floodplain woodland scenarios significantly increased the cumulative flood volume stored within the modelled reach. The complete woodland cover led to a 71% enhancement of flood storage, compared with 15% for the smaller block. This effect results from the higher water levels within the wooded reach in Scenario 2 and both within and above the woodland in Scenario 3.

Velocity

As expected, the presence of trees, undergrowth and woody debris decreased the water velocity over the floodplain, both within and upstream of the wooded area (Fig. 6). The reduction was greatest on the faster flowing sections, with decreases of 60–70% in mean water velocity. If the channel and floodplain are considered as separate entities, it becomes apparent that the decrease in floodplain velocity is partly compensated by an

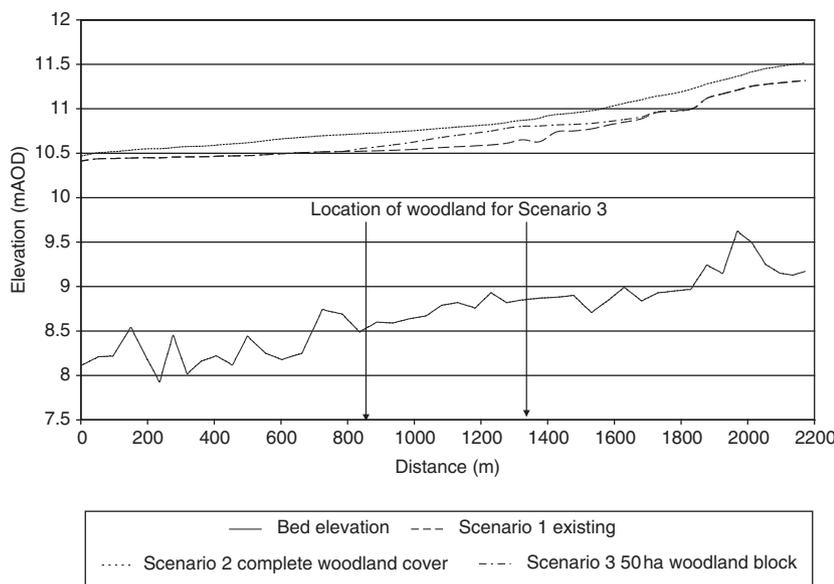


Fig. 4. Longitudinal profile displaying water and bed levels along the modelled reach, as well as the location of the wooded area in Scenario 3. mAOD, metres above ordnance datum.

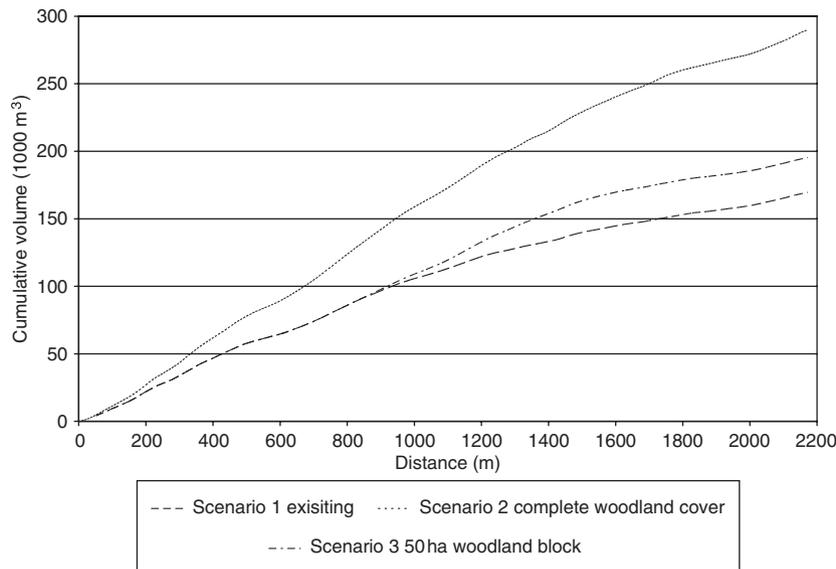


Fig. 5. Flood storage volume with distance along the modelled reach.

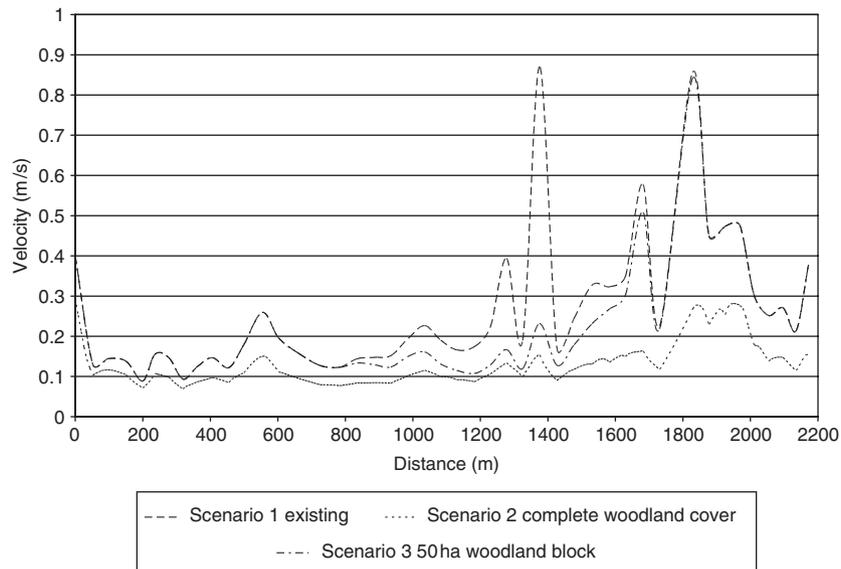


Fig. 6. Average water velocity profile along the modelled reach.

increase in channel velocity resulting from the funnelling effect of the adjacent woodland (Fig. 7).

Flood peak travel time

Figure 8 presents the results for the average travel time of the flood peak within the modelled reach. Scenario 3 shows that the presence of a 50 ha central block of woodland would increase the downstream progression of the flood peak by 30 min. In contrast, the completely wooded stretch along the northern bank is predicted to increase the travel time by around 140 min.

River2D model

The main hydraulic impacts that can be determined using the River2D model software are in terms of flood depth, flood level and water velocity.

Flood depth

Figure 9(a)–(c) compares the effects of the three scenarios on flood depth. The presence of woodland along the whole north bank of the floodplain raised the flood depth by up to 190 mm. In contrast, the horizontal extent of the flooding was relatively unchanged, probably

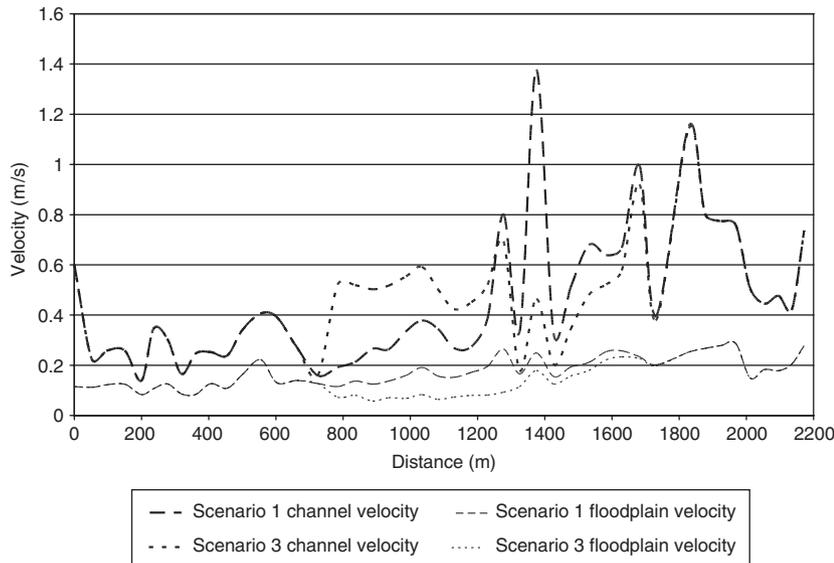


Fig. 7. Comparison of water velocity profiles for the main channel and the wooded north bank of the floodplain.

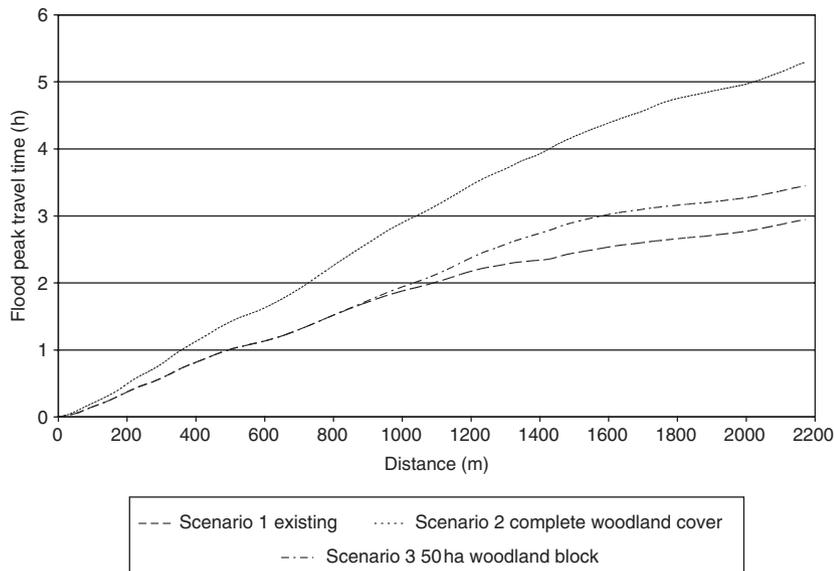


Fig. 8. Average travel time of the flood peak along the modelled reach.

because the topographical limit of the floodplain is already reached in many areas. It is possible that the impact of the floodplain woodland on the width of the flooding would become more apparent for lower-magnitude floods.

A comparison of Scenarios 1 and 3 shows that the increase in water depth is directly related to the roughness height in the woodland and reaches a maximum of 120 mm at the upstream edge. There is also evidence of an increase in water depth upstream of the woodland, as well as an increase in the extent of the flooding. An examination of the longitudinal water surface profile shows that the central block of floodplain woodland

generates a backwater effect that increases the flood level by up to 118 mm for a distance of 300 m upstream.

Velocity

The flood flow velocity vectors are displayed in Fig. 9(a)–(c) and flow velocity is mapped in Fig. 10(a)–(c). Scenario 1 shows a relatively uniform velocity distribution across the floodplain with no abrupt changes. As expected, the velocity gradually decreases towards the outer edge of the flood. Velocities within the main area of flooding generally range from 0.05 to 0.2 m/s in the lower end to 0.15–0.5 m/s in the upper section. Areas with highest

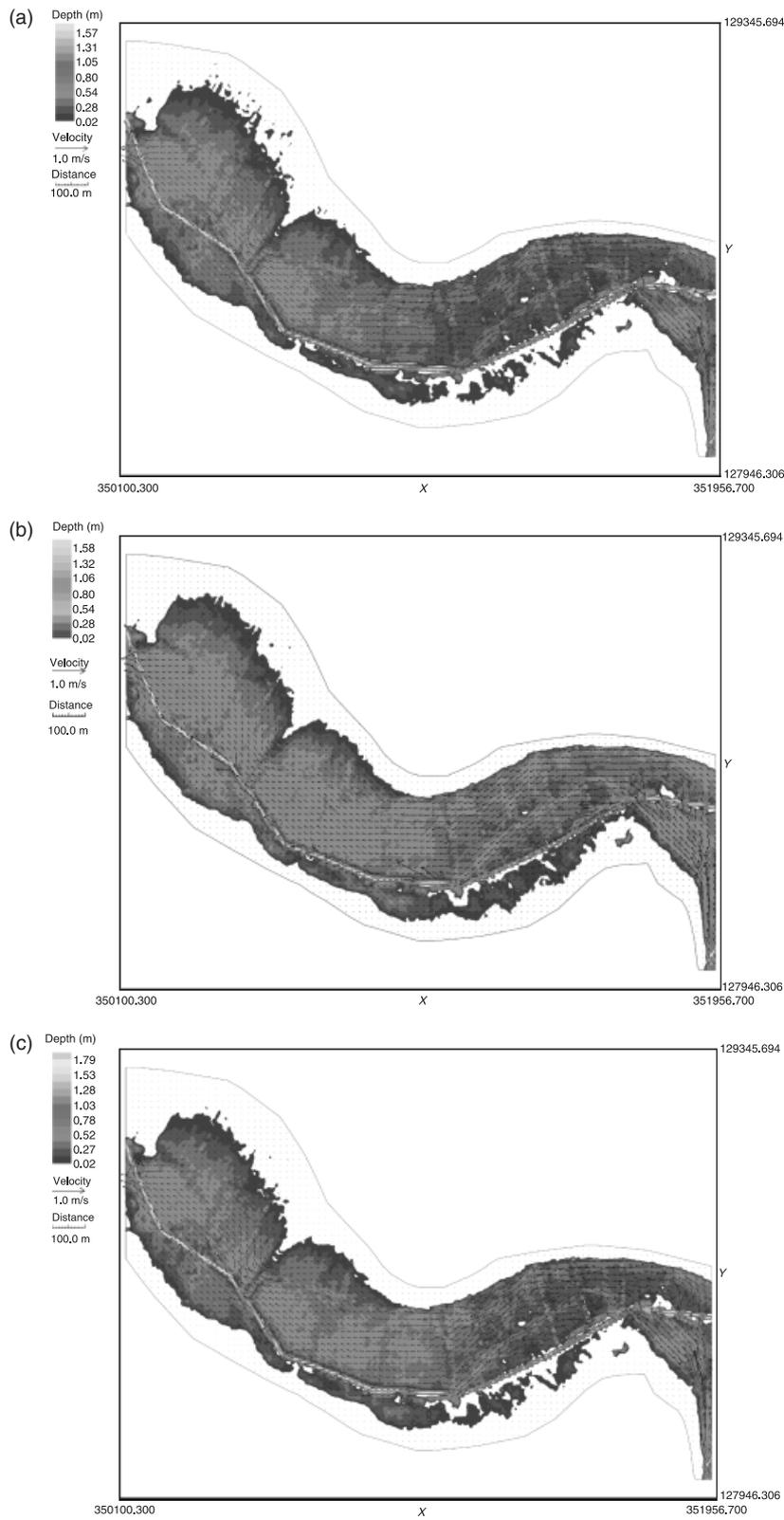


Fig. 9. (a) Flood depth and flow velocity assuming the floodplain is covered by pasture (Scenario 1). Arrow length is proportional to velocity. (b) Flood depth and flow velocity for a complete cover of floodplain woodland on the north bank of the floodplain (Scenario 2). Arrow length is proportional to velocity. (c) Flood depth and velocity for a central block of woodland over the whole width of the floodplain (Scenario 3: area of woodland outlined in black). Arrow length is proportional to velocity.

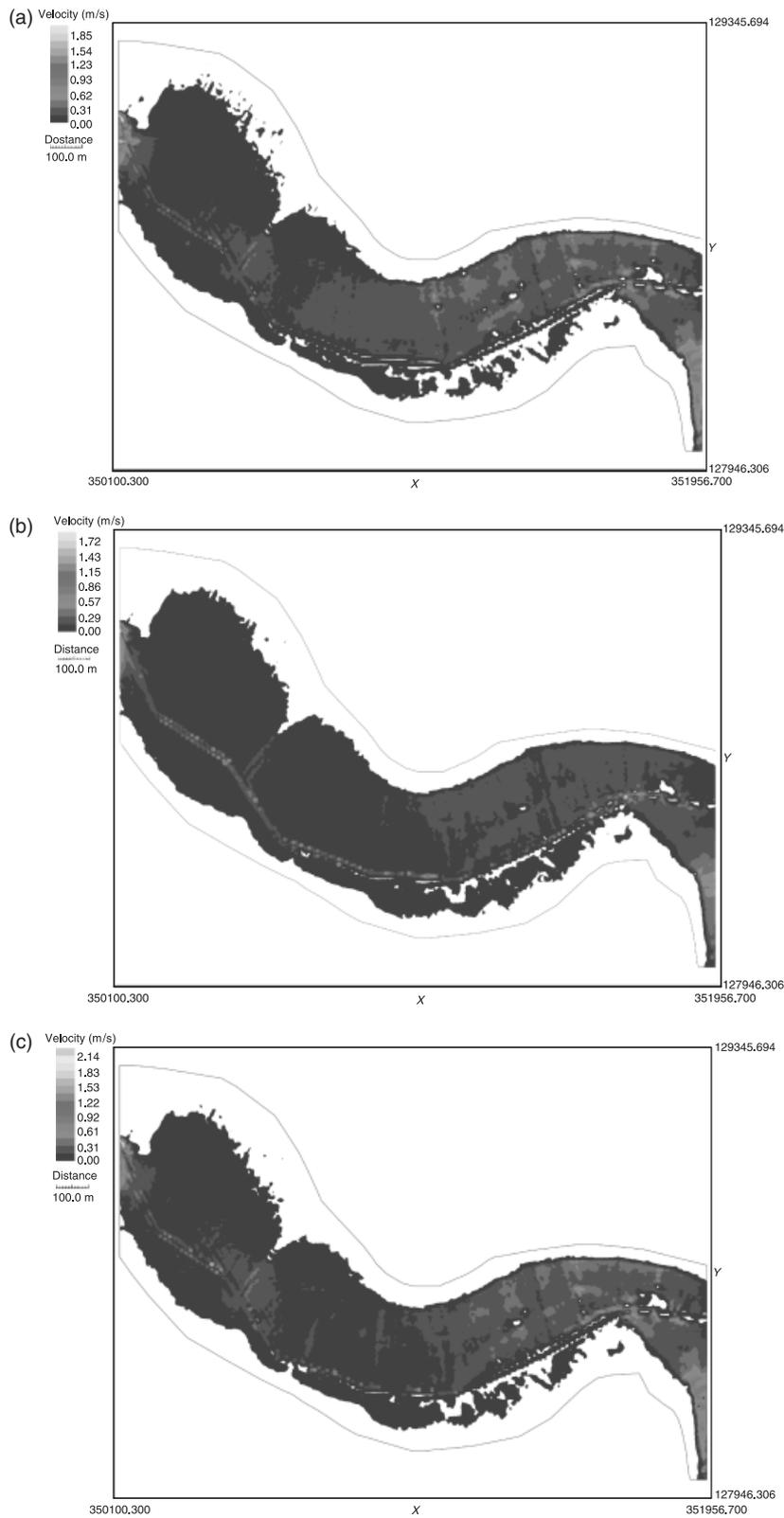


Fig. 10. (a) Flow velocity map for a floodplain covered with pasture (Scenario 1). (b) Flow velocity map for a complete cover of floodplain woodland on the north bank of the floodplain (Scenario 2). (c) Flow velocity map for a central block of floodplain woodland extending over the whole width of the floodplain (Scenario 3: area of woodland outlined in black).

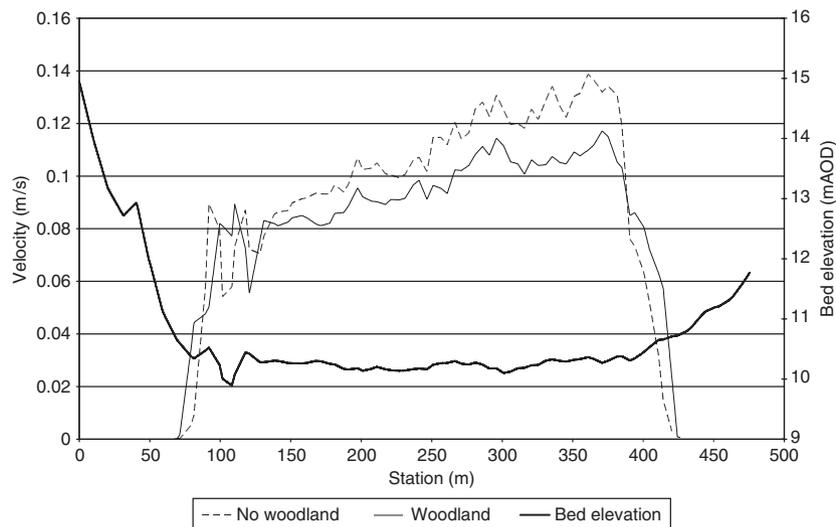


Fig. 11. Cross section of floodplain and channel comparing changes in velocity for non-wooded (Scenario 1) and partly wooded (Scenario 3) scenarios.

velocities of > 1.5 m/s occur in and around the river channel and at the downstream limit, where both the channel and floodplain are fairly steep and narrow.

The woodland in Scenario 2 causes a reduction in flow velocity across the floodplain on both banks (Fig. 10b), but especially at the upper end of the reach. Values generally range from 0.04 to 0.07 m/s in the lower half to 0.14–0.3 m/s in the upper section. The reduction is not as marked for Scenario 3, but still significant, with a maximum decrease of 0.28 m/s. There is also evidence of reduced velocities immediately upstream of the woodland, as well as across the downstream floodplain. Values tend to be enhanced within the main river channel flowing through the wooded area.

Figure 11 compares the flow velocity profile across a selected cross section of the channel and floodplain for Scenarios 1 and 3. This confirms that flow velocity decreases across the wooded floodplain but increases within the channel. The woodland is shown to increase the lateral extent of the flooding by up to 9 m on either bank.

Discussion

Application of the 1D and 2D models using appropriate roughness values suggests that the establishment of floodplain woodland along the entire north bank of a 2.2 km reach of the River Cary could have a marked hydraulic effect on the 1% a.p.e. flow. The additional resistance presented by the woodland was predicted to reduce the velocity of water flow across the floodplain by around 50%, with the result that the depth of floodwater within the woodland increased by 50–270 mm. This represented a 71% increase in the flood storage volume and had the

effect of delaying the downstream progression of the flood peak by 140 min.

The presence of a 50 ha block of floodplain woodland within the central section of the modelled reach had a smaller but still significant effect. There was a similar rise in flood depth within the woodland area, amounting to a maximum of between 120 mm (2D model) and 180 mm (1D model), although the overall effect on flood storage was limited to a 15% increase. The effect on the timing of the flood peak was to retard its passage by 30 min. Of particular interest was the upstream response, with the woodland causing a backing-up of floodwaters that extended for a distance of nearly 400 m.

The magnitude of these effects is important in flood management terms. For example, in the context of planning control, the Environment Agency regard a 50 mm rise in water level to be 'significant' in terms of the impact of building developments on the floodplain. On this basis, floodplain woodland could be expected to make a very valuable contribution to alleviating downstream flood levels. The additional time generated by the predicted lag in the downstream progression of the flood peak would also be very beneficial in terms of extending flood warnings (Fig. 12).

It is notable that the size of the modelled floodplain woodland was relatively small in relation to the extent of the catchment of the River Cary. The 2.2 km modelled reach comprised a total area of 133 ha in the main scenario (2), which is less than 2% of the total catchment area of 82.4 km². A larger floodplain woodland or a series of similar-sized woodlands in other parts of the catchment could therefore be expected to exert an even greater effect.

The modelling exercise has demonstrated that floodplain woodland is capable of delaying the downstream

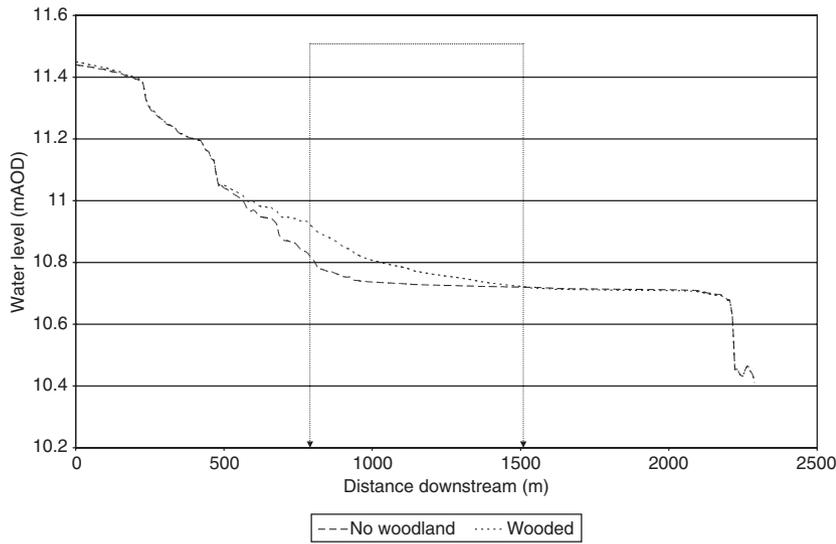


Fig. 12. Longitudinal water surface profile along a section of modelled river reach (arrows define limits of woodland in Scenario 3). mAOD, metres above ordnance datum.

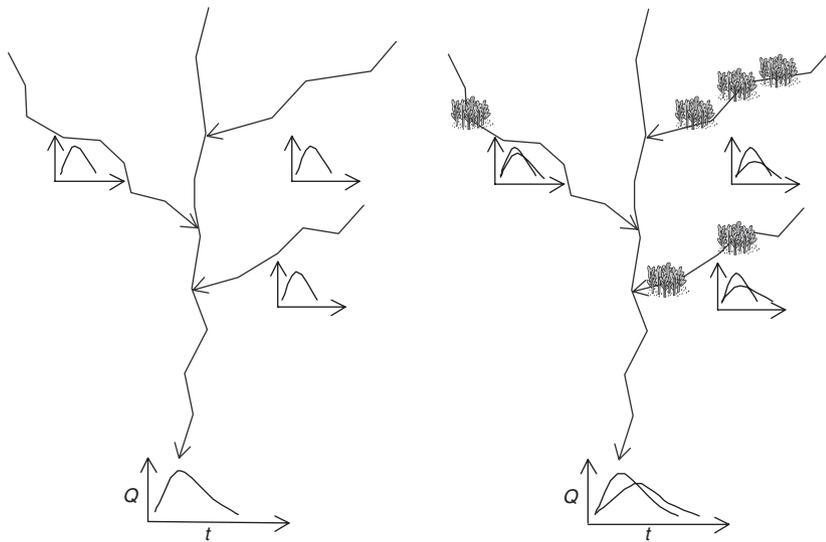


Fig. 13. Conceptual diagram showing the cumulative effect of restoring floodplain woodland within a larger catchment on the flood hydrograph of individual tributaries and the main river (Q , discharge; t , time).

passage of the flood peak. The timing of the flood peak is very important in practical terms, especially for flood-prone areas with a high risk of flooding damage, such as towns and cities. A detailed analysis of the hydrographs of individual tributaries could identify where the restoration of floodplain woodland would exert the greatest benefit in terms of desynchronising subcatchment contributions and therefore the size of the main flood peak. Desynchronisation, however, is likely to extend the flood hydrograph with possible implications for longer duration or consecutive flood events. This concept is depicted diagrammatically in Fig. 13 and would need to be investigated further when assessing the best location for any major restoration schemes.

The model predictions are based on using a roughness value associated with a relatively dense stand of willow with limited amounts of dead wood on the woodland floor (Acrement & Schneider 1990). It should be possible to create additional roughness by adopting management practices aimed at increasing levels of dead wood. Large woody debris forms a very important component of the roughness or flow resistance of both the floodplain and river channel, mainly arising from the formation of debris dams. The formation of multiple channels and pools typical of natural floodplain woodland could also be expected to enhance floodplain roughness and flood storage. The obstruction provided by individual trees and debris dams restricts water flow and contributes to scouring and channel development.

The results of the 1D modelling exercise revealed that the benefits of floodplain woodland in terms of reducing the velocity of water flow across the floodplain and increasing flood depth were partly countered by a corresponding increase in water velocity in the main river channel. Opportunities exist for ameliorating this effect, including introducing baffles or similar in-channel structures, as well as woody debris dams, to dissipate the energy within the channel and divert more water onto the floodplain. Such structures could potentially increase the frequency of flooding on the floodplain and so enhance the ability of floodplain woodland to alleviate flood flows.

Concern has been raised about the backing-up of floodwaters upstream of floodplain woodland, which could threaten properties in the immediate vicinity. The modelling work demonstrated that water levels were raised by up to 190 mm immediately above the forest. The implications of this factor would need to be carefully considered on a site-by-site basis when assessing the suitability of individual sites for the restoration of floodplain woodland.

Another potential threat posed by the restoration of floodplain woodland is the blockage of downstream structures such as bridges and culverts by woody debris. Further work is required to quantify the amount and nature of woody debris generated by floodplain woodland and the risk of this being washed out and moved downstream. Floodplain woodlands are thought to be reasonably retentive for large woody debris and it may be possible to enhance this function through management. One option could be to have a series of floodplain woodlands along a river system, with the lowest one managed to maximise debris retention.

Conclusions

- (1) Application of 1D and 2D hydraulic models to a 2.2 km reach of the River Cary in Somerset demonstrates that the planting of floodplain woodland could have a marked effect on flood flows. The additional roughness created by a complete cover of woodland along the right bank of the floodplain increased flood water storage by 71% and delayed the downstream progression of the flood peak by 140 min. A smaller 50 ha central block of woodland that spanned the full width of the floodplain had less of an effect but was still significant in storing 15% more flood water and delaying the flood peak travel time by 30 min. This caused a backwater effect that extended for a distance of 300–400 m upstream of the woodland.
- (2) These findings suggest that there is considerable scope for using floodplain woodland as an aid to flood control. The scale of the modelled woodland was very small in

relation to the size of the catchment, implying that a larger woodland block or a series of similar-sized ones could exert a much greater downstream impact. In particular, if this pattern was replicated across other tributary catchments, it should be possible to influence flood flows even within very large catchments, such as the River Parrett.

(3) A detailed analysis of the flood hydrograph would identify where the restoration of floodplain woodland would have the greatest benefit in terms of desynchronising subcatchment contributions and therefore in attenuating the main flood peak. Desynchronisation, however, could extend the flood hydrograph, with possible implications for a longer duration or consecutive flood events.

(4) Although it is very unlikely that floodplain woodland on its own would be able to provide complete protection for downstream towns or cities, it could make a valuable contribution alongside existing flood defences to tackling the increased risk of flooding associated with climate change. Similarly, it could have an important role to play in helping to manage smaller-scale flooding problems where the high cost of constructing hard defences cannot be justified.

Acknowledgements

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