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Energy crops and floodplain flows

Report - SC060092/R2

Flood and Coastal Erosion Risk Management Research and Development Programme

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Email: enquiries@environment-agency.gov.uk

Author(s):
Steve Rose, Zdenka Rosolova

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Research Contractor:
JBA Consulting
South Barn, Broughton Hall, Skipton, North Yorkshire BD23 3AE
Tel: 01756 799919

Environment Agency's Project Manager:
Adam Baylis, Evidence Directorate

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Miranda Kavanagh

Director of Evidence

Executive summary

Rural land use and land management on floodplains can have a considerable impact on flood dynamics and flood risk management. To date, research and modelling have explored the impact of land use changes such as floodplain afforestation, changes to management of upland moorlands, and the re-establishment of wet meadows on flood generation, flood attenuation and flood storage. However, no such detailed investigation has been carried out into the impact on floodplain flows of growing new energy crops.

There was a strong emphasis in the UK to the promotion of renewable energy, with grants available to growers through the Energy Crops Scheme (applications closed August 2013). Farmers are encouraged to plant energy crops such as miscanthus (harvested annually) or short rotation coppice (SRC) crops (such as willow, poplar or ash harvested every three years) in suitable locations. These locations typically exclude farmland in Flood Zone 3 (that is, areas likely to be flooded by an event with a 100-year return period).

However, there is a lack of understanding as to what impact, if any, the dense character of these crops planted on floodplains and how they are managed might have on flood risk elsewhere along the river. At present, there is no guidance or policy to advise whether allowing farmers to establish energy crop plantations in Flood Zone 3 could alter the existing flood risk in the locality of new plantings and/or further afield. In certain locations, new energy crop plantations could potentially provide a flood risk management function, an economic return and additional environmental benefits.

To help fill in this gap in knowledge, a project was carried out to investigate the possible scale of impact of growing energy crops on river and floodplain flows, flood depth and the overall impact on flood risk locally as well as upstream/downstream. Linked one dimensional to two dimensional (1D–2D) hydraulic modelling using ISIS-TUFLOW software was deemed the most appropriate approach for these investigations.

A review of the lifecycle and management regime of miscanthus and SRC willow, and their likely behaviour when flooded, informed the establishment of feasible modelling scenarios representing likely mature energy crop plantations in terms of their size, location, distribution, orientation to flow and percentage cover on the floodplain. A baseline scenario assuming complete floodplain coverage with an arable crop cover (winter wheat) was included to enable comparison of results.

Two existing Environment Agency flood risk management models were adapted for use as case studies in this project – the first on the River Severn at Uckinghall near Tewkesbury in the West Midlands, and the second on the River Isle at Ashford Mill near Ilminster in south-west England. A simple theoretical model was also set up to help define scenarios producing the greatest impacts, but excluding the effect of local subtleties that are different in each case study.

The model results were used to assess how new energy crop plantations generate changes to river flow, flow pathways on the floodplain, flood depths, and flood velocities on the floodplain. The main model outputs were as follows.

- The impacts caused by miscanthus and SRC willow plantations are broadly similar. However, shallow floodplain flooding up to about 1 m is likely to be more affected by miscanthus than by SRC willow, primarily due to the different roughness characteristics up to this depth.

- The very dense nature of the main vegetative body of the mature plantation acts like a ‘green leaky dam’ to hold water back both within and immediately upstream of the plantation and to slow the speed of water propagation across the floodplain. In most cases there will be a corresponding, but smaller, decrease in flood levels in an area immediately downstream of the plantation.
- Where the energy crop plantation fully covers the floodplain, the highest overall impacts on the flood dynamics (flood depth, velocity of flow, main channel flow hydrographs) are observed.
- Well distributed and dispersed plantations with less than 30% floodplain coverage, set away from the main channel and not significantly blocking the floodplain width (and therefore the flow of water across the floodplain) would produce only very localised effects.
- Plantation headlands and rides (with a short vegetative cover) provide faster preferential (short circuit) flow pathways than the main vegetative block.
- Distributed blocks or a central plantation block did not change the maximum flood extent significantly.

The evidence presented in this report could be used to inform decisions about energy crop plantations on floodplains. It provides advice on the selection of Manning’s n roughness coefficients to use with energy crop plantations in hydraulic models.

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Contents

1.	**Introduction**	**1**
1.1	Background	1
1.2	Project details	1
1.3	Report structure	3
2.	**Modelling energy crop characteristics**	**4**
2.1	Data review and consultation	4
2.2	Planting and management of energy crops	4
2.3	Hydraulic modelling	6
2.4	Modelling scenarios	12
3.	**Case study floodplains**	**15**
3.1	River Severn at Uckinghall	15
3.2	River Isle at Ashford Mill	18
3.3	Theoretical model floodplain	23
4.	**Case study modelling results**	**29**
4.1	River Isle at Ashford Mill	29
4.2	Summary results	37
5.	**Discussion and conclusions**	**39**
5.1	Assumptions and limitations	39
5.2	Discussion	40
5.3	Conclusions	41
6.	**Recommendations for further work**	**43**
6,1	Modelling	43
6.2	Experimental studies	43
References		**45**
Bibliography		**46**
Abbreviations		**47**
Appendix A: Background to 1D–2D ISIS-TUFLOW hydraulic modelling		**48**
Appendix B: Electronic appendices (model scenario results)		**50**

List of Tables

Table 2.1	Typical floodplain roughness values [1,2]	8
Table 2.2	Further typical floodplain roughness values	8
Table 2.3	Overview of floodplain roughness coefficient and its variability with flooded depth for various floodplain vegetation (specifically for SRC willow at the lowest and highest velocities [1])	9
Table 2.4	Floodplain roughness coefficients adopted for miscanthus, SRC willow, baseline (arable cereal – wheat) and headland/rides	10
Table 2.5	Summary of modelling scenario characteristics for miscanthus and SRC willow	12
Table 3.1	Key characteristics of the case study floodplains	15
Table 4.1	Summary results matrix	38

List of Figures

Figure 2.1	Mature miscanthus and harvesting	5
Figure 2.2	Mature SRC willow plantation and harvesting	6
Figure 2.3	Example of modelling scenario layouts	14
Figure 3.1	River Severn at Uckinghall – site location	16
Figure 3.2	Modelled scenario configurations for Severn at Uckinghall [1]	18
Figure 3.3	River Isle at Ashford Mill – site location	19
Figure 3.4	Modelled scenario configurations for Isle at Ashford Mill [1]	23
Figure 3.5	Theoretical model river cross-section	25
Figure 3.6	Theoretical model floodplain cross-section	25
Figure 3.7	Theoretical model – model layout and topography	26
Figure 3.8	Modelled scenario configurations for River Isle at Ashford Mill [1]	28
Figure 4.1	River Isle at Ashford Mill – flood depth patterns	31
Figure 4.2	River Isle at Ashford Mill – flood velocity patterns	33
Figure 4.3	River Isle at Ashford Mill – main channel flood hydrographs [1]	37

1. Introduction

1.1 Background

Under the UK's Renewable Energy Strategy, the aim is to achieve 15% of the UK's energy needs from renewable sources by 2020, with 30% of the renewable energy target coming from biomass, including energy crops (HM Government 2009).

The Energy Crops Scheme (ECS) managed by Natural England actively encourages landowners and farmers to increase the amount of energy crops grown in England in appropriate locations (Natural England 2009).[1] These crops will be used as a substitute for fossil fuels so they can contribute to a reduction in greenhouse gas emissions and help to combat climate change. The government believes that energy crops can also play an important role in contributing to sustainable development. The scheme is part of the Rural Development Programme for England (RDPE) and is funded by the European Union through the European Agricultural Fund for Rural Development.

The scheme offers grants to farmers in England for the establishment of miscanthus (to be harvested annually) and short rotation coppice (SRC) (to be harvested every three years). An establishment grant is a payment designed to cover a percentage of the set-up costs of establishing approved energy crops. This includes activities such as ground preparation, fencing, purchase of planting stock, planting, weed control and first year cutback. Eligible SRC crops are willow, poplar, ash, alder, hazel, silver birch, sycamore, sweet chestnut and lime. The European Union confirmed that the rate of grant offered to farmers to grow biomass crops (miscanthus and SRC) under the ECS could be increased to 50% (from 40%) for all costs incurred after 1 January 2010. At the time of writing this report (November 2010), ECS had several years to run and the expectation was for a greater uptake by landowners and farmers as it progressed.

The Environment Agency provides advice to Natural England on the operation of the ECS with respect to flood risk. However, there is still a general lack of understanding of the potential impacts (both positive and negative) that dense plantings of these energy crops on the floodplain might have on fluvial flooding dynamics and upstream or downstream flood risk, particularly within the Environment Agency Flood Zone 3 areas. Within the fluvial flooding context, Flood Zone 3 represents the area that could be affected, in the absence of defences, by flooding from a river by a flood that has a 1% (1 in 100) or greater chance of happening each year.

If the presence of appropriately designed energy crop plantations on the floodplain could potentially provide a coupled benefit of a renewable energy resource and a flood mitigation or attenuation function, then this should be actively encouraged.

1.2 Project details

The Environment Agency recognised that developing a complete understanding of the potential impacts of energy crops on its flood risk management responsibilities could take several years to achieve. However, there was an urgent need for some initial evidence to provide a steer for the relevant policymakers and scheme assessors.

[1] The Energy Crops Scheme closed for new applications on 31 August 2013. Guidance for existing agreements is available from: https://www.gov.uk/energy-crops-scheme-terms-and-conditions-of-your-agreement [Accessed 18 May 2015].

JBA Consulting was therefore commissioned by the Environment Agency to carry out a short-term modelling project with the overall aim of:

- investigating the potential impact of growing energy crops on river and floodplain flows
- quantifying any changes these new plantings might make to upstream and downstream flood risk

The choice of energy crops under investigation was restricted to miscanthus and SRC willow.

1.2.1 Project aims and objectives

The overall aims and objectives of the modelling work had the following three elements.

- An investigation of how the impact of energy crop plantations on floodplains might affect the flood dynamics and what implication this might have on flood risk. The background to this investigation should include:
  - a review of modelling approaches and the selection of the approach most appropriate for the study
  - a review of how the energy crops can be represented in the chosen models (that is, resistance to flow)
  - consideration of any related technical issues
- The representation of energy crop plantations in the form of specific plantation scenarios and their reconciliation with the Project Steering Group. The results of the modelled scenarios should be compared against an agreed baseline flood condition to enable comparative quantitative and qualitative assessment of the potential impact of the energy crops on flood dynamics.
- A synthesis of the findings and their assessment in terms of providing supplementary material to existing Environment Agency guidelines, 'Flood Risk Management: Woodland, Tree Planting and Flood Risk', on this type of floodplain development.

The project was seen as an initial phase of work in this area – a forerunner of further phase(s) to follow if a need was identified, particularly in terms of further modelling or the validation of the modelling work with the collection of monitoring datasets from new field studies.

1.2.2 Project Steering Group

Only four months was available for the research and modelling work. Therefore, it was crucial that the methodology, interim findings and any issues arising during the work were discussed as early as possible by the project team and parties relevant to the technical and management aspects of the project to ensure the aims could be met within the restricted timescale. For this purpose, a Project Steering Group was set up at early stage. This group was consulted about decisions regarding the model scenarios and the interpretation of the findings, which were also reviewed in terms of the technical approach.

1.3 Report structure

Chapter 2 presents the background research carried out to advise the choice of methodology. It includes:

- a short summary of the characteristics of the energy crops in question
- a review of the literature and research regarding the representation of floodplain vegetation in hydrodynamic models
- a review of recent modelling approaches
- a set of conclusions regarding the modelling methodology applied in this project

Chapter 3 introduces the case study floodplains modelled in this study, along with more detailed information about the hydraulic models for each site.

Chapter 4 summarises the results analysed for each case study and presents an example of the complete set of results for one site only, the River Isle case study. The synthesis of the findings from all the case studies is presented in this chapter in the form of a summary results matrix, which provides a qualitative as well as a quantitative interpretation of the findings.

Chapter 5 summarises the discussions and conclusions of this study, together with the assumptions and limitations that had to be adopted to meet the project’s aims and objectives.

Chapter 6 presents recommendations for further modelling and monitoring work.

2. Modelling energy crop characteristics

2.1 Data review and consultation

A range of existing datasets, published academic papers, guidance notes and information sources on the planting, management and harvesting of miscanthus and SRC willow was reviewed to better understand the likely behaviour of these energy crops when flooded. The timing and seasonality of management operations, together with typical planting configurations, were also reviewed.

A review was also carried out of existing one-dimensional (1D) and two-dimensional (2D) modelling approaches to simulate the effects of these energy crops on floodplain flows. In particular, the review considered:

- the effect energy crops might have on floodplain roughness
- generation of woody debris as barrier to flow
- the physical response of the standing crop to an increase in floodplain depth, velocity and flow

The review was further informed by consultation with the Project Steering Group and with a number of organisations with experience of either the planting and management of these crops (for example, ADAS and Wales Biomass Centre) or the modelling of the hydraulic effect of these crops (for example, Forest Research, Cardiff University and Rothamsted Research). Reconciliation of the findings helped establish the modelling approach for this short study.

2.2 Planting and management of energy crops

2.2.1 Miscanthus

Miscanthus is a perennial, rhizomatous grass which can grow to heights of more than 3.5 m, forming a plantation of dense bamboo-like canes (Defra 2007). Miscanthus is planted in spring, and once the plantation is established, it can stay in the ground for at least 15–20 years. Mature miscanthus is harvested annually in the winter season, typically in February. New shoots appear in March each year and grow rapidly in June–July. Miscanthus dies back in the autumn and, during the winter, sheds its leaves and only the canes stay to be harvested. Figure 2.1 shows a mature miscanthus plantation and its physical state at harvest.

In the UK, the establishment period for the first crop is three years. After this initial period, the crop is fully established for long-term harvesting cycles.

In the first year of planting, the crop reaches 1–2 m height in August. The stems are usually unbranched and contain solid pith. This, together with the very dense character of the plantation, is likely to make them reasonably robust and sturdy when flooded with shallow water. From late July, the lower leaves start to dry, and by late autumn, leaves fall off thereby developing a deep leaf litter. By February, the crop is composed of almost leafless canes. From the second season the crop can grow to its maximum height of 2.5–3.5 m.

Figure 2.1 Mature miscanthus and harvesting

Source: DEFRA, 2007. *Planting and growing miscanthus. Best practice guidelines for applicants to Defra's Energy Crops Scheme*.

2.2.2 SRC willow

Willow, a short rotation coppice crop, is a perennial crop that can produce acceptable yields for about 30 years after the initial planting. It is typically planted in spring in either single 1.5 m rows or in double rows 60–70 cm apart, potentially forming conveyance areas for flood propagation on the floodplain. Within the first year of its growth, SRC willow can reach up to about 4 m in height (Defra 2004).

During the winter season after planting, the stems are cut back to ground level. This encourages further growth of multiple stems, causing the plantation to become quite dense. Willow can be established on a wide range of soil types including clay, sandy soils or even reclaimed soil from gravel, making it a suitable plant for floodplain areas.

During the late autumn/winter period (typically October to December) after establishment, the crop is coppiced to a height of about 10 cm above ground. The willow then grows back during the next two years. It can then be harvested again and the plant grows back to the harvesting stage during the following three years. The three-year cycle is repeated throughout the lifetime of the plantation. SRC willow can grow to about 8 m in height.

Figure 2.2 Mature SRC willow plantation

Source: DEFRA, 2004. *Growing short rotation coppice. Best practice guidelines for applicants to Defra's Energy Crops Scheme*.

2.3 Hydraulic modelling

2.3.1 Representation of energy crops on floodplains

Floodplain vegetation such as rough grass, brush or wet woodland (including stems, branches and leaves on the ground) can increase the surface roughness and hence the hydraulic resistance of the floodplain to water flow. Conversely, smooth vegetation (for example, short grass) and most arable crops provide little resistance to flow. They are therefore likely to contribute to the conveyance of floodplain flows downstream. Thus, vegetation cover on floodplain can have a greater or lesser impact on propagation of flooding downstream depending on the degree of hydraulic resistance of the cover to flow.

The physical characteristics of floodplain vegetation, in terms of their impact on floodplain flows, are determined by the type of plant stems, tree trunks or leaf material, their quantity and distribution on the floodplain. Other aspects are also important such as the proportion of the vegetation submerged when flooded, the potential of blockage of flow path, impact of turbulence and flow structure. The effects of all these factors are represented empirically in hydraulic models by the use of roughness coefficients such as, for example, Manning's n roughness coefficient.

Appropriate roughness coefficient values for different substrate and vegetation types are well documented. Roughness values have also been published on agricultural floodplains with coverage of cereals, grassland and woodland.

Wet woodlands or wet meadows have recently been seen as potential flood mitigation and flood attenuation measures on floodplains. They have been subject to a small number of hydraulic modelling studies such as those undertaken by Forest Research (Nisbet and Thomas 2008). In the USA, a number of studies have investigated roughness characteristics of densely vegetated floodplains (for example, Acrement and Schneider 1989). However, there is little or no information specifically on appropriate values of roughness of energy crops such as miscanthus and SRC willow.

The roughness effects of some vegetation types are discussed, for example, in the 'roughness review' (Defra 2003), by Acrement and Schneider (1989), Chow (1959) and Thomas and Nisbet (2004). Cardiff University and other institutions such as Rothamsted Research have also reported on resistance to flow, particularly in terms of SRC willow.

A number of field and laboratory experiments exploring how the type, density and placement of vegetation, flow depth and velocity influence the resistance to flow, both for submerged and non-submerged flexible (for example, long grass) or stiff (for example, willow) vegetation have been reported.

For example, Järvelä (2002) used laboratory experiments to investigate the impact of grasses and willows (both with leaves and leafless) on the Darcy friction factor, which is a parameter describing friction losses in open channel flow and can empirically be related to Manning's n roughness (Chow 1959); the greater the friction factor, the greater Manning's n coefficient. The study showed that the friction factor was mostly dependent on flow depth in the case of leafless willows and on the flow velocity for willows with leaves. Crucially, Järvelä demonstrated that for velocities up to 0.5 m/s, willow stems do not bend and stay more or less erect.

Wilson and Horritt (2002) studied the flow resistance of flexible vegetation when submerged in a laboratory flume. They concluded that Manning's n roughness coefficient increases significantly as the flow depth approaches the vegetation depth, tending towards a constant value at higher levels of submergence. On average, the Manning's coefficient for the tested conditions was found to be greater than the values traditionally applied for grassed floodplains. Further investigations by Wilson have shown changes in flow resistance of SRC willow with depth and flood velocities (Wilson, C.A.M.E., personal communication, 2009).

Tables 2.1 and 2.2 summarise the typical Manning's n roughness coefficients for the vegetation types most relevant for this study. Although the values are quoted from specific research papers, they represent a synthesis of information in the literature.

Table 2.1 Typical floodplain roughness values [1,2]

Manning's n	Description of floodplain
0.15	The vegetation of the floodplain is a mixture of large and small trees including oak, gum and ironwood. The base is firm soil and has minor surface irregularities caused by rises and depressions. Obstructions are negligible (some expose roots). Ground cover is negligible and undergrowth is minimal.
0.18	The vegetation of the floodplain is large trees including oak, gum, pine and ironwood. The base is firm soil and has minor surface irregularities caused by rises and depressions. Obstructions are negligible. Ground cover and undergrowth are negligible.
0.20	The vegetation of the floodplain is a mixture of small and large trees including oak, gum and ironwood. The base is firm soil and has minor surface irregularities. Obstructions are minor. Ground cover is medium and the large amount of undergrowth includes vines and palmettos.
0.20	The vegetation of the floodplain is a mixture of small and large trees including oak, gum and ironwood. The base is firm soil and has minor surface irregularities. Obstructions are minor (some downed trees and limbs). Ground cover is medium and the large amount of undergrowth includes vines and palmettos.

Notes [1] Taken from Acrement and Schneider (1989)
[2] Although the values given relate to procedures limited to the selection of roughness coefficients for application of 1D open channel flow, they do specifically consider dense vegetation on floodplains.

Table 2.2 Further typical floodplain roughness values

Manning's n			Description of floodplain
Average	Lower	Upper	
0.035	0.030	0.050	High grass [1]
0.040	0.030	0.050	Mature field crops [1]
0.150	0.110	0.200	Dense willows, summer, straight [1]
0.100	0.080	0.120	Stiff grass, height 1.8 m (height of water depth 1.4 m) [2]
0.047	0.040	0.055	Stiff grass, height 1.8 m (height of water depth 2.5 m) [2]

Notes [1] Taken from Chow (1959)
2 Taken from Defra (2003)

According to Chow (1959), Manning's n usually varies with the stage of submergence of the vegetation at low stages (Table 2.3). However, Chow points out that the vegetation has a marked effect only up to a certain stage and the roughness coefficient can, usually, be considered constant for determining overbank flow discharges. Wilson found different results for SRC willow (Table 2.3); the resistance to flow increases with increased flow depth, but less so with increased velocity.

Table 2.3 Overview of floodplain roughness coefficient and its variability with flooded depth for various floodplain vegetation (specifically for SRC willow at the lowest and highest velocities [1])

Manning's n			Description of floodplain and inundation	
Average	**Lower**	**Upper**	**Flood velocity (m/s)**	**Flood depth (m)**
			Floodplain vegetation – Corn [2]	
0.060	n/a	n/a	n/a	<0.6
0.070	n/a	n/a	n/a	0.9
0.070	n/a	n/a	n/a	1.2
0.060	n/a	n/a	n/a	>1.2
			Floodplain vegetation – Brush and waste [2]	
0.110	n/a	n/a	n/a	<0.6
0.100	n/a	n/a	n/a	0.9
0.090	n/a	n/a	n/a	1.2
			Floodplain vegetation–- SRC willow [3]	
0.181	0.106	0.274	1	<0.5
0.204	0.120	0.307	1	1.0
0.229	0.134	0.345	1	2.0
0.105	0.062	0.158	3	<0.5
0.118	0.069	0.177	3	1.0
0.132	0.077	0.199	3	2.0

Notes [1] As presented by C.A.M.E. Wilson (personal communication, 2009)
3 From Chow (1959)
4 Supplied by Wilson
n/a = not available

For the purpose of this study, the following assumptions regarding the energy crop plantations were adopted.

- The energy crops are modelled as fully grown, well-established mature plants (for example, 3 m tall dense miscanthus or even taller SRC willow) to avoid additional complexity should different growing stages also be concerned.
- The bamboo-like stems of miscanthus when flooded were assumed to have a uniform character in terms of its behaviour throughout the flood inundation. The hydraulic character of SRC willow was assumed to be more likely to vary with flooded depth due to the changing physical character of the stems (C.A.M.E. Wilson, personal communication, 2009).
- The crop is assumed not to be fully submerged during the flood events (as it is highly unlikely that flooding as deep as over 3 m would occur on a floodplain where the energy crops would be planted). In such conditions, the resistance of the vegetation to flow is likely to remain constant for deep flows (Defra 2003). This could be particularly likely in the case of miscanthus because the vegetative characteristics of these plants, when mature, are reasonably uniform throughout their height.

- Headlands and rides, which are typically present bordering or within the plantations respectively, are assumed to be managed as short grass.

The baseline condition against which this project compared the impact of the energy crop plantations is represented by an arable cereal crop, that is, winter wheat grown across the floodplain.

As noted by Defra (2003), there remains a need for further research to provide calibration and verification data for 2D analysis of roughness. There are also questions remaining about exactly:

- how the effective resistance to flow should be partitioned between boundary friction and from drag
- how the total resistance is affected by flow depth
- how best to represent the influence of vegetation height, density and rigidity

In situations where vegetation is present, the amount of plant submerged or emerging and plant type are both important parameters in defining the relationship between roughness coefficient and flow depth.

In this study there was also a need for a pragmatic approach. The literature was therefore reviewed to draw out values for the Manning's n coefficient that could correspond to the postulated energy crop vegetation types – albeit subject to uncertainty owing to the difficulty in representing the factors discussed above. Table 2.4 shows the final Manning's n coefficients adopted in this project.

Table 2.4 Floodplain roughness coefficients adopted for miscanthus, SRC willow, baseline (arable cereal – wheat) and headland/rides

Vegetation type	Manning's n	Comments
Miscanthus	0.2	Manning's n applied for the full depth of inundation. This value is representative of dense mature vegetation with firm stems and thick undergrowth with minor irregularities in the ground.
SRC willow	0.1–0.34	Manning's n varies linearly with depth of inundation between the following values (typical for flood velocities at 1 m/s, which is the value closest to the velocities achieved in the baseline and scenario case studies): n = 0.1 flooded depth 0.5 m n = 0.34 flooded depth 2.0 m These values are a synthesis of the Manning's n values determined by Wilson (2009) and comprise the low to upper recommended values, which help give an indication of the envelope (and sensitivity testing) for the expected impact of mature SRC willow on floodplain flows.
Headlands/rides	0.04	Manning's n typically used for managed short grass for the full depth of inundation.
Baseline	0.06	Manning's n typically used for arable crop (wheat) for the full depth of inundation.

2.3.2 Hydraulic models

A range of different hydraulic modelling approaches is currently used in practice.

The choice of the approach to modelling a river system with its floodplain as a complex, linked entity with accurate simulation of water transfer between the two systems is crucial. It can be approached in a number of ways.

The first involves using a 1D model is used to represent the river system and a linked 2D model to represent the floodplain system (as used in this study). These two systems communicate via a 1D–2D boundary which has to be set up separately within the 2D model. When the linked 1D–2D model is run, the water levels in the 1D component are compared with the ground levels in the 2D model; water can spill into the floodplain when the former are higher than the latter at the borderline area defined by the 1D–2D boundary (for example, a riverside embankment). Alternatively, the model can be set up to exchange flow directly using lateral spill set up in the 1D river model. The underlying principle here is that the fluxes are exchanged horizontally.

An alternative to the above – and increasingly more in practice – is an exchange of fluxes vertically. This can be achieved by nesting the 1D model component 'underneath' the 2D floodplain model. The advantage of this approach is that there is no need to define the 1D–2D boundary through which the two models exchange water while still conserving the momentum. Therefore, the uncertainties related to design of the 1D–2D boundary (largely dependent on the modeller's judgement) are eliminated. This also means that one of the main sources of instability in the 2D model, the transition between the 1D and 2D models, is almost eliminated and the transition is smooth.

A third alternative is to model both the river system and the floodplain system using a single 2D model, that is, with no need for the 1D model component. This modelling approach offers better description of physical processes in the near channel area than the two methods above. It is much more demanding on data input and model run time (due to more complex representation of the in-channel flows than when using a 1D model), but less demanding in terms of model set-up. In order to represent the river channel accurately, a detailed sonar bathymetry survey of the channel (obtained, for example, by the Environment Agency) would be needed.

A fourth option is to model the river and floodplain as a series of 1D cross-sections, but with a more physically detailed approach to the lateral distribution of velocity. The Conveyance Estimation System (McGahey 2006, Knight et al. 2010) embodies this approach and may be thought of as a '1.5D model with 3D features' that captures some important physical processes in the turbulence and internal circulation patterns that occur within the flow. However, this approach could be inappropriate where there are complex lateral flows over the floodplain, as may be the case for flows along the rides in between plantation blocks.

Finally, a fully three-dimensional (3D) modelling approach could also be applied. However this would be very expensive and demanding in terms of model set-up, input data requirements and computational time.

The choice of models for application in this study had to satisfy the following criteria:

- appropriate representation of the floodplain and floodplain features, and the capacity to capture the change of the floodplain hydraulic properties caused by the energy crops in sufficient degree of detail (for example, surface roughness and conveyance)
- availability of suitable existing models for this project
- reasonable complexity and calculation time for the models to complete the modelling scenarios within the project timescale

With these criteria in mind, the 2D approach to representation of a floodplain in hydrodynamic models was deemed the most suitable. The linked 1D–2D ISIS-TUFLOW was considered an appropriate software package for the purpose of this study. The model versions used in this study were TUFLOW 2009 07 AE and ISIS v3.3.0.88. Appendix A provides detailed information on the linked 1D–2D ISIS-TUFLOW model.

2.4 Modelling scenarios

A list of crop plantation configurations to be modelled was established in consultation with the Project Steering Group. These included a maximum impact scenario (dense, fully mature energy crop plantation with 100% coverage on the floodplain).

The scenarios chosen considered the following parameters:

- planting location
- size of planting (typically 1–3 ha)
- planting configuration

A winter wheat cereal crop is represented in the baseline (control) model against which the results of the modelled scenarios are compared.

Table 2.5 summarises the modelling scenario characteristics adopted (combined into specific modelling scenarios as listed in Chapter 3). A balance between a practical number of model scenarios that could realistically be analysed within the scope of this project and the need to capture appropriate plantation characteristics was achieved.

The intention was not to repeat each scenario type for both miscanthus and SRC willow. Rather the main modelling focus was on miscanthus first. The model scenarios with potentially the greatest and the least impact were analysed first as a sensitivity test, which helped determine the magnitude of change to be expected. This test, further modelling and consultation with the Project Steering Group determined the scenarios taken forward as modelling scenarios for SRC willow or any additional scenarios required.

The total number of the final scenarios modelled was 40 (including those for the baseline condition), ranging from nine to 16 scenarios per case study.

Table 2.5 Summary of modelling scenario characteristics for miscanthus and SRC willow

Plantation characteristics	**Modelled flood magnitude 1% AEP (100-year return period)**
	Description
Size	3 ha blocks
	1 ha blocks
Configuration	10 m rides/headlands parallel to river
	10 m rides/headlands perpendicular to river
	5 m rides/headlands parallel to river
	5 m rides/headlands perpendicular to river
Location	One side of river
	Both sides of river
Coverage	100%

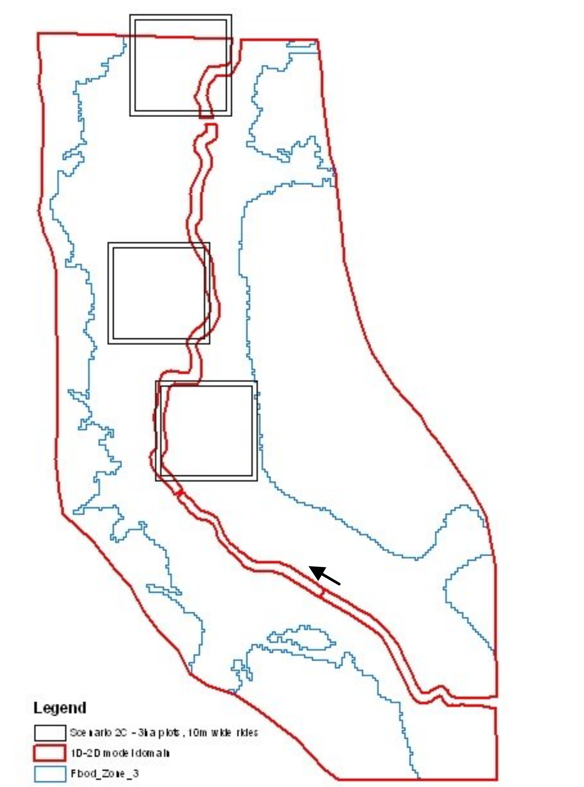
Plantation characteristics	Modelled flood magnitude 1% AEP (100-year return period)
	Description
	Up to 30%

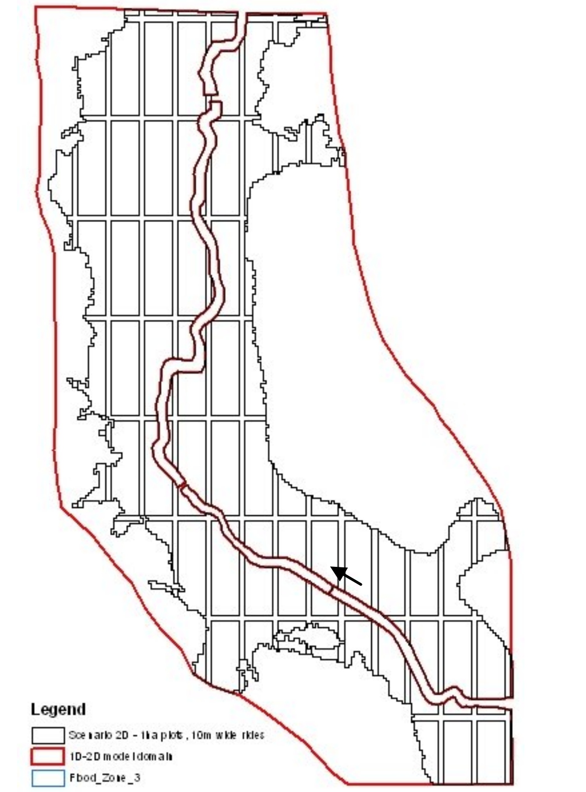
Notes: AEP = annual exceedance probability

An example of the layout of a selection of the modelling scenarios is given in Figure 2.3. As can be seen in this example, the classification of rides 'parallel' and 'perpendicular' to floodplain flow can be somewhat confusing depending on the meandering nature of the river channel and the shape of the wider floodplain.

It was also not possible within the scope of this project to include scenarios with more realistic plantation shapes that would, for example, follow existing field boundaries or ownership boundaries. Such a plantation configuration would have to be designed manually and would have been extremely time-consuming. Instead, a bespoke procedure was developed in the geographical information system (GIS) environment, which allowed automated generation of the desired plantation layouts.

Scenario 2C: 3 ha miscanthus plantation blocks with 10 m rides around, floodplain coverage 30%, distributed plots	**Scenario 2D**: 1 ha miscanthus plantation blocks with 10 m perpendicular rides, floodplain coverage 100%





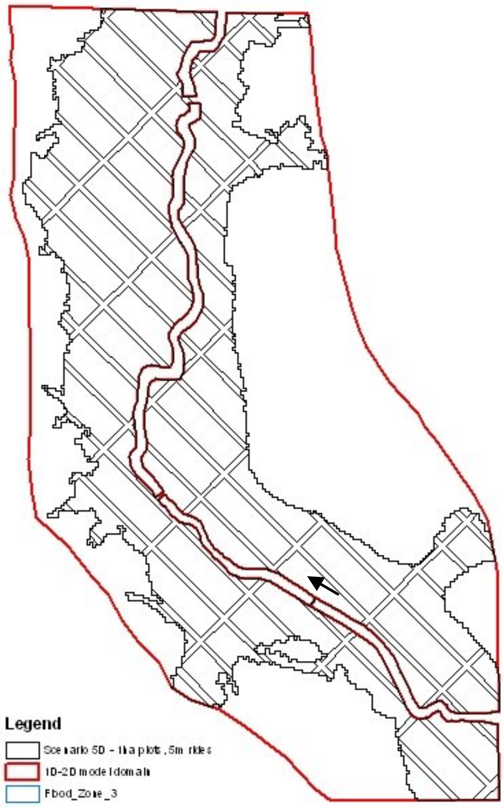
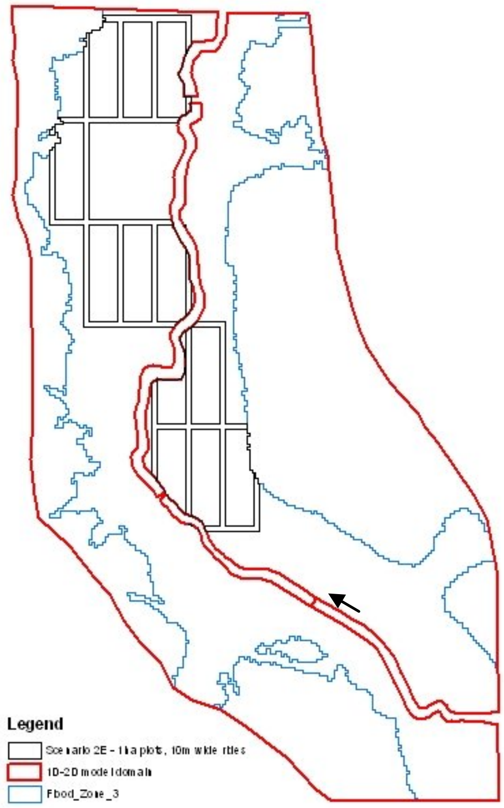
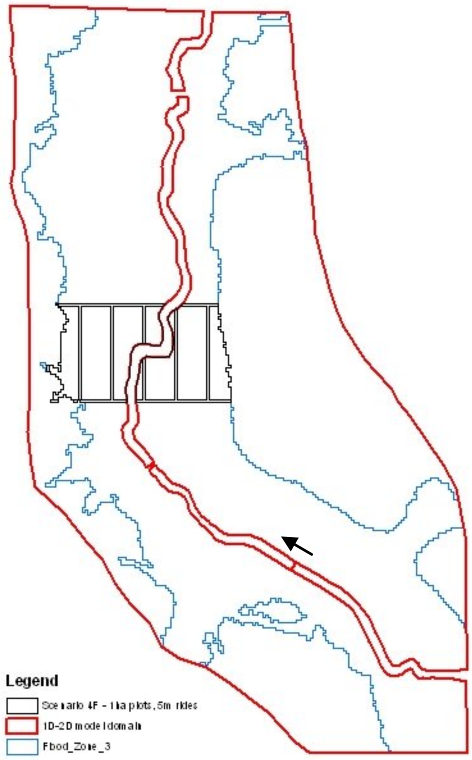
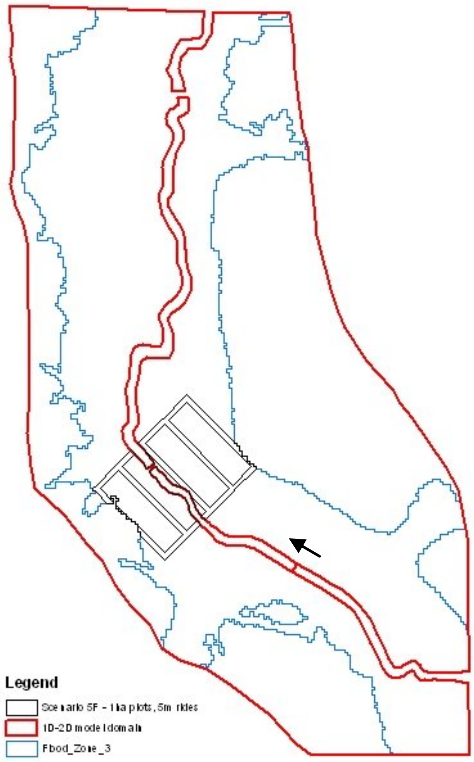
Scenario 5D: 1 ha miscanthus plantation blocks with 10 m parallel rides, floodplain coverage 100%	**Scenario 2E**: 1 ha miscanthus plantation blocks with 10 m perpendicular rides, floodplain coverage 30%, distributed plots
	
Scenario 4F: 1 ha miscanthus plantation blocks with 5 m perpendicular rides, floodplain coverage <30%	**Scenario 5F**: 1 ha miscanthus plantation blocks with 10 m parallel rides, floodplain coverage <30%
	

Figure 2.3 Example of modelling scenario layouts

Notes: 2D model domain in red, extent of Flood Zone 3 in blue and plantation plots with rides around in black. The arrow signifies the direction of flow.

3. Case study floodplains

Given the nature, scope and time constraints of this study, it was not possible to build, calibrate and validate appropriately detailed new hydraulic models and therefore existing models suitable for adaptation were sought.

In consultation with the Project Steering Group, floodplains where these crops might realistically be grown within the ECS were identified. Of these, those floodplains having major physical constraints that might make the interpretation of the results difficult (for example, narrow bridges and high river embankments) were discarded. Further criteria included complete/good quality LIDAR topographic coverage of the floodplain, reasonably short model run times and, ideally, design inflow hydrographs.

From an assessment of a number of possible models that were identified, two real case study floodplains were chosen for this project. These were the River Severn at Uckinghall (near Tewkesbury in the West Midlands) and the River Isle at Ashford Mill (near Ilminster in south-west England).

A third simple theoretical (or 'idealised') model was set up to help determine which scenarios gave rise to the biggest impacts, without introducing local floodplain subtleties that are different in each case study.

The case studies are briefly presented in this chapter, alongside with the complete set of modelling scenario configurations for each site. The key characteristics of the three case study floodplains are summarised in Table 3.1.

Table 3.1 Key characteristics of the case study floodplains

Floodplain	100-year flood magnitude (m^3/s)	Extent of modelled river reach, that is,1D river model (km)	Extent of modelled floodplain, that is, 2D floodplain model (km^2)
River Severn at Uckinghall	763.5	7	4.4
River Isle at Ashford Mill	61.3	1.8	0.8
Theoretical model	409.8	2.2	5.3

3.1 River Severn at Uckinghall

An existing linked 1D–2D ISIS-TUFLOW model was available for a 7 km stretch of the River Severn at Uckinghall. The river reach runs in a north–south direction through a valley with steep slopes on the right (western) side of the river and with about a 1 km wide floodplain on the left (eastern) side. The left floodplain was represented in the 2D domain of the linked model. Deep flooding to about 3.5 m was observed in places within the baseline model results on this floodplain. This is a high depth of flooding that could, in reality, discourage farmers from establishing plantations in such a location.

The existing land use on the floodplain is predominantly arable (horticulture) or grassland, which makes it a suitable potential candidate for energy crop plantations. An overview map of the study site and the modelled floodplain boundary are presented in Figure 3.1.

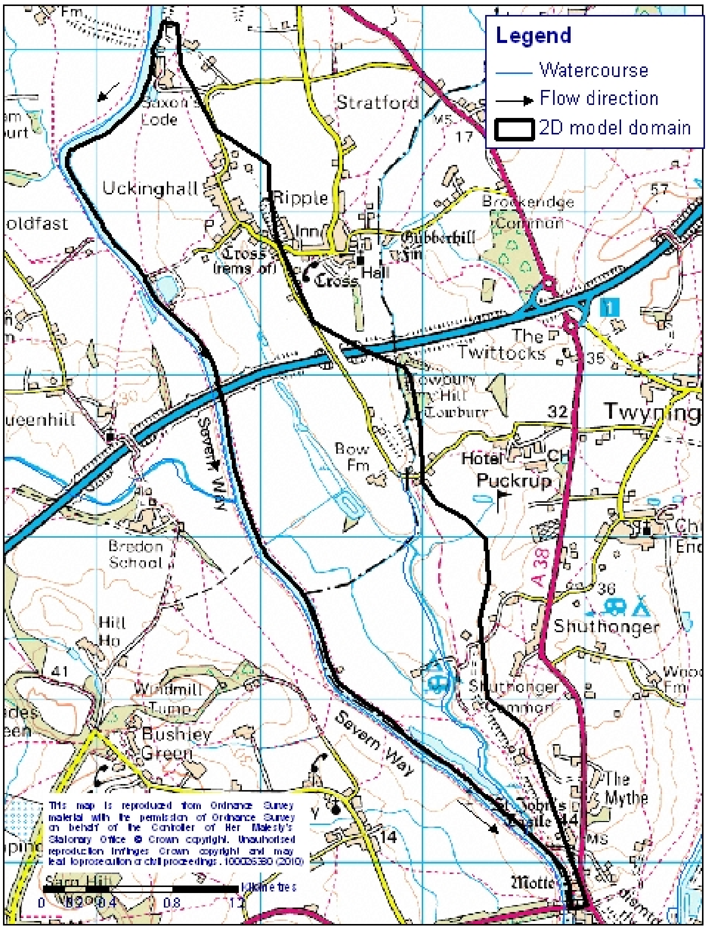


Figure 3.1 River Severn at Uckinghall – site location

3.1.1 The 1D–2D model

The area of the floodplain modelled in the 2D model is 4.4 km^2, of which 3.3 km^2 falls within the Environment Agency's Flood Zone 3 (that is, the area potentially at risk of flooding by a 100-year flood event). There are several water bodies on the floodplain including old drainage channels and a few ponds. The M50 motorway embankment cuts across the floodplain and acts as a partial barrier to the flow on the floodplain, though the bridge opening is very wide.

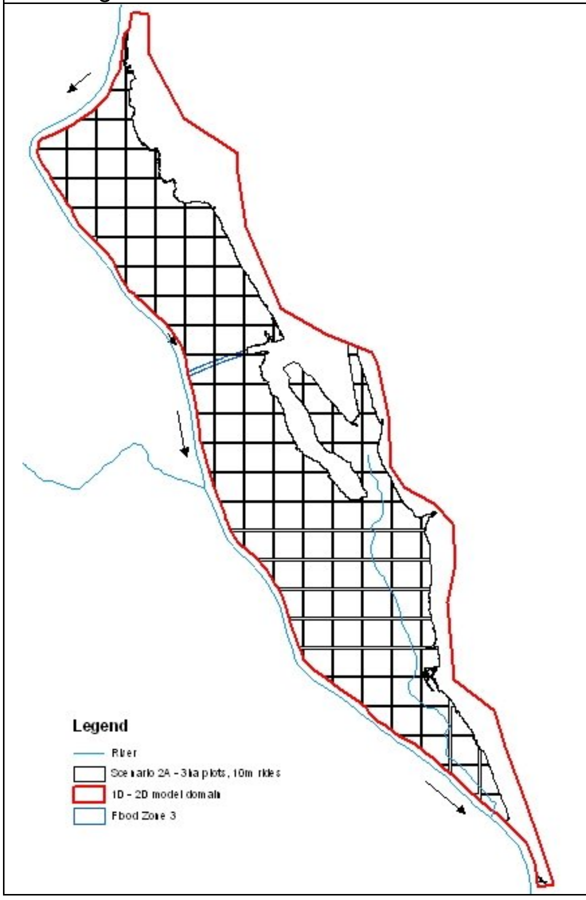
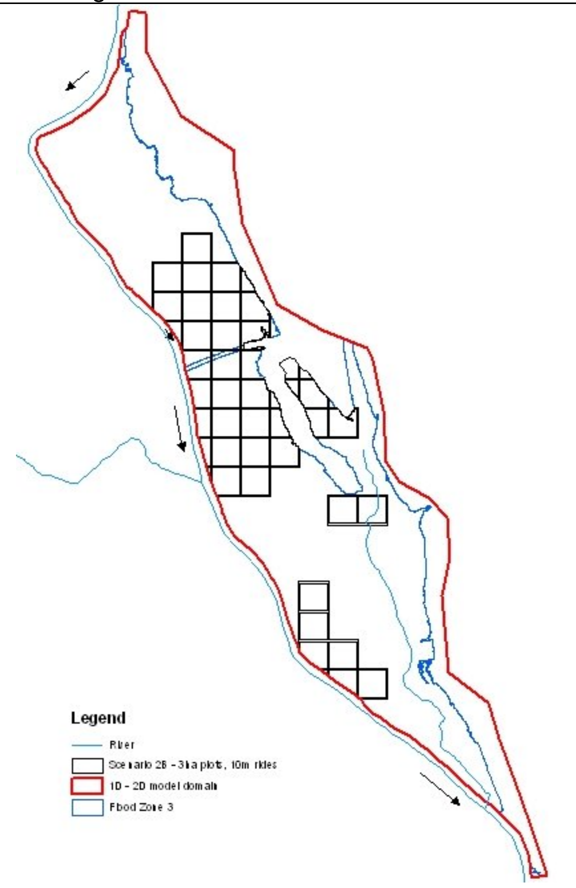
The complete model including an inflow hydrograph with a peak at 763.5 m^3/s (100-year return period) and a complete set of baseline results were available for this study. A 10 m wide buffer strip of grass was also simulated along the river banks to ensure that the plantation remained set away from the river channel. This 10 m strip was already included in the baseline model.

The 2D model domain resolution as received for this study was 10 m, which made it possible to satisfactorily simulate the 10 m wide rides around the plantation plots. A sensitivity test was, however, carried out to determine whether the 10 m cell size was too coarse and water could have artificially been prevented from flowing along the rides. The sensitivity showed that the 10 m resolution gave satisfactory results and therefore the model as supplied was used.

Unfortunately, a model run time of 11.5 hours restricted the exploration of a greater range of scenarios and further development of the methodology. The modelled scenarios were therefore restricted to the basic plantation configurations as described in this section.

3.1.2 Severn at Uckinghall – modelled scenarios

The 1D–2D model was run to simulate eight different scenarios – four for miscanthus and four for SRC willow. Figure 3.2 presents the layout of each modelled scenario

Scenario 2A/3A: 3 ha miscanthus/SRC willow plots, 10 m perpendicular rides, floodplain coverage 100%	**Scenario 2B/3B:** 3 ha miscanthus/SRC willow plots, 10 m perpendicular rides, floodplain coverage 30%
	

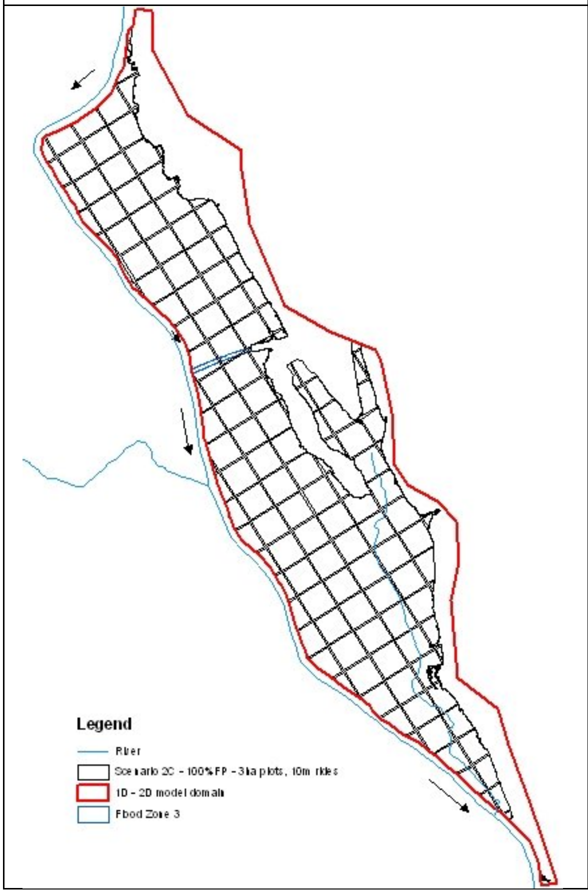
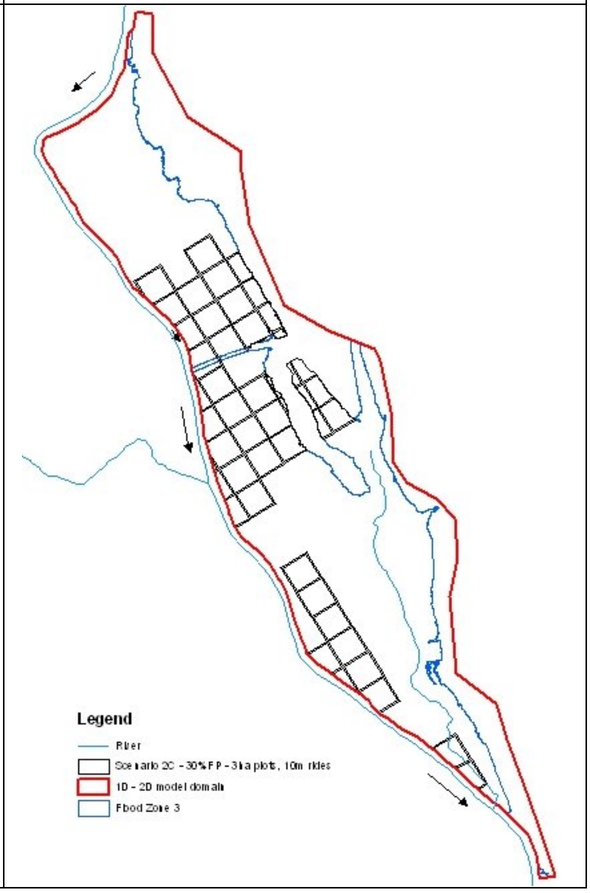
Scenario 2C/3C: 3 ha miscanthus/SRC willow plots, 10 m parallel rides, floodplain coverage 100%	**Scenario 2C/3C**: 3 ha miscanthus/SRC willow plots, 10 m parallel rides, floodplain coverage 30%
	

Figure 3.2 Modelled scenario configurations for Severn at Uckinghall [1]

Notes: [1] The modelled floodplain area is shown in red, rivers and Flood Zone 3 outline in blue, and the energy crop plantation configuration with 10 m rides/headlands in black. The arrows signify the direction of river flow.

3.2 River Isle at Ashford Mill

The second case study model is a small 1D–2D ISIS-TUFLOW model of the River Isle in Somerset. The modelled river reach is only 1.8 km long, flowing in a south–north direction. The floodplain is relatively wide particularly on the right (eastern) bank side, and narrower on the left (western) side at Ashford Mill Farm. There are two bridges, one in the middle section of the model area and one further downstream, and one gauging station operated by the Environment Agency – Ashford Mill, National River Flow Archive (NRFA) ref. 52004. The land use is predominantly arable with localised areas of grassland. Figure 3.3 shows the location of the River Isle and the extent of the 1D–2D model.

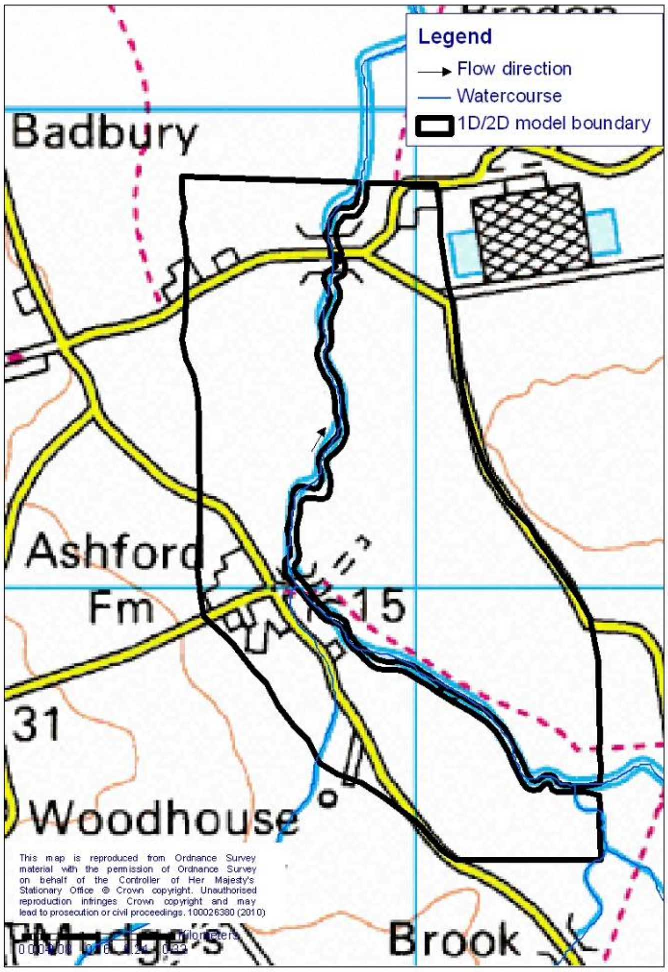


Figure 3.3 River Isle at Ashford Mill – site location

3.2.1 The 1D–2D model

The modelled floodplain has an area of 0.8 km^2, of which 0.5 km^2 falls within Flood Zone 3. The 100-year return period peak flow is 61.3 m^3/s.

The original baseline model employed a 4 m resolution on the floodplain. This, together with the much smaller size of the floodplain, offered greater flexibility in the range of scenarios to test, for example, rides/headlands narrower than 10 m. In addition, the shape of the floodplain allowed a greater range of scenarios to be tested than at Uckinghall, such the plantations on one side of the floodplain only and plantation plots alternating on opposite sides of the floodplain. A 10 m buffer strip of grass along the river banks was also included in the model (represented as a strip of roughness typically used for rough bank vegetation) to prevent immediate interaction of the plantation with the river banks, which would not happen in reality. The buffer strip also helps stabilise the interaction between the 1D and 2D components of the model.

The coupled 1D-2D model run time was only 1.5 hours, which enabled a wide range of scenarios to be tested in a very time-efficient way.

3.2.2 Isle at Ashford Mill – modelled scenarios

In total, 14 scenarios were simulated both for miscanthus and SRC willow plantations. Initially emphasis was given to miscanthus. Further development of the plantation configuration types was then based on the initial results.

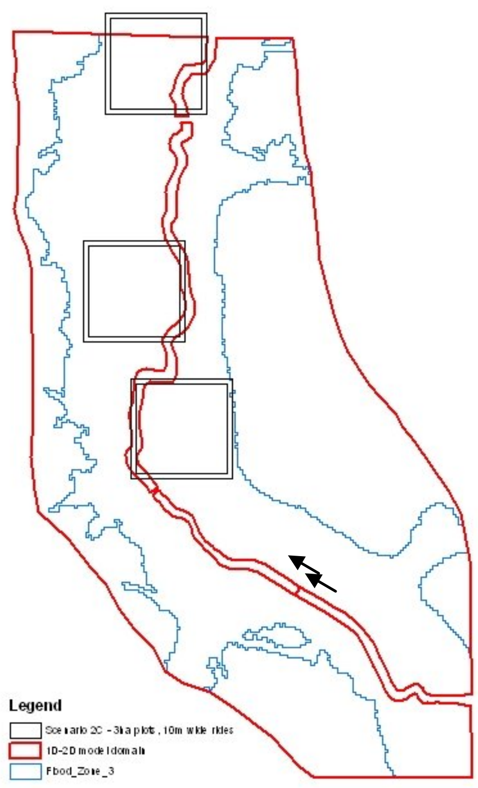
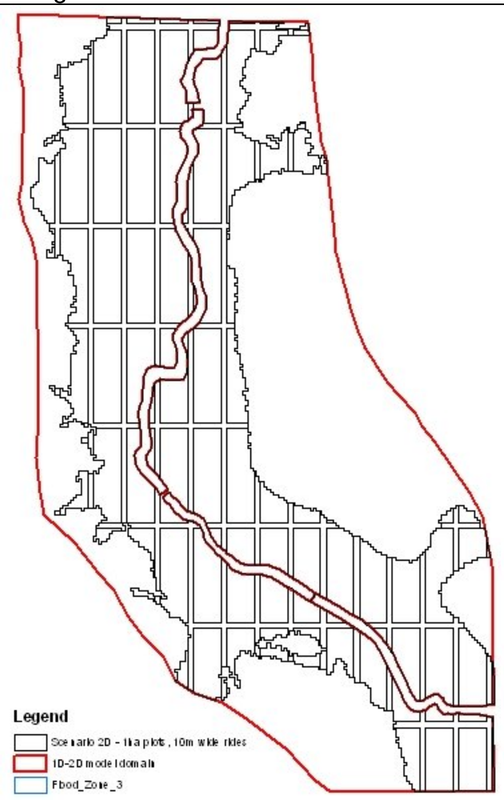
Due to the small size of the floodplain, a 1 ha plantation was applied (with the exception of Scenario 2C), which allowed a greater range of spatial combinations of the plantation configuration to be tested than if only a maximum size of 3 ha plots were used as in the Uckinghall case study (Figure 3.4).

Initially the full floodplain coverage scenarios (that is, Scenario D series) and the 30% floodplain coverage scenarios (that is, Scenario E series) were tested to determine an 'envelope' for the scale of change to flood depths, flood extent, velocities on the floodplain and peak flow in the river at key locations. Further scenarios were then designed that examined, for example:

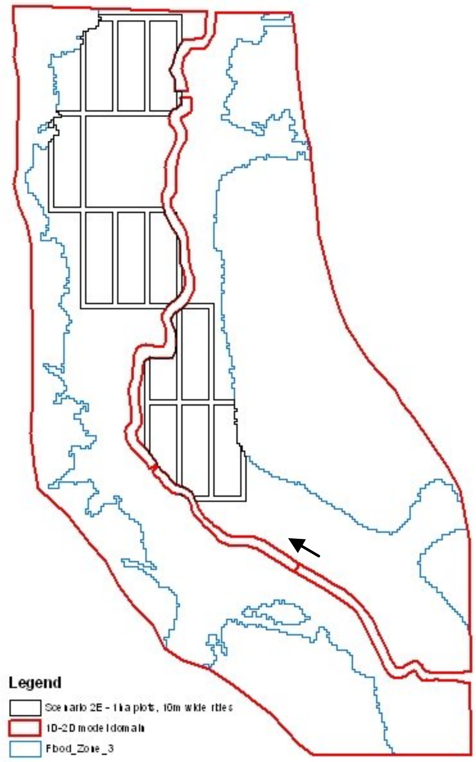
- the impact of plantation plots in a single block across the floodplain acting as a barrier to the flow (for example, Scenarios 2F, 4F or 5F)
- plots with narrower rides (for example, Scenarios 4D, 6D or 4F)
- plots with perpendicular versus parallel rides (for example, Scenarios 5D, 5F or 6D)
- a single block of miscanthus plantation covering one side of the floodplain without rides (for example, Scenario 2C)

The majority of the scenarios modelled miscanthus. SRC willow was represented by three main scenarios (for example, Scenarios 3D, 3E and 3F).

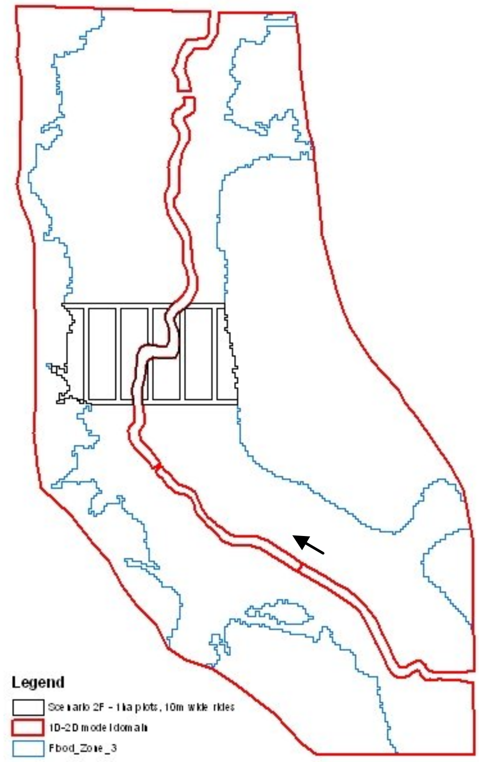
Figure 3.4 presents the complete set of the various plantation configurations used in the modelled scenarios. As mentioned above, the classification of 'perpendicular' and 'parallel' relative to the floodplain flow could be disputed in some of the scenarios, as the floodplain flow direction changes alongside with the general river channel shape. The river channel runs from a south–east to a north–west direction in its upper section and changes direction in the middle of the modelled floodplain to northerly.

Scenario 2C: 3 ha miscanthus plots, 10 m parallel rides around, floodplain coverage 30%	**Scenario 2D/3D**: 1 ha miscanthus/SRC willow plots, 10 m perpendicular rides, floodplain coverage 100%
	

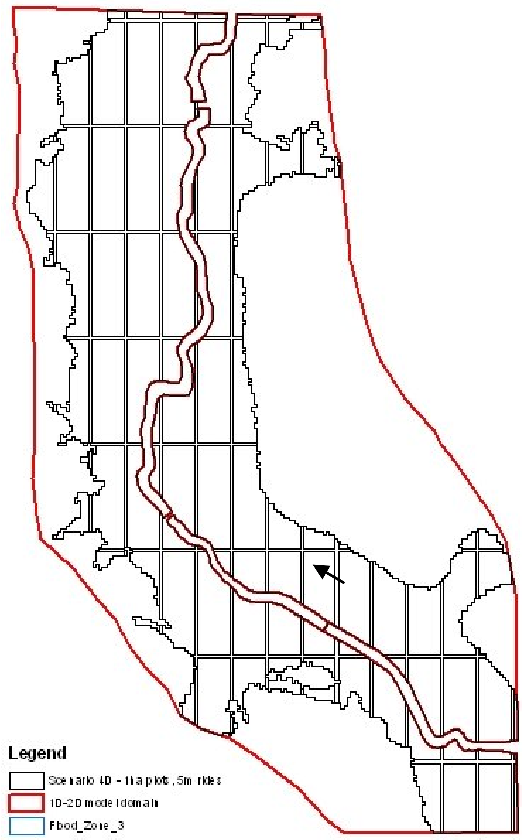
Scenario 2E/3E: 1 ha miscanthus/SRC willow plots, 10 m perpendicular rides, floodplain coverage 30%, distributed plots



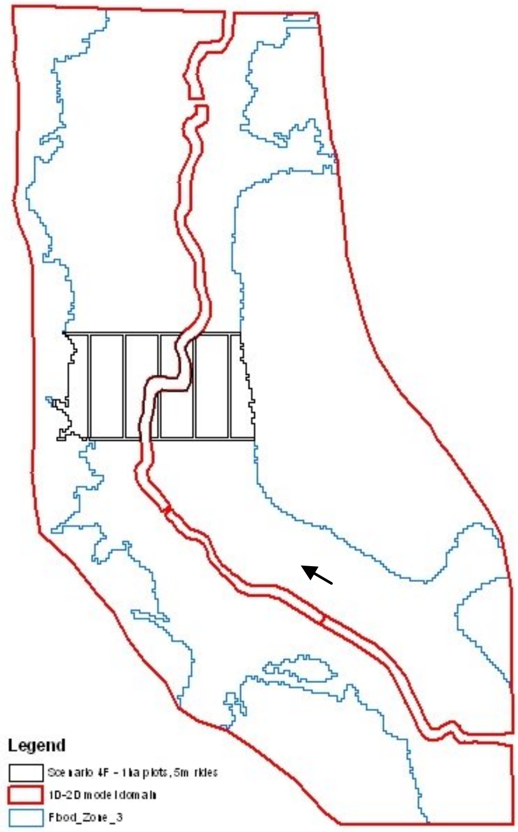
Scenario 2F/3F: 1 ha miscanthus/SRC willow plots, 10 m perpendicular rides, floodplain coverage <30%



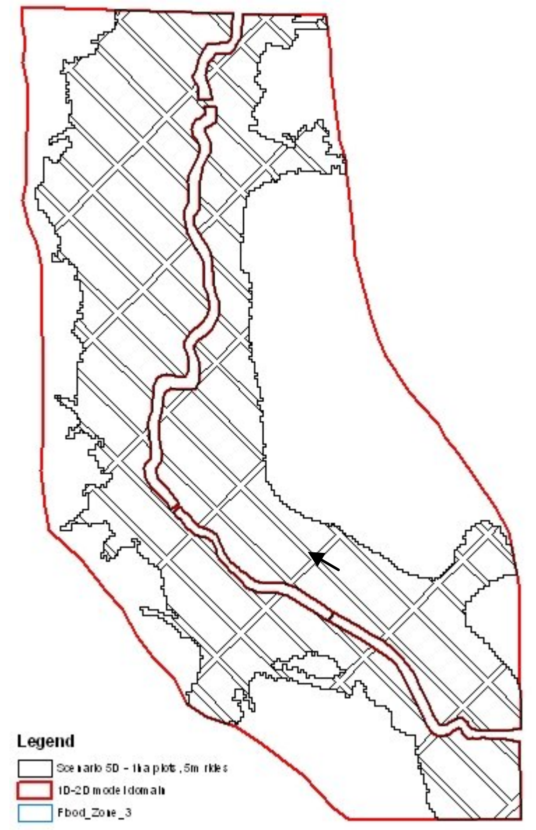
Scenario 4D: 1 ha miscanthus plots, 5 m perpendicular rides, floodplain coverage 100%



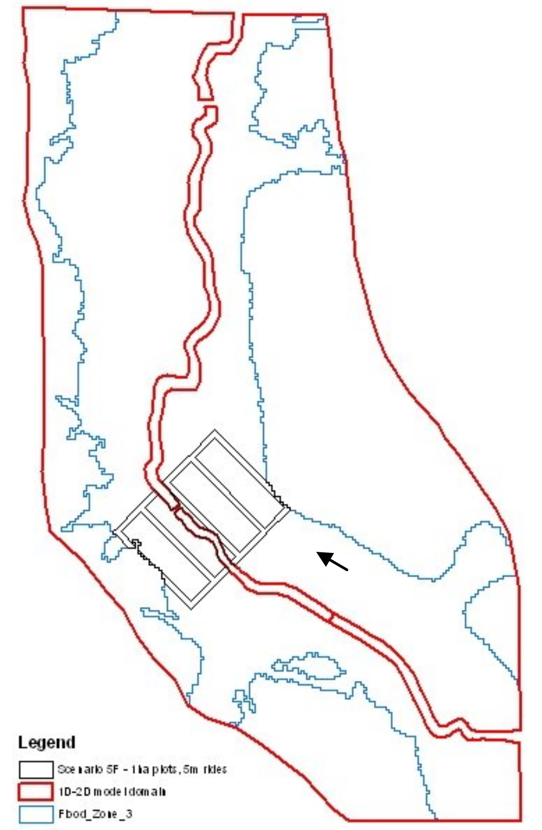
Scenario 4F: 1 ha miscanthus plots, 5 m perpendicular rides, floodplain coverage <30%



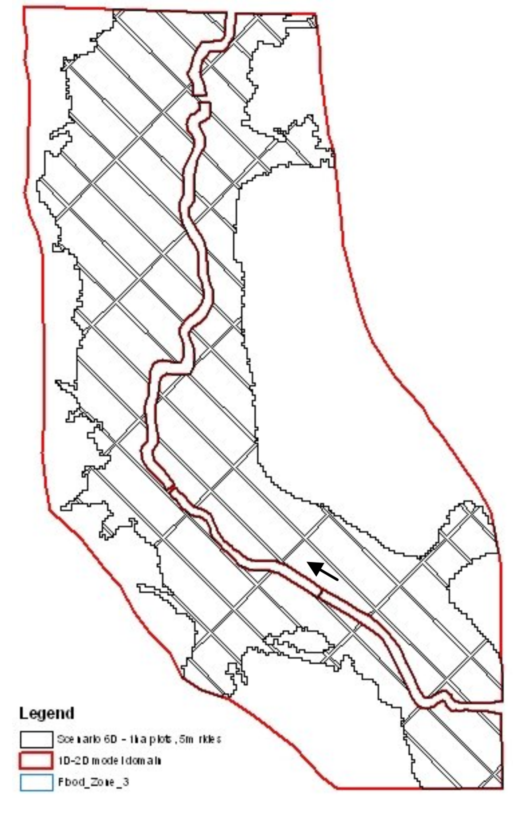
Scenario 5D: 1 ha miscanthus plots, 10 m parallel rides, floodplain coverage 100%



Scenario 5F: 1 ha miscanthus plots, 10 m parallel rides, floodplain coverage <30%



Scenario 6D: 1 ha miscanthus plots, 5 m parallel rides, floodplain coverage 100%



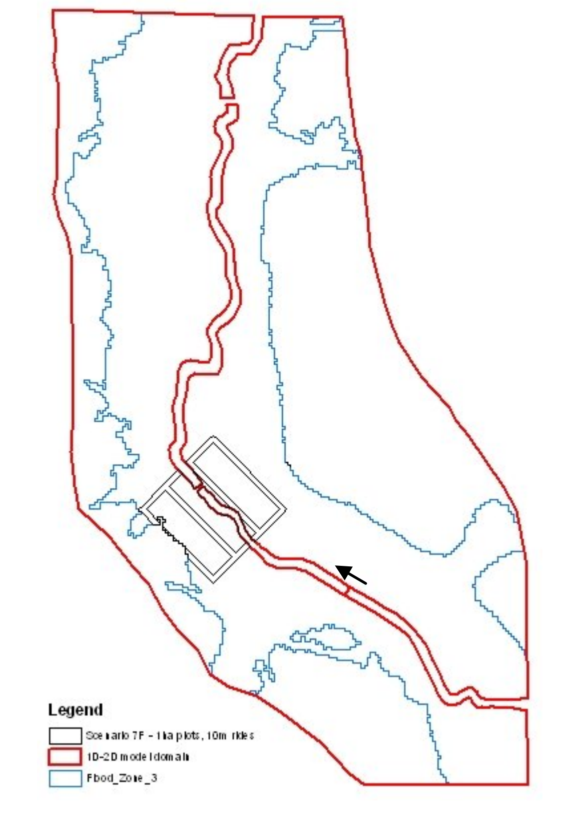
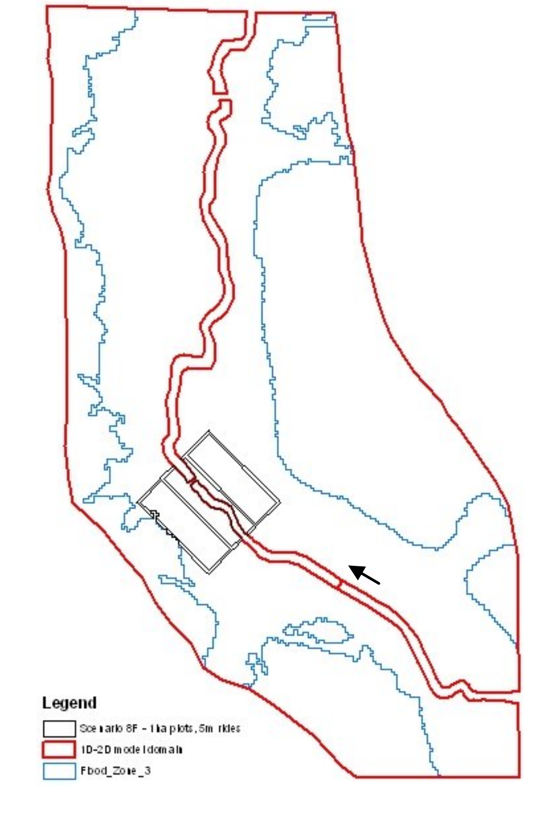
Scenario 7F: 1 ha miscanthus plots, 10 m parallel rides, floodplain coverage <30%	**Scenario 8F**: 1 ha miscanthus plots, 5 m parallel rides, floodplain coverage <30%
	

Figure 3.4 Modelled scenario configurations for Isle at Ashford Mill [1]

Notes [1] The modelled floodplain area is shown in red, Flood Zone 3 outline in blue and the energy crop plantation configuration with rides in black. The arrows signify the direction of river flow.

3.3 Theoretical model floodplain

A simple theoretical 1D–2D ISIS-TUFLOW model was constructed for this project to enable the energy crop scenarios to be tested on an idealised, wide U-shaped floodplain in which the influence of particular local features in the floodplain topography, its shape or the presence of constrictions on the floodplain is minimised. However, the model needed to be realistic in terms of the magnitude of flow, river channel shape and slope.

To aid this, various features of an existing 1D–2D model of the River Exe at Thorverton in Devon were used to help design the theoretical river model cross-sections, the channel slope and sinuosity. The theoretical model also needed to represent a reasonably large floodplain on both sides of the river – ideally a size between the small floodplain of the River Isle at Ashford Mill and the larger floodplain of the River Severn at Uckinghall.

3.3.1 The 1D–2D model

The resulting model represented an idealised river stretch of 2.2 km, flowing in a north–south direction. The altitude of the river banks was taken from the River Exe floodplain and used to develop a new digital terrain model of a smooth, flat 1 km wide U-shaped floodplain gently sloping downstream following the longitudinal slope of the theoretical river.

The river was represented by 12 uniform 1D ISIS cross-section units spaced 200 m apart. The generic dimensions of the river cross-sections and the 100-year inflow hydrograph were taken from the River Exe model. No structures such as bridges or weirs were included in the model set-up. Examples of the typical theoretical river cross-section and the floodplain cross-section are shown in Figure 3.5 and Figure 3.6 respectively.

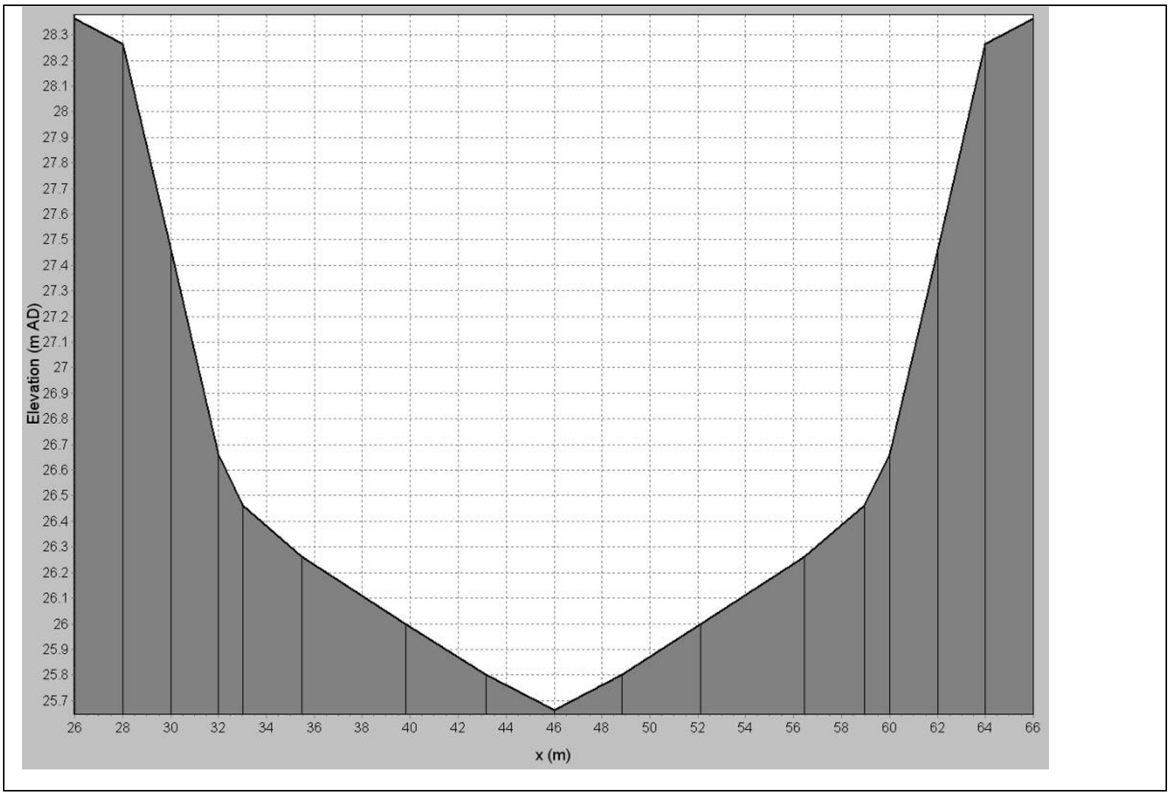


Figure 3.5 Theoretical model river cross-section

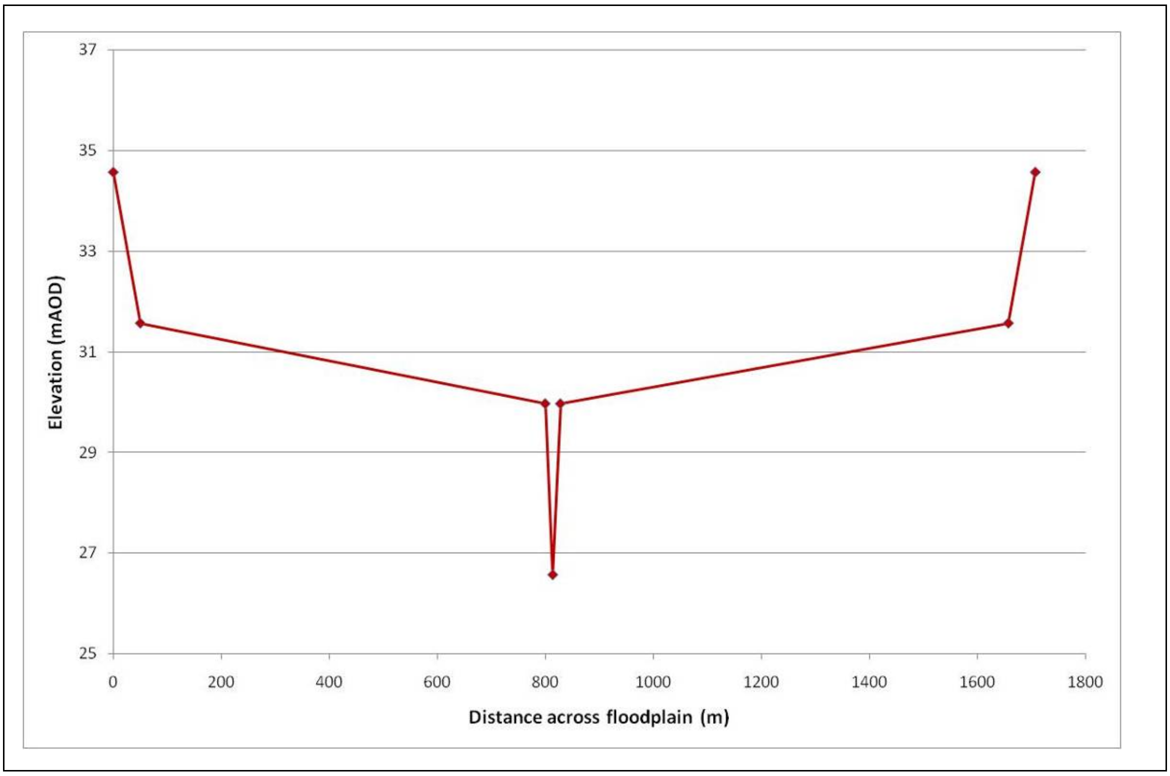


Figure 3.6 Theoretical model floodplain cross-section

The modelled floodplain area was 5.3 km^2, 2.3 km^2 of which were inundated during the simulations. The peak flow of the inflow hydrograph was 409.8 m^3/s. The baseline model was set up with 4 m model domain resolution. As with the previous models, a 10 m buffer strip of grass along the river banks was included. The coupled 1D-2D model run time was eight hours.

Figure 3.7 shows the layout of the theoretical model and the underlying topography designed for the model.

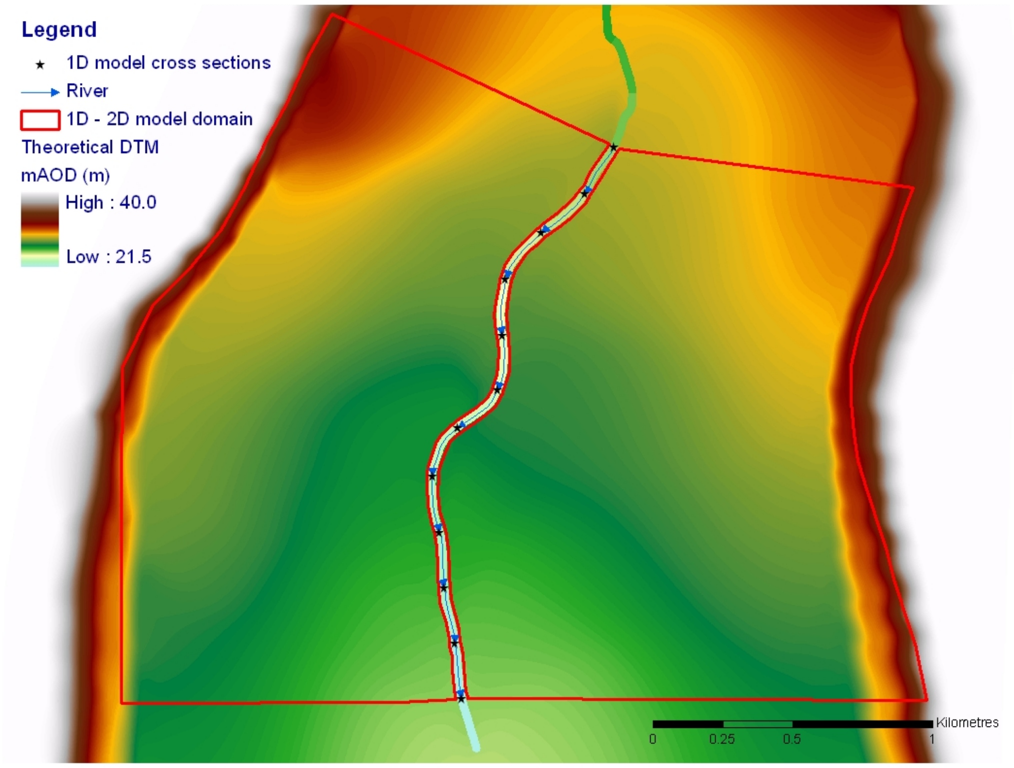


Figure 3.7 Theoretical model – model layout and topography

3.3.2 Theoretical model – modelled scenarios

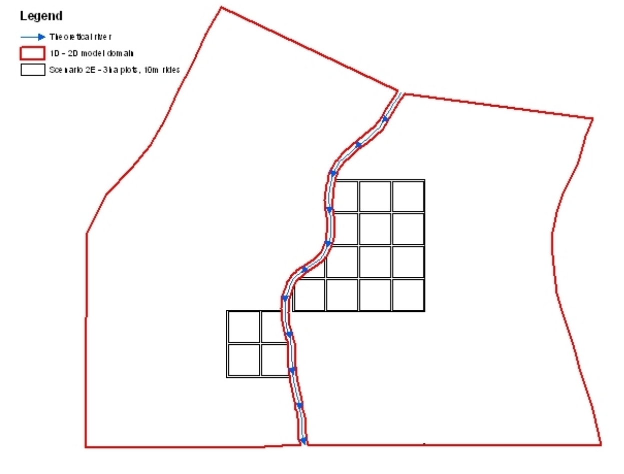
In total, 16 scenarios including the baseline were simulated in the theoretical model for both miscanthus and SRC willow plantations. The scenarios used primarily 3 ha plots with 10 or 5 m rides/headlands around or within.

Unlike in the other case studies, the 100% floodplain coverage scenario was not represented. Instead, focus was given to using the shallow floodplain on both sides of the river and examining:

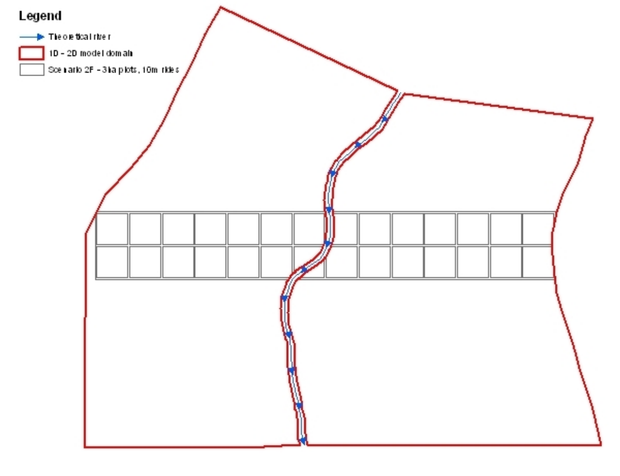
- scenarios with plantations placed across the entire floodplain (for example, Scenarios 2F, 4F, 5F or 6F)
- scenarios with plantations distributed on both sides (for example, Scenarios 2E, 4E, 5E or 6E)
- an additional scenario that aimed to investigate the effect of the plantation being set further away from the river (Scenario 9E).

Figure 3.8 illustrates the scenarios modelled.

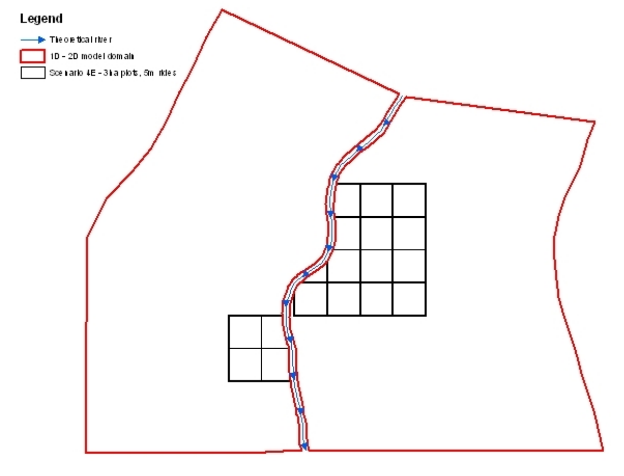
Scenario 2E/3E: 3 ha miscanthus/SRC willow plots, 10 m perpendicular rides, floodplain coverage 30%



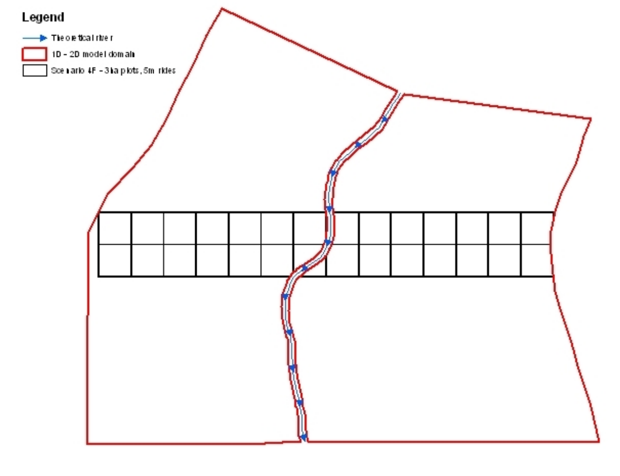
Scenario 2F/3F: 3 ha miscanthus/SRC willow plots, 10 m perpendicular rides, floodplain coverage <30%



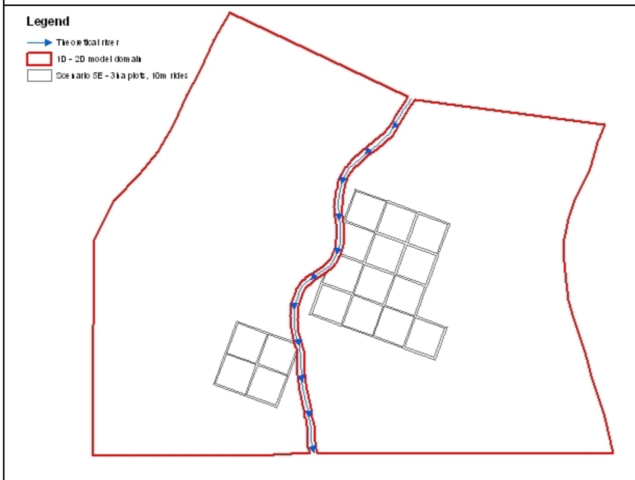
Scenario 4E: 3 ha miscanthus plots, 5 m perpendicular rides, floodplain coverage 30%



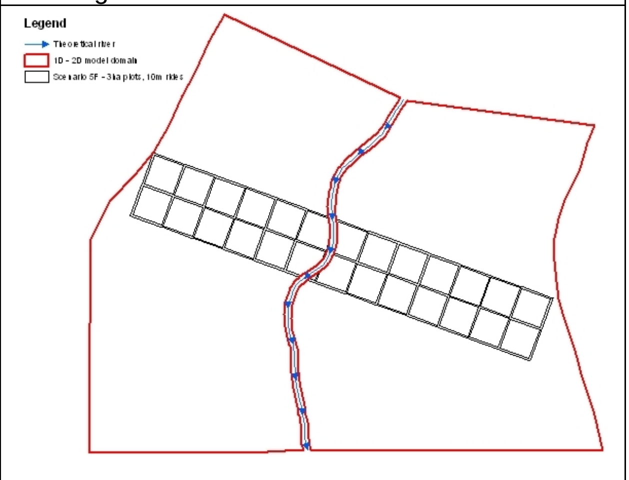
Scenario 4F/4F willow: 3 ha miscanthus/SRC willow plots, 5 m perpendicular rides, floodplain coverage <30%



Scenario 5E: 3 ha miscanthus plots, 10 m parallel rides, floodplain coverage 30%



Scenario 5F/5F willow: 3 ha miscanthus/SRC willow plots, 5 m parallel rides, floodplain coverage <30%



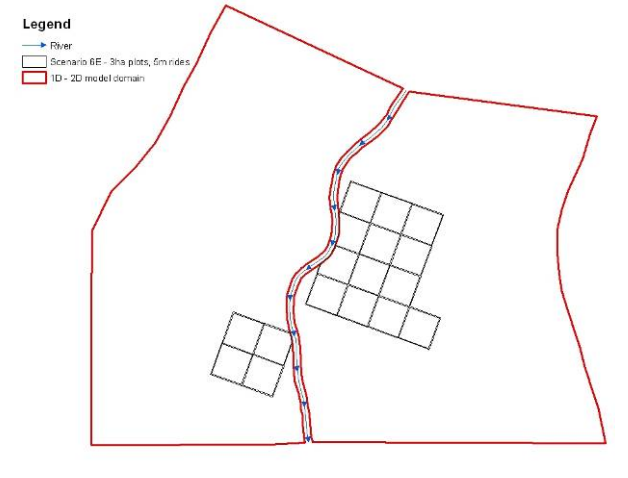
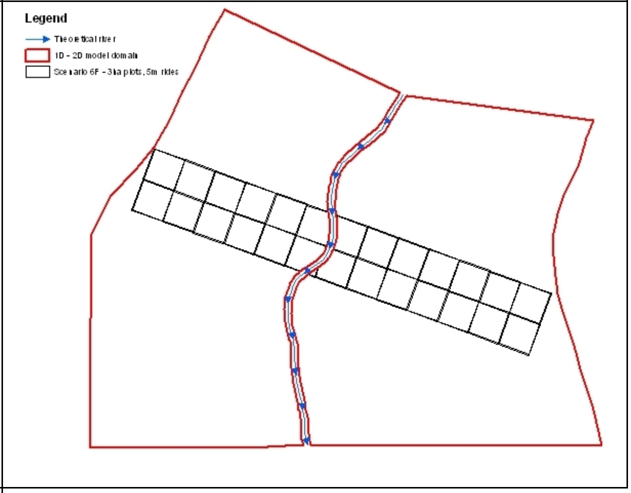
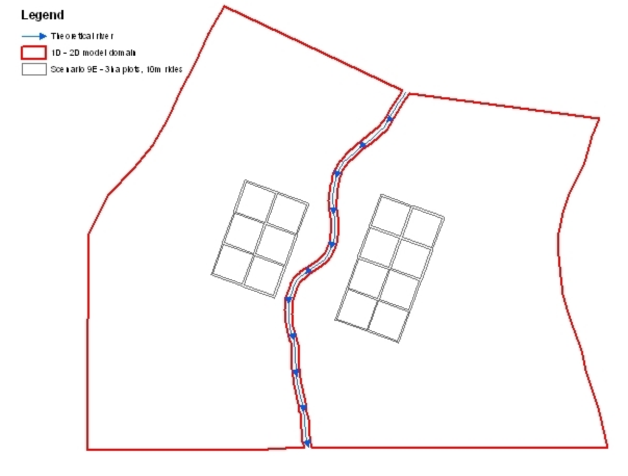
Scenario 6E/6E willow: 3 ha miscanthus/SRC willow plots, 5 m parallel rides, floodplain coverage 30%	**Scenario 6F**: 3 ha miscanthus plots, 5 m parallel rides, floodplain coverage <30%
	
Scenario 9E/9E willow: 3 ha miscanthus/SRC willow plots, 10 m parallel rides, floodplain coverage <30%	
	

Figure 3.8 Modelled scenario configurations for River Isle at Ashford Mill [1]

Notes: [1] The modelled floodplain area is shown in red, river in blue, and the plantation configuration with rides/headlands in black. The arrows signify the direction of river flow.

4. Case study modelling results

The final set of modelling scenario characteristics taken forward for the 100-year flood event are summarised in Table 2.5. The 100% floodplain coverage scenario provides an insight into the maximum possible impact of a plantation on flood dynamics, although is unlikely to apply in practice. The scenarios with a much more distributed and/or dispersed pattern of plantation blocks across the floodplain better reflect actual planting regimes. Plantation blocks that extend across the central portion of the floodplain, thus acting as a form of a ‘leaky green dam’, are also considered.

For each particular scenario, flood depth on the floodplain, velocity and in-channel flows were extracted from the model results.

A comprehensive set of results graphics for all the case studies is given in electronic format in Appendix B. A summary matrix that encapsulates all the modelling results from all the case studies is given in Section 4.2.

4.1 River Isle at Ashford Mill

An example set of the final modelling scenarios for the River Isle at Ashford Mill are presented below for one particular distributed plantation configuration for both miscanthus (Scenario 2E) and SRC willow (Scenario 3E). These are compared with the baseline floodplain scenario, that is, complete coverage of the floodplain with a winter wheat crop.

4.1.1 Flood depth

Modelling scenarios – miscanthus

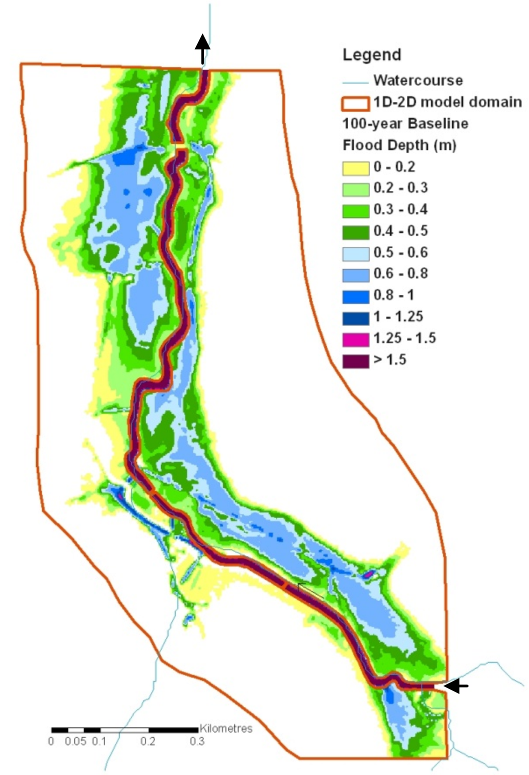
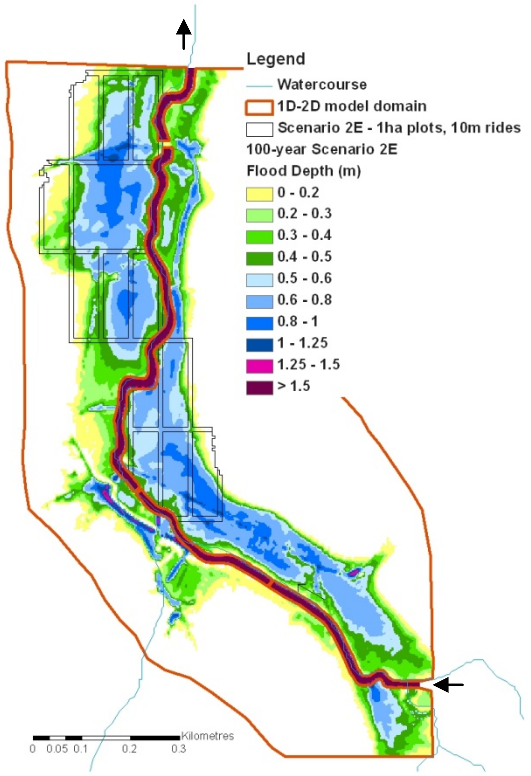
Compared with the baseline condition, the miscanthus plantation blocks (Scenario 2E) act to generally hold the water levels up within the plantation block itself and within an area immediately upstream of the plantation block, with maximum flood depth reaching 0.8–1 m (Figure 4.1A). This had the effect of widening the maximum flood extent slightly.

Figure 4.1B shows the actual increase or decrease in maximum flood depth compared with the baseline condition. Increases in maximum flood depths of 10–20 cm are observed within the two northernmost plantation blocks and for a distance up to about 80 m immediately upstream of the block. The most southern block produced a slightly higher increase in maximum flood depth of 10–30 cm, both within the plantation and up to about 200 m immediately upstream of the block. Across the rest of the floodplain increases in flood depth were less than 10 cm.

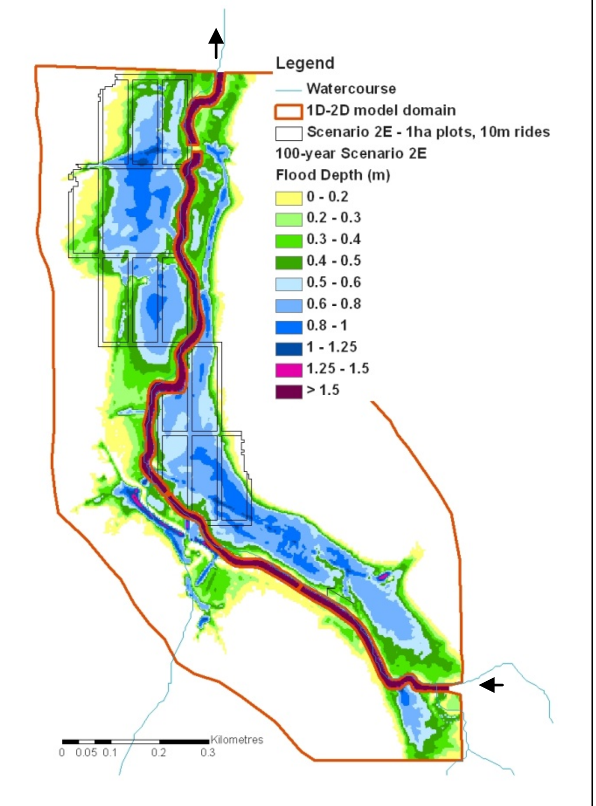
Interestingly the central block and southern block, both of which extend across one half of the floodplain width, did force some of the floodwater to preferentially move over to floodplain on the other side of the main river and raise the water levels there. This water diversion effect may be quite important on those floodplains where land ownership does not extend to both sides of a river.

Modelling scenarios – SRC willow

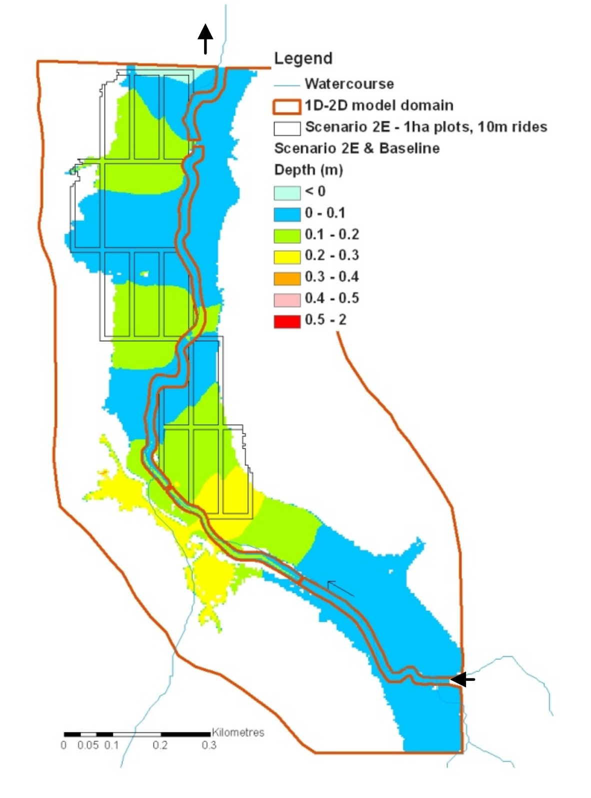
In contrast to miscanthus, the blocks of SRC willow in the same configuration and coverage (Scenario 3E) produced much smaller impacts on the maximum flood depths compared with the baseline (Figure 4.1C). This can be attributed to the decreased roughness for smaller depths of flood inundation compared with miscanthus. The maximum flood level was only increased by 10–20 cm on the upstream edge of the southernmost block. Throughout the rest of the floodplain, flood depths changed by less than 10 cm compared with the baseline.

<table>
<tr><td>A. Flood depth (max) baseline (winter wheat across entire floodplain)</td><td>A. Flood depth (max) Scenario 2E (1 ha miscanthus plantation blocks with 10 m rides, 30% floodplain coverage)</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

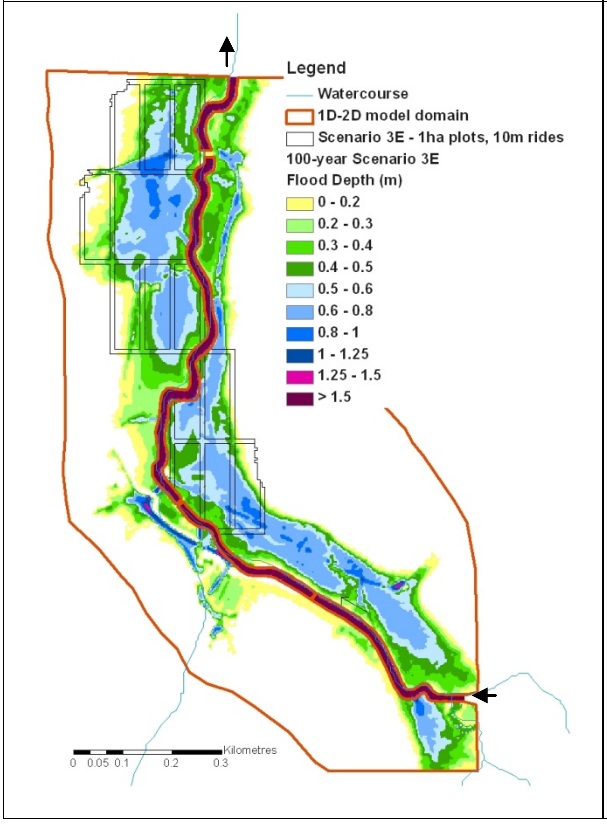
B. Flood depth (max) Scenario 2E miscanthus



B. Flood depth (max) difference (miscanthus) – Scenario 2E minus baseline



C. Flood depth (max) Scenario 3E (1 ha SRC willow plantation blocks with 10 m rides, 30% floodplain coverage)



C. Flood depth (max) difference (SRC willow) – Scenario 3E minus baseline

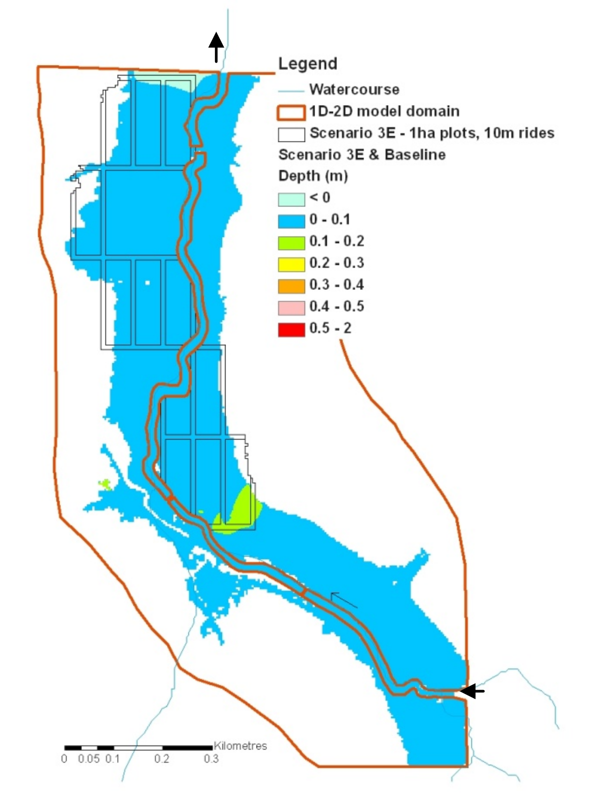


Figure 4.1 River Isle at Ashford Mill – flood depth patterns

4.1.2 Flood velocity and floodplain flow pathways

The configuration of the plantation blocks also influenced the velocity (speed) of water movement across the surface of the floodplain, together with the flow pathways or routes that the floodwater took across the floodplain (through and around the plantation blocks).

When the floodwater reached the plantation area, it either travelled through the main body of the plantation (over and/or around the surface vegetation, debris, plant stems and tree trunks), along the vegetated headlands (surrounding the perimeter of the plantations) or along the vegetated access rides (that pass through the plantations). This enforced split of the flood flow into multiple pathways caused the floodwater to change speed depending on which pathway was taken.

Modelling scenarios – miscanthus

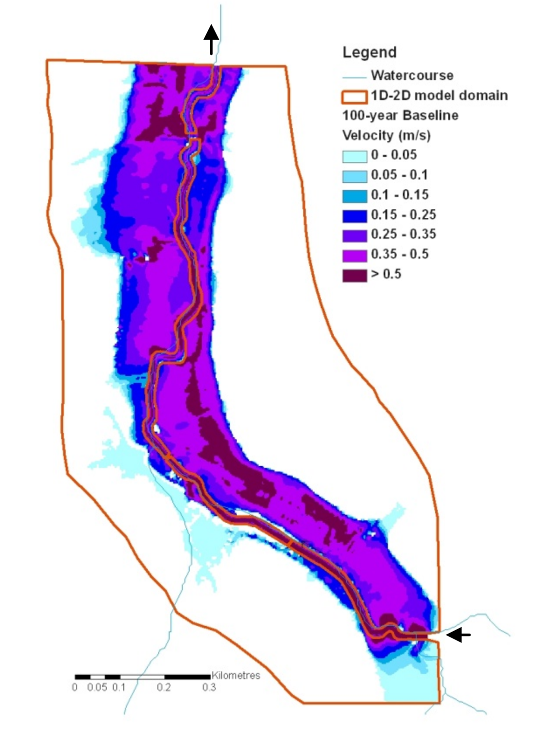
The miscanthus plantation blocks (Scenario 2E) caused a reduction compared with the baseline from over 0.5 m/s to 0.15–0.25 m/s in the maximum flow velocity within the main vegetative body of the plantation. Faster preferential flow routes (or ‘short circuit’ pathways) were created along both the rides and headlands (Figure 4.2A).

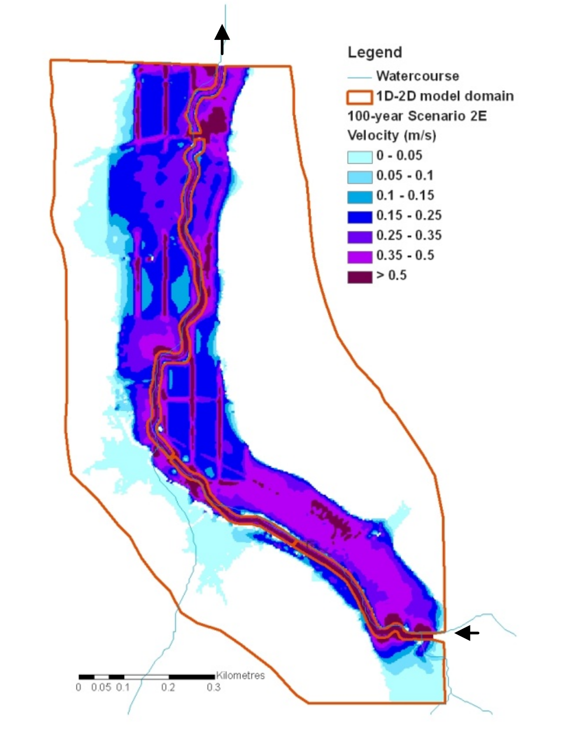
Where floodwater was forced across onto the other side of the floodplain due to the presence of the plantation block, the extra floodwater on the opposite floodplain also flowed faster than the baseline condition. The maximum flow velocity along the headlands and rides (>0.5 m/s) was similar to that predicted over the unrestricted baseline floodplain. This is a consequence of the basic hydraulic characteristics of the vegetation within the headlands and rides being very similar to those of the baseline (winter wheat) condition.

Modelling scenarios – SRC willow

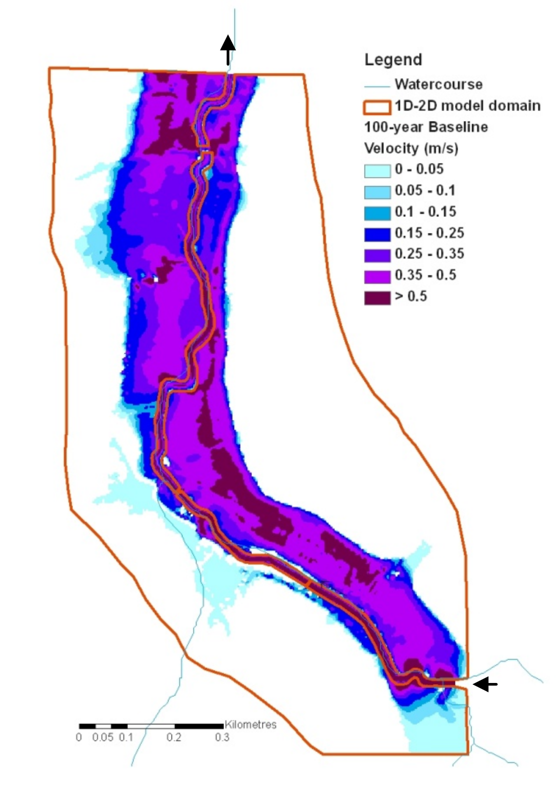
As observed for flood depths, SRC willow (Scenario 3E) had a smaller impact on flow velocities than an equivalent plantation of miscanthus (Figure 4.2B). Flow velocities within the main vegetative body of the plantation were only reduced from about 0.5m/s to 0.25–0.35 m/s. The changes in the pattern of the new flow pathways caused by the SRC willow plantation blocks were, however, very similar to those for miscanthus.

A. Flood velocity (max) baseline (winter wheat across entire floodplain)	**A.** Flood velocity (max) Scenario 2E (1 ha miscanthus plantation blocks with 10 m rides, 30% floodplain coverage)





B. Flood velocity (max) baseline (winter wheat across entire floodplain)	**B.** Flood velocity (max) Scenario 3E (1 ha SRC willow plantation blocks with 10 m rides, 30% floodplain coverage)



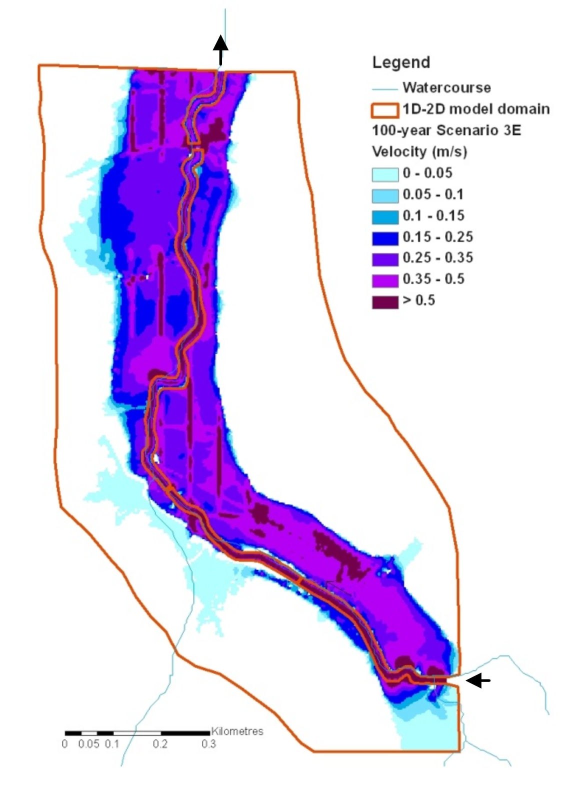


Figure 4.2 River Isle at Ashford Mill – flood velocity patterns

4.1.3 Flood hydrographs

The modelled in-river channel hydrograph for the 100-year flood event (that is, 1% AEP) was generated for each model cross-section in explore how flow in the main channel interacts with, and is also influenced by, out of bank floodplain flows.

Figure 4.3 shows the in-channel hydrographs (that is, as modelled in the 1D ISIS river channel model) for a number of the model nodes along the River Isle. In all cases shown, the black line is the baseline case, the red line is Scenario 2E (that is, 1 ha miscanthus plantation blocks with 10 m rides, 30% floodplain coverage) and the blue line is Scenario 3E (1 ha SRC willow plantation blocks with 10 m rides, 30% floodplain coverage).

Impact on in-channel river flows upstream of the plantation

At a location about 400 m upstream of the first (most southern) plantation, the in-channel hydrograph (that is, showing only the flow in the river, regardless of the flow on floodplain) is not affected by the presence of the plantation further downstream (Figure 4.3A). However, at a distance of about 200 m upstream of the plantation, the presence of the plantation (whether miscanthus or SRC willow) caused the in-channel flood peak flow to be lowered compared with the baseline (Figure 4.3B). The influence of the miscanthus block is greater (7% decrease in peak flow) than that of SRC willow (3% decrease). More water is being directed onto the wide eastern floodplain in this area by the plantation blocks further downstream, thereby creating a decrease in the flow rate within the main channel.

Impact on in-channel river flows at the plantation

In contrast, the localised effect of the vegetation causes an increase in in-channel flows (by 7% for miscanthus and 5% for SRC willow) within the main body of the plantation (Figure 4.3C). This increase in peak flow continues downstream within the plantation (Figure 4.3D), where the interactions with the miscanthus plantation cause the peak flow to increase by 10% for miscanthus and by 3% for SRC willow. The narrowness of the floodplain width on the eastern bank restricts floodplain flow to the near river corridor (including the riverside headland area). In the area in between two plantation blocks (Figure 4.3E), where water is able to more freely flow over a more unrestricted floodplain, the influence of the plantation falls (miscanthus 5% increase, SRC willow 2% increase).

Impact on whole floodplain flows

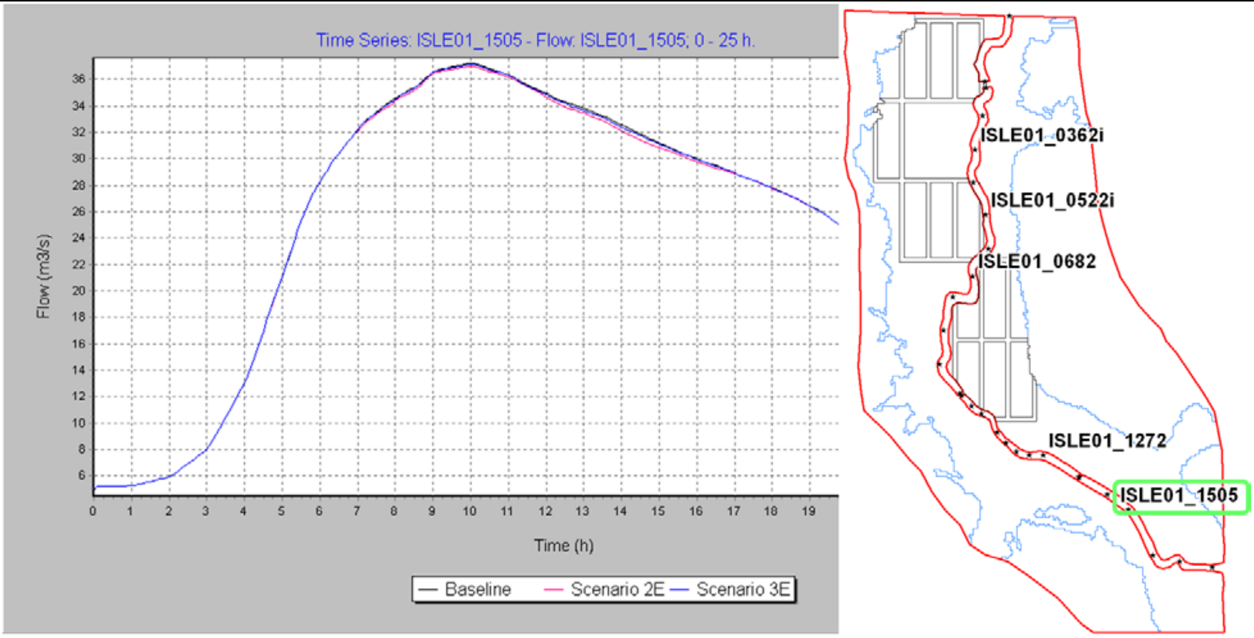
In general, increased flood depth and decreased flood velocities were, by implication, associated with decreased floodplain flows due to the water moving at slower rate through a larger greater area (imposed by the increased depths).

The floodplain hydrographs were extracted for a selection of scenarios and the magnitude of the change ranged as follows:

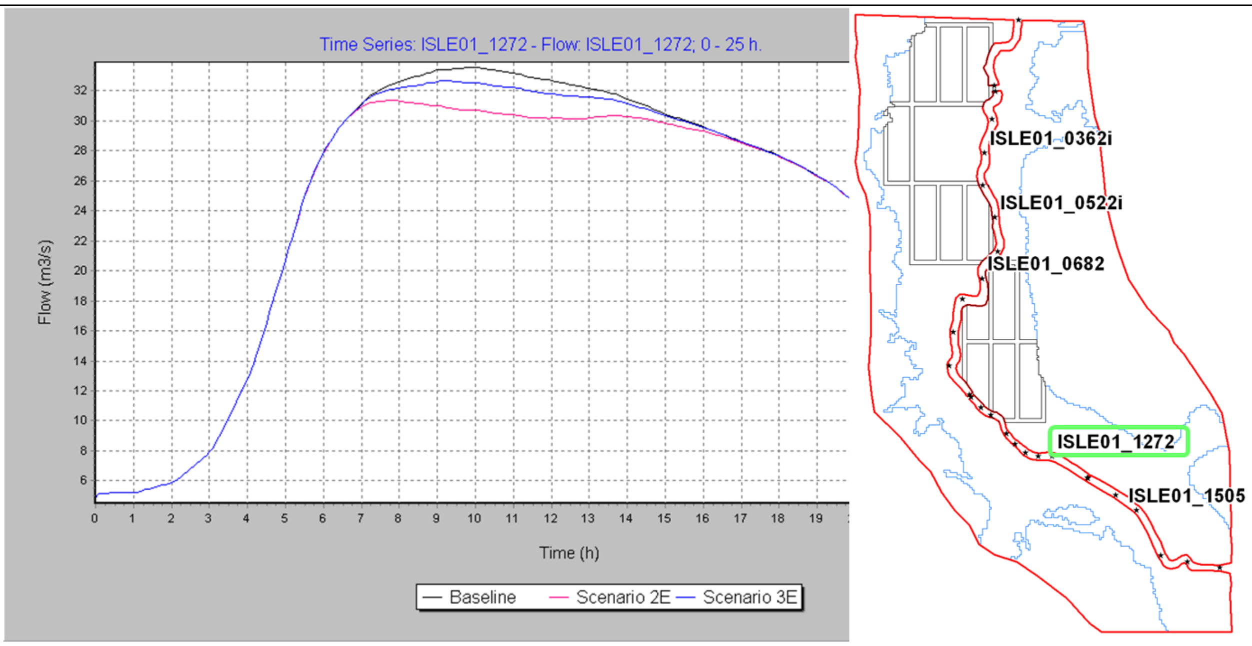
- 14–23% decrease of flood peak on the floodplain for Scenario 4D (1 ha miscanthus plots with 5 m perpendicular rides, 100% floodplain coverage)
- up to 8% decrease along the miscanthus plantation plots for Scenario 2E (that is, the distributed 1 ha plots with 10 m rides, 30% floodplain coverage)

- up to 32% decrease directly at the miscanthus plots for Scenario 4F (that is, a stripe of 1 ha miscanthus plantation plots with 5 m rides) and only up to 1% decrease elsewhere
- up to 14% decrease directly at the SRC willow plantation plots for Scenario 3F (that is, a stripe of 1 ha SRC willow plots with 10 m rides) and only negligible decrease elsewhere

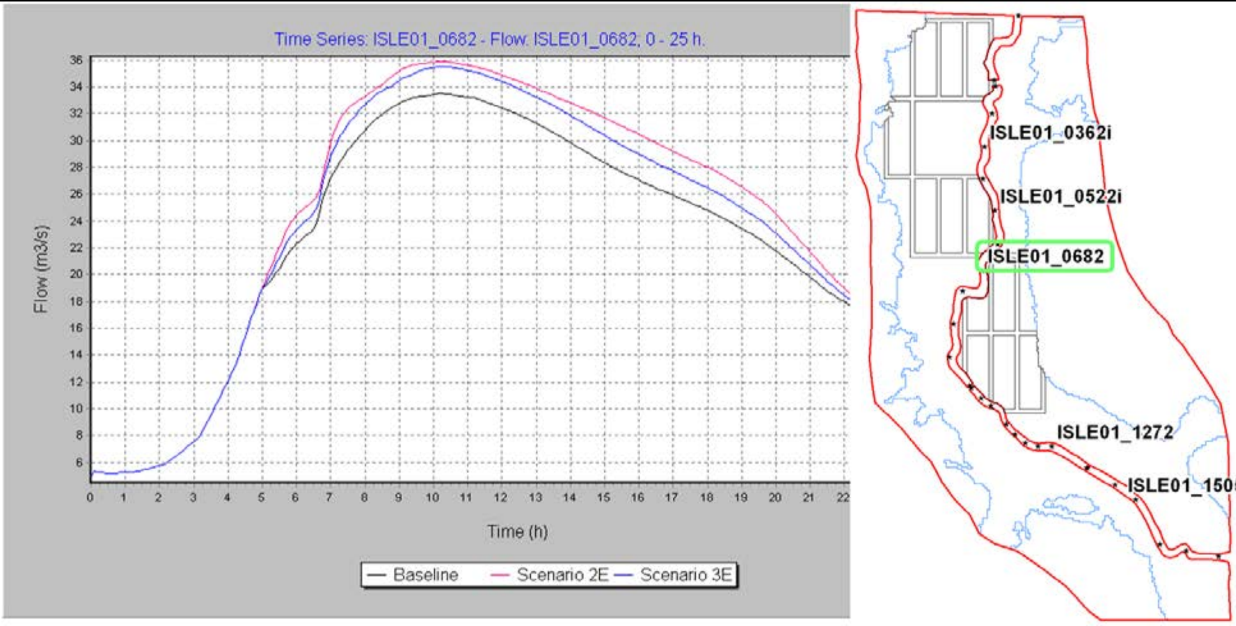
A 400 m upstream of plantation (model node 1505)



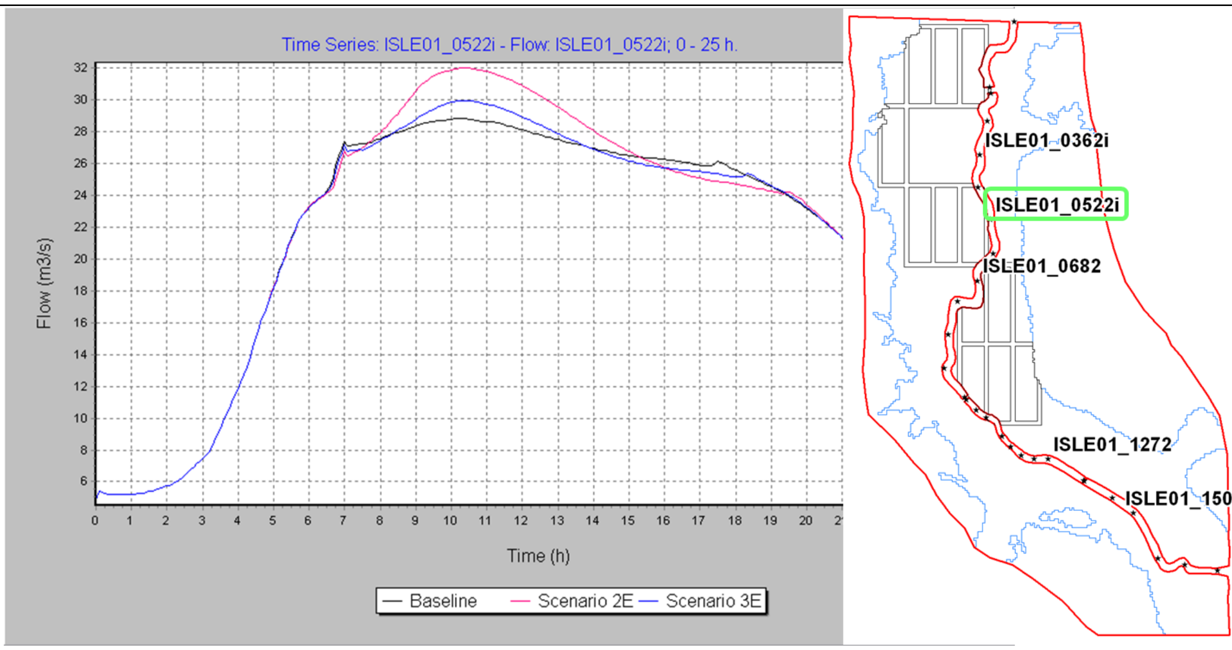
B 200 m upstream of plantation (model node 1272)



C Next to small plantation on eastern floodplain (model node 0682)



D Next to larger plantation on western floodplain (model node 0522)



E Between two plantation blocks (model node 0362)

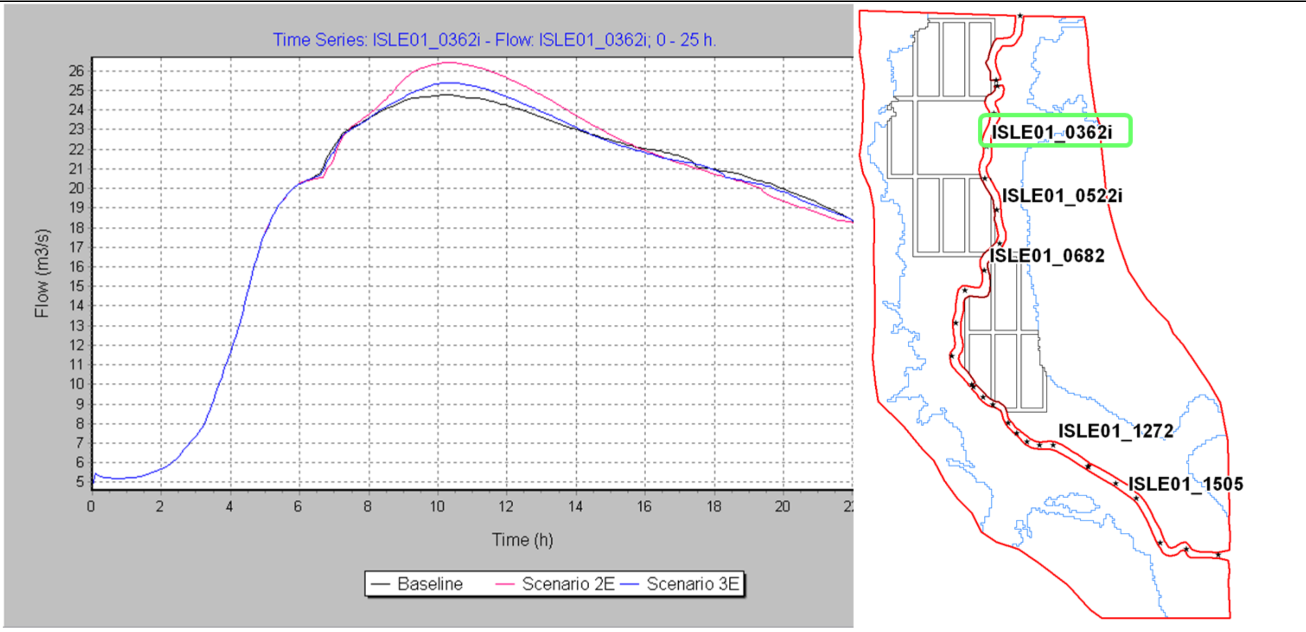


Figure 4.3 River Isle at Ashford Mill – main channel flood hydrographs [1]

Notes: [1] Modelled floodplain in red, plantation layout in black and Flood Zone 3 extent in blue).

4.2 Summary results

In total, 40 scenarios were modelled and their results analysed for all the three case studies. A summary results matrix was generated based on the analysis (Table 4.1), which represents a synthesis of the model predictions for the 100-year flood event over the range of scenarios explored across the three case study floodplains. The matrix presents the findings from the modelling scenarios in a generic, qualitative way and hence allows a general understanding of the results in wider context with regard to the location of energy crop plantations on a floodplain.

The modelling scenarios do not represent an exhaustive set of floodplain plantation configurations and therefore neither does the matrix.

Table 4.1 Summary results matrix

Plantation configuration on floodplain	Flood depth (max)			Flood velocity (max)				In-channel flood flow (max)		
	Upstream plantation	Within plantation	Downstream plantation	Upstream plantation	Within plantation	Within ride	Downstream plantation	Upstream plantation	Within plantation	Downstream plantation
Complete (100%) coverage	n/a	+/++	n/a	n/a	—	+	n/a	n/a	+	n/a
Distributed blocks (30% coverage)	+	+/++	+/0	–	—	+	–	–/0	+	+/0
Central block (full floodplain width)	++	++	–	–	—	+	0	–/0	++	+/0
Central block (part floodplain width)	+	+	–	0	—	0	0	–/0	+	+/0

Notes:

Symbol	Definition	Maximum flood depth change	Maximum velocity change	In-channel peak flow change
++	Increase	>20 cm increase	>40% change	>10% increase
+	Slight increase	5–20 cm increase	10–40% increase	2–10% increase
0	Minimal effect	±5 cm increase/decrease	±10% increase/decrease	±2% increase/decrease
–	Slight decrease	5–20 cm decrease	10–40% decrease	2–10% decrease
—	Decrease	>20 cm decrease	>40% decrease	>10% decrease
n/a	Not applicable (not in model domain)	n/a	n/a	n/a

5. Discussion and conclusions

5.1 Assumptions and limitations

5.1.1 The modelling approach

A number of assumptions had to be made concerning the way in which the energy crops were represented in the hydraulic models. These assumptions were based on a review of recent publications and research available, but in effect no specific field study datasets were available to verify exactly what floodplain roughness values should be used for mature miscanthus and SRC willow vegetation. There are still gaps in knowledge in this area despite recent advances about how to represent roughness (for example as part of the Conveyance Estimation System) and how it should vary with scale within 2D models. Interest in the impact of various vegetation types (including energy crops and woodland) on floodplain flows and on the floodplain environment means this has increasingly become the subject of research.

5.1.2 Representation of energy crop plantations

The modelling work had a number of limitations relating to the simulated plantation configurations (that is, no allowance was included for the local field boundary structure) and the plantations were square/rectangular (which would not be the case in the reality). It was also not possible to properly assess the concept of ‘parallel’ and ‘perpendicular’ rides/headlands next to a meandering river channel.

The lifecycles of miscanthus and SRC willow include a period of time every year in the case of miscanthus, or once in three years in the case of SRC willow, when the crops are harvested and the bare earth is exposed before regrowth occurs. This implies that the resistance to flow of the plantations would be expected to be much less than that of the fully grown mature crop. This same condition would also apply during the establishment period after planting the energy crops. Such situations were not part of the investigations in this project and therefore the modelling scenarios tested only considered the fully grown mature crop just before harvest.

There is a lack of knowledge regarding the behaviour of the energy crops when they are inundated with deep floodwater and/or fast floodwater velocities, and the associated change this would generate on their resistance to flow.

No account could be taken of leaf litter as an additional barrier to flow, or for the potential modifications to near ground levels due to the root system and, particularly for SRC willow, the thick tree trunk-like stems that occur after repeated coppicing.

The choice of the depth-varying hydraulic roughness for SRC willow was based on the recent findings by Wilson (personal communication, 2009) that focused on this type of vegetation cover. However, data in the roughness review by Defra (2003) seem to suggest that the effective value of Manning’s n should decrease as the degree of submergence of the floodplain vegetation increases. This is deemed applicable for grass cover, but not for agricultural crops (such as wheat) or coniferous trees.

Within the scope of this project it was possible for the scenarios to be exhaustive and they did not aim to explore all the possible combinations of the plantation configurations on the floodplain. The aim was to give a flavour of the likely scale of the impact on the river and floodplain flood dynamics so as to identify whether certain combinations of the plantation are acceptable on a floodplain (that is, within Flood Zone 3) without increasing flood risk elsewhere.

5.2 Discussion

The general trend of the results for the scenarios and case study floodplains examined was for the increased floodplain roughness due to the presence of the energy crop plantations to cause:

- flood depths to increase within, and upstream of, the plantation
- increased in-channel river flows next to plantation blocks that extended near to the main river channel (due to less water being able to escape onto the floodplain)

The magnitude of these effects could potentially be important in flood management terms. A predicted 5–10 cm rise in water level would be deemed by the Environment Agency to be important in terms of the potential impact of building developments on the floodplain.

The most important consideration is the proximity of important flood risk receptors to the influence of an increased flood risk. People and property are the most important flood risk receptors. In a rural floodplain context, the property element (which could include the farmland) would need to include the potential impacts on third party land. On some floodplains, however, there may also be important environmental (for example, Sites of Special Scientific Interest) and heritage (for example, Scheduled Ancient Monuments) receptors that require careful consideration.

The spatial extent of the hydraulic effect of a plantation block (whether fully or partially covering the floodplain width) or distributed plantations was, in general, for a distance less than 300 m upstream or downstream of the plantation edge. A similar predicted distance of influence was reported by Thomas and Nisbet (2008) for a floodplain woodland modelling case study on the River Cary in Somerset. However, this study was limited to three case study floodplains and could not fully examine the impact further downstream without coming quite close to the downstream boundary of the model, where the simulated results can be influenced by the boundary conditions more than by what is happening on floodplain (although any backwater effect was minimised).

To meet the modelling aims and objectives of this study, the 2D approach to representation of a floodplain was selected as the most suitable and the linked 1D–2D ISIS-TUFLOW was chosen as an appropriate software package. However, the 1D–2D model linkage configuration can have an important impact on the model results, particularly when the floodplain area near the river banks is concerned – as is the case in this project. This is because it governs the transition of water between the 1D river model and the 2D floodplain model. This link is therefore crucial in determining the amount of water spilling onto the floodplain and the interaction between the flows in the river and on the floodplain.

One of the test cases in a recent benchmarking study of 2D hydraulic models (including ISIS and TUFLOW) explored the linkage of the 1D river and 2D floodplain interaction and the relationship between in-channel flood flow and floodplain flood flow (Néelz and Pender 2010). The study highlighted discrepancies between the tested models in simulated peak water levels on floodplains (that is, once the river embankments were overtopped), which depend critically on river bank overtopping discharges and on flow through structures. The study concluded that large differences in the modelled results of the predicted floodplain water levels originated from differences in how accurately the models represented the geometry of the embankments. However, this is critical to accuracy in overtopping discharge, especially for shallow overtopping depths.

The increase in flood depth and water levels around the plantation blocks, as modelled in this study, is in line with expectations. The apparent increases in flow within the river channel (Figure 4.3) may merit further investigation. In linked 1D–2D models, it is known that the precise way in which the links are set up influences the results. Case studies carried out in the Environment Agency's 2D model benchmarking study for the River Severn illustrate this point (Néelz and Pender 2010). Linked ISIS-TUFLOW models exchange mass across the links between the main (1D) channel model and the floodplain (2D) model according to the relative water levels at each side of the link. In reality, there are also transfers of momentum at the interface between channel and floodplain flows, with complex patterns of turbulence created in some circumstances. For example, Knight et al. (2010) showed how the retarding effects of the shear layers between slower moving floodplain flows and faster moving main channel flow were apparent in detailed measurements for overbank flows at the Montford Bridge on the River Severn. It is possible that, if these processes are not represented in a 1D–2D linkage, then elevated water levels on a rough floodplain could raise water levels in the main channel leading to an increase in flow that may be, at least in part, an artefact of the modelling approach.

As the mathematical complexity of model increases so, in general, do the number of coefficients options that can influence the precise solution obtained in any particular simulation. The TUFLOW software used here includes a number of options that influence exactly how the model represents certain features of the physical system and also how numerical techniques are used to solve the flow equations. The solution of the shallow water equations is based on an alternating direction implicit (ADI) scheme. The model includes a treatment of turbulence, which is modelled using two additional equations to account for the energy in the turbulence and the scale of the turbulence. This turbulence closure includes coefficients that may influence the model predictions but that are rarely adjusted (and for which there is rarely a good basis for making such adjustments). In this study the default values were used.

Environment Agency and Natural England staff involved in the assessment of new ECS applications will be able to use the findings from this study to determine, in general terms, the potential effect of a particular plantation configuration on the local flood dynamics. However, the limitations and uncertainties of the results associated with the modelling approach and uncertainty in the crops' representation need to be kept in mind when applying the results. The assessors should hopefully be able to determine those applications that would not increase the flood risk, bearing in mind any local landownership issues, and may actually provide a valuable downstream flood risk management function. Alternatively, those applications that appear to have the potential to generate larger impacts (either locally or further afield) could then be put forward for a more detailed level of assessment, including the potential need for a formal Flood Risk Assessment to be provided by the applicant.

5.3 Conclusions

The general findings from this short-term modelling work simulating the potential impacts of mature 1–3 ha energy crop plantations (with integral managed rides or headlands) on the 100-year return period flood magnitude are as follows.

- The impacts caused by miscanthus and SRC willow plantations are broadly similar. However, shallow floodplain flooding up to about 1 m is likely to be more affected by miscanthus than by SRC willow, primarily due to the different roughness characteristics up to this depth. The difference is expected to disappear with deeper flooding (for example, greater than 2 m depth).

- The very dense nature of the main vegetative body of the plantation acts like a 'green leaky dam' to hold water back both within and immediately upstream of the plantation and to slow the speed of water propagation across the floodplain. In most cases there will be a corresponding, but smaller, decrease in flood levels in an area immediately downstream of the plantation.
- Where the energy crop plantation fully covers the floodplain, the highest overall impacts on the flood dynamics (flood depth, velocity of flow, main channel flow hydrographs) are observed.
- Well distributed and dispersed plantations with less than 30% floodplain coverage, set away from the main channel, and not significantly blocking the floodplain width (and therefore the flow of water across the floodplain) would only produce very localised effects.
- The extent of the hydraulic effect of a plantation block (whether fully or partially covering the floodplain width) or distributed plantations is, on general, less than 300 m upstream or downstream of the plantation edge.
- Plantation headlands and rides provide faster preferential (short circuit) flow pathways than the main vegetative block.
- Varying of the headland and ride width (5–10 m) did not significantly change the flood dynamics.
- Varying the ride orientation relative to the main river channel orientation did not significantly change the flood dynamics.
- Distributed blocks or a central plantation block did not change the maximum flood extent significantly.
- The greater the plantation coverage, the more water is forced to move in the vicinity of the main channel (and at greater flow velocity and flow rate).

The outcomes of this project were used to develop supplementary guidance to existing Environment Agency guidelines, 'Flood Risk Management: Woodland, Tree Planting and Flood Risk'. This guidance will help to inform future decisions with respect to the establishment of woodland and other similar vegetative types, such as new energy crop plantations, on floodplains. It also provides advice on the selection of Manning's n roughness coefficients to use when representing energy crop plantations in hydraulic models.

6. Recommendations for further work

6,1 Modelling

The nature and scope of this short-term modelling study meant it was only possible to consider a relatively simple modelling approach applied to a limited number of case study floodplains. The following recommendations for further modelling work are made for a more robust and comprehensive consideration of the impacts of energy crop plantations on floodplain flows and flood risk.

- Consider and compare the use of 1D or 2D models only. In particular, the use of a 2D model to simulate both river and floodplain flows, or only floodplain flows in a simplified case, is believed to be an appropriate method. Alternatively, 3D hydrodynamic models could be used. However, these are a 'step up' in terms of cost, input data and computational power demands. The modelling packages that could be used include HEC-RAS, ISIS-CES and MIKE11 (1D models), TELEMAC and MIKE21 (2D models), and CFX, PHOENICS (3D models). For analysis using 2D models and, in particular linked 1D–2D models, the results of the Environment Agency's 2D model benchmarking study (Néelz and Pender 2010) should be taken into account.
- Explore and improve the model representation of the dynamic nature of the variation in the roughness characteristics of energy crops through their growing and harvesting cycles. This could be based on results of recent research, for example, by the Hydro-Environmental Research Centre at Cardiff University, where studies of hydrodynamic drag caused by flooded vegetation and the resistance of flexible and stiff vegetation depending on depth and velocity of flooding and other parameters have been carried out (for example, by Xavier 2009).
- Apply the approach to additional case study floodplains, including more complicated floodplain situations such as those with flow constrictions or flood embankments.
- Carry out a systematic analysis of a wider range of flow conditions in terms of depth (relative to vegetation height) and velocity.
- Improve the methodology to consider more realistic plantation shapes and field boundary characteristics (that is, hedges, walls and fences) on the floodplain.
- Analyse the potential long-term effect of energy crop plantations on river and floodplain sediment dynamics due to the considerable alteration in flow velocities both in-channel and on the floodplain surface during out of bank flood events.

6.2 Experimental studies

Quantitative evidence of the impacts of energy crop plantations on floodplain flows to inform and validate the modelling approach could be obtained through laboratory and field studies.

Laboratory studies involving the actual physical representation of energy crops in terms of their hydraulic characteristics could be conducted in a large flume facility where close control and measurement can be made over flow rates, flood depths and water velocities. Researchers at Cardiff University have used such a facility to explore the roughness characteristics of SRC willow, and how this varies with water depth and with the dynamic seasonal growth characteristics of these trees.[2] To date, very little data exist on the hydraulic characteristics of miscanthus grown as an energy crop and this is an area where the knowledge could be substantially improved through additional flume-based research.

The setting up of field studies on floodplains containing energy crop plantations with the ability to comprehensively measure the parameters of flood depth, flow rates and floodplain water velocities could prove to be very costly to implement and manage to the level of detail needed to validate the hydraulic models. In addition, the uncertainty in the occurrence, frequency and magnitude of natural flood events suitable for measurement and analysis would also make successful completion of such an investigation somewhat uncertain – especially if the study had a limited duration.

However, relatively simple monitoring of water levels upstream and downstream of an energy crop plantation (both for a baseline period before the crop was planted and then during the course of a number of subsequent growth and harvesting cycles) using automatic water level recorders with integral data loggers would provide very useful datasets on how the plantation influences the flood levels in the locality. Ideally, this would be replicated in some way across a range of floodplains.

A similar simple approach was implemented by Forest Research for an investigation on the possible effect of new floodplain woodland plantations on flooding dynamics in the Ripon catchment in North Yorkshire (Nisbet and Thomas, 2008). Unfortunately, during the baseline monitoring period of this study, the decision was taken by the landowners not go ahead to plant the trees and the work could not be completed.

[2] At the time of writing this report (November 2010), publication of the final results from this work were expected in the near future.

References

ACREMENT, G.J. JR. AND SCHNEIDER, V.R., 1989. *Guide for selecting Manning's roughness coefficients for natural channels and flood plains.* United States Geological Survey Water-Supply Paper 2339. Reston, VA: US Geological Survey.

CHOW, V.T., 1959. *Open Channel Hydraulics.* New York: McGraw-Hill.

DEFRA, 2003. *Reducing uncertainty in river flood conveyance: roughness review*. Project W5A-057. Defra/Environment Agency Flood and Coastal Defence R&D Programme. London: Department for Environment, Food and Rural Affairs.

DEFRA, 2004. *Growing short rotation coppice. Best practice guidelines for applicants to Defra's Energy Crops Scheme*. London: Department for Environment, Food and Rural Affairs.

DEFRA, 2007. *Planting and growing miscanthus. Best practice guidelines for applicants to Defra's Energy Crops Scheme*. London: Department for Environment, Food and Rural Affairs.

HM GOVERNMENT, 2009. *The UK Renewable Energy Strategy*. Cm 7686. London: HMSO.

JÄRVELÄ, J., 2002. Flow resistance of flexible and stiff vegetation: a flume study with natural plants. *Journal of Hydrology*, 269 (1-2), 44-54.

KNIGHT, D.W., MCGAHEY, C., LAMB, R. AND SAMUELS, P., 2010. *Practical Channel Hydraulics: Roughness, Conveyance and Afflux*. Boca Raton, FL: CRC Press.

MCGAHEY, C., 2006*. A practical approach to estimating the flow capacity of rivers*. PhD thesis. Faculty of Technology, The Open University.

NATURAL ENGLAND, 2009. *Rural Development Programme for England. Energy Crops Scheme. Establishment Grants Handbook*, 3rd edn. Peterborough: Natural England. Available from: http://webarchive.nationalarchives.gov.uk/20120829070713/http://www.naturalengland.org.uk/Images/ECShandbook3ed_tcm6-12242.pdf [Accessed 18 May 2015].

NÉELZ, S. AND PENDER, G., 2010. *Benchmarking of 2D hydraulic modelling packages*. Science Report SC080035/SR2. Bristol: Environment Agency.

NISBET, T.R. AND THOMAS, H., 2008. *Restoring floodplain woodland for flood alleviation*. Final Report. Project SLD2316. London: Department for Environment, Food and Rural Affairs.

THOMAS, H. AND NISBET, T.R., 2004. *An assessment of the hydraulic impact of floodplain woodland*. Final Report to the Forestry Commission. Farnham: Forest Research.

WILSON, C.A.M.E. AND HORRITT, M.S., 2002. Measuring the flow resistance of submerged grass. *Hydrological Processes*, 16 (13), 2589-2598.

XAVIER, P.A., 2009. *Floodplain woodland hydrodynamics*. PhD thesis, Cardiff School of Engineering, Cardiff University. Available from: http://orca.cf.ac.uk/54961/ [Accessed 18 May 2015].

Bibliography

GHAVASIEH, A.R., POULARD, C.H. AND PAQUIER, A., 2005. Effect of roughened strips on flood propagation: assessment on representative virtual cases and validation. *Journal of Hydrology*, 318 (2006), 121-137.

SELLIN, R.H.J., BRYANT, T.B. AND LOVELESS, J.H., 2003. An improved method for roughening floodplains on physical river models. *Journal of Hydraulic Research*, 41 (1), 3-14.

Abbreviations

AEP	annual exceedance probability
ESC	Energy Crops Scheme
GIS	geographical information system
SRC	short rotation coppice

Appendix A: Background to 1D–2D ISIS-TUFLOW hydraulic modelling

TUFLOW is a 2D inundation model that simulates the hydrodynamics of water flowing over the land surface by solving the shallow water equations for both momentum and continuity. The shallow water equations represent components of the depth-averaged velocity in two directions. Two-dimensional models allow for calculation of flow patterns on the floodplain during partial inundation and drainage, where topography typically plays major role in controlling the direction and velocity of the flow.

A TUFLOW 2D model is structured as a set of layers (in the format of MapInfo GIS files) which define model topography for the floodplain, model boundary conditions, roughness of the floodplain, and features such as buildings, roads or water bodies. The 2D model outputs include:

- floodplain flood depths
- flood levels and velocities
- optional level monitoring sections across the floodplain that output floodplain flood hydrographs
- the variation of the Manning’s n floodplain roughness with depth of inundation (if specified)

The model results can be viewed using specific software such as the SMS Surface Water Modelling System, or exported in a MapInfo grid format for presentation within a GIS.

The model topography layer is defined by the underlying high resolution Digital Terrain Model (DTM) and the features on floodplain are typically defined by polygons or lines to represent buildings and roads as per Ordnance Survey mapping background. All these features influence the flood propagation across the floodplain and help represent the floodplain inundation in a realistic way. The accuracy of the modelled floodplain inundation depends, among other aspects, on the resolution of the model domain. It can be only as accurate as the underlying DTM (for example, 1 m cell size), but such a high degree of detail requires a very long computational time for the model to complete the simulation. The computational time can be, in the case of large models, up to several days in duration. Therefore, the model domain resolution is decreased (that is, the cell size increased) so as to achieve practical model run times while retaining sufficient detail of the topography. Typically, smaller models are set up with a 4 m cell size, or a 10 m cell size for larger models or models where the floodplain inundation is not the major modelled element.

The model layers can easily be modified outside TUFLOW in a GIS environment. This is a crucial practical advantage of the TUFLOW model, particularly within the context of this project, because it allows the different energy crop plantation layouts to be easily represented and modified for the various scenarios.

The 2D model can be linked with a 1D hydraulic model (for example, ISIS Flow) of the river system in the area of interest via a set of 1D–2D boundary conditions. While the 1D model simulates the flow and water levels in the river channel, the 2D model simulates flood propagation onto and across the floodplain. The 1D component provides inflows into the 2D model every time the modelled river water level overtops the river banks. The proportion of the flood hydrograph that overtops the river banks then enters the 2D model and is routed on the floodplain within the 2D model domain. Conversely, the inundation can flow back from the floodplain into the channel further downstream, depending on the topography and water levels. Thus, the propagation of the floodwater in the river (1D model) and on the floodplain (2D component) is modelled as a complex, fully linked unit.

Outputs from 1D-2D ISIS-TUFLOW models include:

- flow hydrographs at each modelled river cross section in the channel (within the 1D component) and at specified locations on the floodplain (within the 2D component)
- water levels associated with these flows
- floodplain water level, velocities, depth and flood extent

Use of a linked 1D–2D modelling approach for this project allowed the modelling of changing patterns of flow pathways associated with different types of surface resistance represented by the friction coefficient, and its ability to simulate a wide range of different energy crop plantation configurations (for example, a single block of miscanthus or SRC willow on one side of the floodplain, full coverage of the floodplain with a network of rides/headlands between the blocks, or spatially distributed plantation blocks of different sizes). This versatility, together with availability of suitable existing 1D–2D models and their reasonable run times, was the main reason for the choice of this modelling approach for this short-term project.

The model versions used in this study were TUFLOW 2009 07 AE and ISIS v3.3.0.88.

Appendix B: Electronic appendices (model scenario results)

- Exe at Uckinghall
- Isle at Ashford Mill
- Theoretical model

JBA consulting

Energy Crops Project

2009s0426

Case Study 1

Modelled results for River Severn at Uckinghall

Modelling approach and methodology

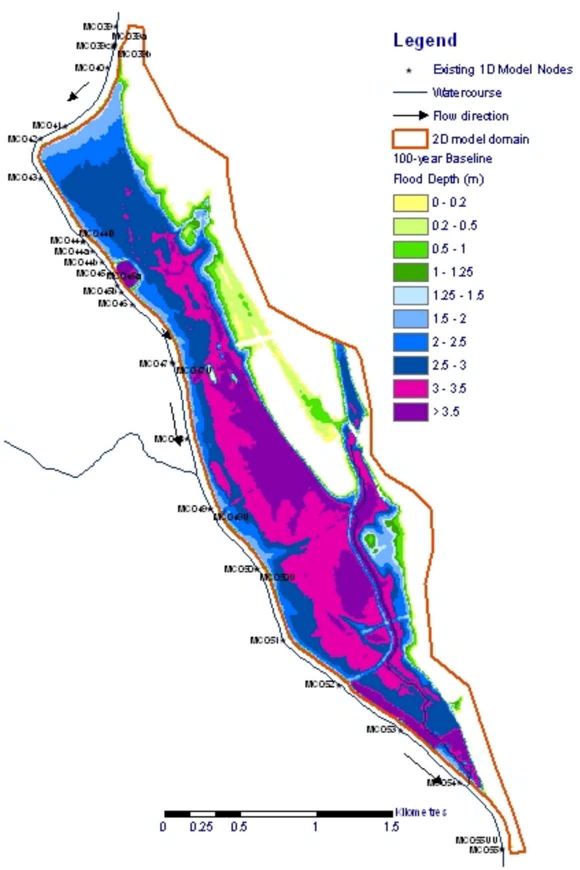
- Plantation type
  - Scenario 2 series – Miscanthus
  - Scenario 3 series – SRC Willow
- Plantation pattern
  - 3ha plots with 10m rides around
- Plantation coverage
  - 100% of floodplain
  - 30% of floodplain (one side of the river)
- Modelled return period: 100years (1%AEP)
- The existing 1D-2D models details:

Modelled floodplain extent in FZ3 (km^2)	100 year flood (m^3/s)	2D model domain resolution (cell size in m)	Simulation duration (hours)
3.3	763.5	10	11

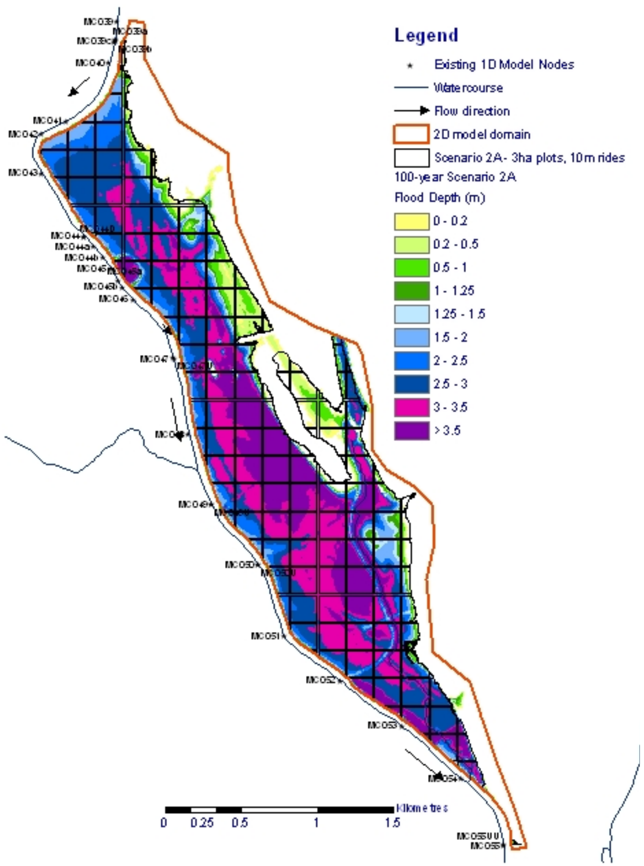
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 2 series (Miscanthus)

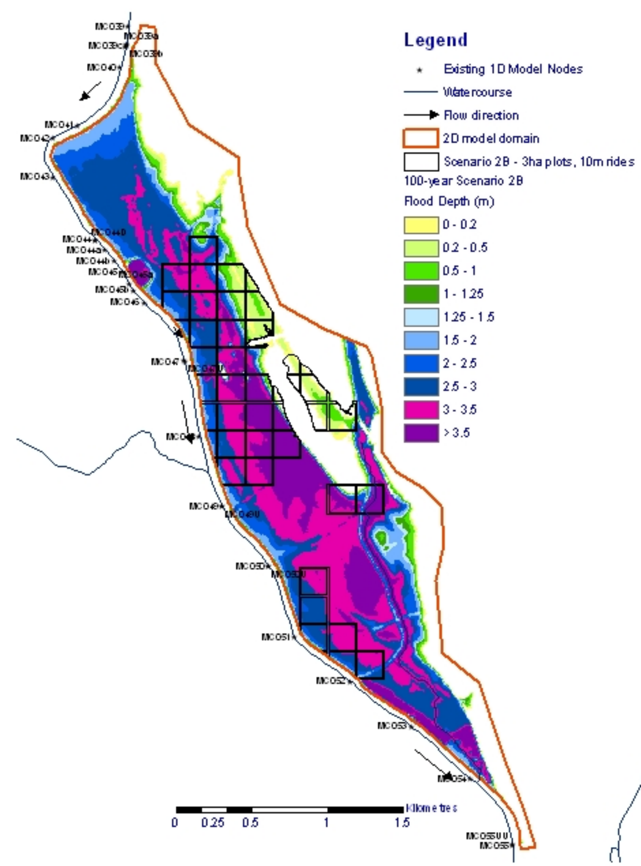
Baseline



Scenario 2A



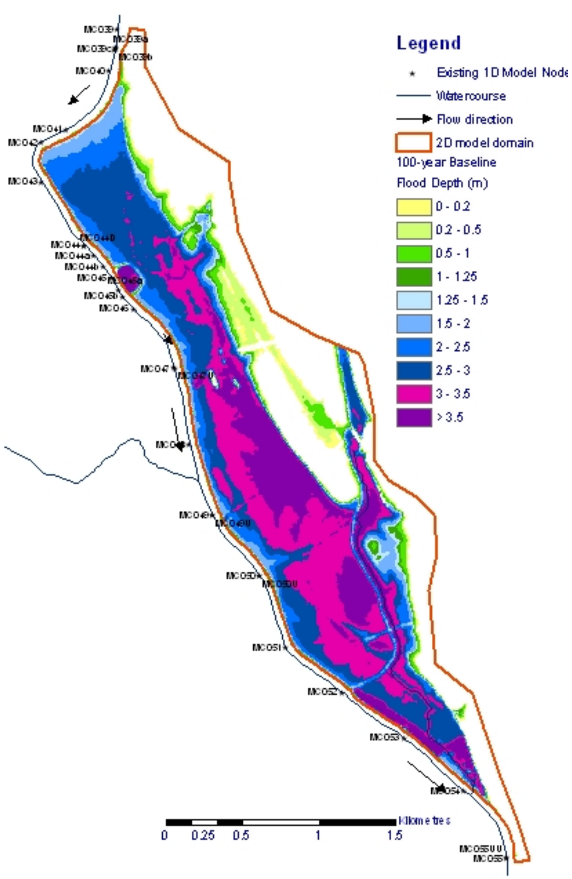
Scenario 2B



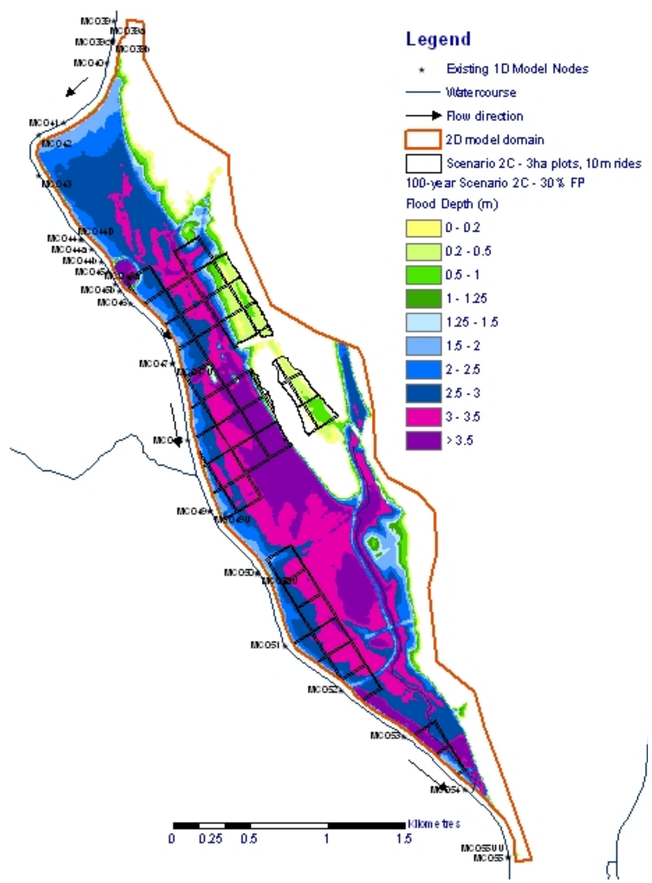
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 2 series (Miscanthus)

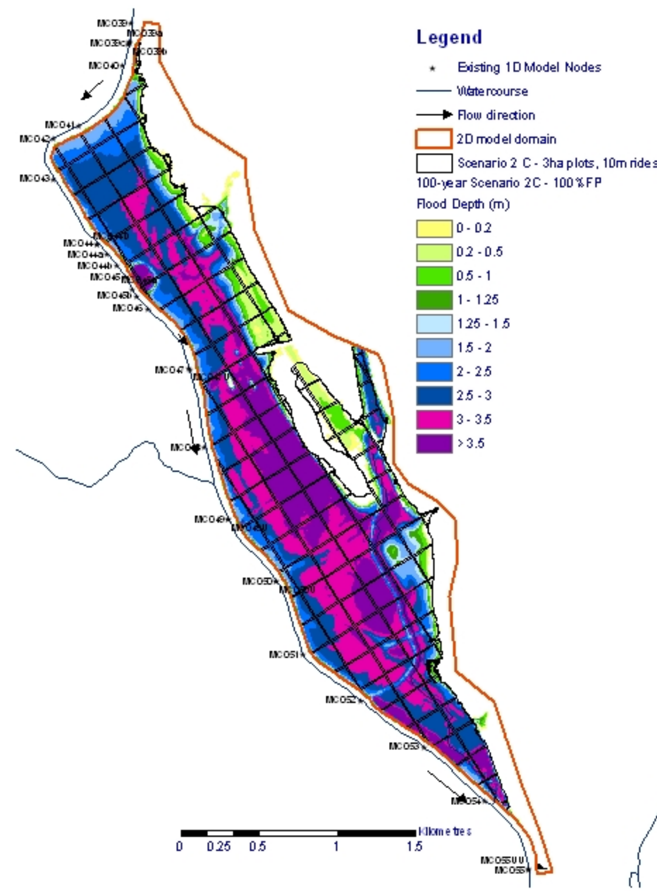
Baseline



Scenario 2C – 30%FP



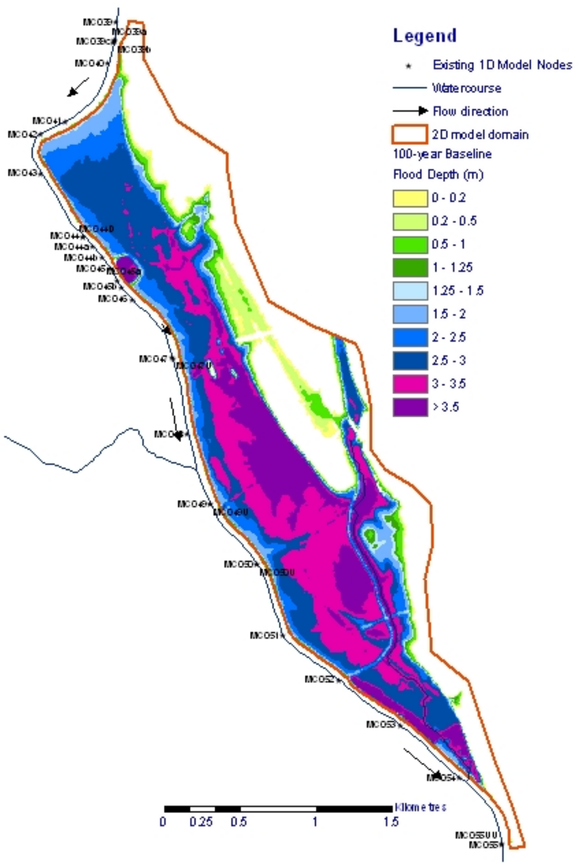
Scenario 2C – 100% FP



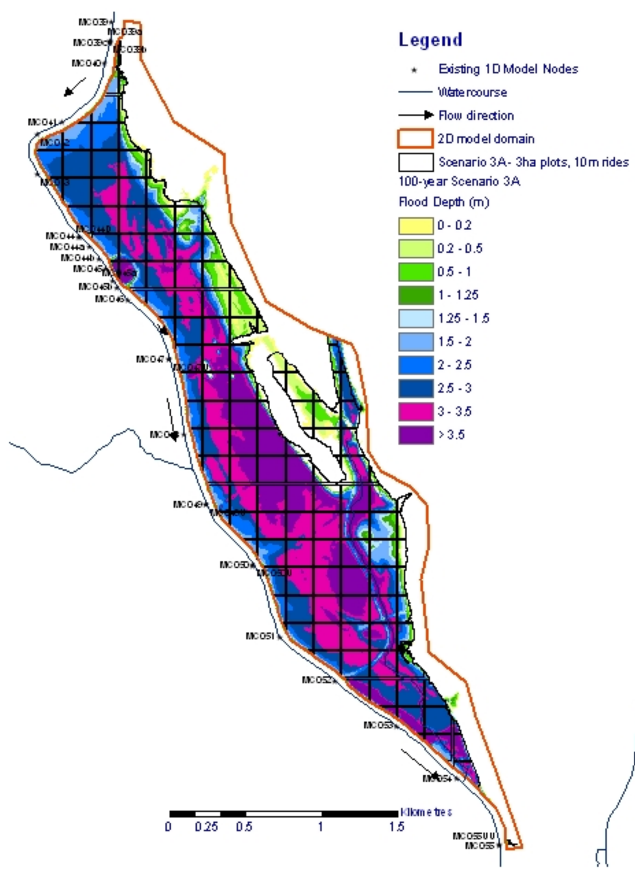
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 3 series (SRC Willow)

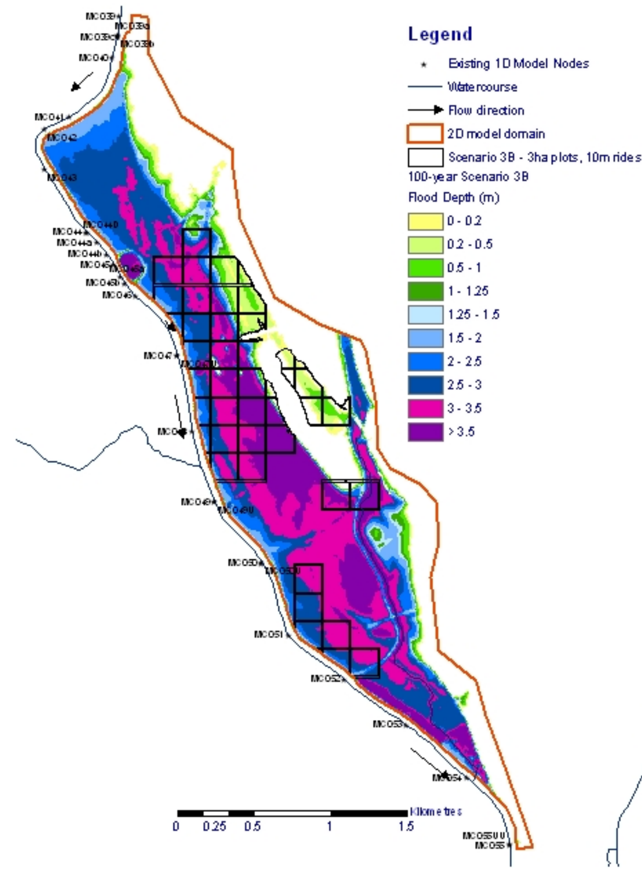
Baseline



Scenario 3A



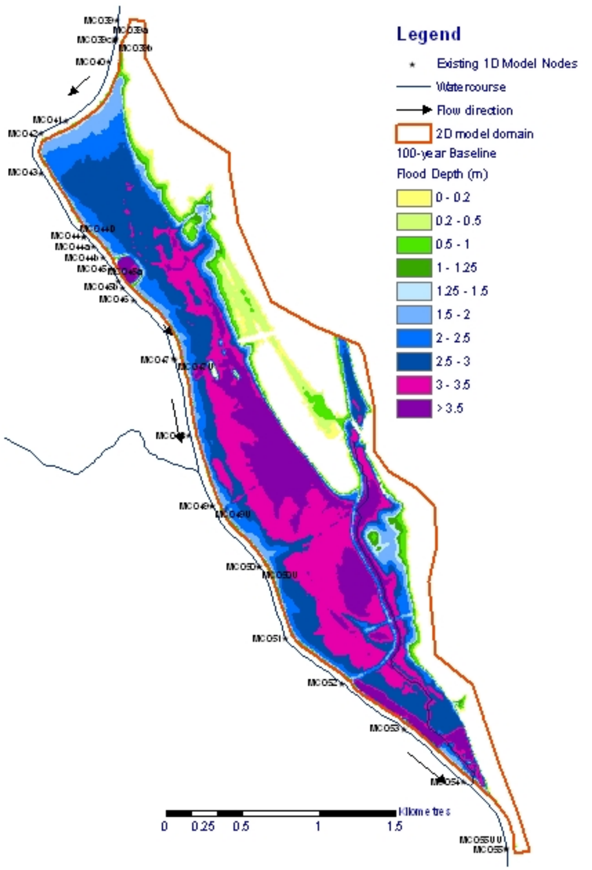
Scenario 3B



Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 3 series (SRC Willow)

Baseline



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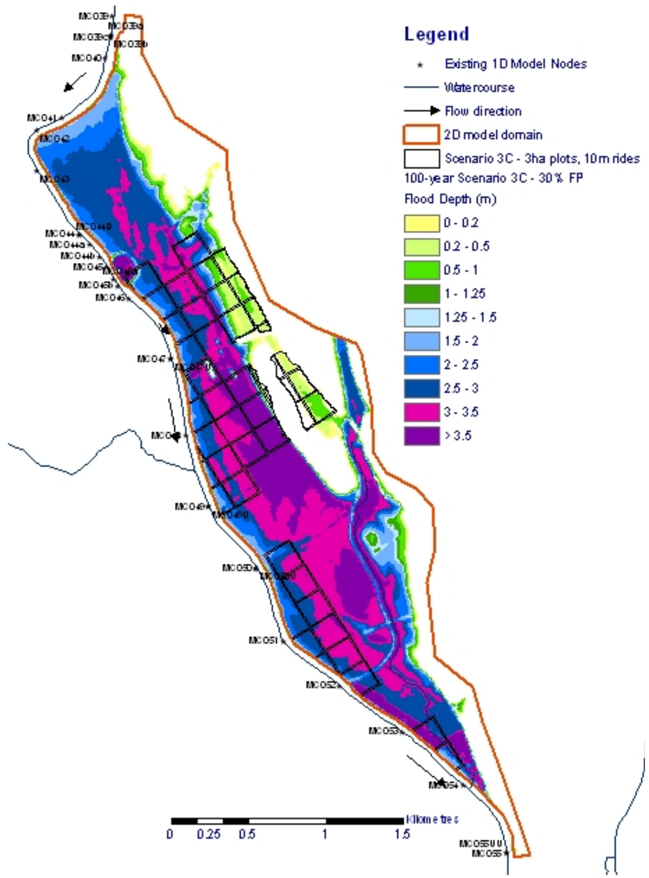
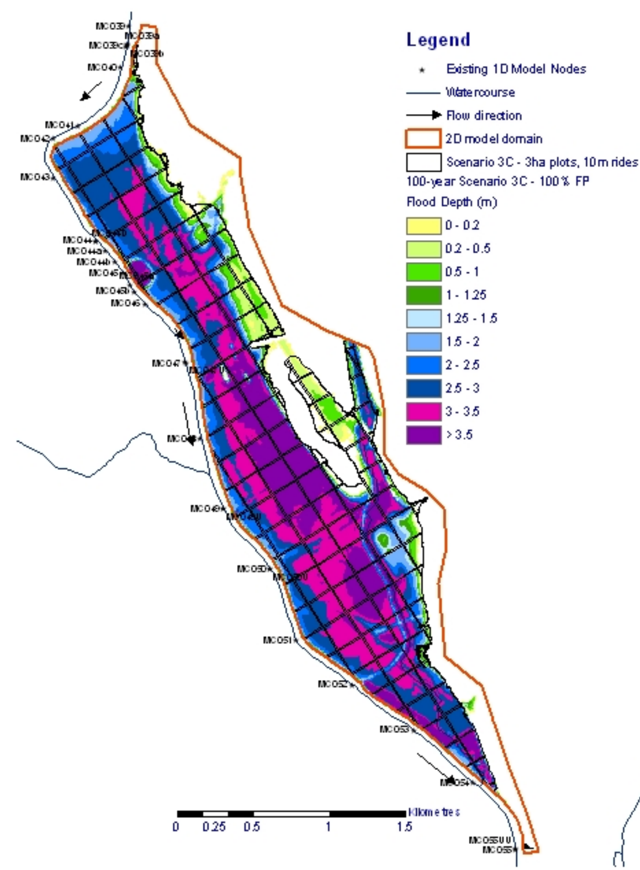


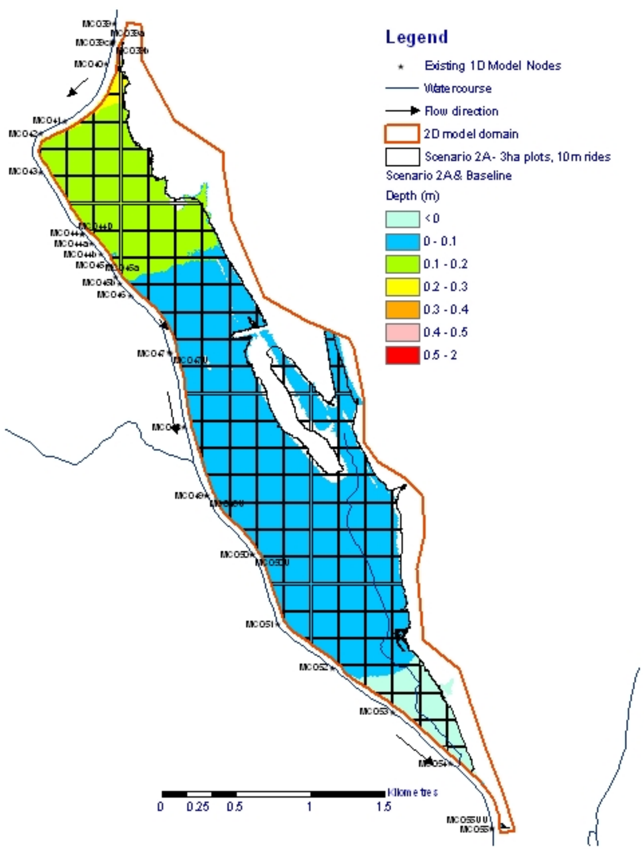
Scenario 3C – 100% FP



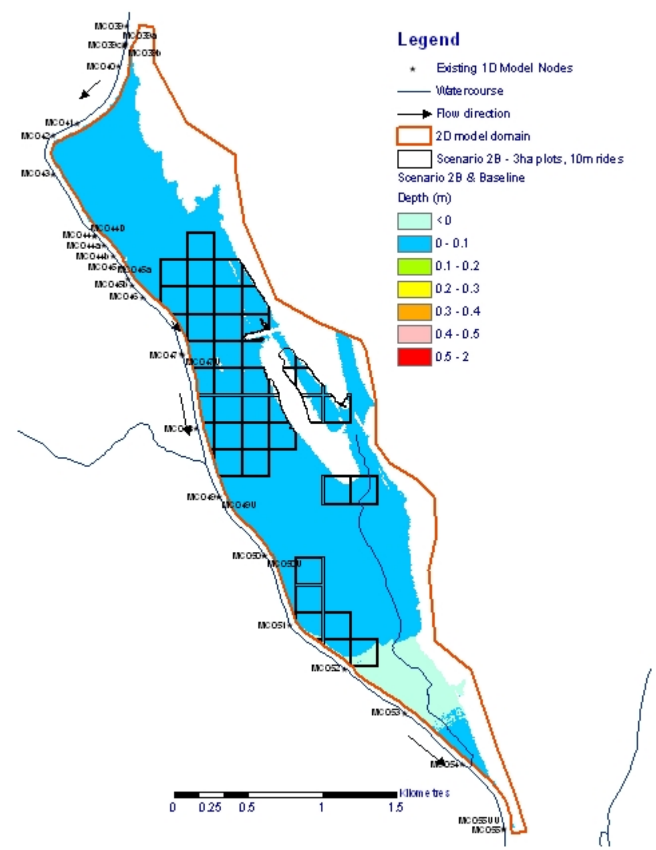
Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 2 series (Miscanthus)

Scenario 2A - Baseline



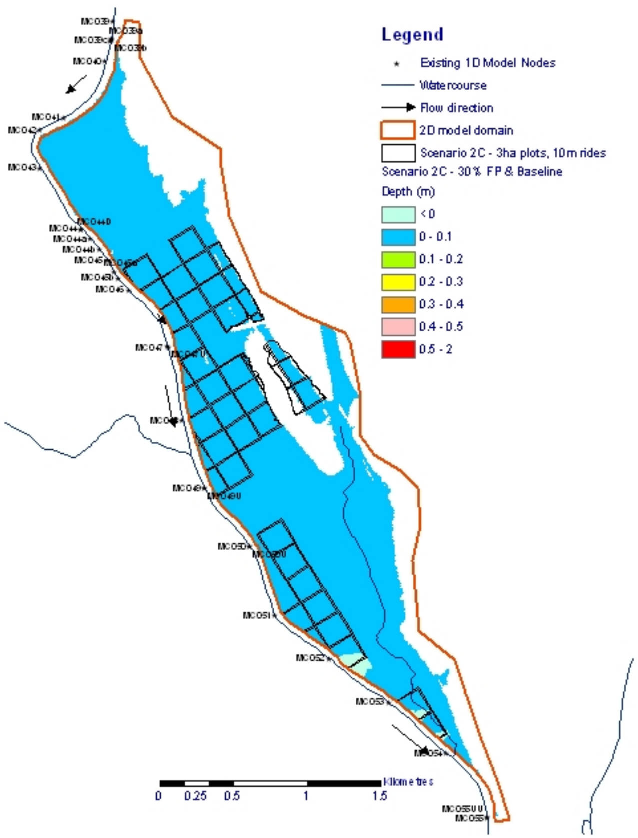
Scenario 2B - Baseline



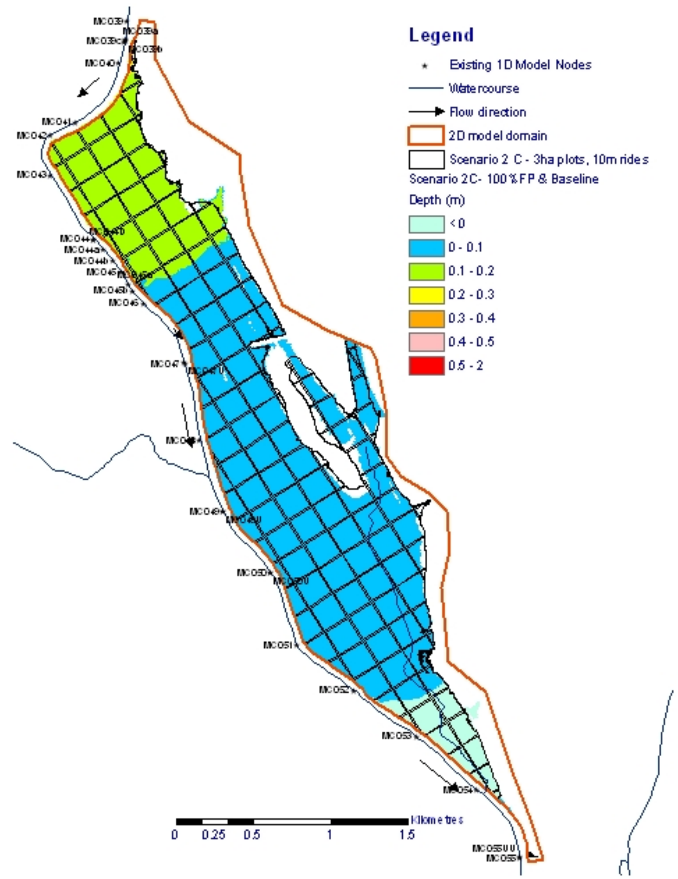
Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 2 series (Miscanthus)

Scenario 2C (30%) - Baseline



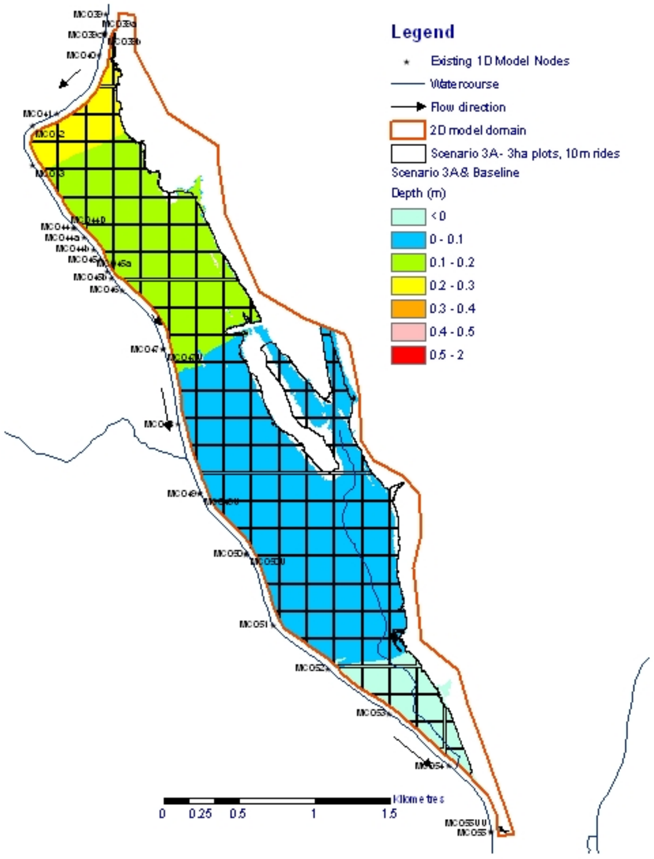
Scenario 2C (100%) - Baseline



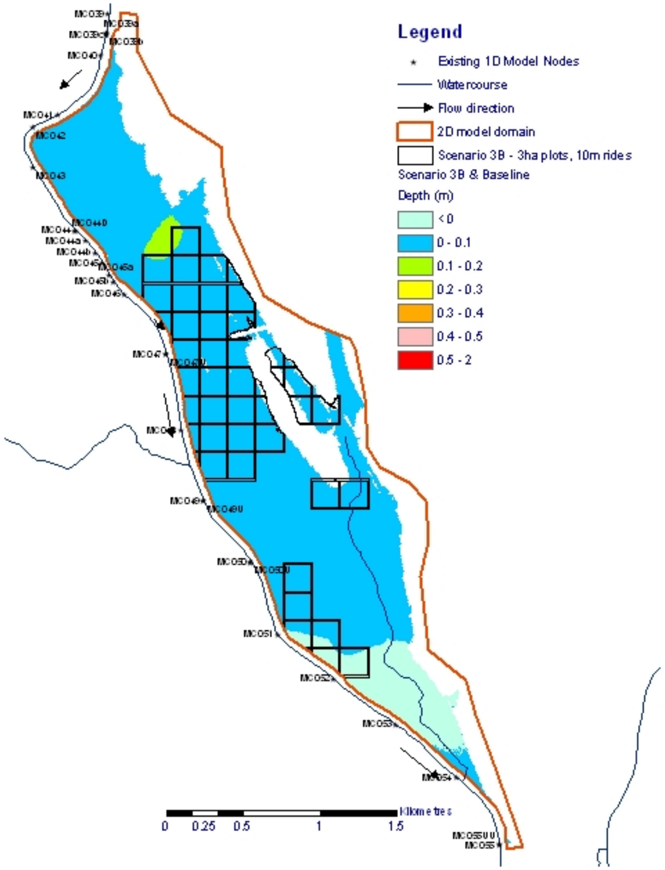
Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 3 series (SRC Willow)

Scenario 3A - Baseline



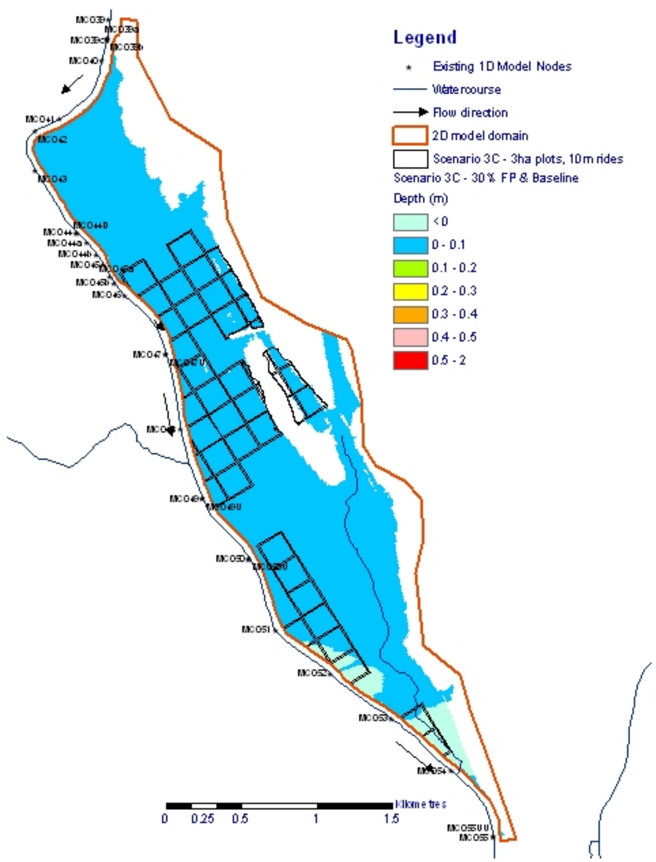
Scenario 3B - Baseline



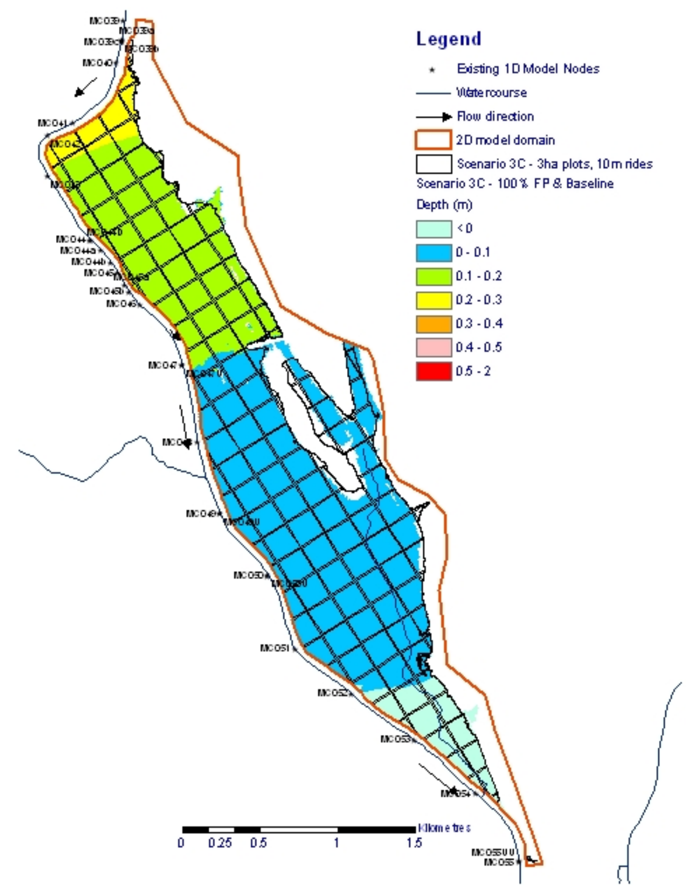
Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 3 series (SRC Willow)

Scenario 3C (30%) - Baseline



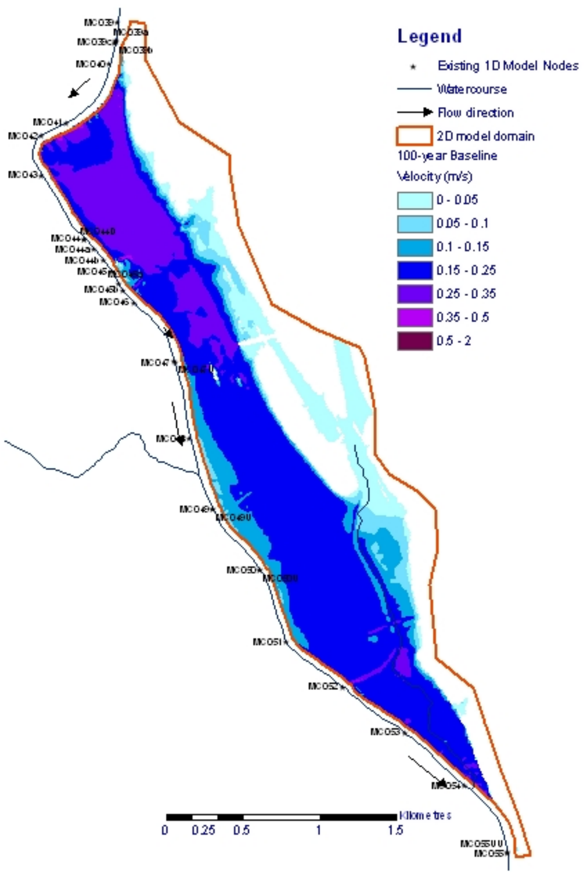
Scenario 3C (100%) - Baseline



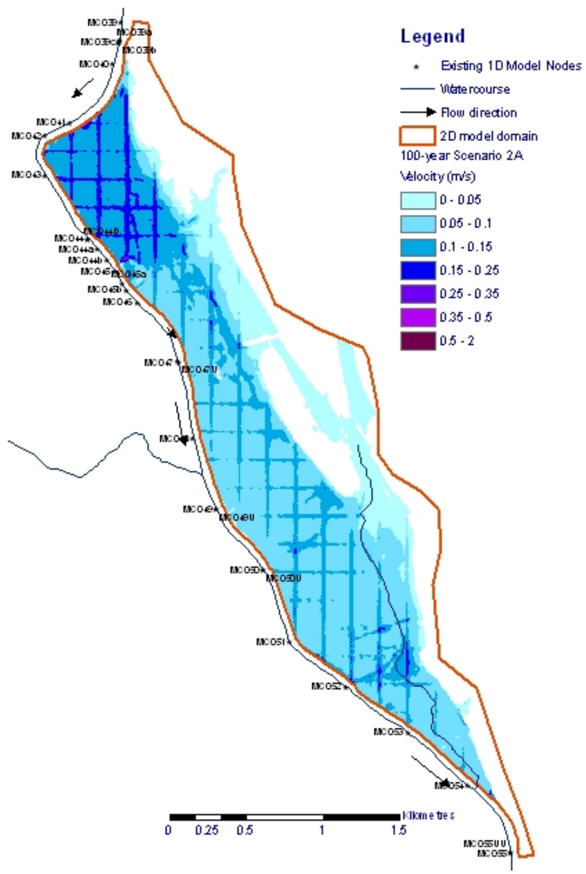
Model results – Velocities

- Flood Velocity (m/s) – Scenario 2 series (Miscanthus)

Baseline



Scenario 2A



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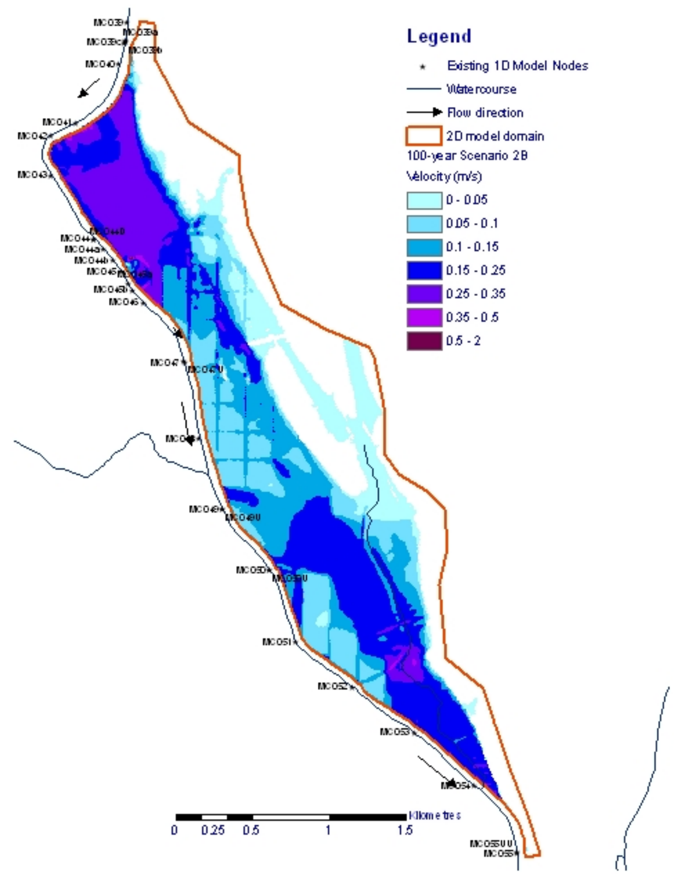
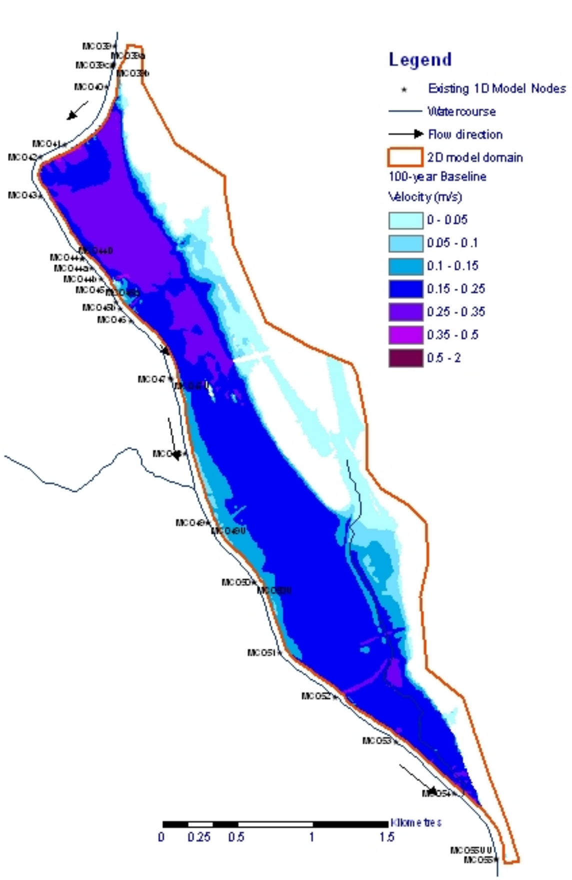


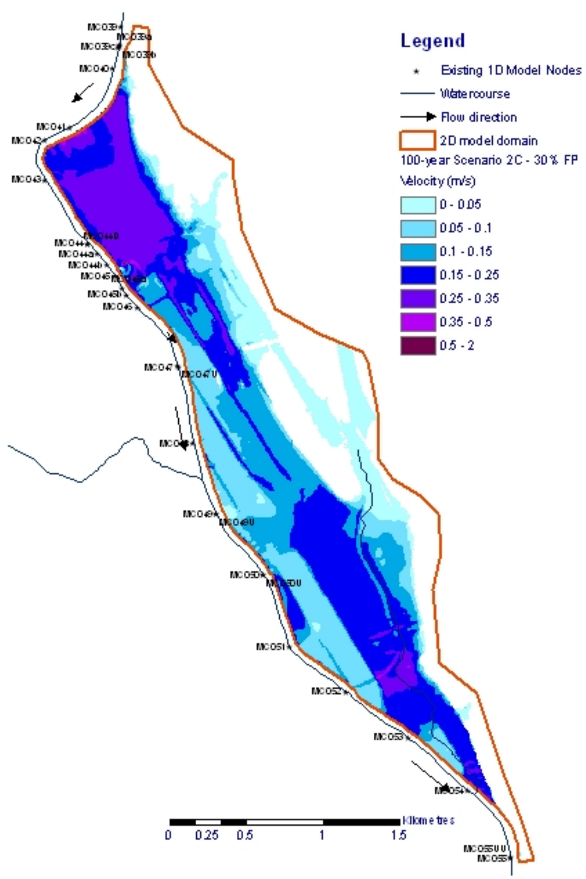
Model results – Velocities

- Flood Velocity (m/s) – Scenario 2 series (Miscanthus)

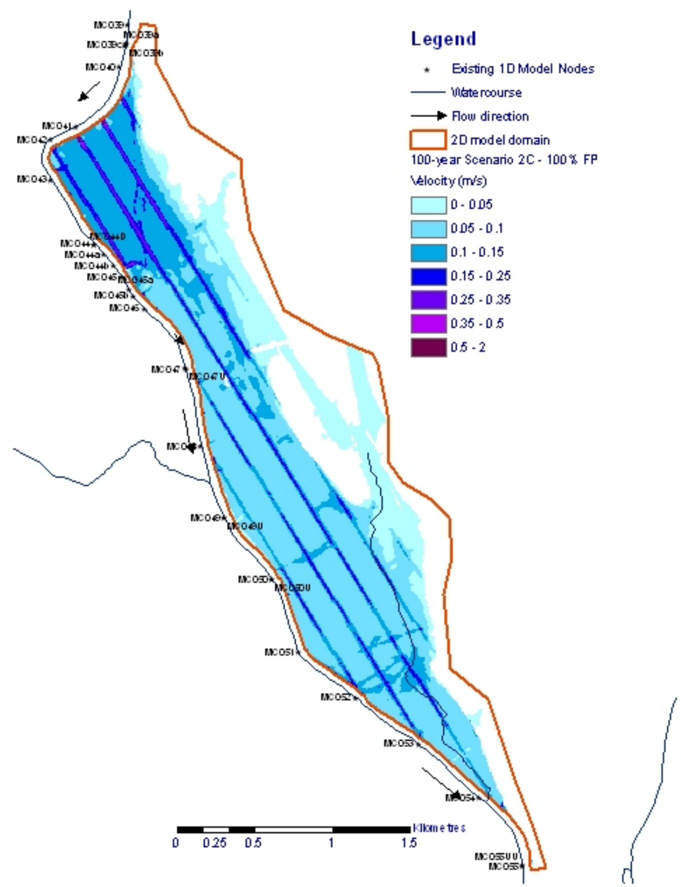
Baseline



Scenario 2C – 30% FP



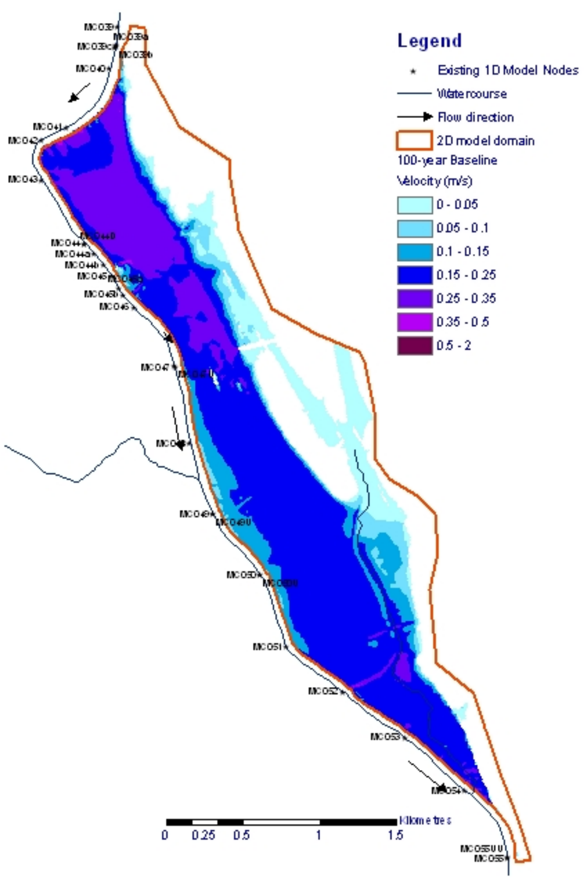
Scenario 2C – 100% FP



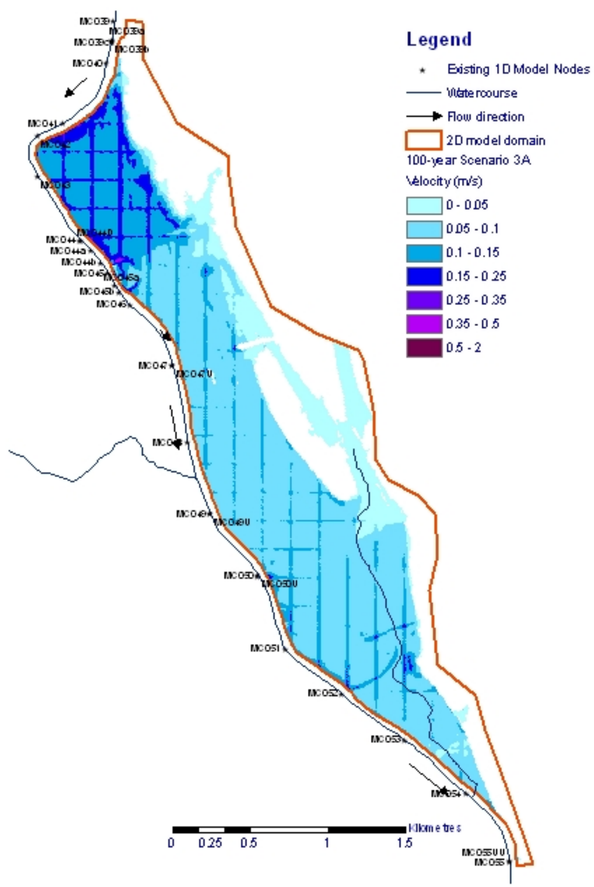
Model results – Velocities

- Flood Velocity (m/s) – Scenario 3 series (SRC Willow)

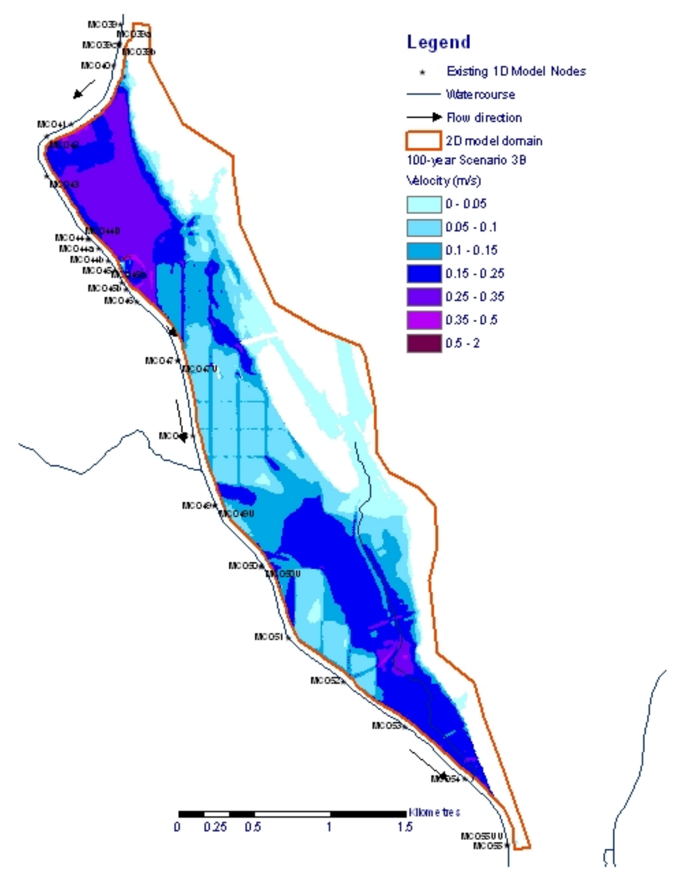
Baseline



Scenario 3A



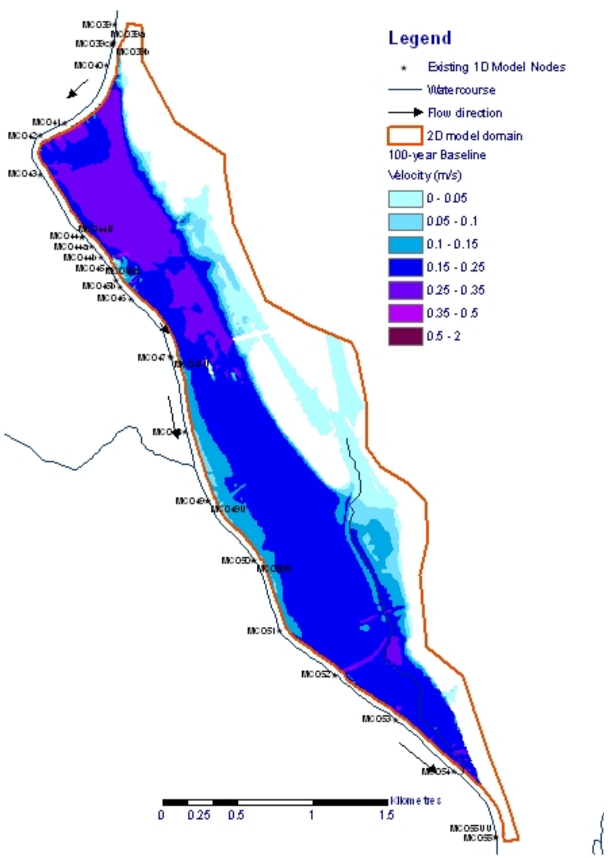
Scenario 3B



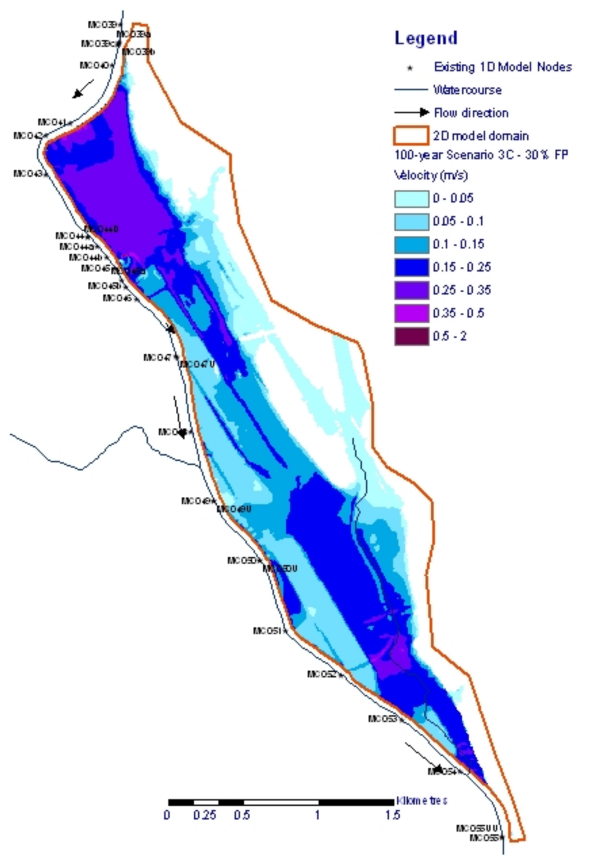
Model results – Velocities

- Flood Velocity (m/s) – Scenario 3 series (SRC Willow)

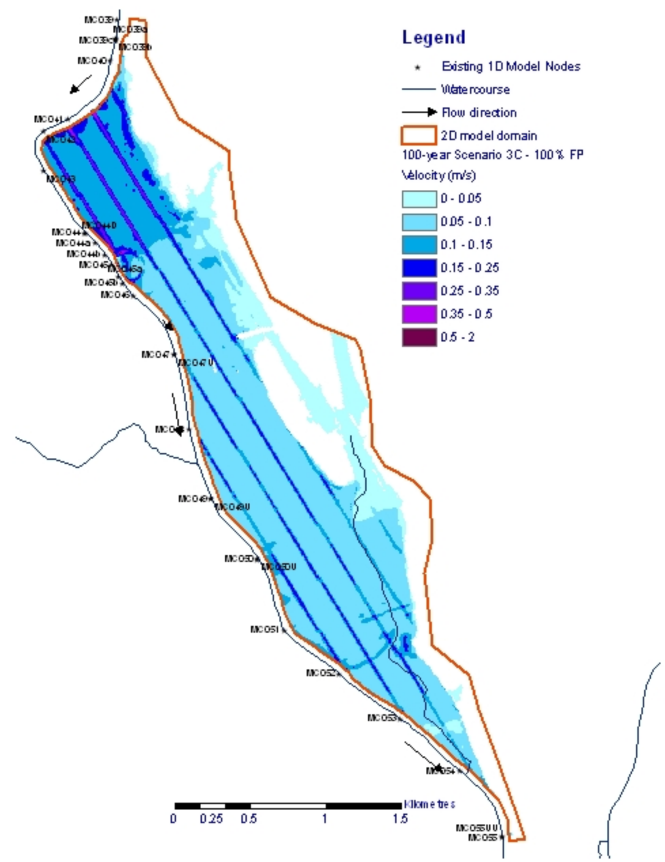
Baseline



Scenario 3C – 30% FP

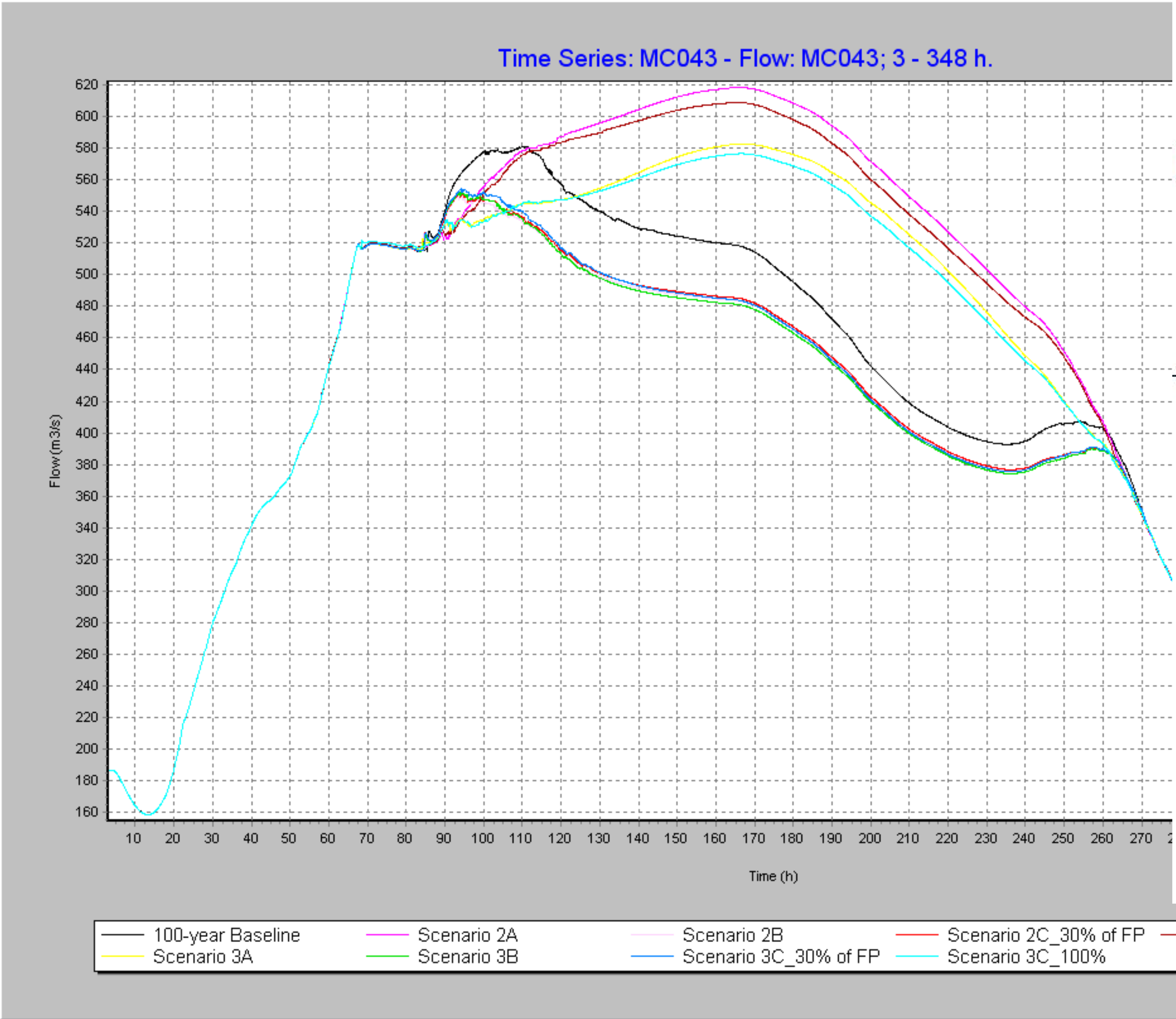


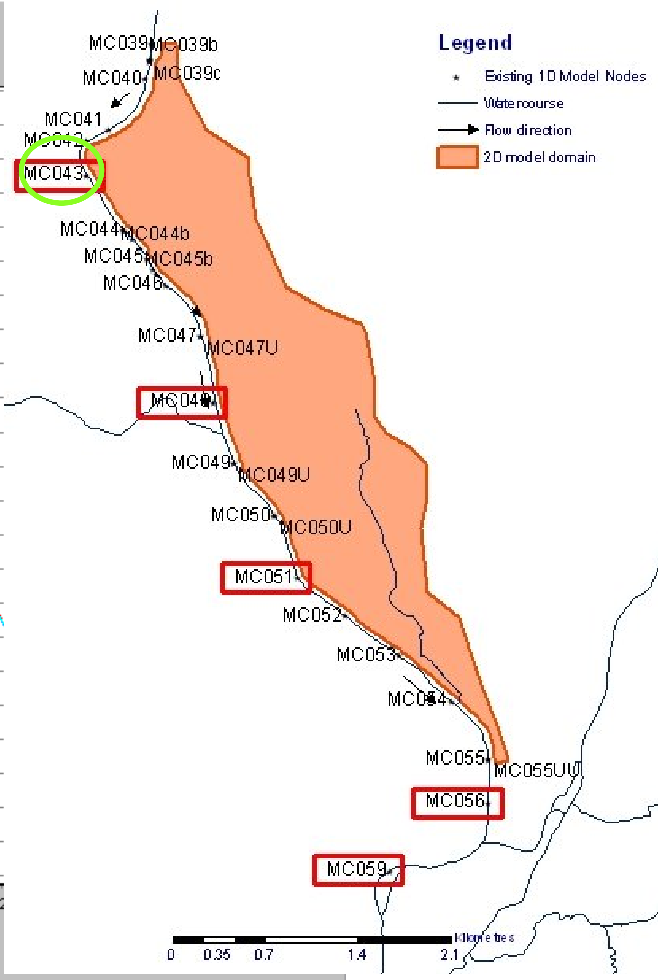
Scenario 3C – 100% FP



Model results – River Flow Hydrographs

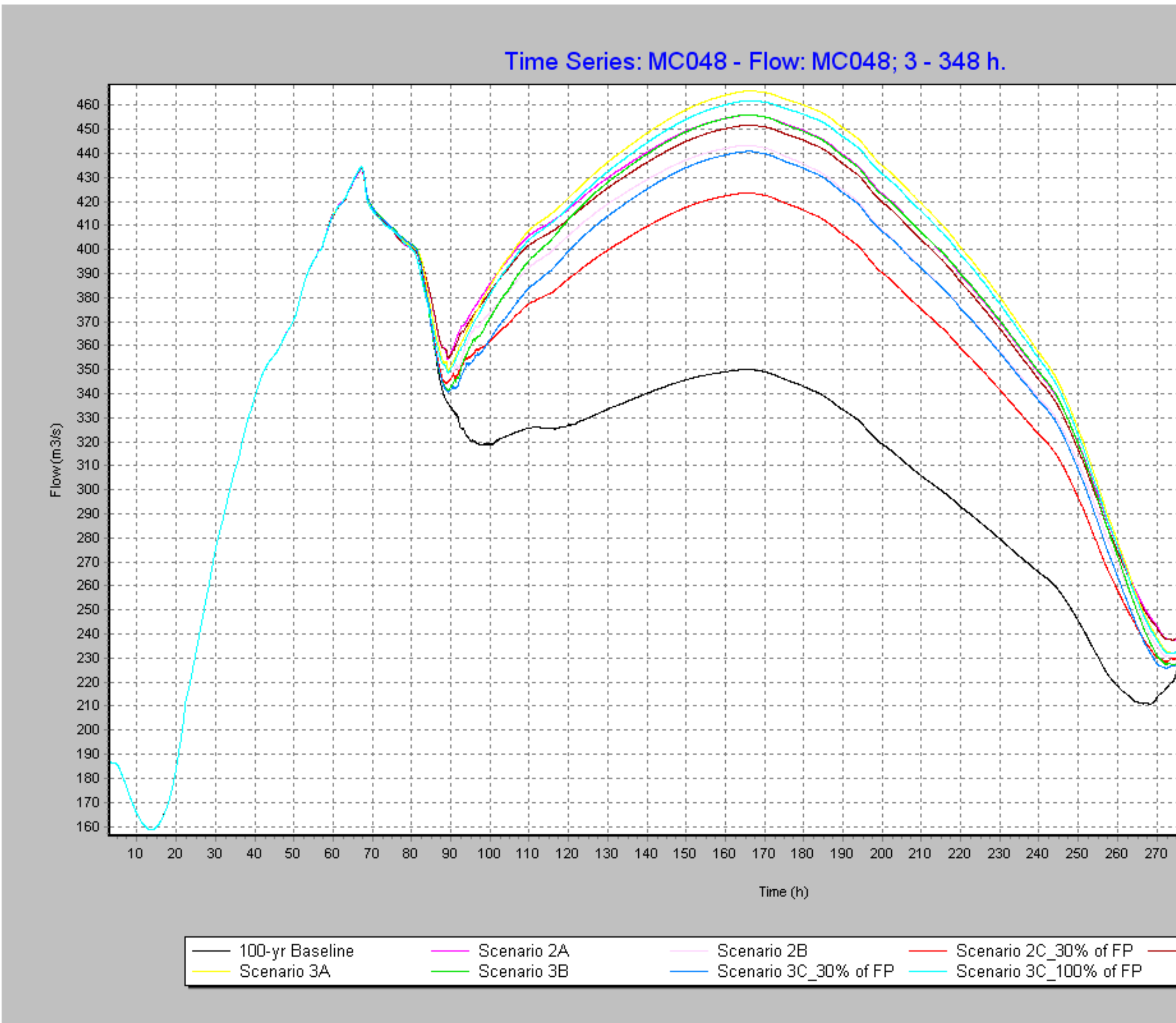
- Flood hydrographs in the upstream area (e.g. upstream of plantation)

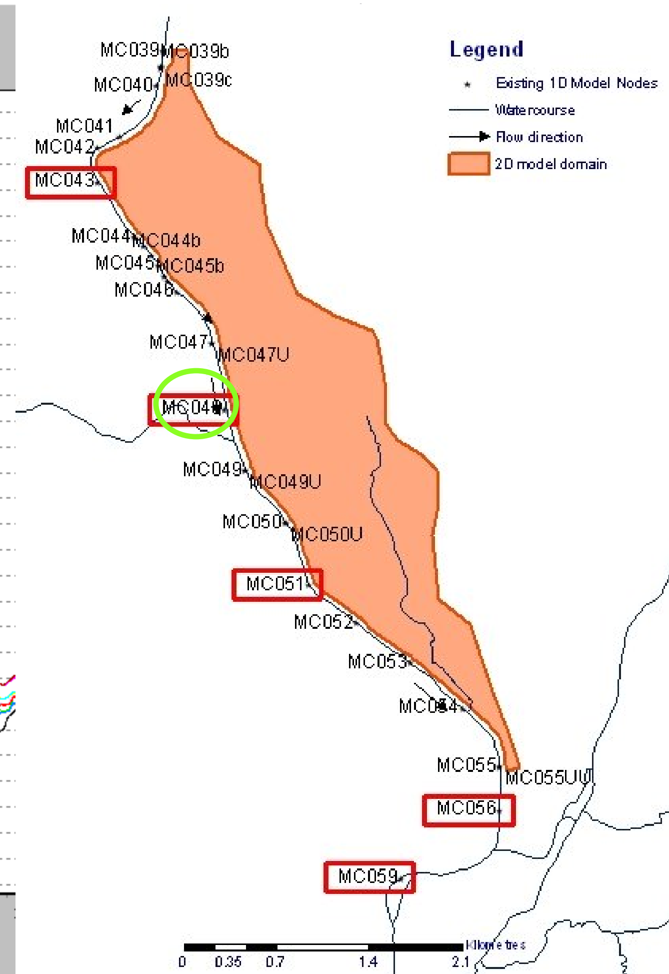




Model results – River Flow Hydrographs

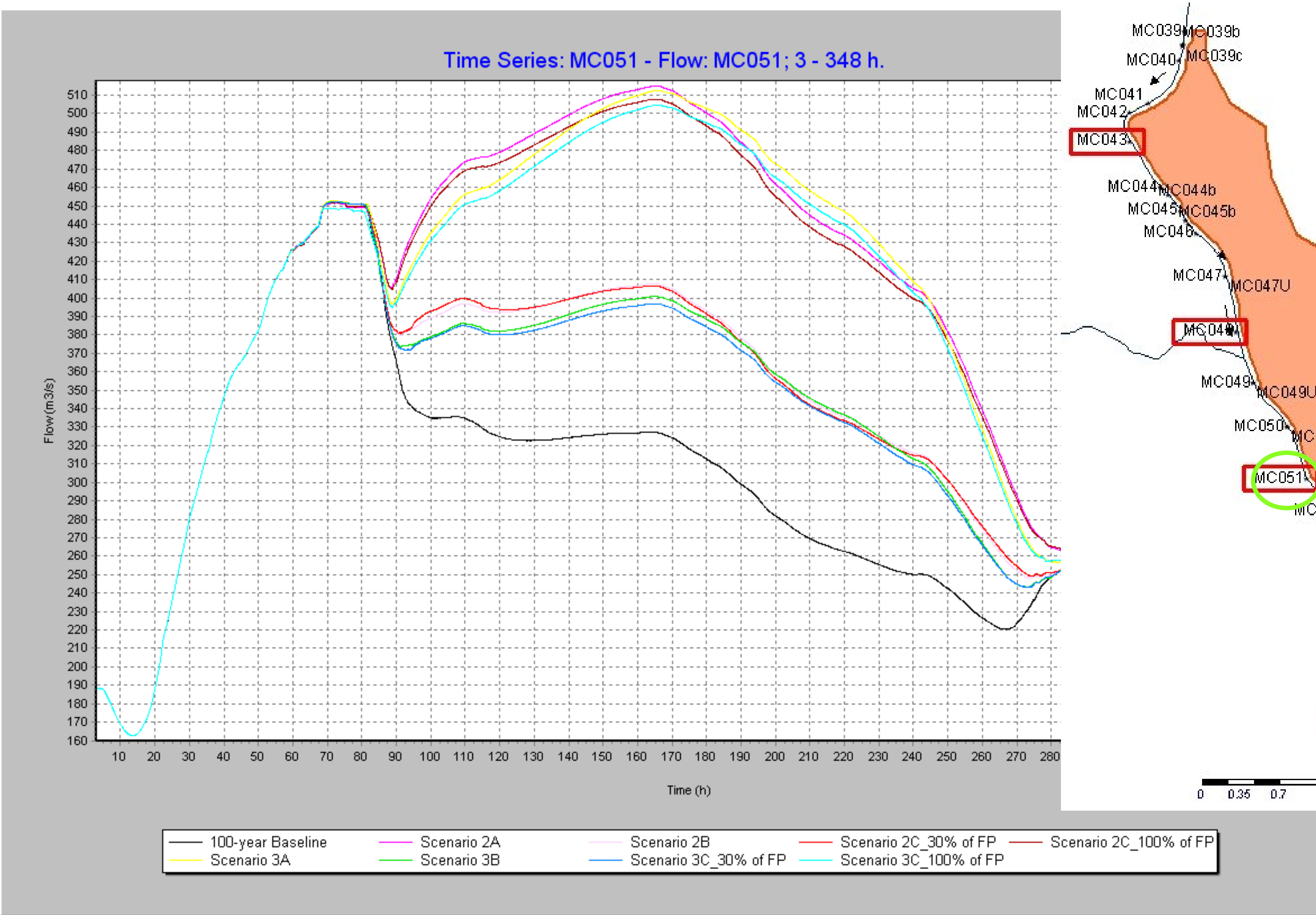
- Flood hydrographs in the middle area (e.g. at plantation)

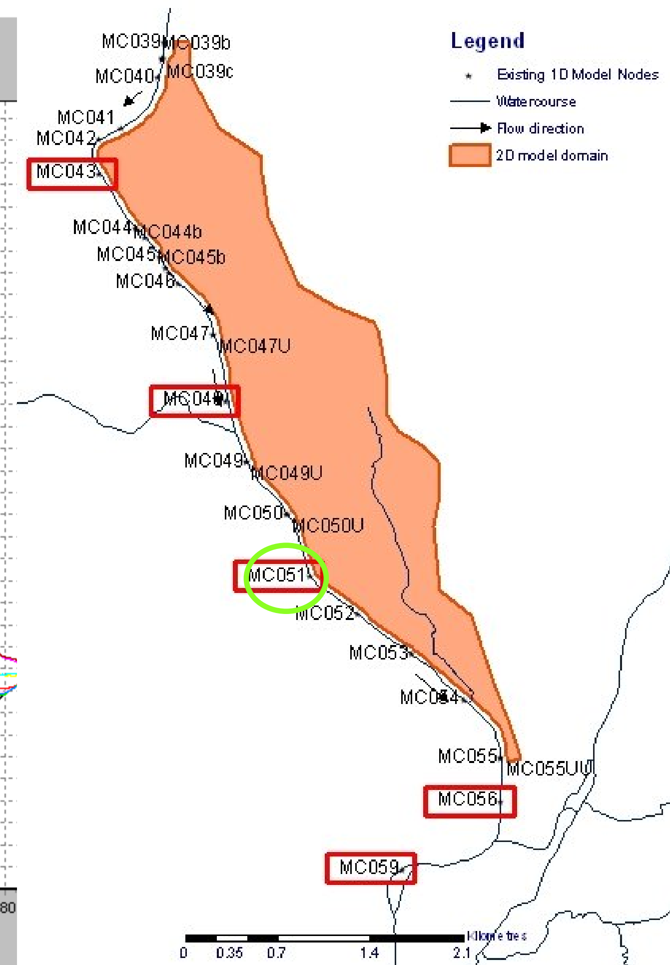




Model results – River Flow Hydrographs

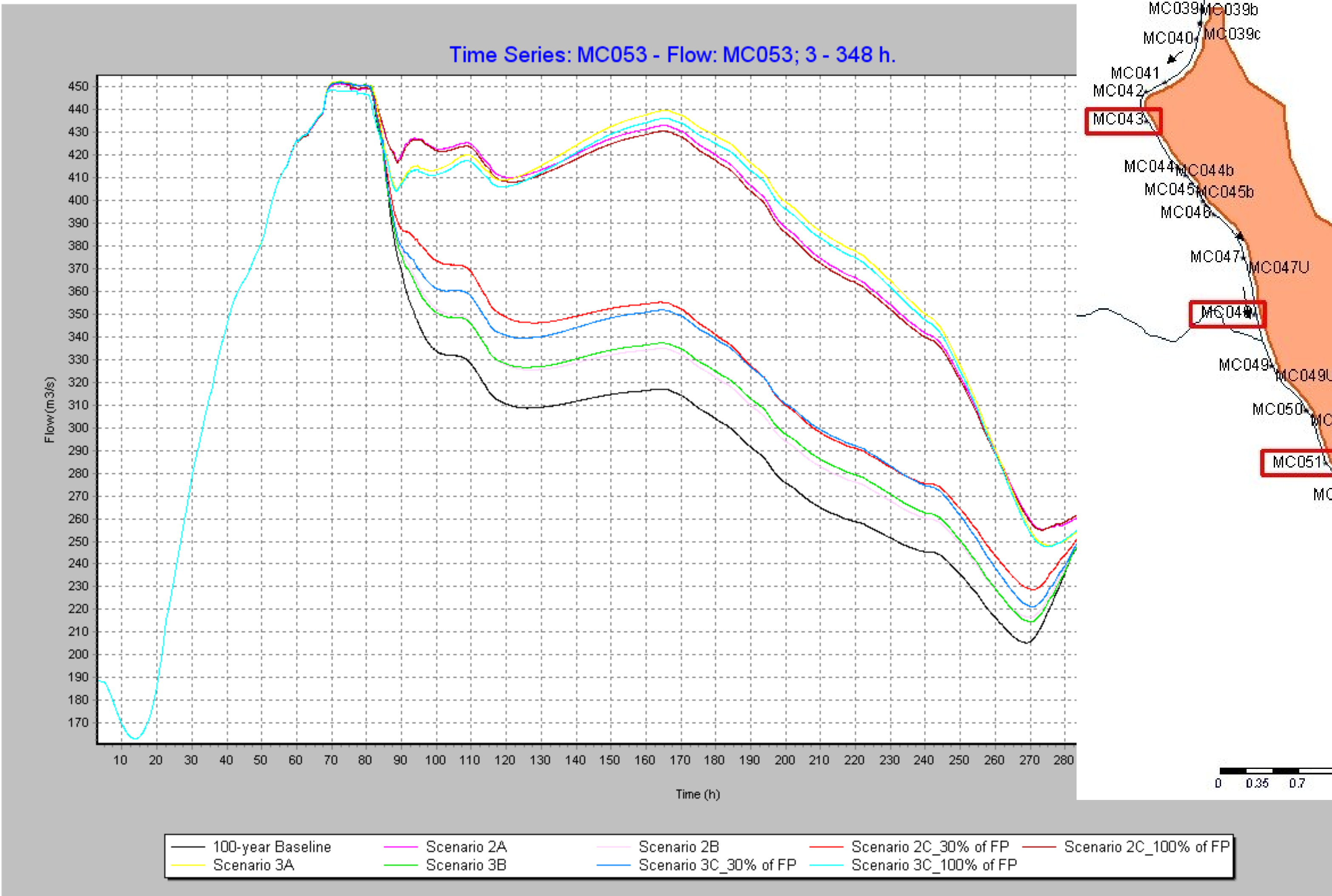
- Flood hydrographs in the middle area (e.g. at plantation)

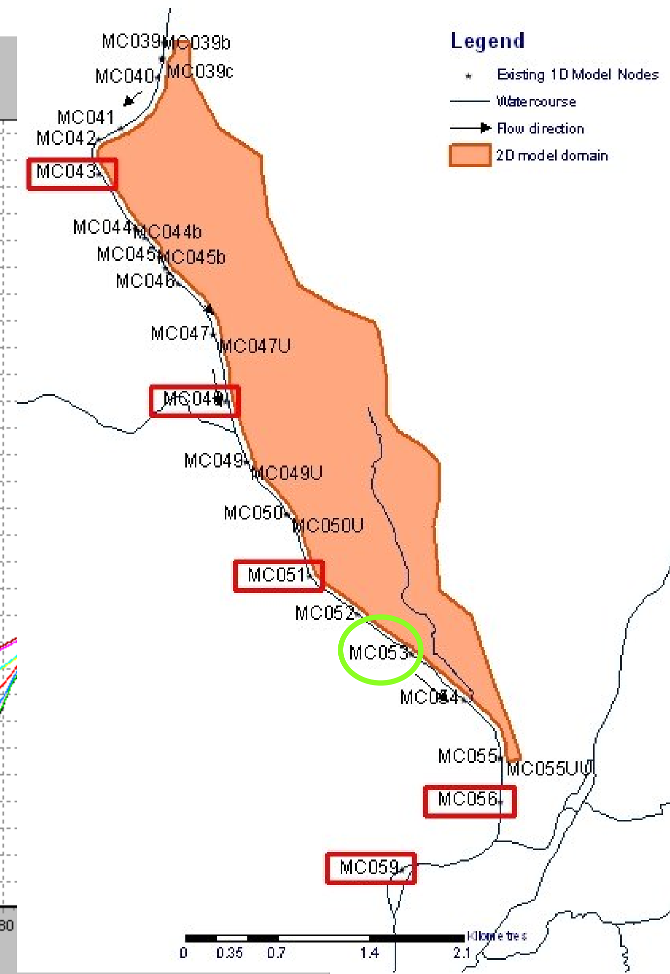




Model results – River Flow Hydrographs

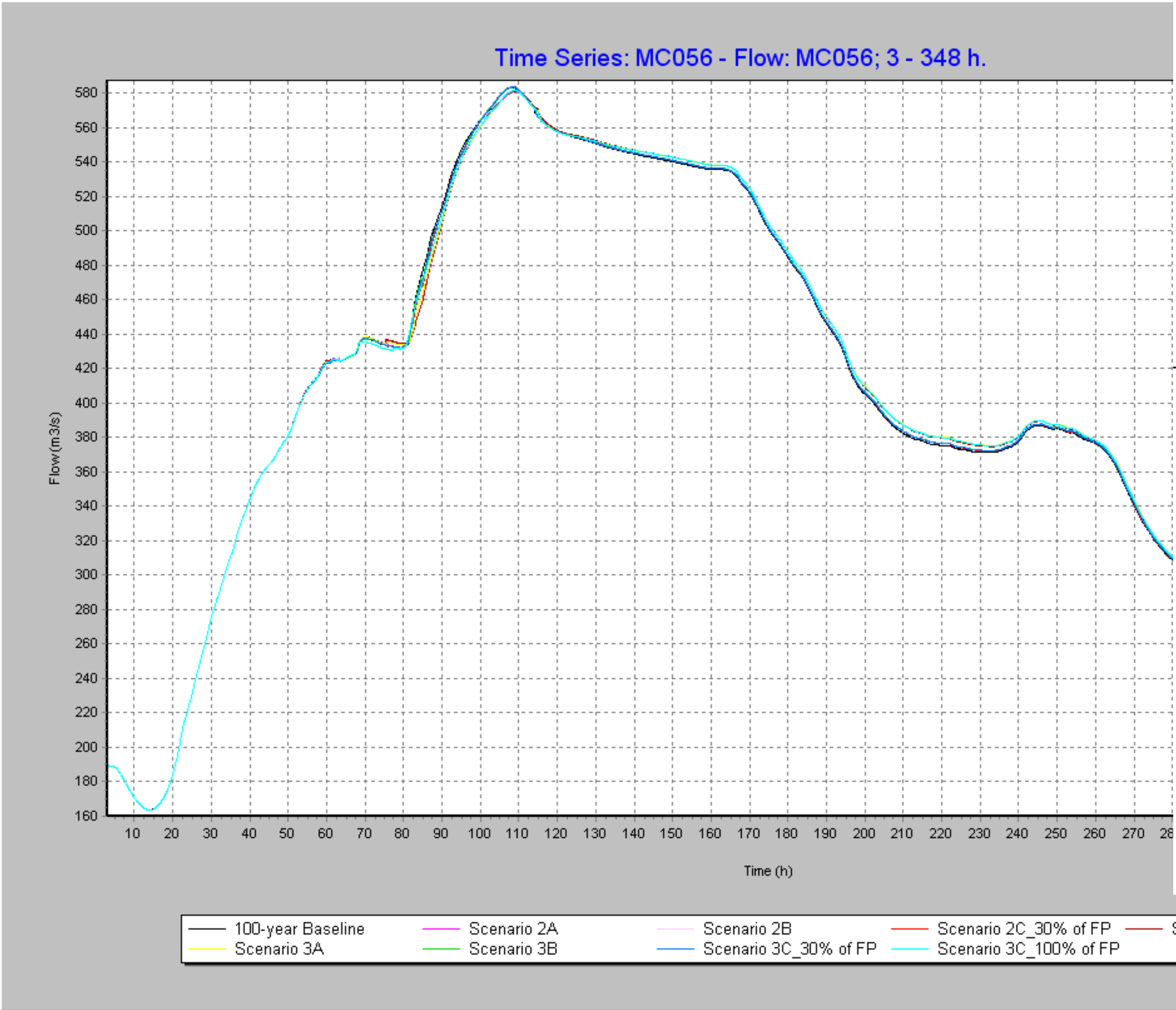
- Flood hydrographs in the downstream area (e.g. downstream of plantation)

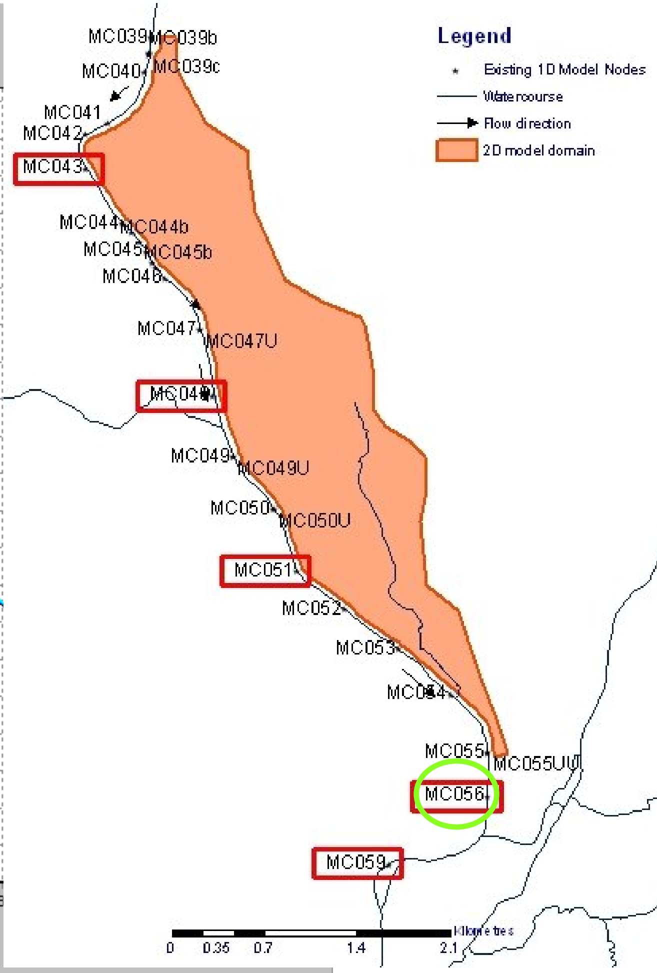




Model results – River Flow Hydrographs

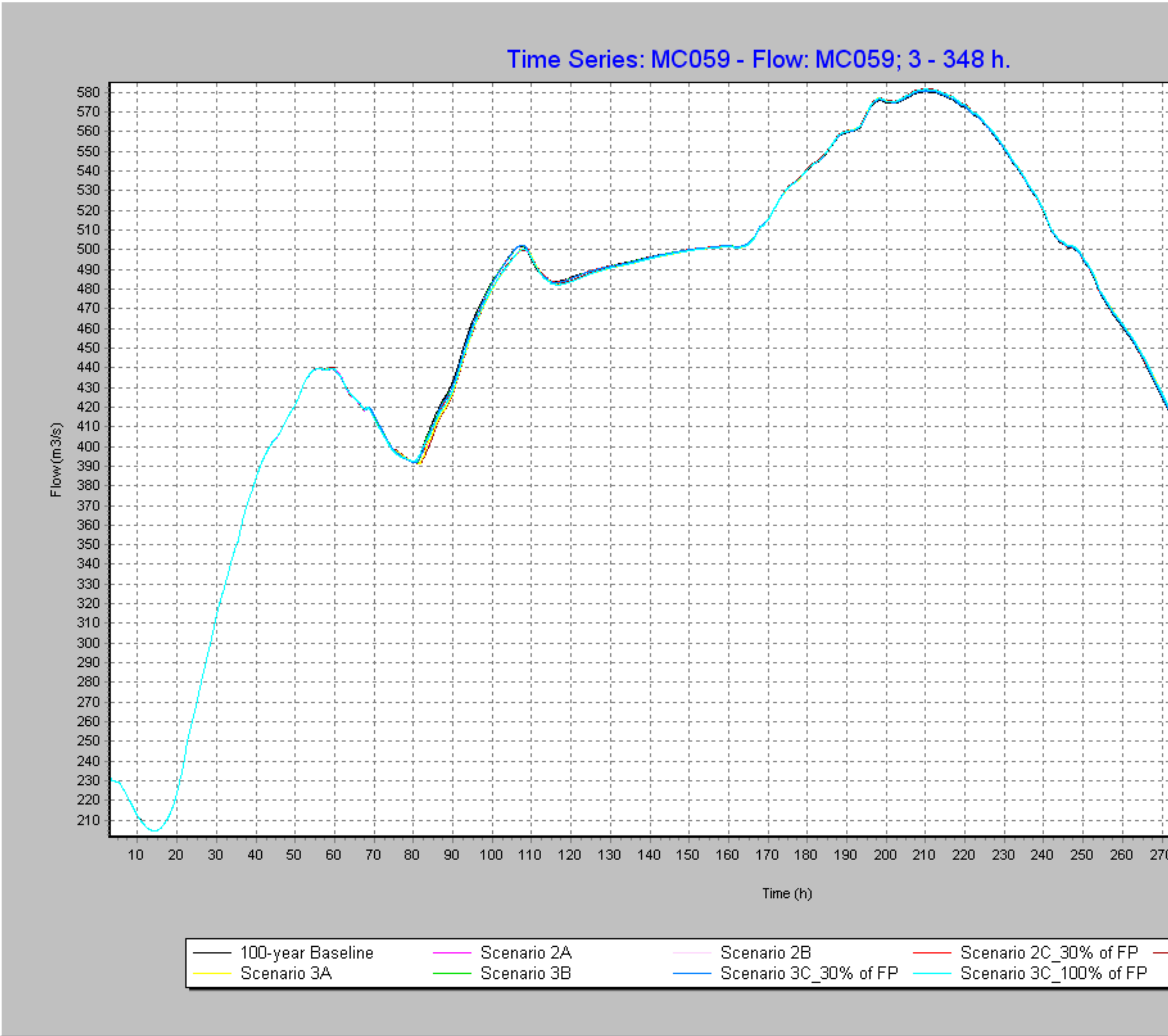
- Flood hydrographs downstream of the modelled floodplain

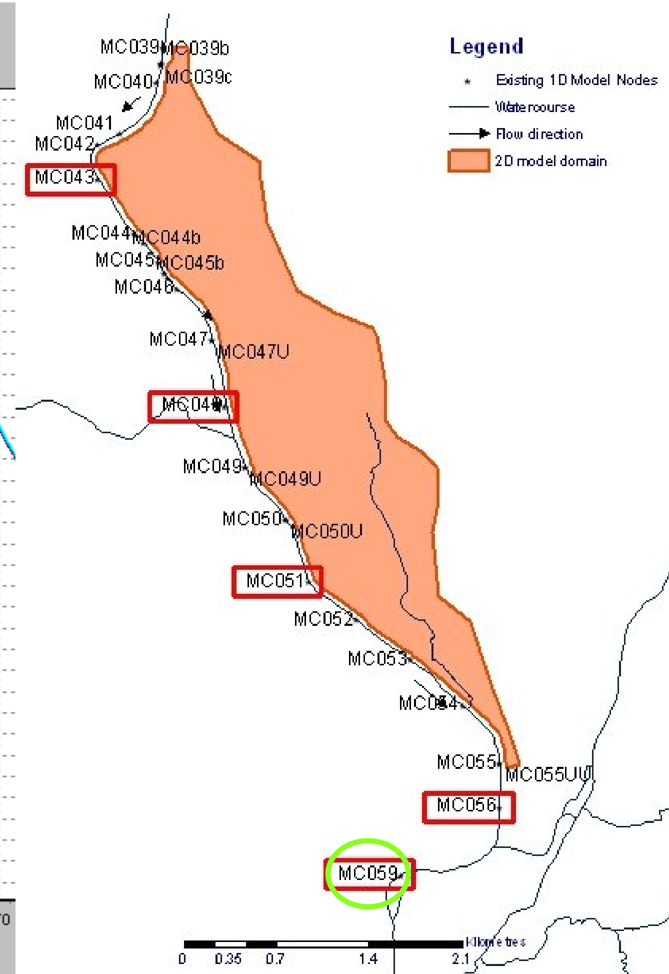




Model results – River Flow Hydrographs

- Flood hydrographs downstream of the modelled floodplain





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Case Study 2

Modelled results for River Isle at Ashford Mill

Modelling approach and methodology

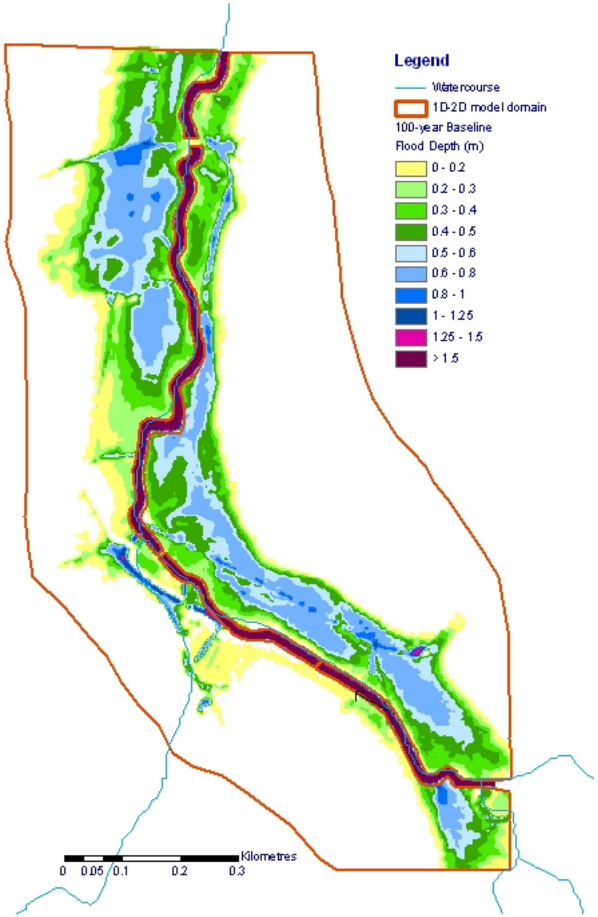
- Plantation type
  - Scenario 2, 4, 5, 6, 7 and 8 series – Miscanthus
  - Scenario 3 series – SRC Willow (i.e. roughness changes with depth of inundation as follows: n=0.1 for 0 – 0.5m, n=0.34 for depth 2m or greater (the 2D model interpolates between these two)
- Plantation pattern
  - 3ha and 1ha plots with 10m or 5m rides around
- Plantation coverage
  - 100% of floodplain
  - 30% of floodplain (both sides of the river) or less
- Modelled return period: 100years (1%AEP)
- The existing 1D-2D models details:

Modelled floodplain extent in FZ3 (km^2)	100 year flood (m^3/s)	2D model domain resolution (cell size in m)	Simulation duration (hours)
0.5	61.3	4	1.5

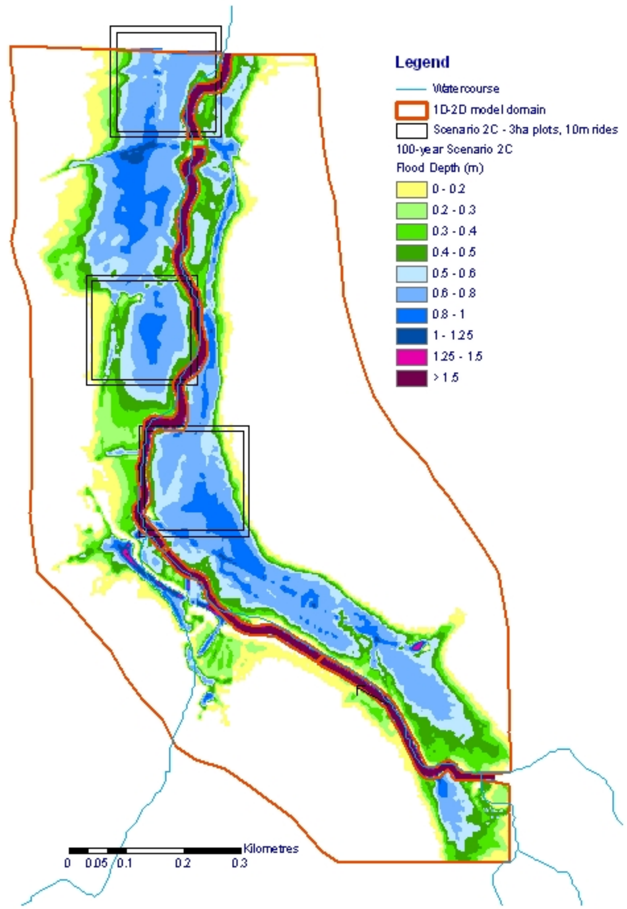
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 2 series (Miscanthus, 10m rides)

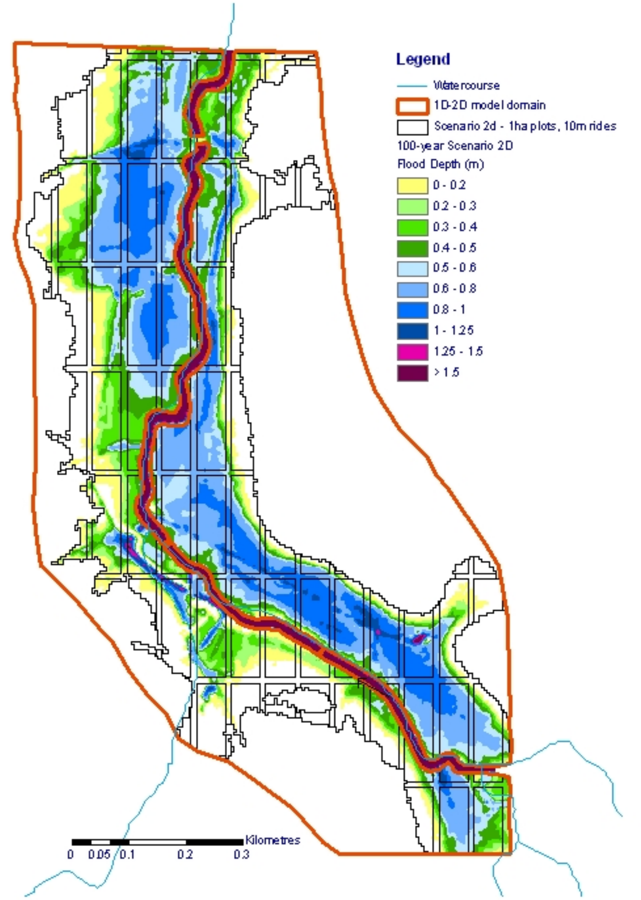
Baseline



Scenario 2C



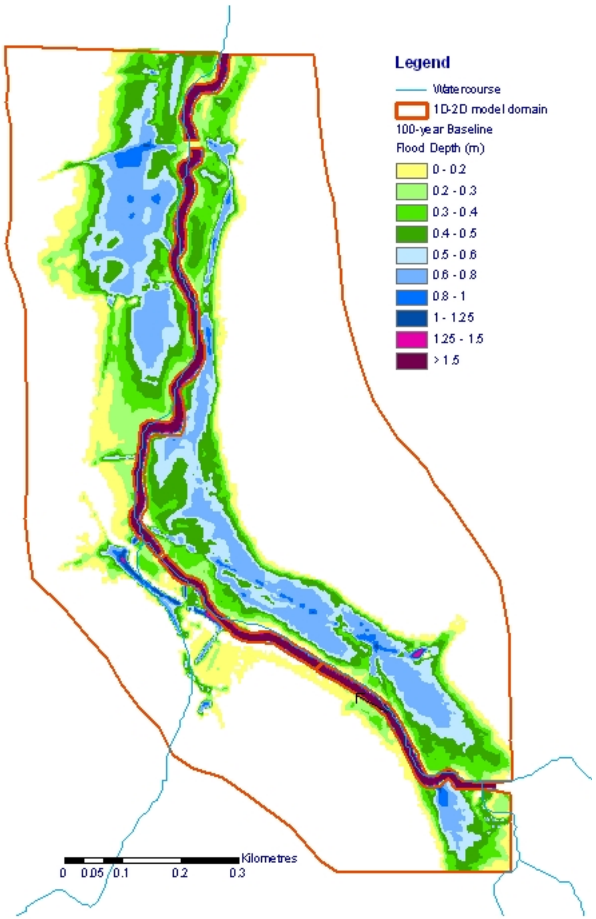
Scenario 2D



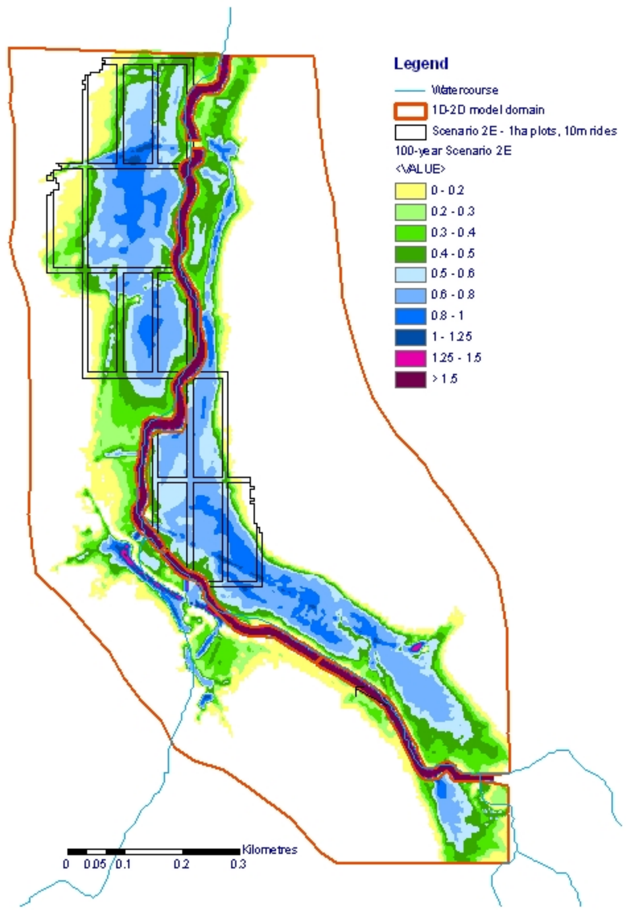
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 2 series (Miscanthus, 10m rides)

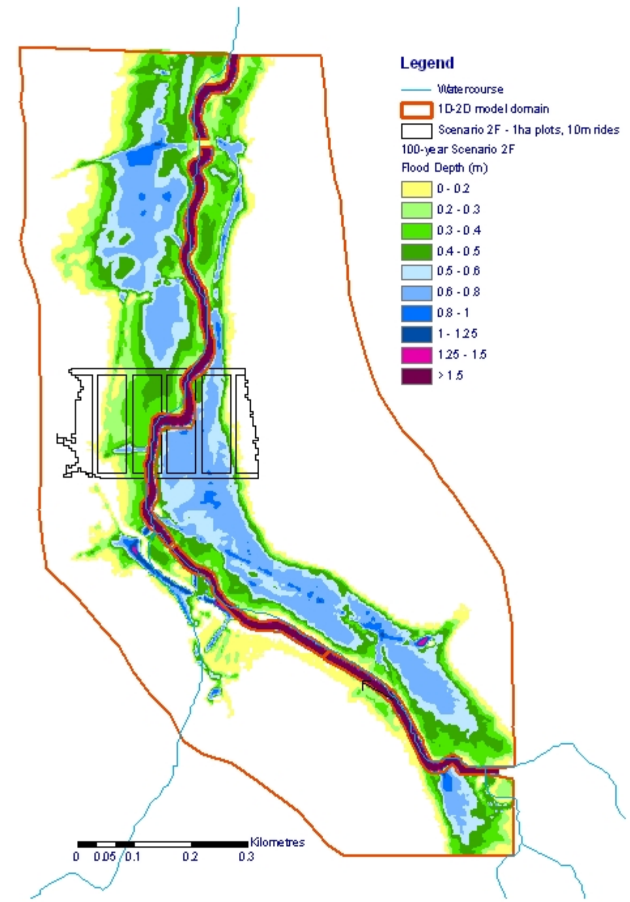
Baseline



Scenario 2E



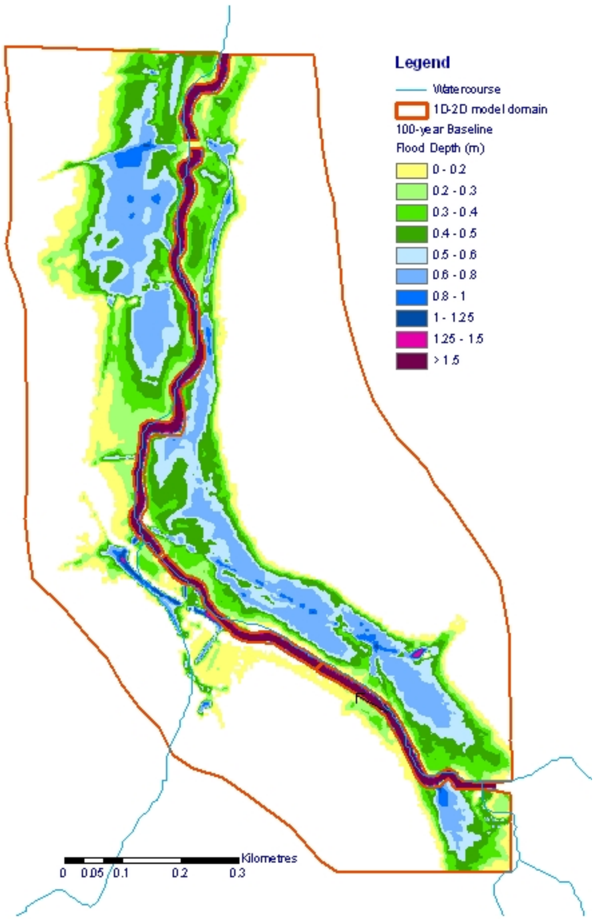
Scenario 2F



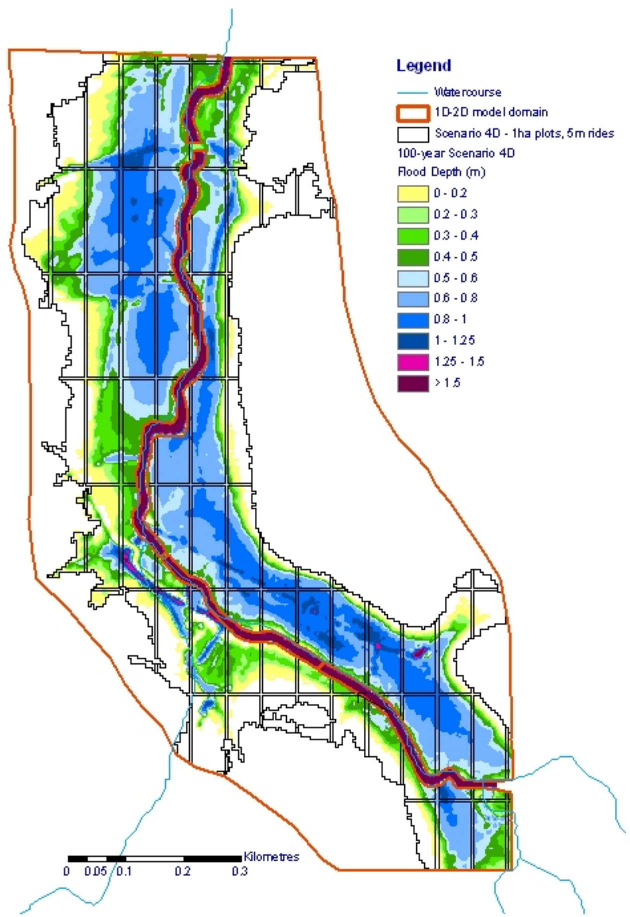
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 4 series (Miscanthus, 5m rides)

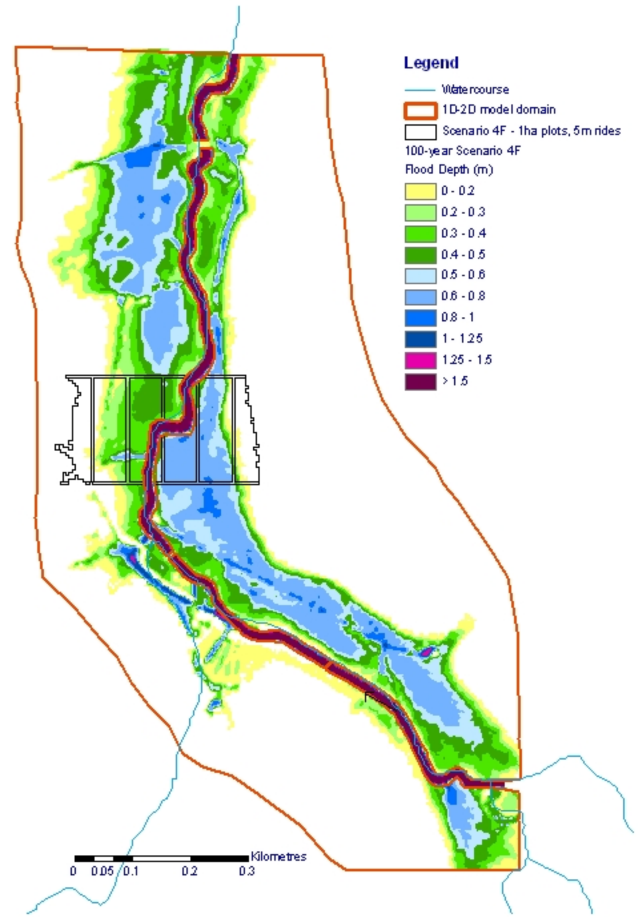
Baseline



Scenario 4D



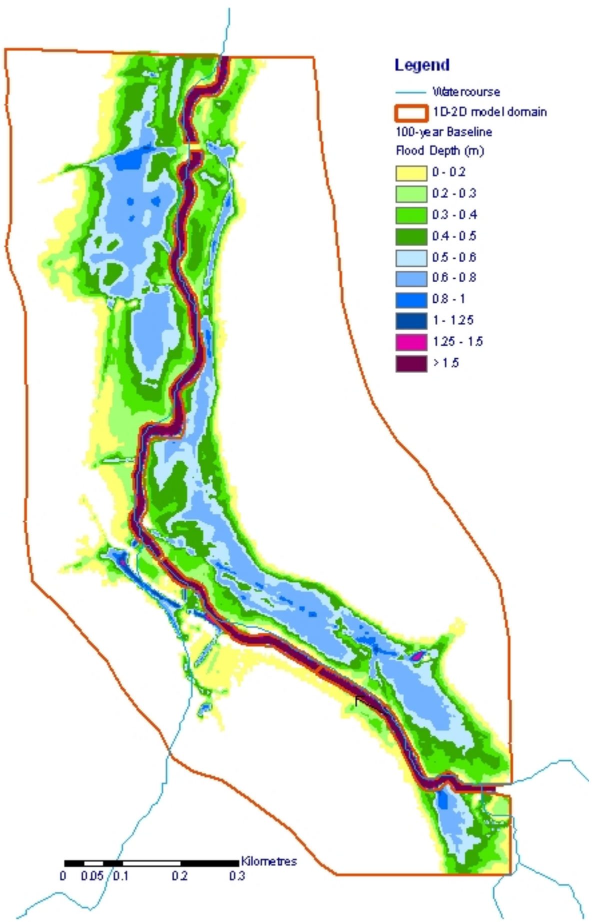
Scenario 4F



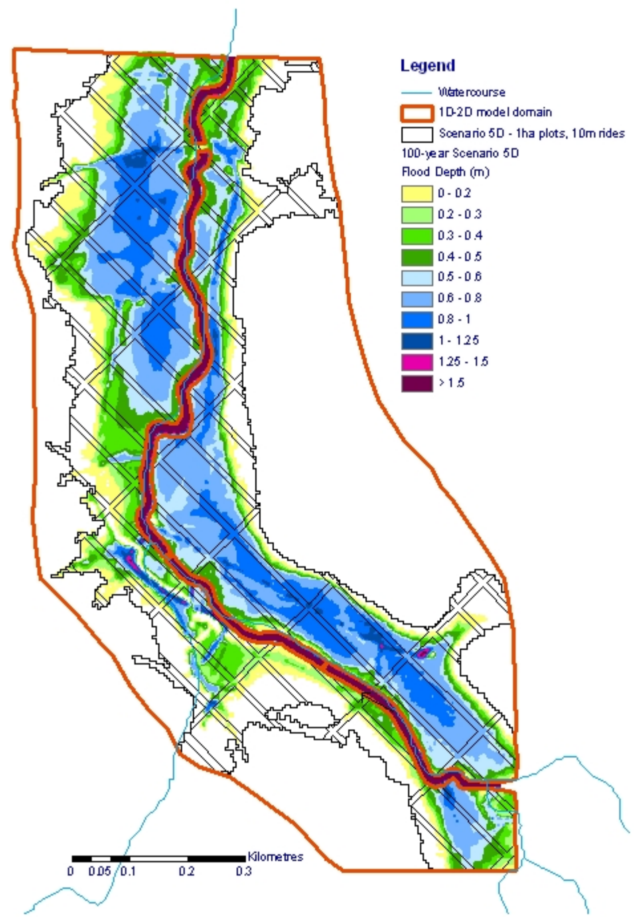
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 5 series (Miscanthus, 10m rides)

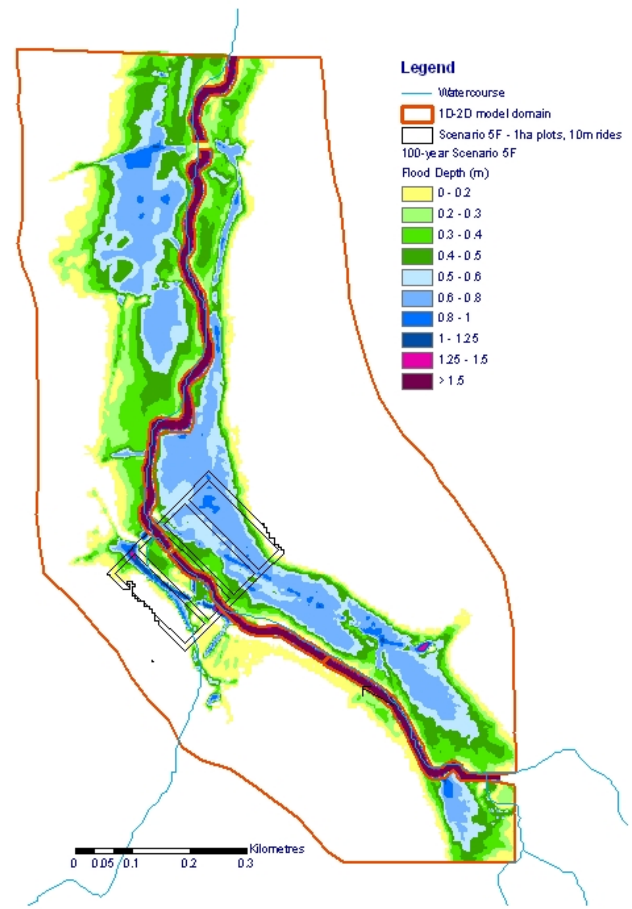
Baseline



Scenario 5D



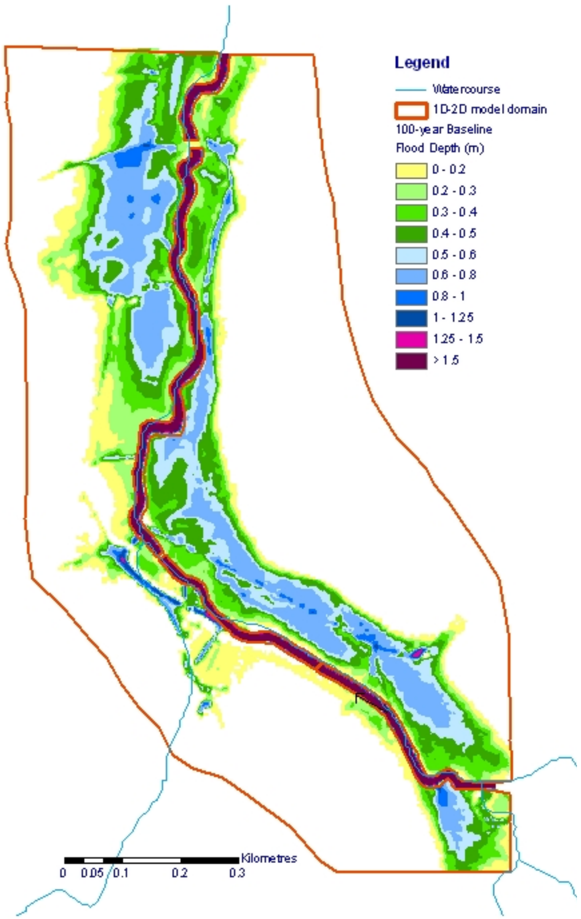
Scenario 5F



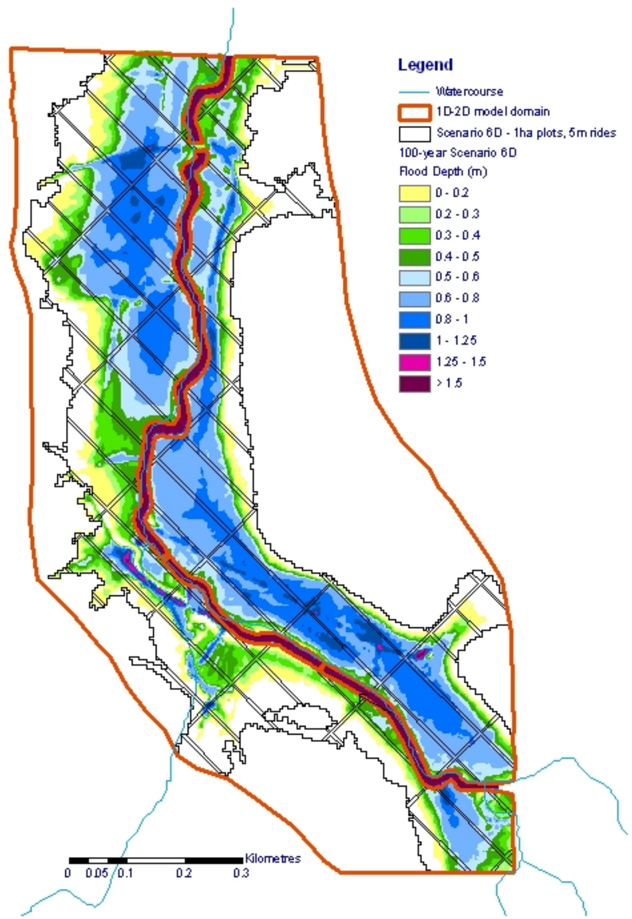
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 6 series (Miscanthus, 5m rides)

Baseline



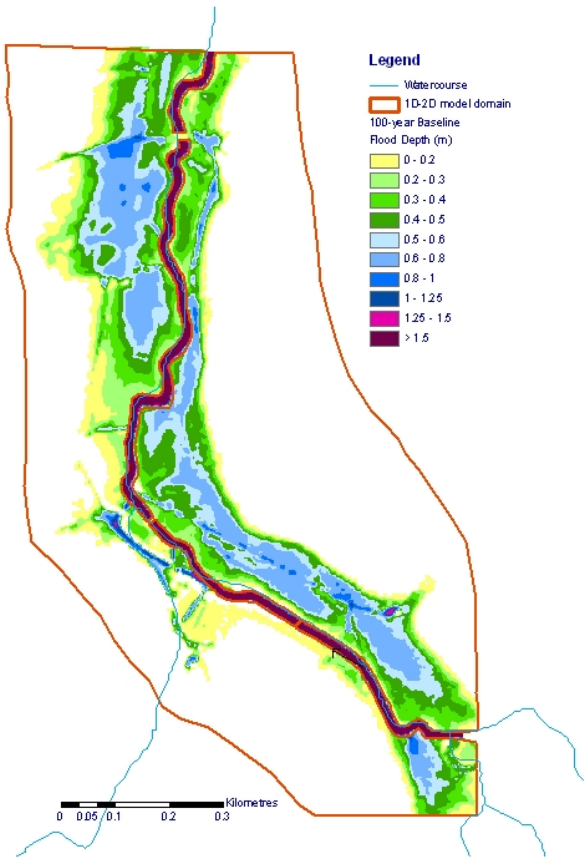
Scenario 6D



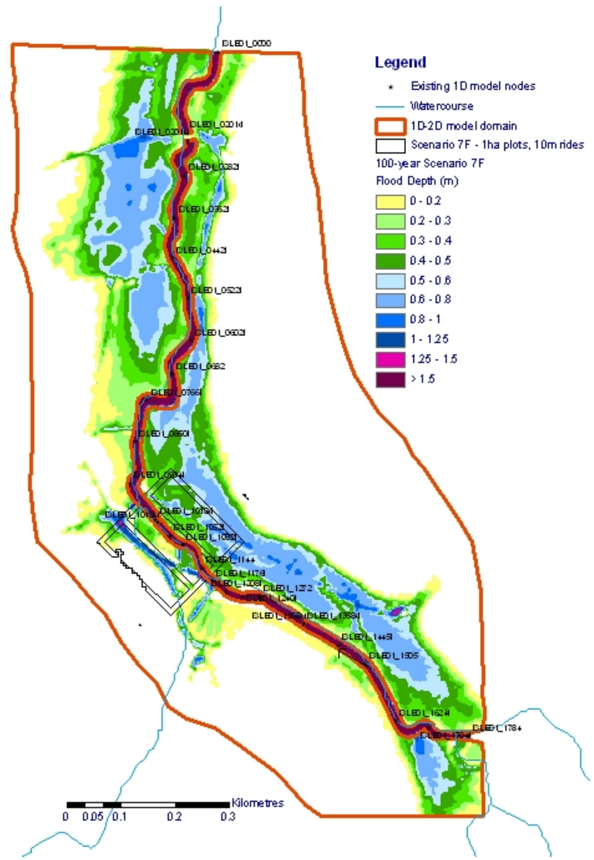
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 7 and 8 series (Miscanthus, 10 and 5m rides, respectively)

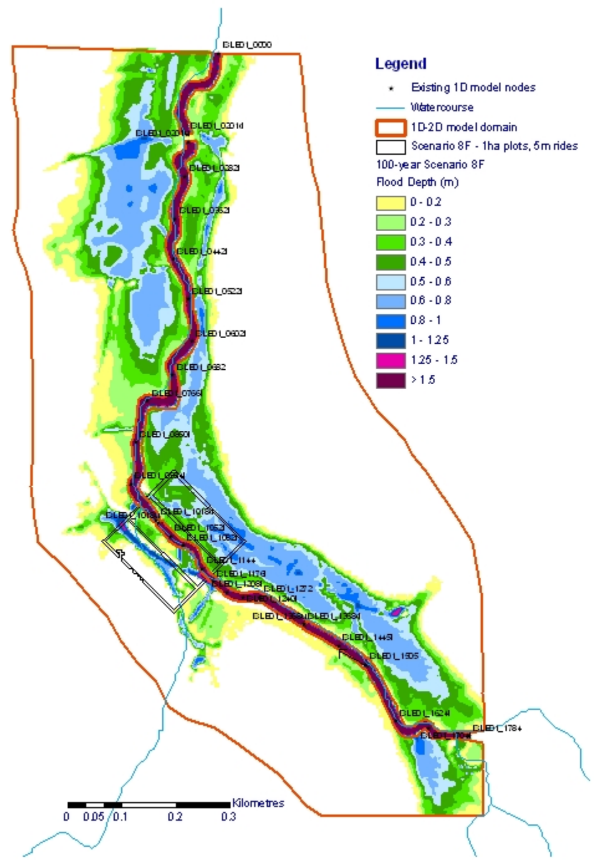
Baseline



Scenario 7F



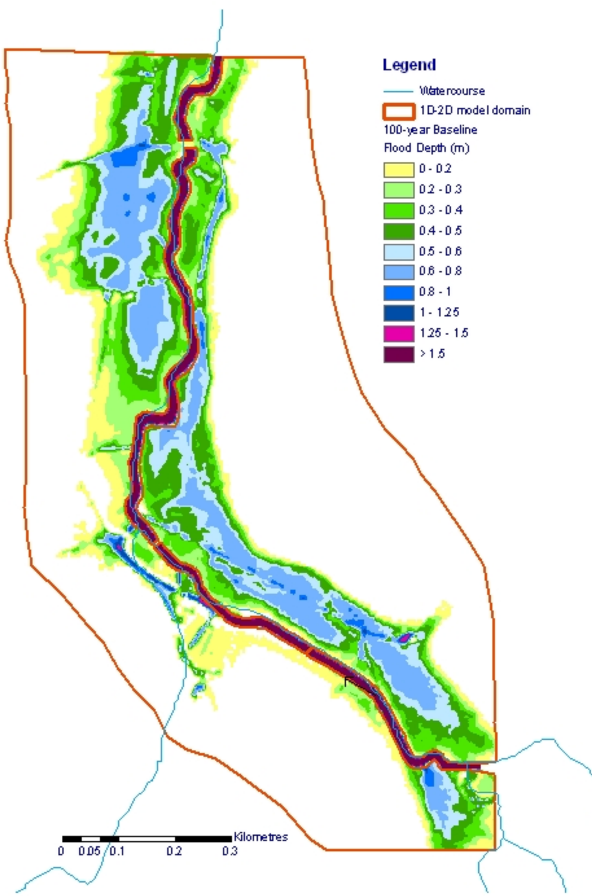
Scenario 8F



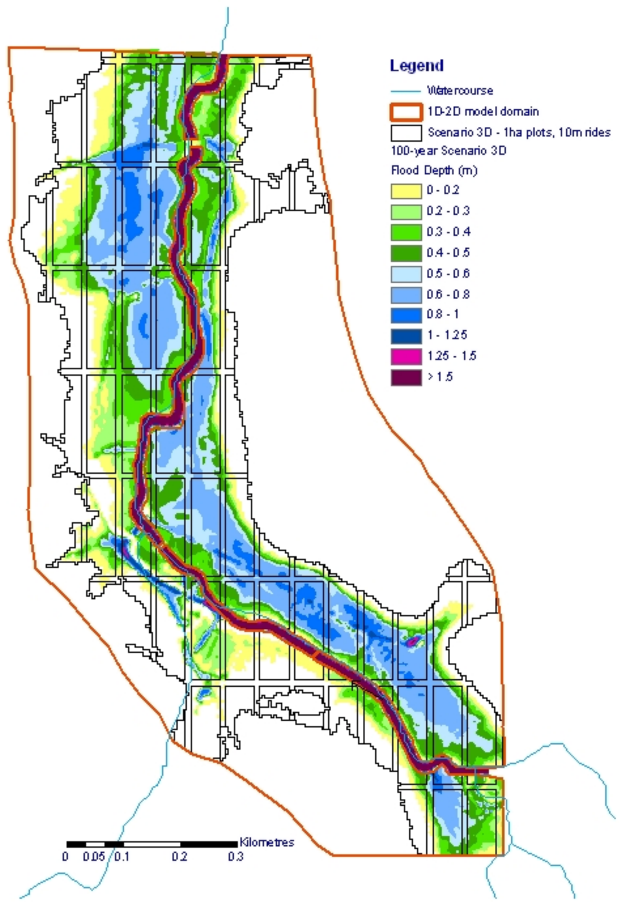
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 3 series (SRC Willow, 10m rides)

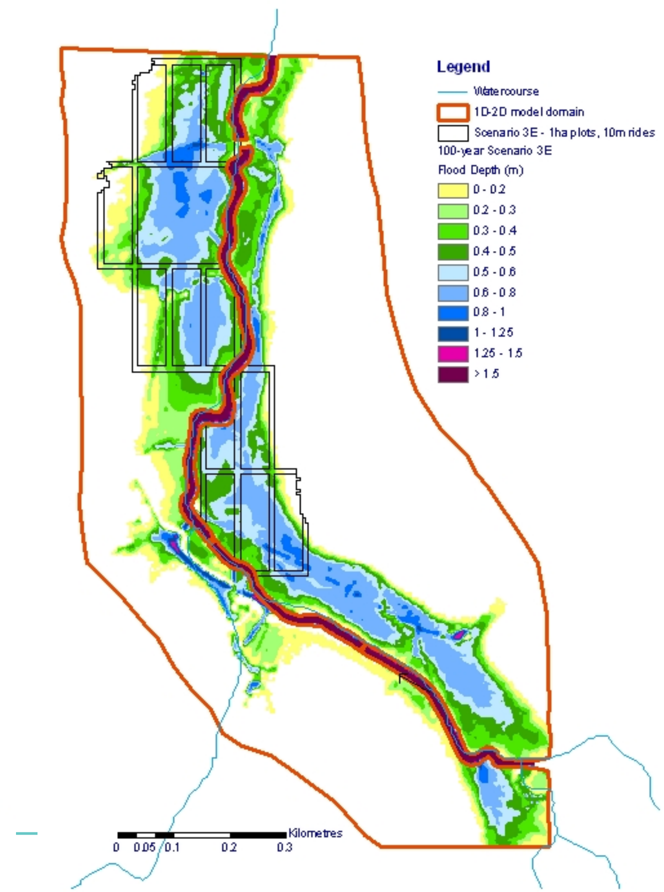
Baseline



Scenario 3D



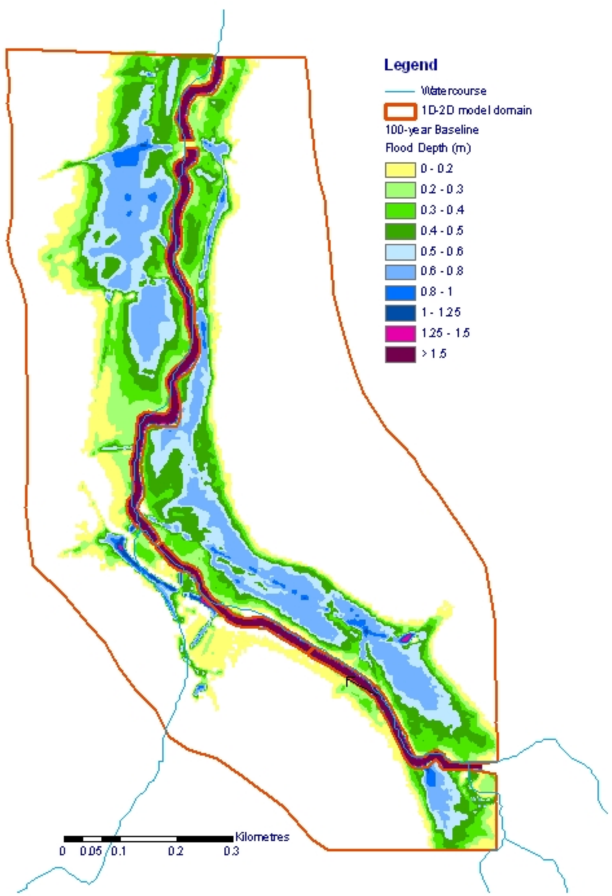
Scenario 3E



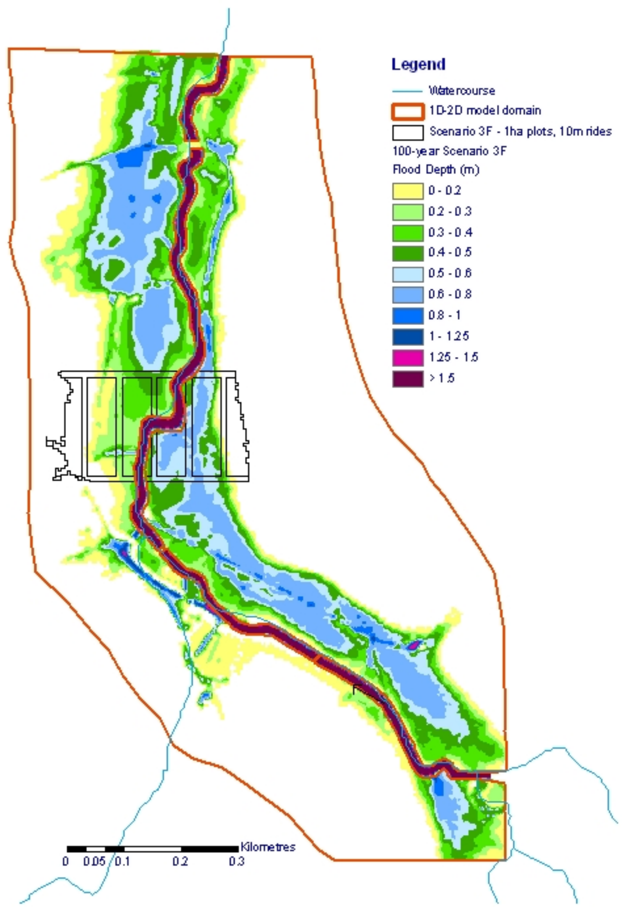
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 3 series (SRC Willow, 10m rides)

Baseline



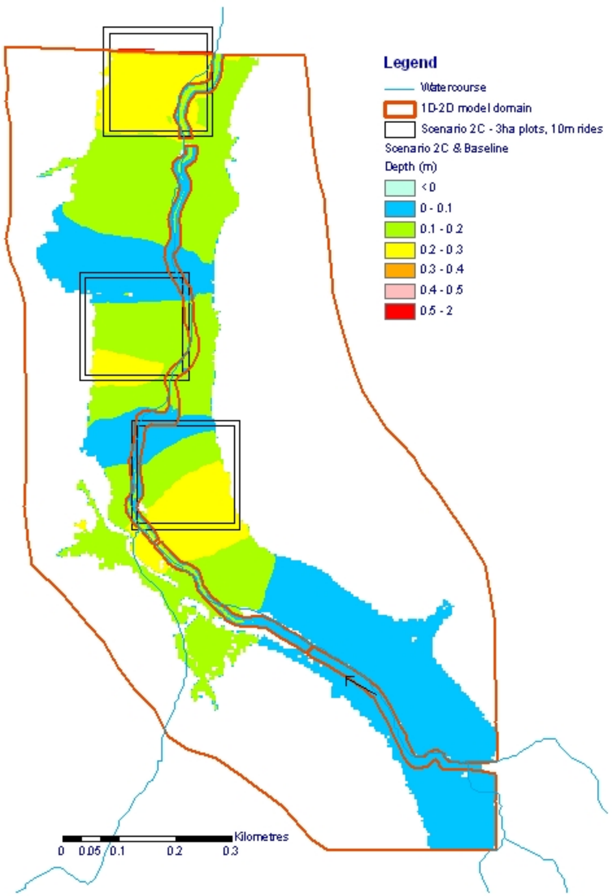
Scenario 3F



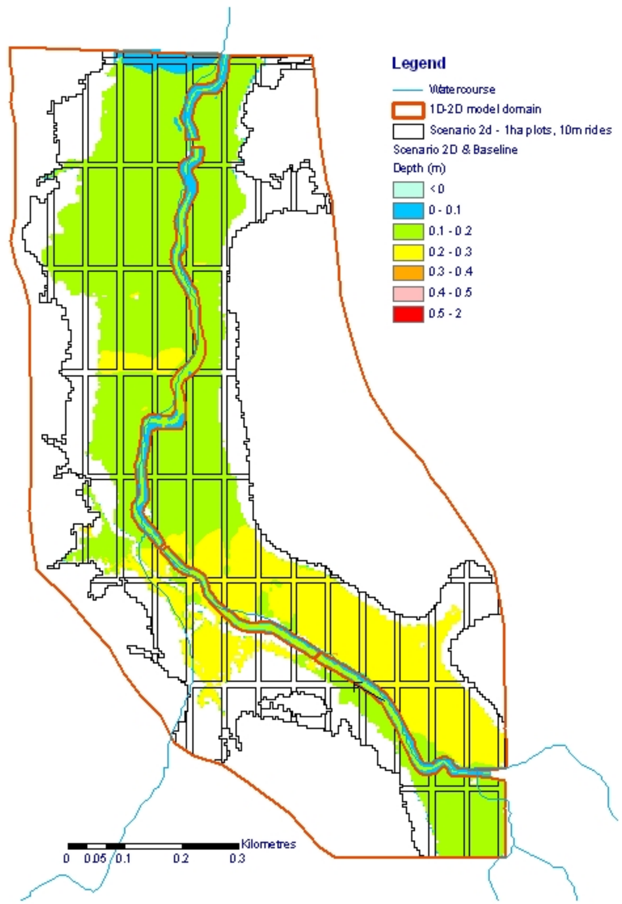
Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 2 series (Miscanthus, 10m rides)

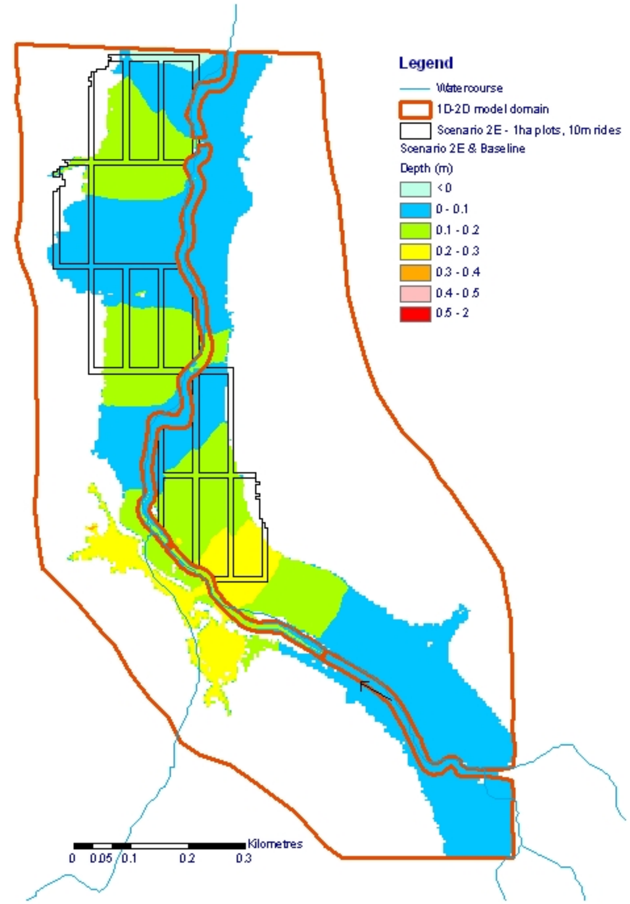
Scenario 2C - Baseline



Scenario 2D – Baseline



Scenario 2E - Baseline



Model results – Floodplain Inundation (difference from Baseline depth)

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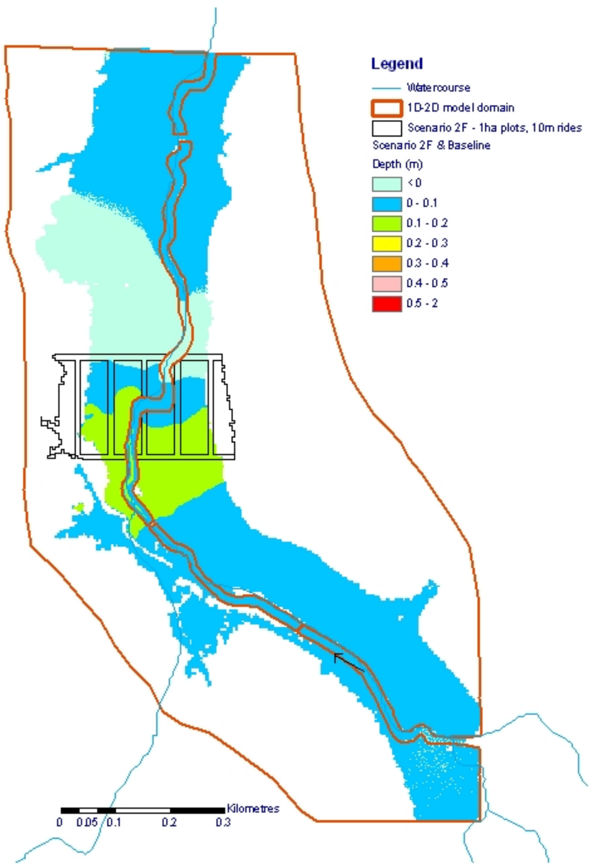
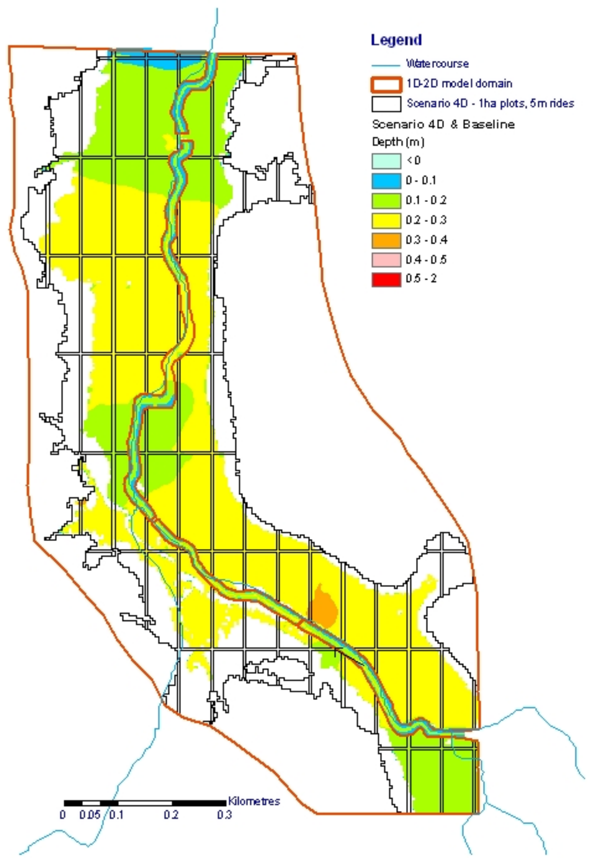
- Flood Depth Difference (m) – Scenario 2 and 4 series (Miscanthus, 10 and 5m rides, respectively)

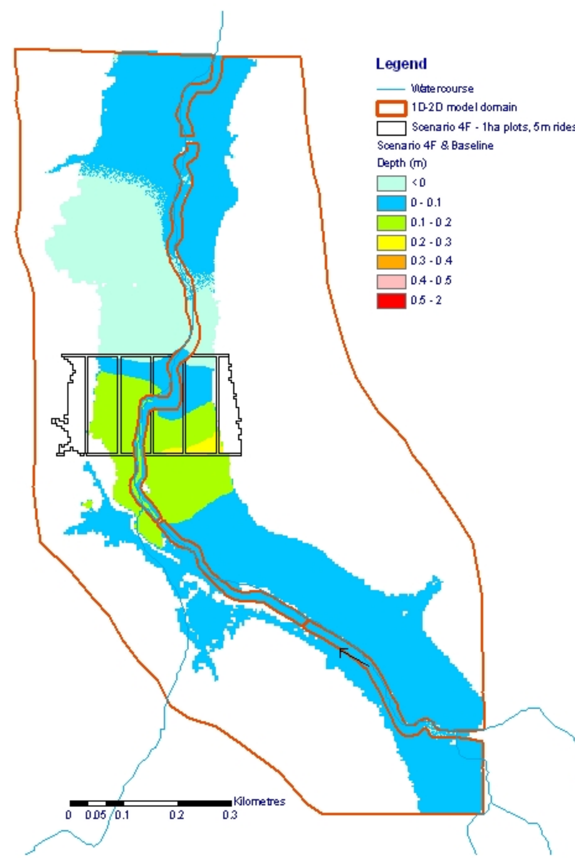
Scenario 2F - Baseline



Scenario 4D – Baseline



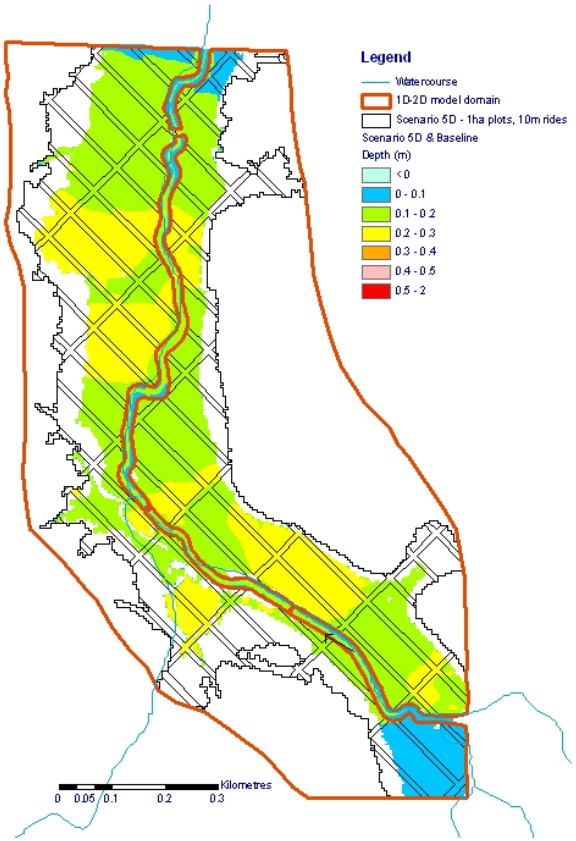
Scenario 4E - Baseline



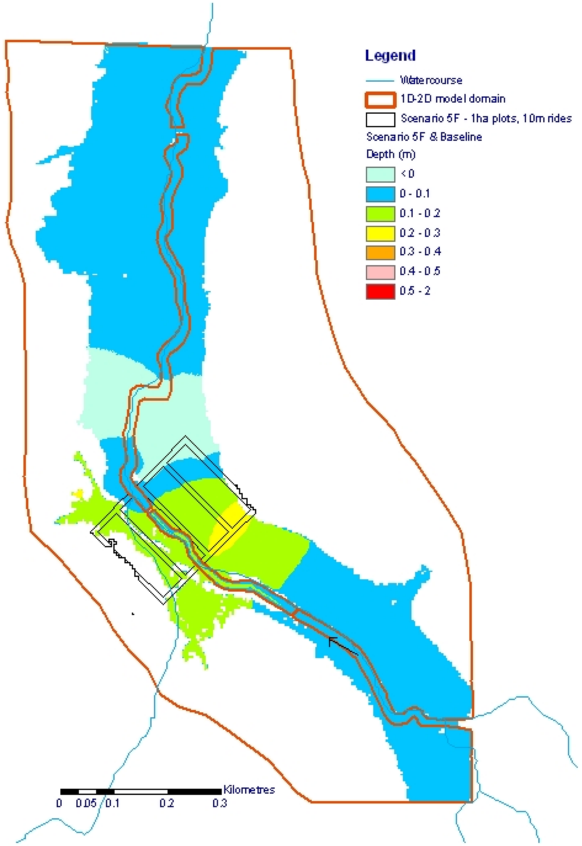
Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 5 and 6 series (Miscanthus, 10 and 5m rides, respectively)

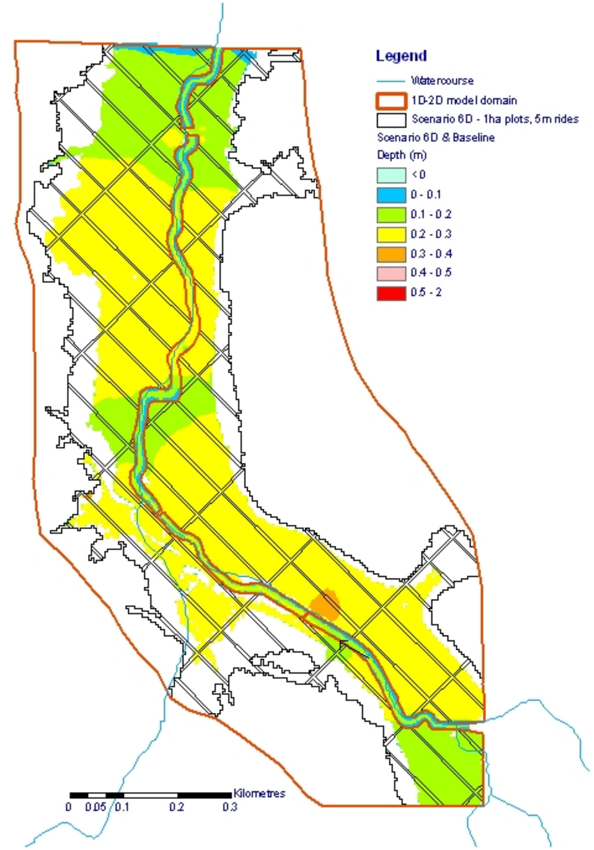
Scenario 5D - Baseline



Scenario 5F – Baseline



Scenario 6D - Baseline



Model results – Floodplain Inundation (difference from Baseline depth)

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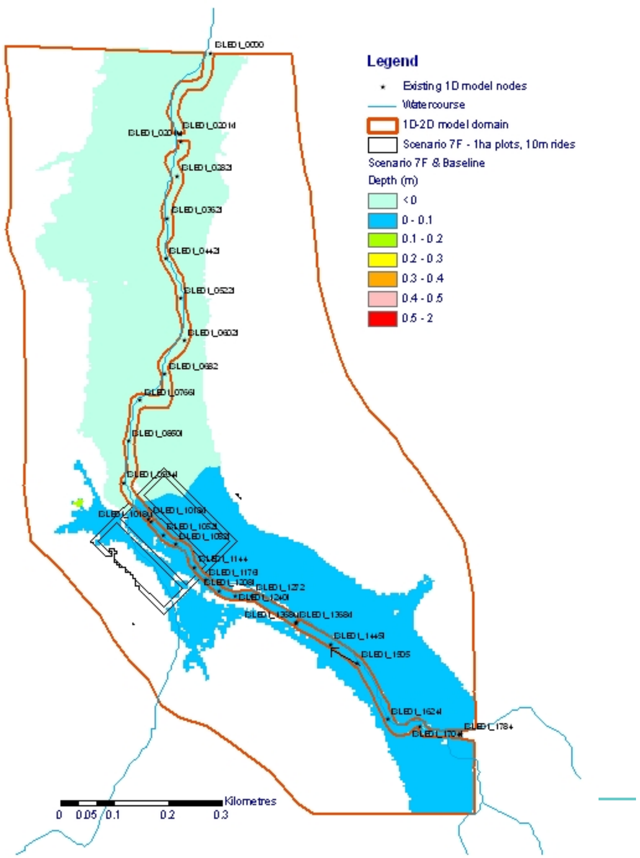
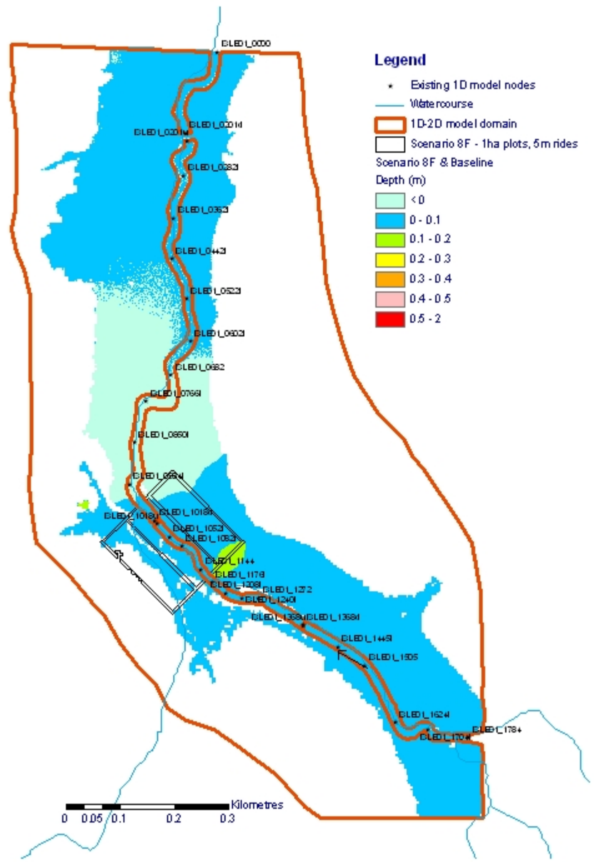
- Flood Depth Difference (m) – Scenario 7 and 8 series (Miscanthus, 10 and 5m rides, respectively)

Scenario 7F - Baseline



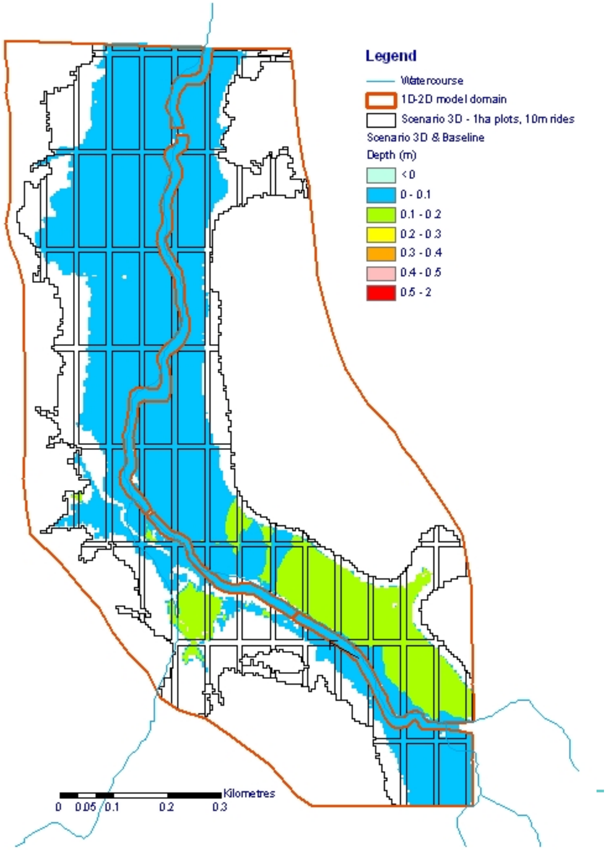
Scenario 8F – Baseline



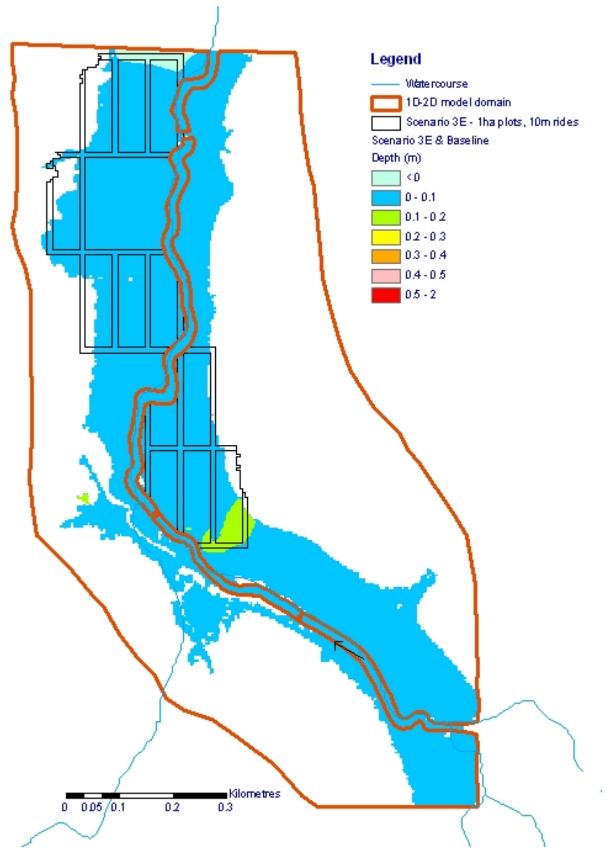
Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 3 series (SRC Willow, 10 and 5m rides, respectively)

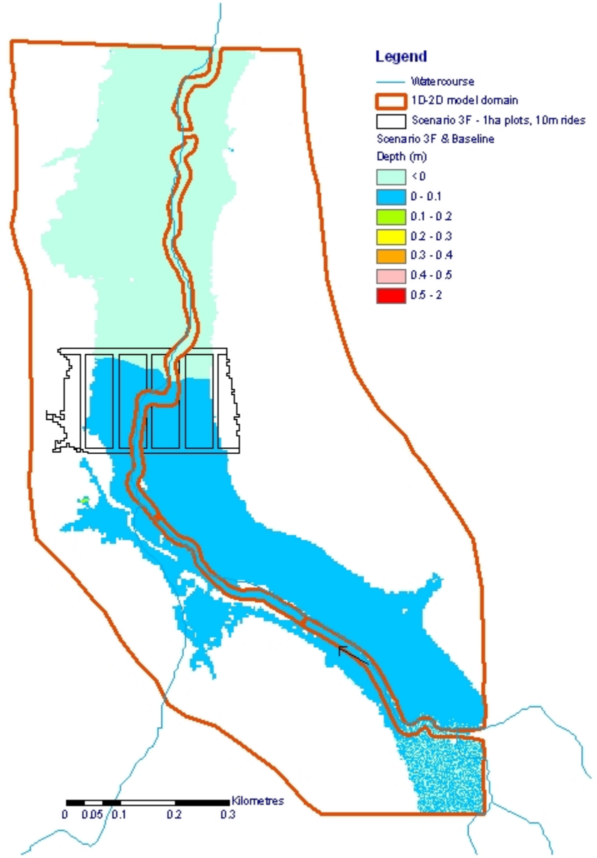
Scenario 3D - Baseline



Scenario 3E – Baseline



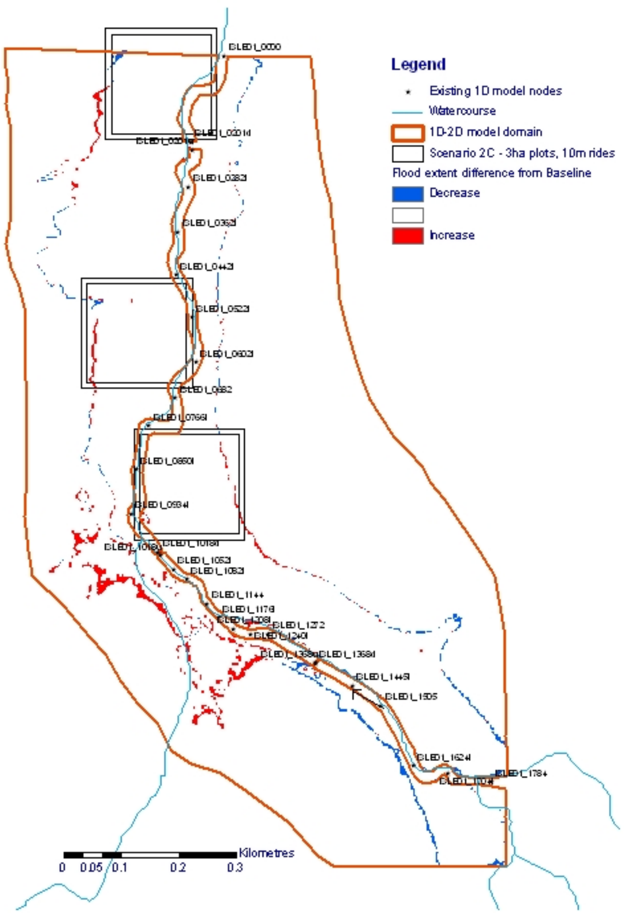
Scenario 3F - Baseline



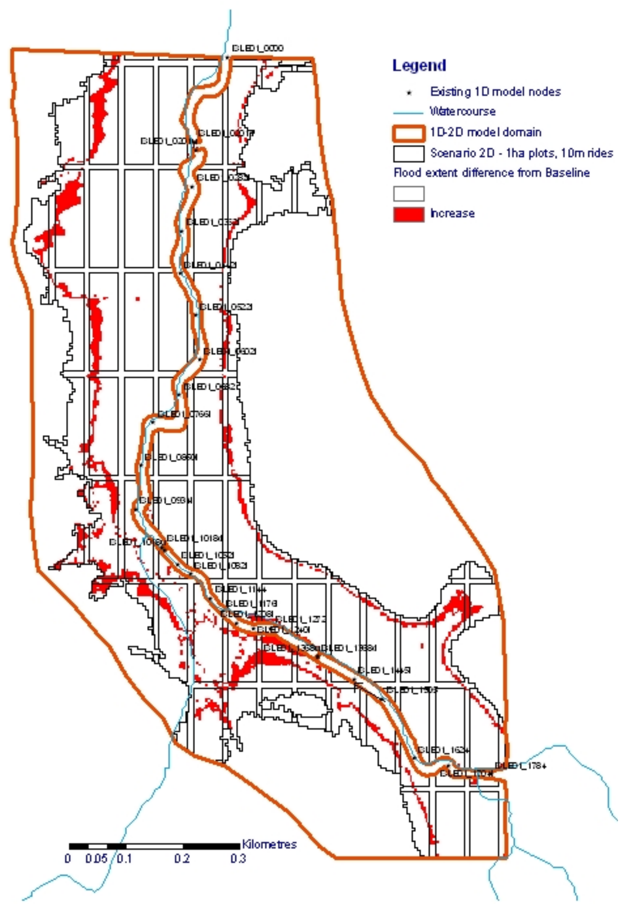
Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 2 series (Miscanthus, 10m rides)

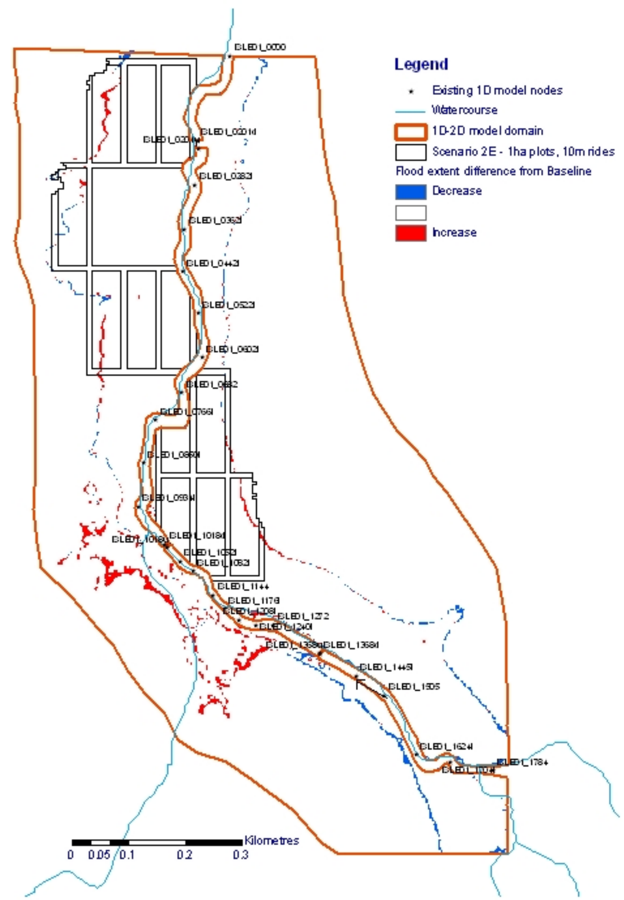
Scenario 2C - Baseline



Scenario 2D – Baseline



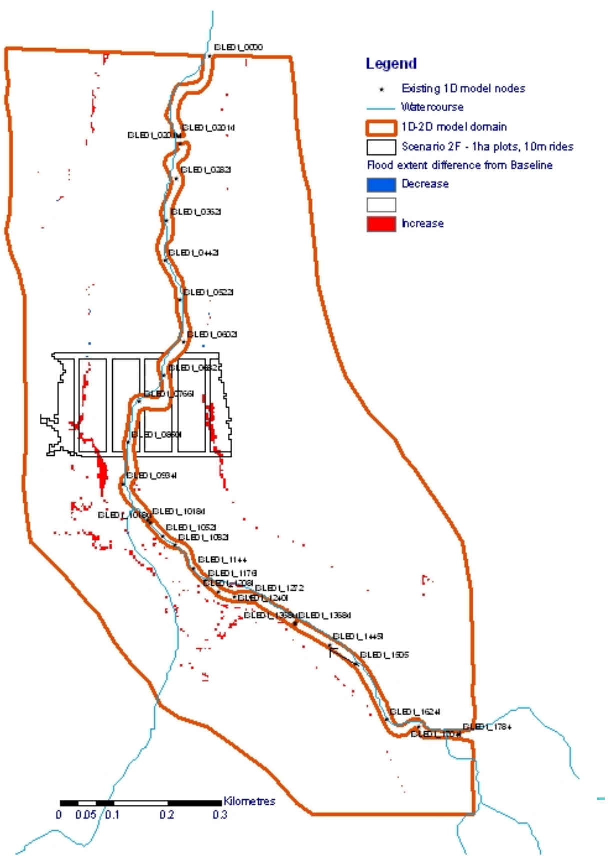
Scenario 2E - Baseline



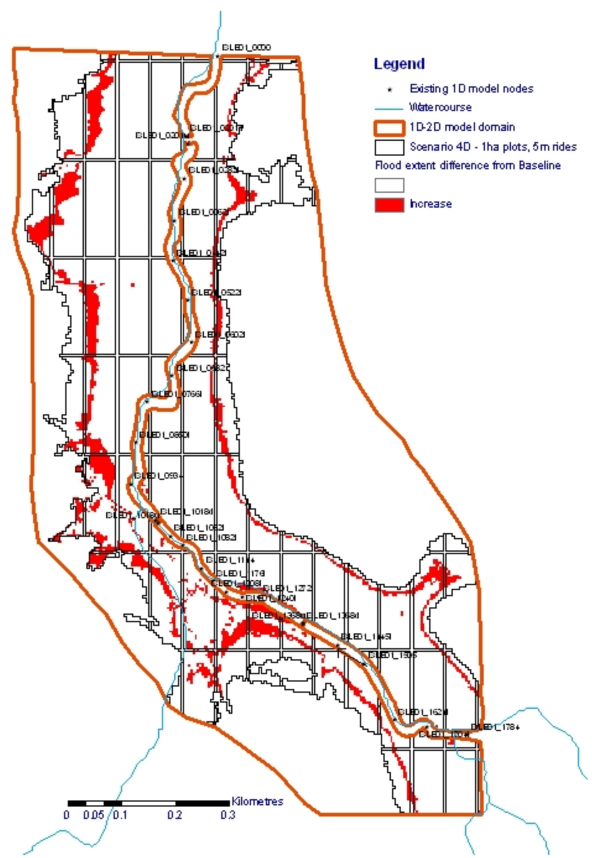
Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 2 and 4 series (Miscanthus, 10 and 5m rides, respectively)

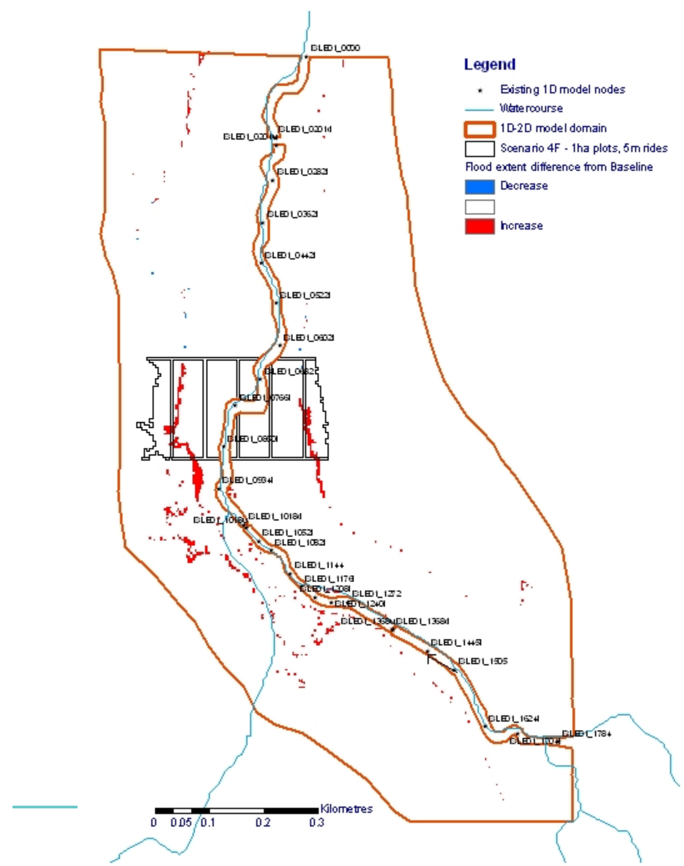
Scenario 2F - Baseline



Scenario 4D – Baseline



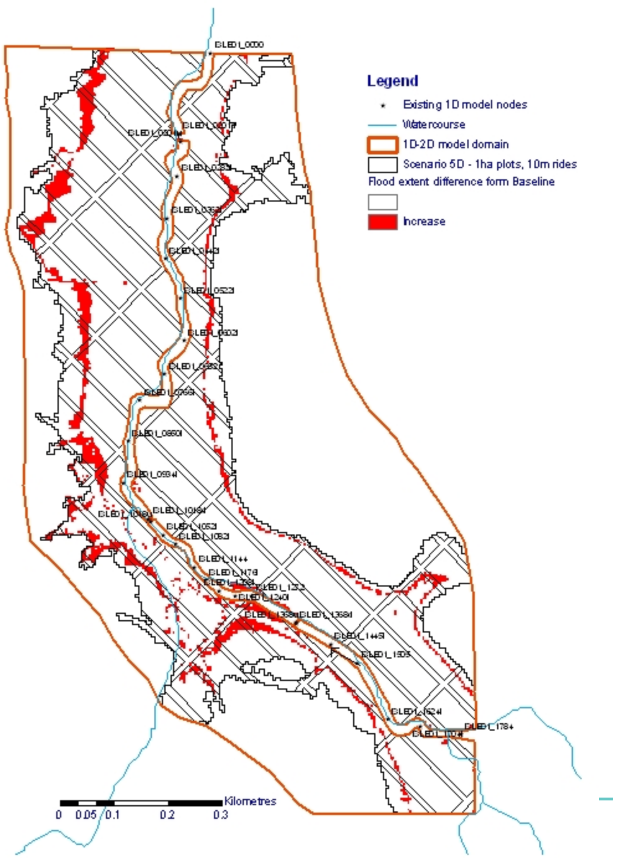
Scenario 4E - Baseline



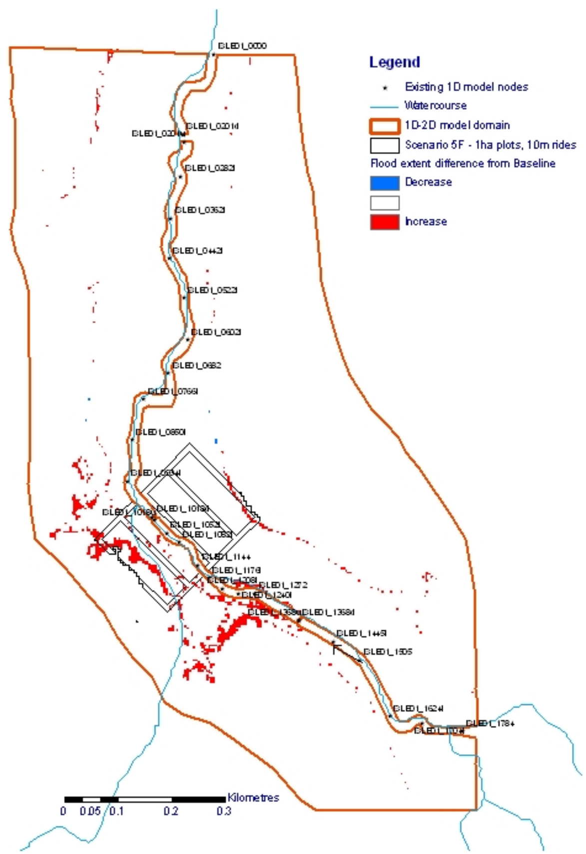
Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 5 and 6 series (Miscanthus, 10 and 5m rides, respectively)

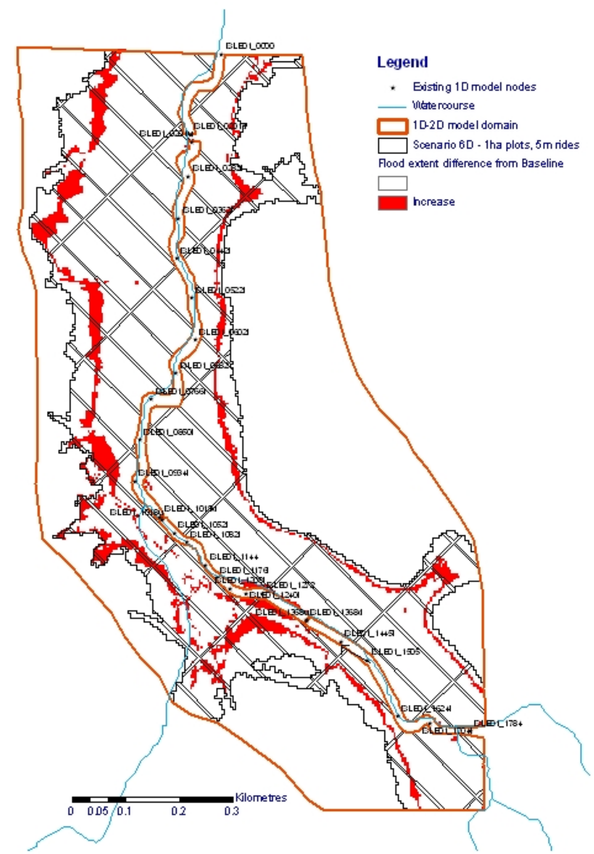
Scenario 5D - Baseline



Scenario 5F – Baseline



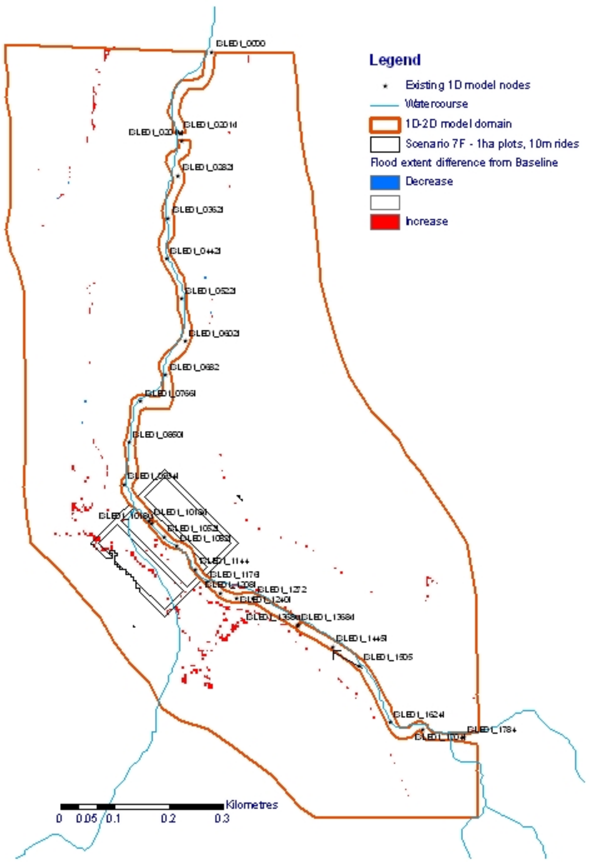
Scenario 6D - Baseline



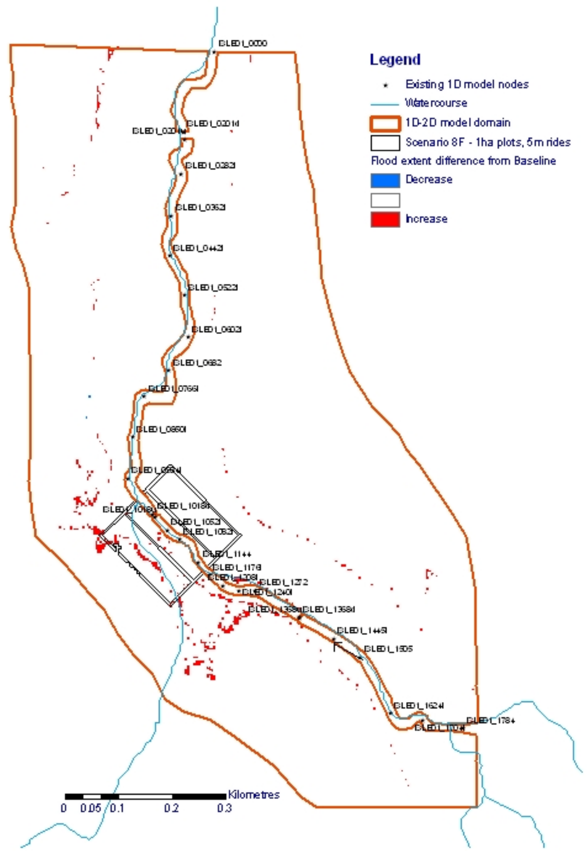
Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 7 and 8 series (Miscanthus, 10 and 5m rides, respectively)

Scenario 7F - Baseline



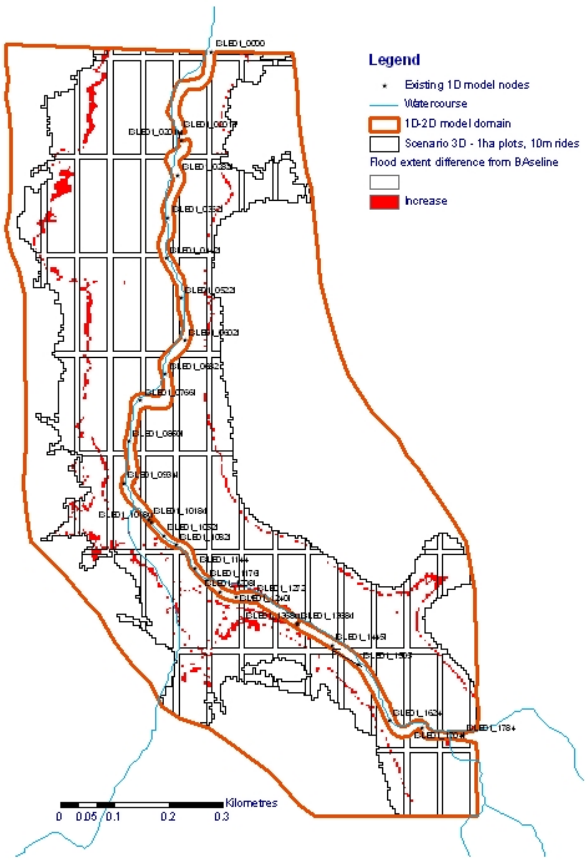
Scenario 8F – Baseline



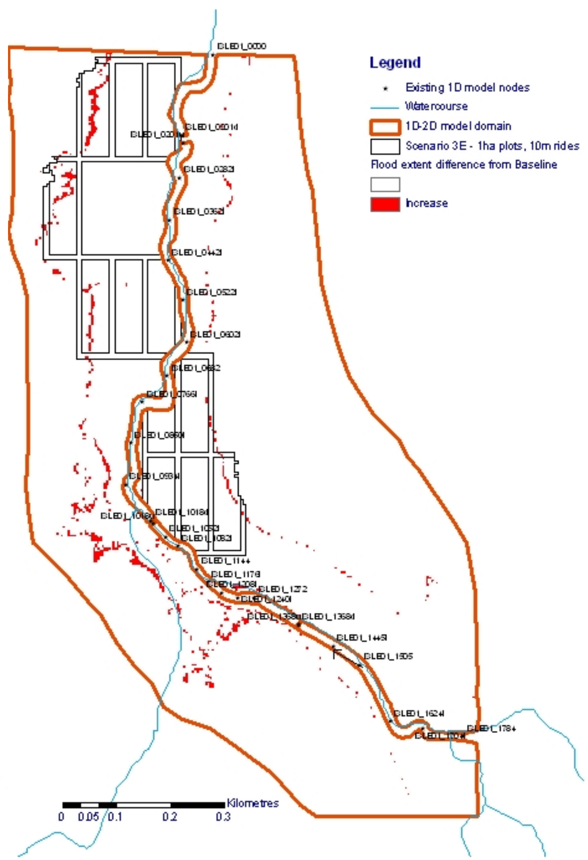
Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 3 series (SRC Willow, 10 and 5m rides, respectively)

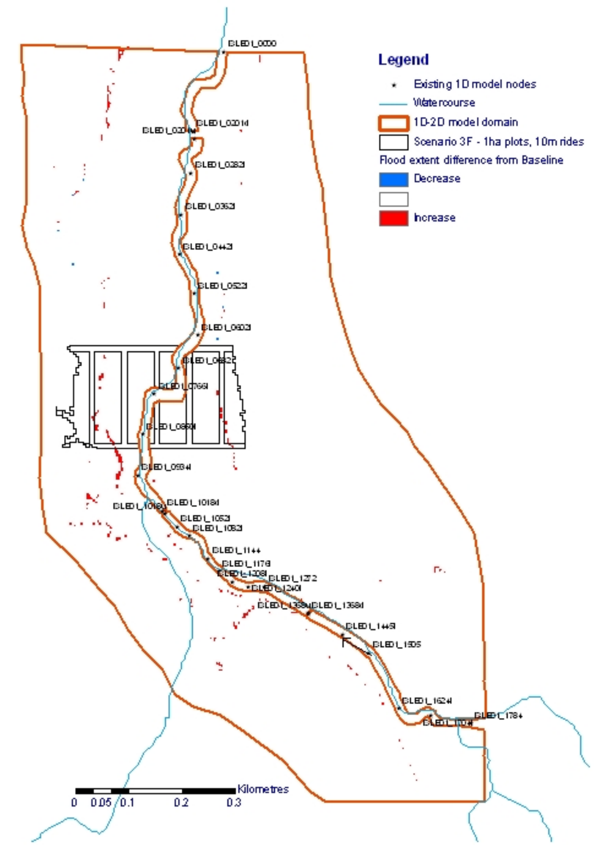
Scenario 3D - Baseline



Scenario 3E – Baseline



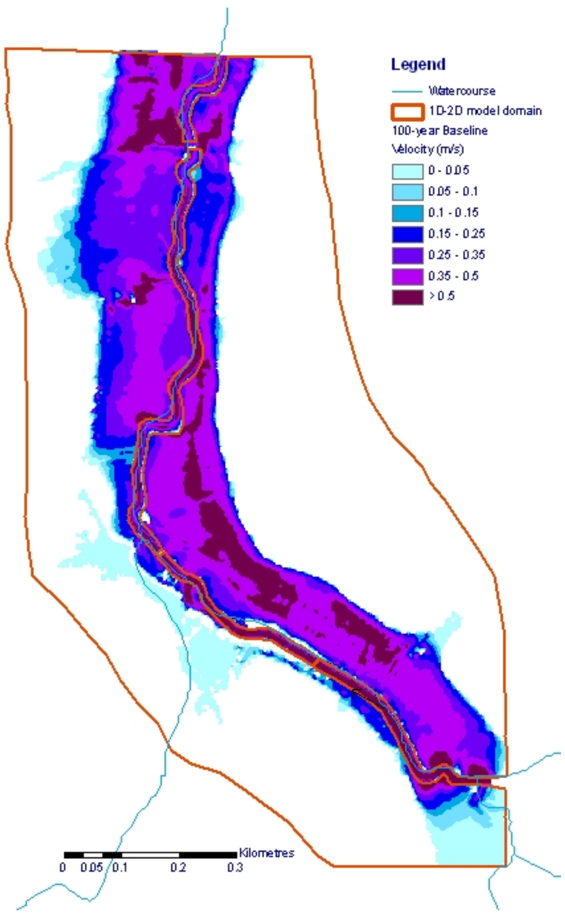
Scenario 3F - Baseline



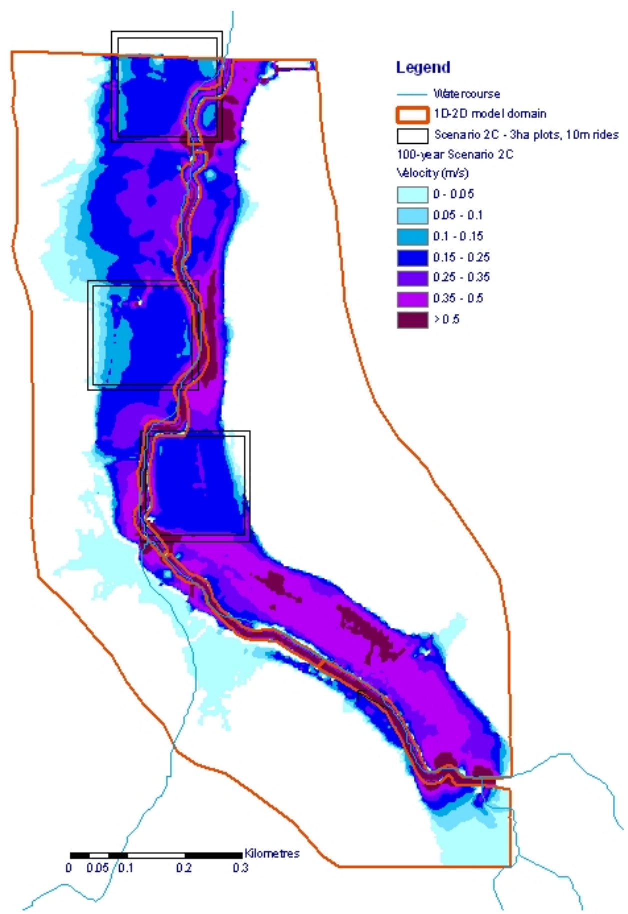
Model results – Velocities

- Flood Velocity (m/s) – Scenario 2 series (Miscanthus, 10m rides)

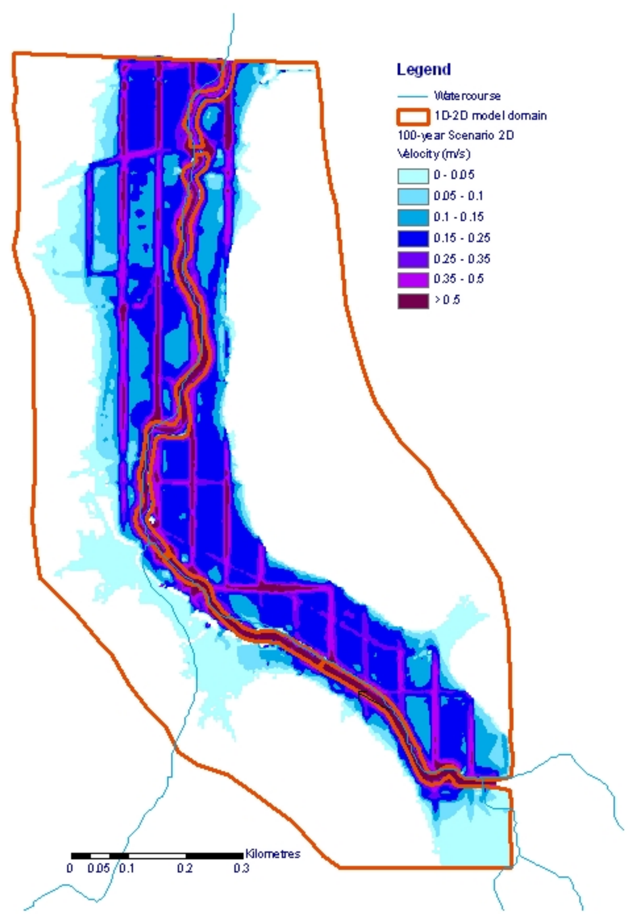
Baseline



Scenario 2C



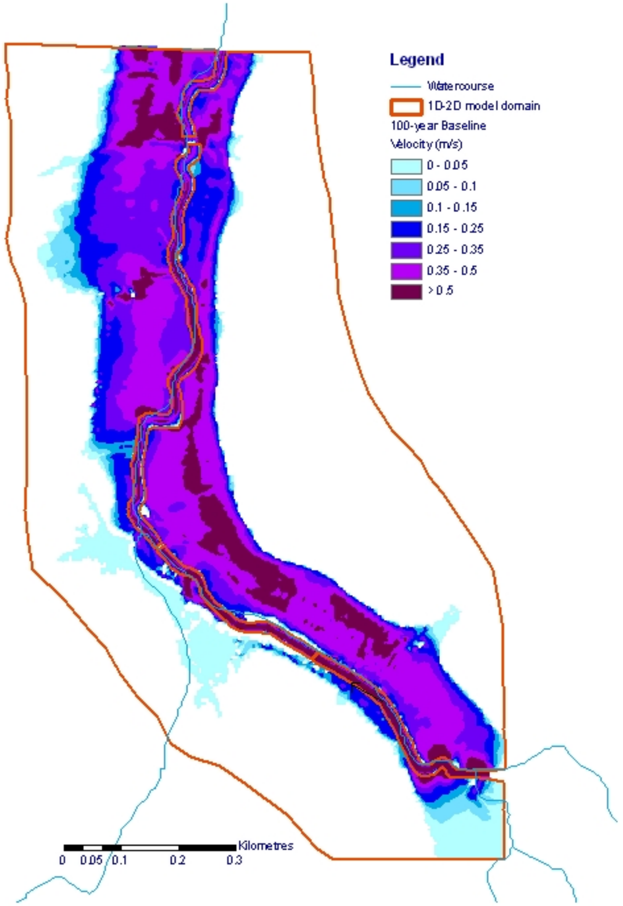
Scenario 2D



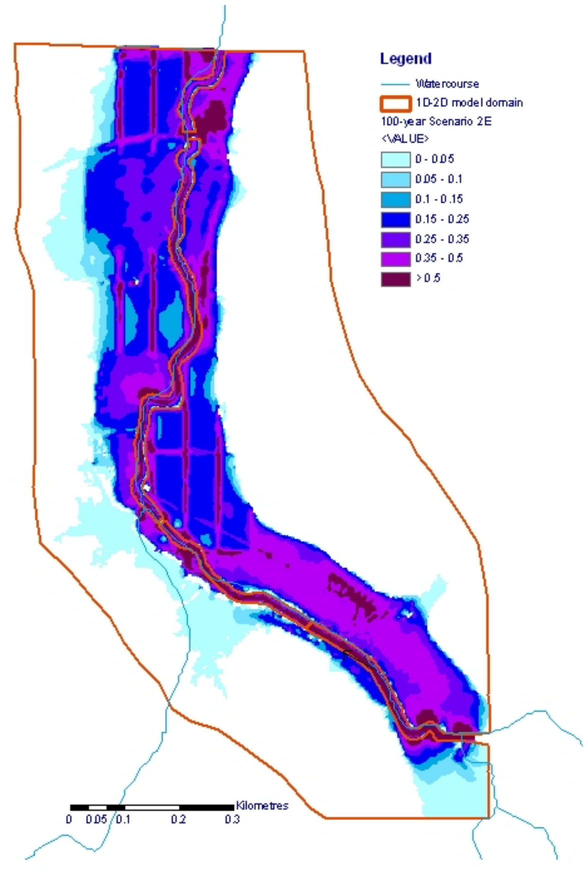
Model results – Velocities

- Flood Velocity (m/s) – Scenario 2 series (Miscanthus, 10m rides)

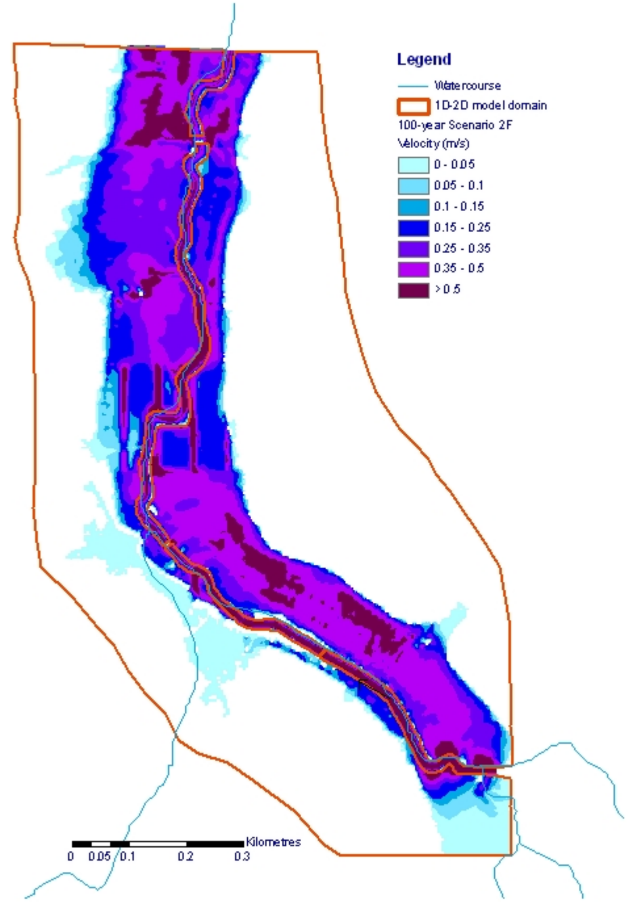
Baseline



Scenario 2E



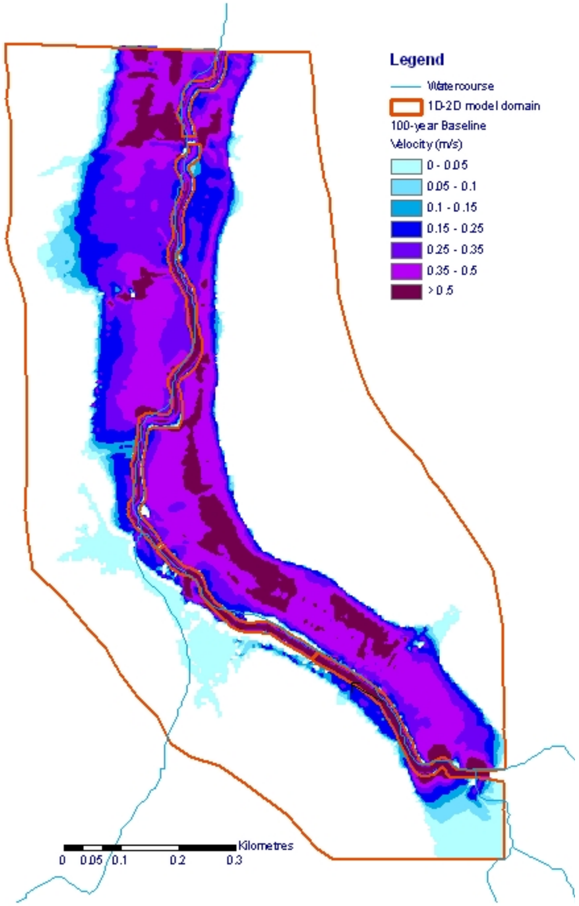
Scenario 2F



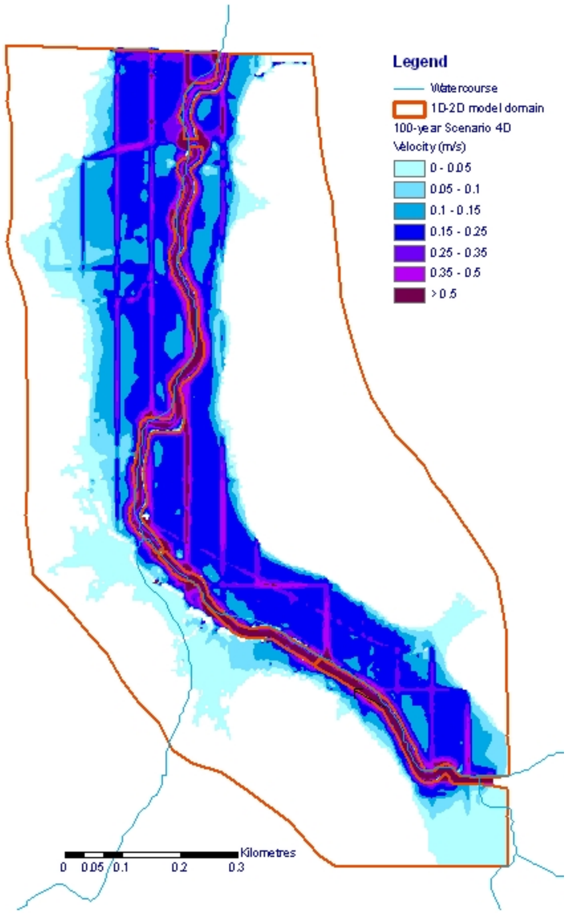
Model results – Velocities

- Flood Velocity (m/s) – Scenario 4 series (Miscanthus, 5m rides)

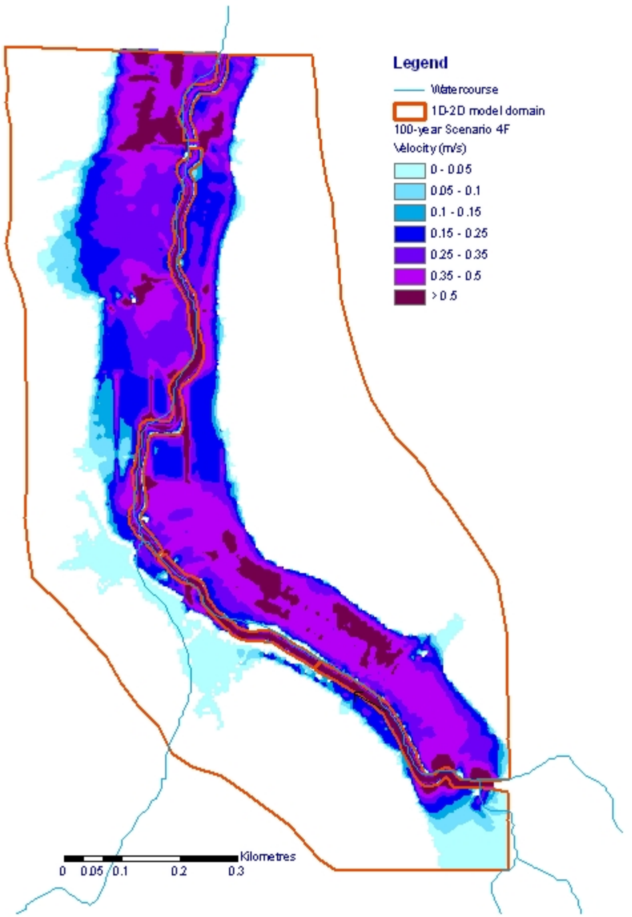
Baseline



Scenario 4D



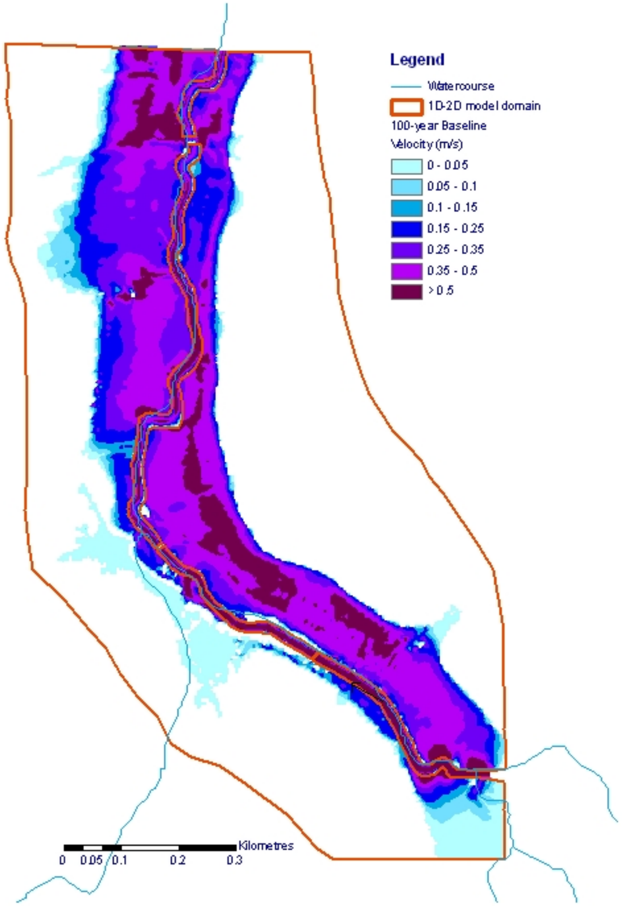
Scenario 4F



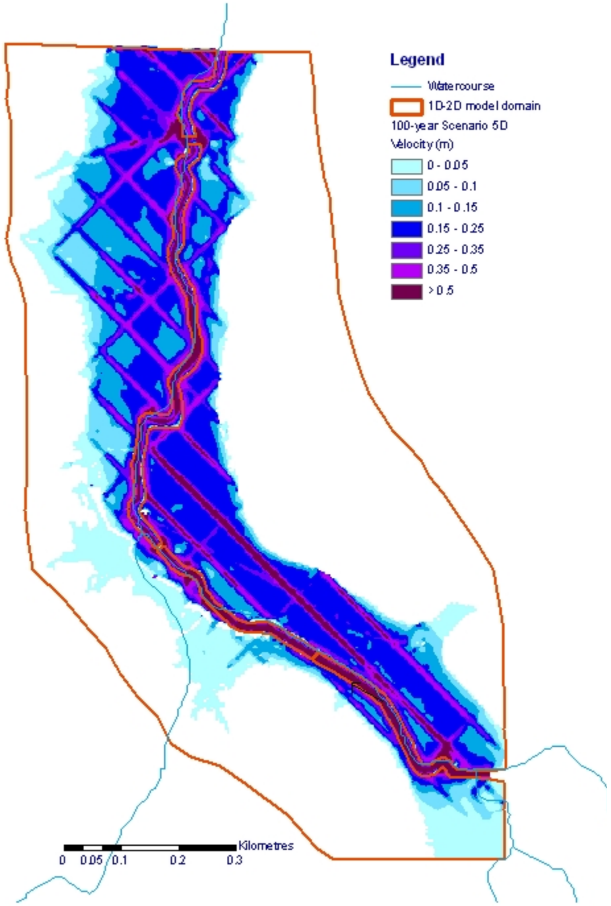
Model results – Velocities

- Flood Velocity (m/s) – Scenario 5 series (Miscanthus, 10m rides)

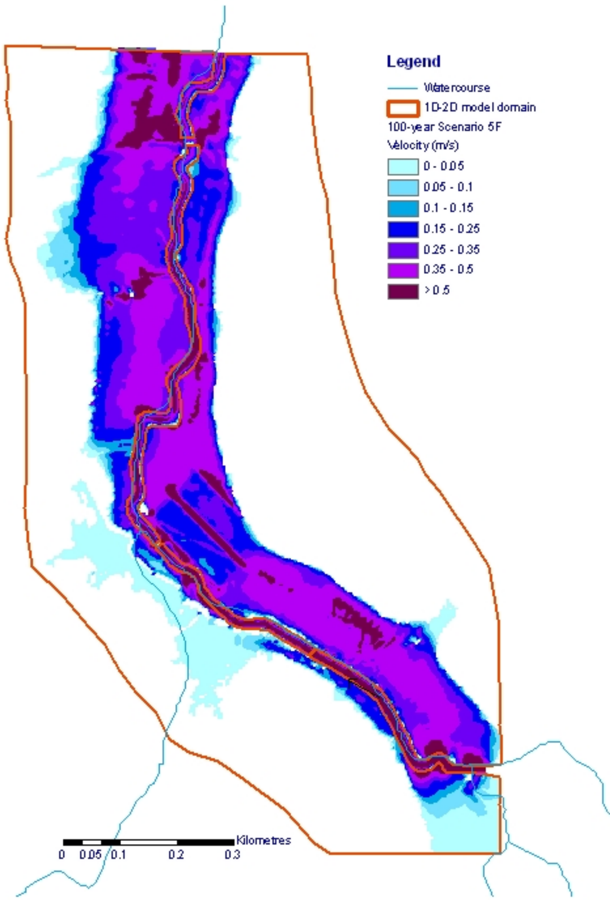
Baseline



Scenario 5D



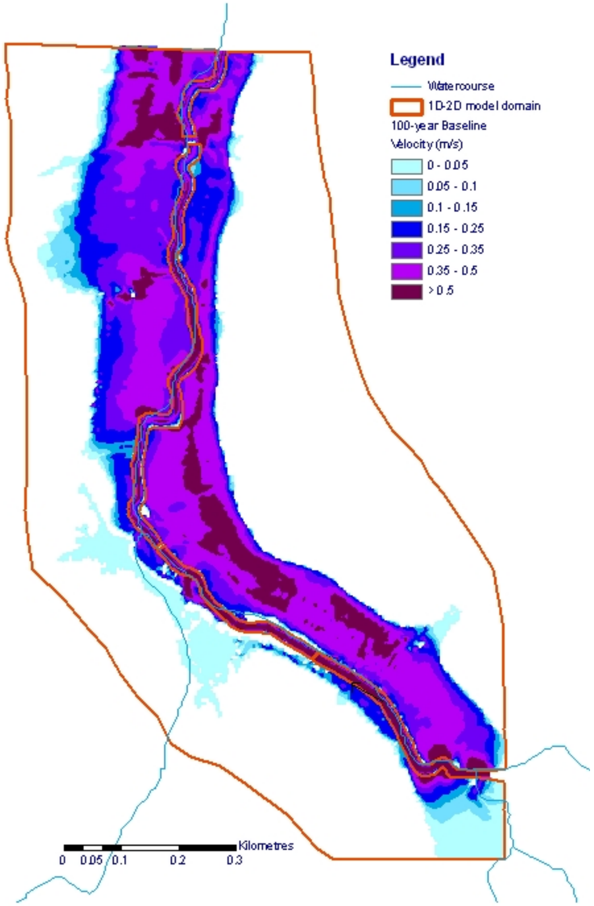
Scenario 5F



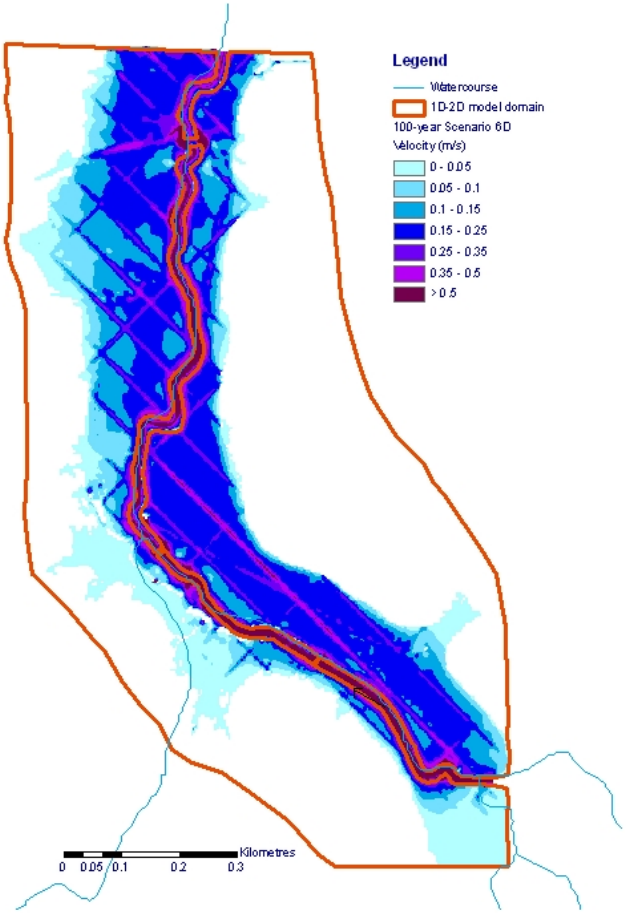
Model results – Velocities

- Flood Velocity (m/s) – Scenario 6 series (Miscanthus, 5m rides)

Baseline



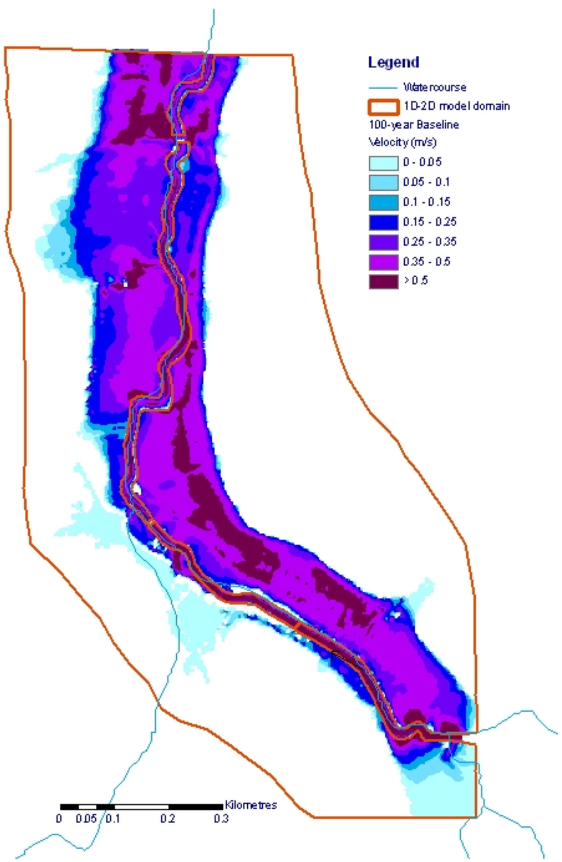
Scenario 6D



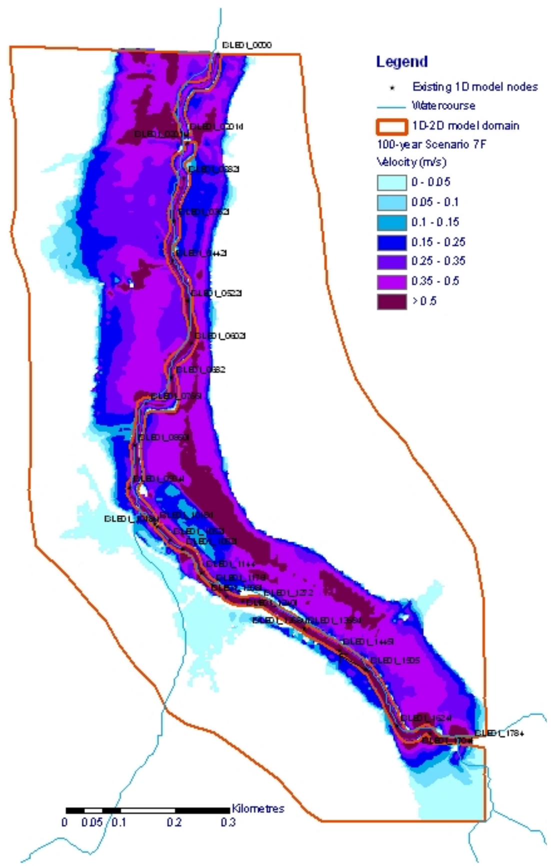
Model results – Velocities

- Flood Velocity (m/s) – Scenario 7 and 8 series (Miscanthus, 10 and 5m rides, respectively)

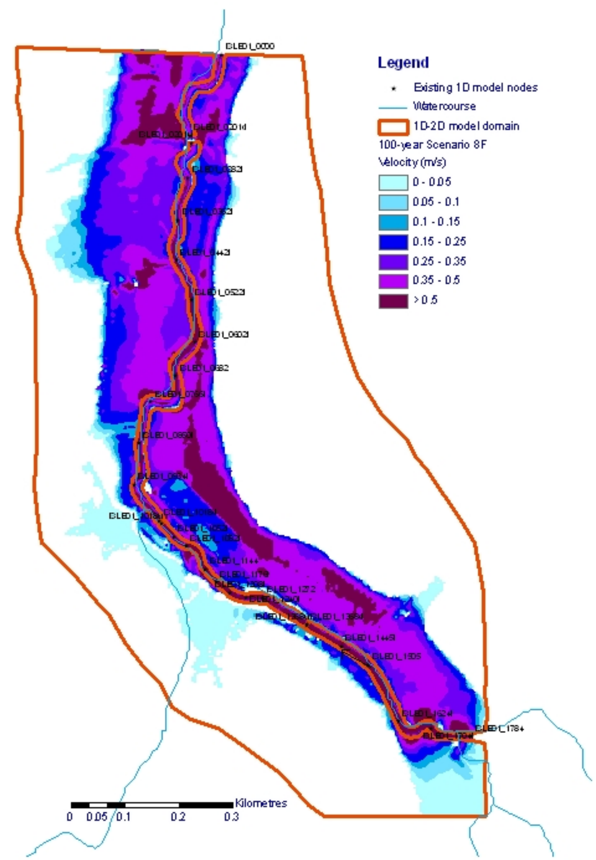
Baseline



Scenario 7F

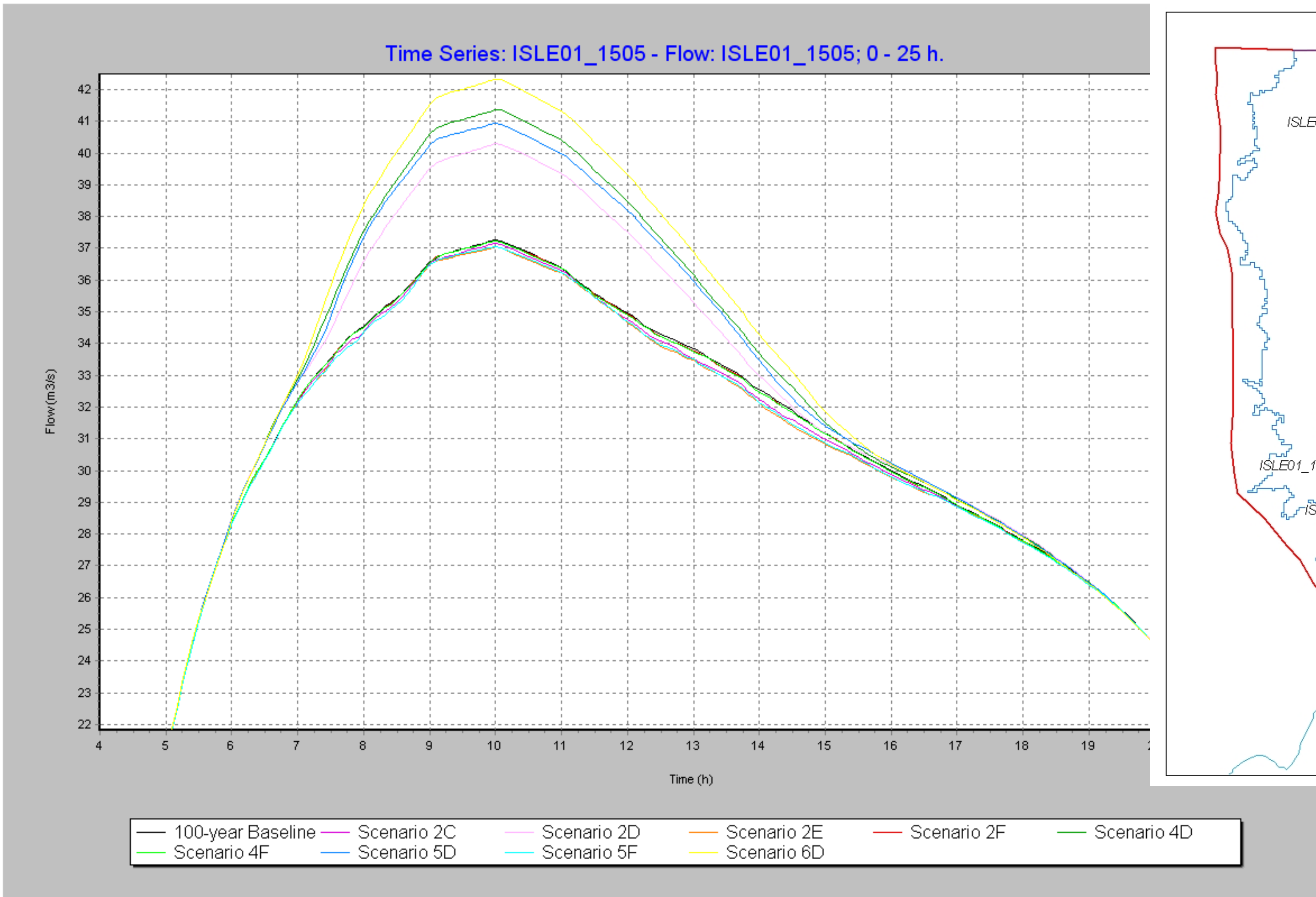


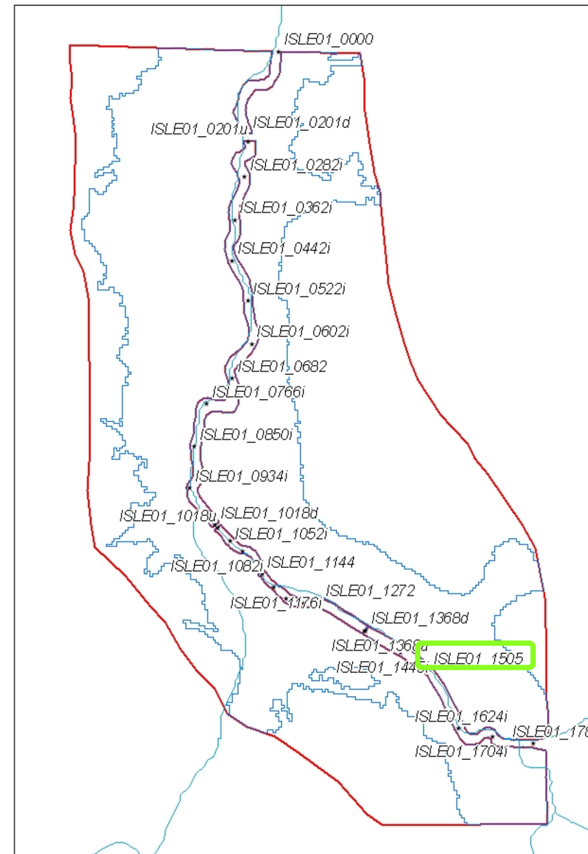
Scenario 8F



Model results – River Flow Hydrographs for Scenario 2, 4, 5 and 6 series (Miscanthus)

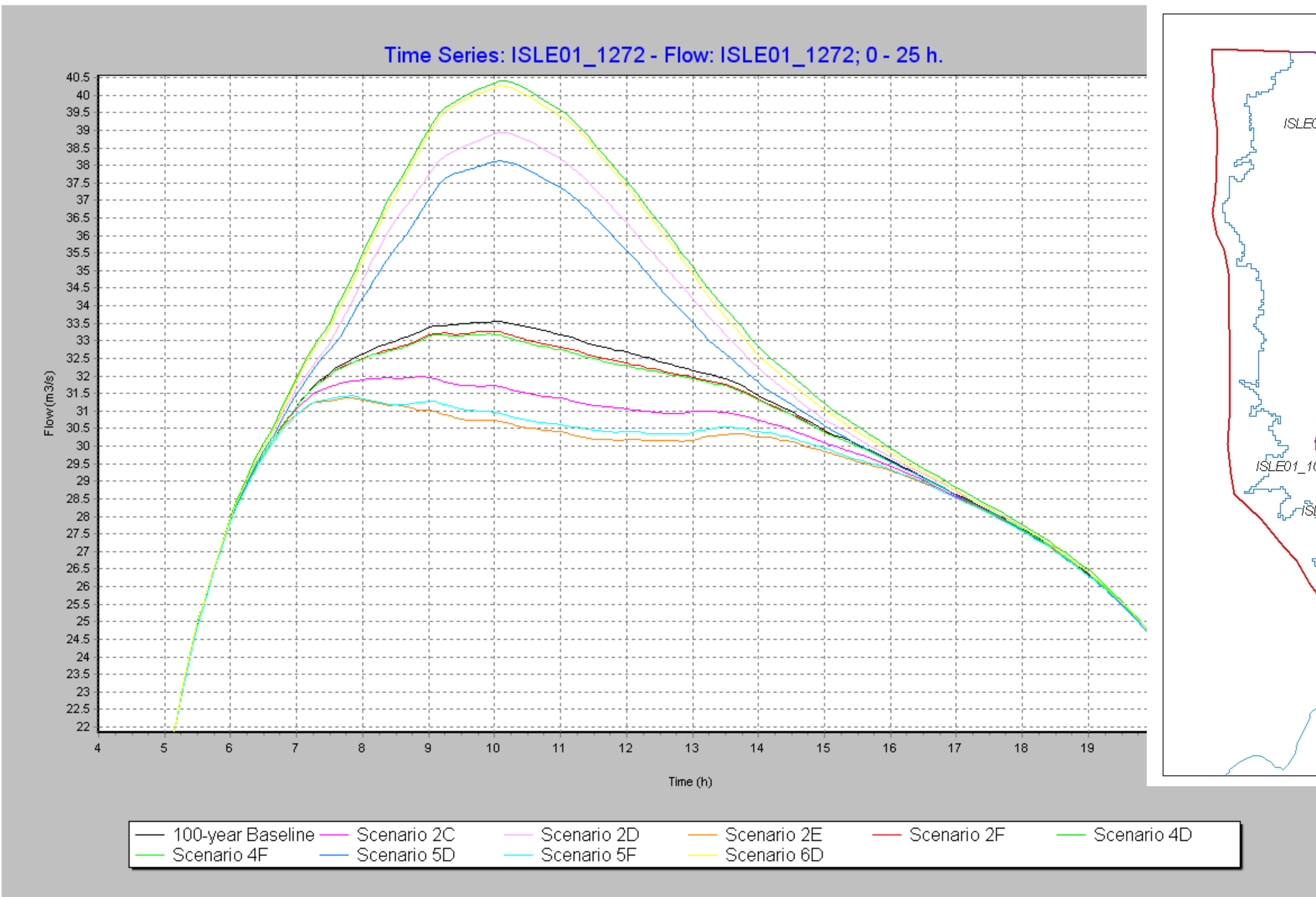
- Flood hydrographs in the upstream area (e.g. upstream of plantation)

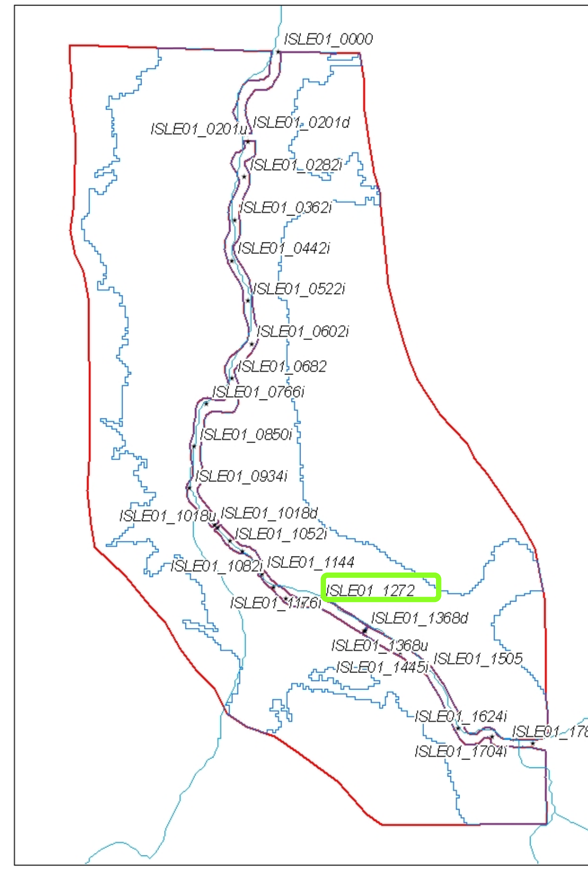




Model results – River Flow Hydrographs for Scenario 2, 4, 5 and 6 series (Miscanthus)

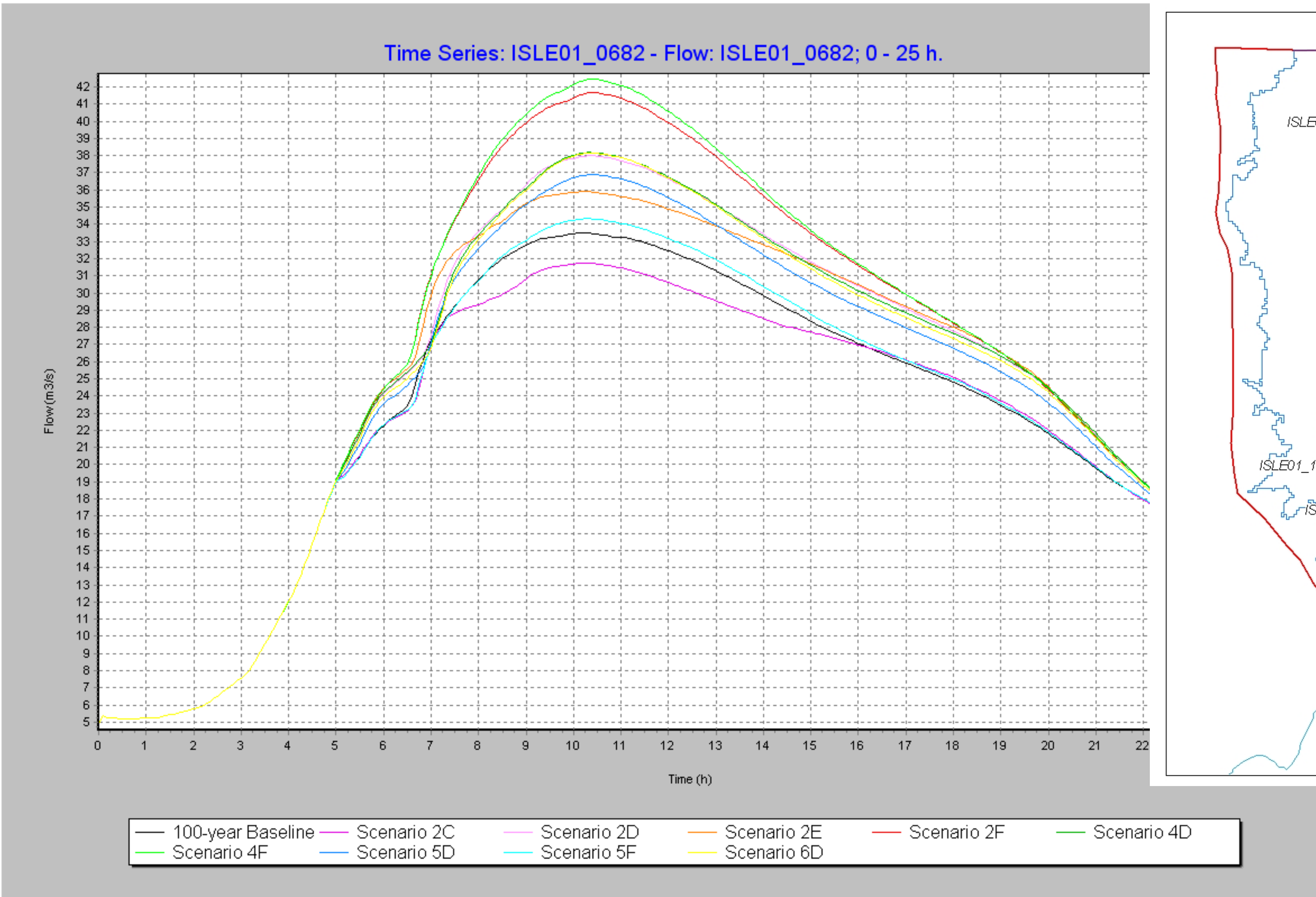
- Flood hydrographs in the upstream area (e.g. upstream of plantation)

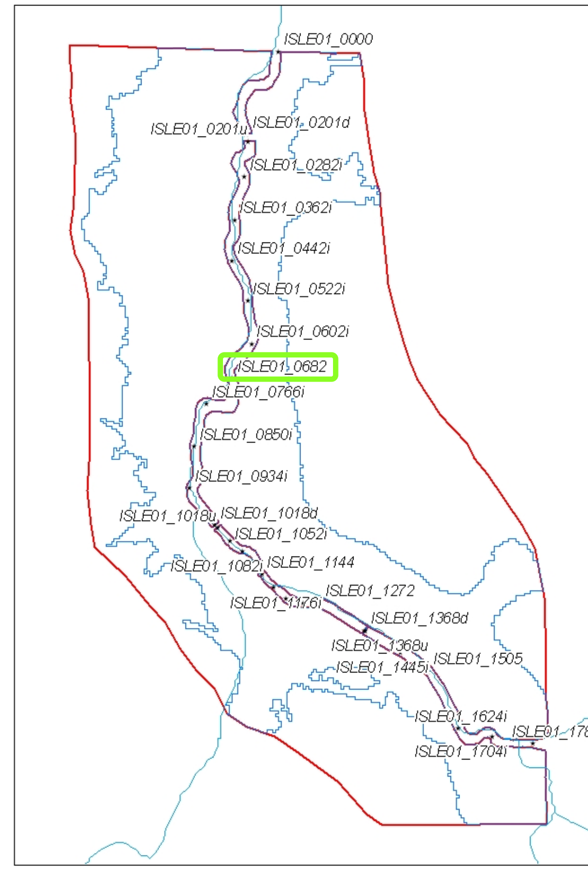




Model results – River Flow Hydrographs for Scenario 2, 4, 5 and 6 series (Miscanthus)

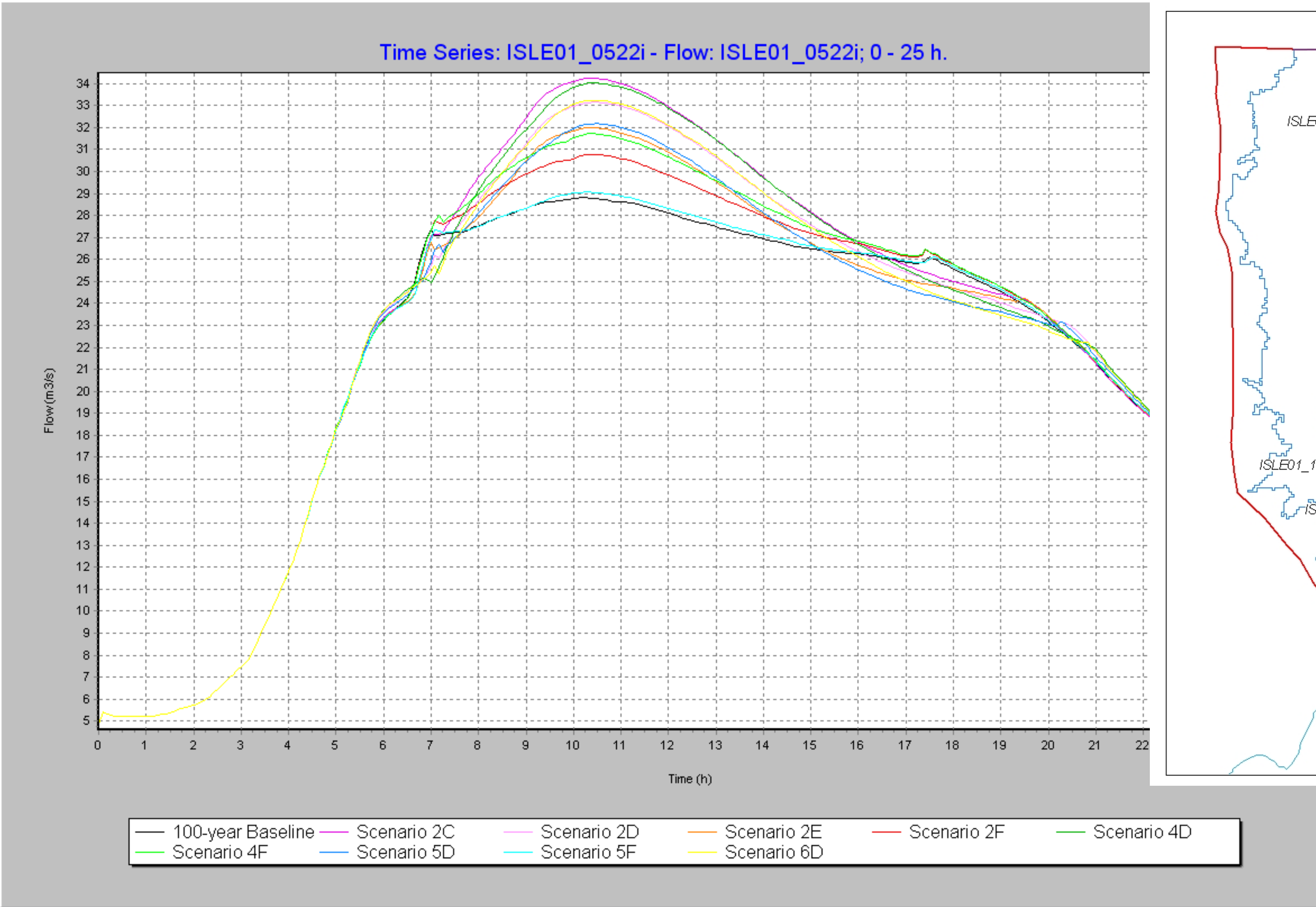
- Flood hydrographs in the middle area (e.g. at plantation)

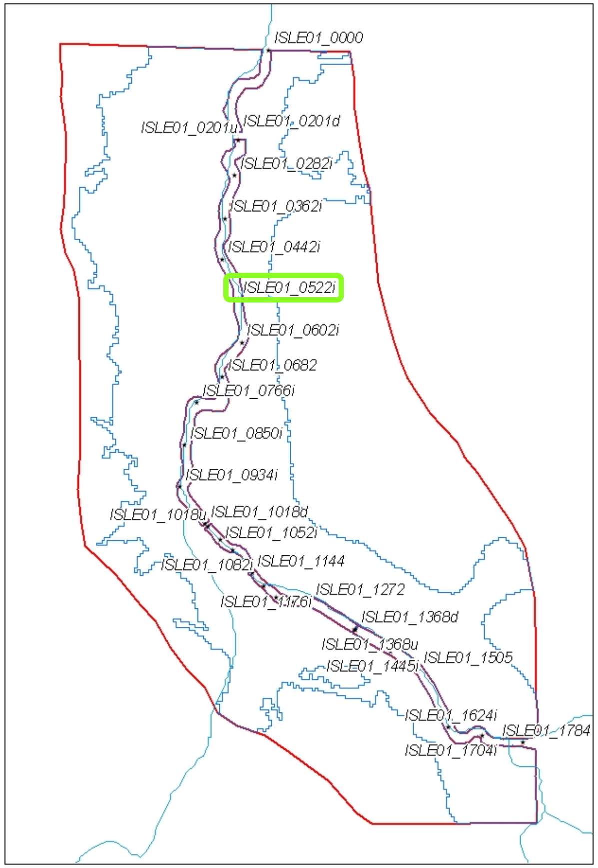




Model results – River Flow Hydrographs for Scenario 2, 4, 5 and 6 series (Miscanthus)

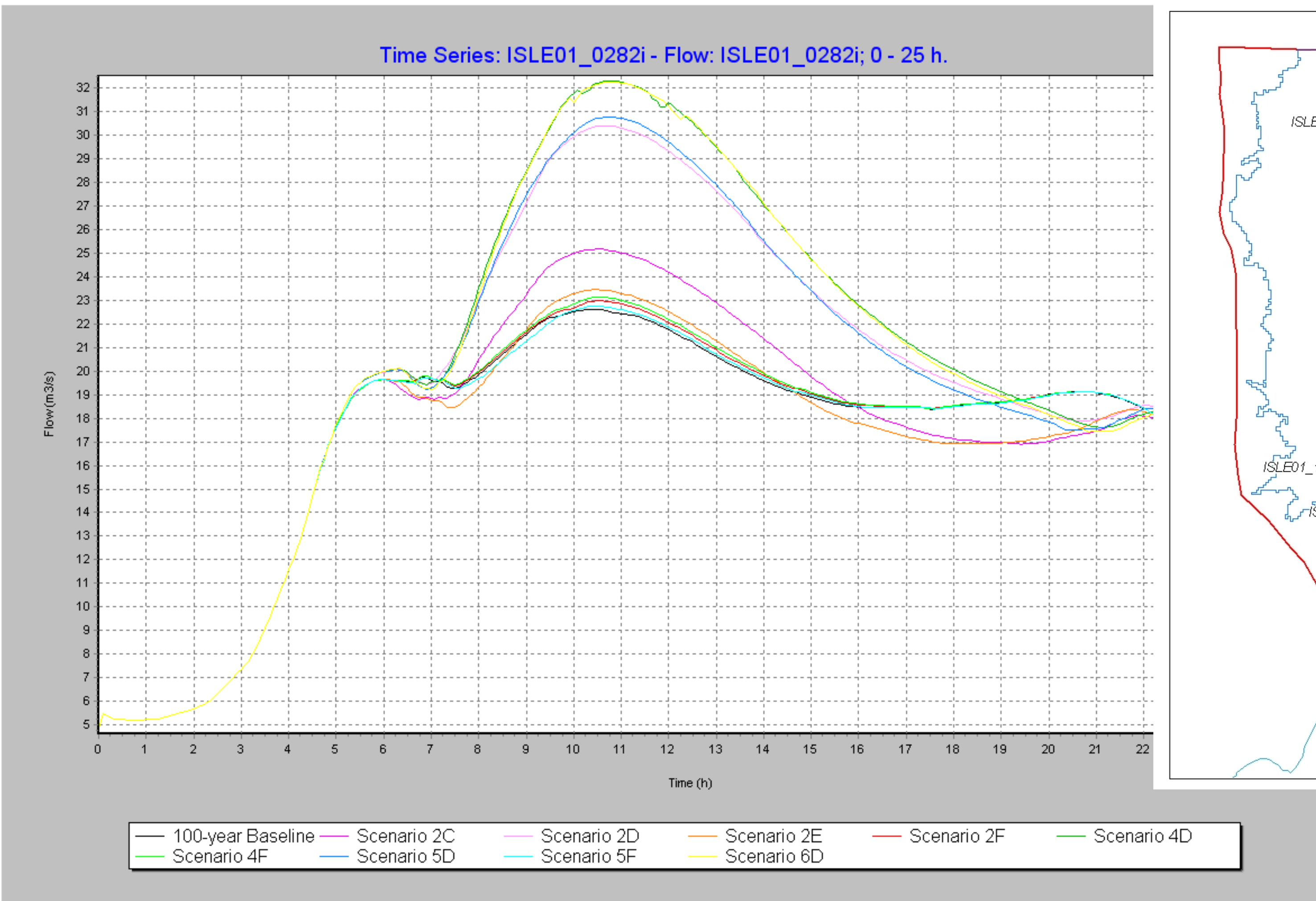
- Flood hydrographs in the middle area (e.g. just downstream of plantation)

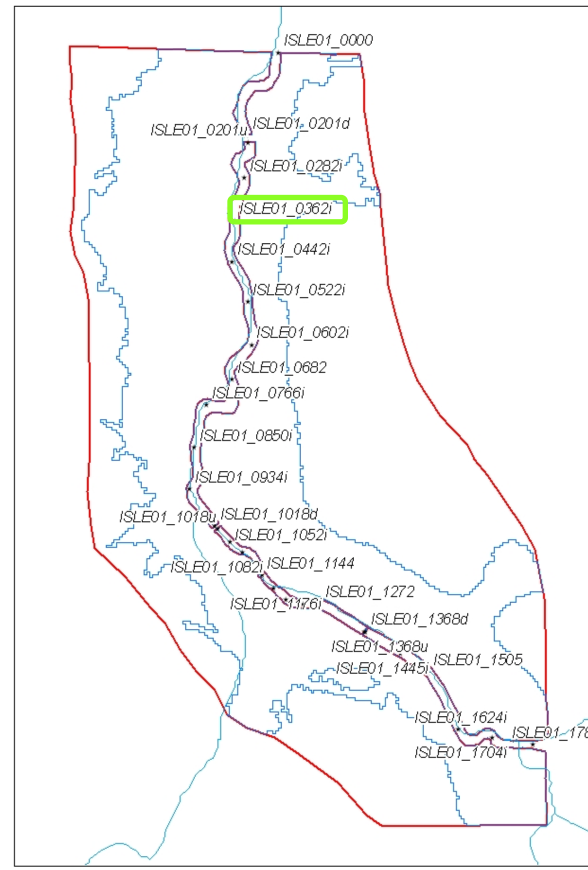




Model results – River Flow Hydrographs for Scenario 2, 4, 5 and 6 series (Miscanthus)

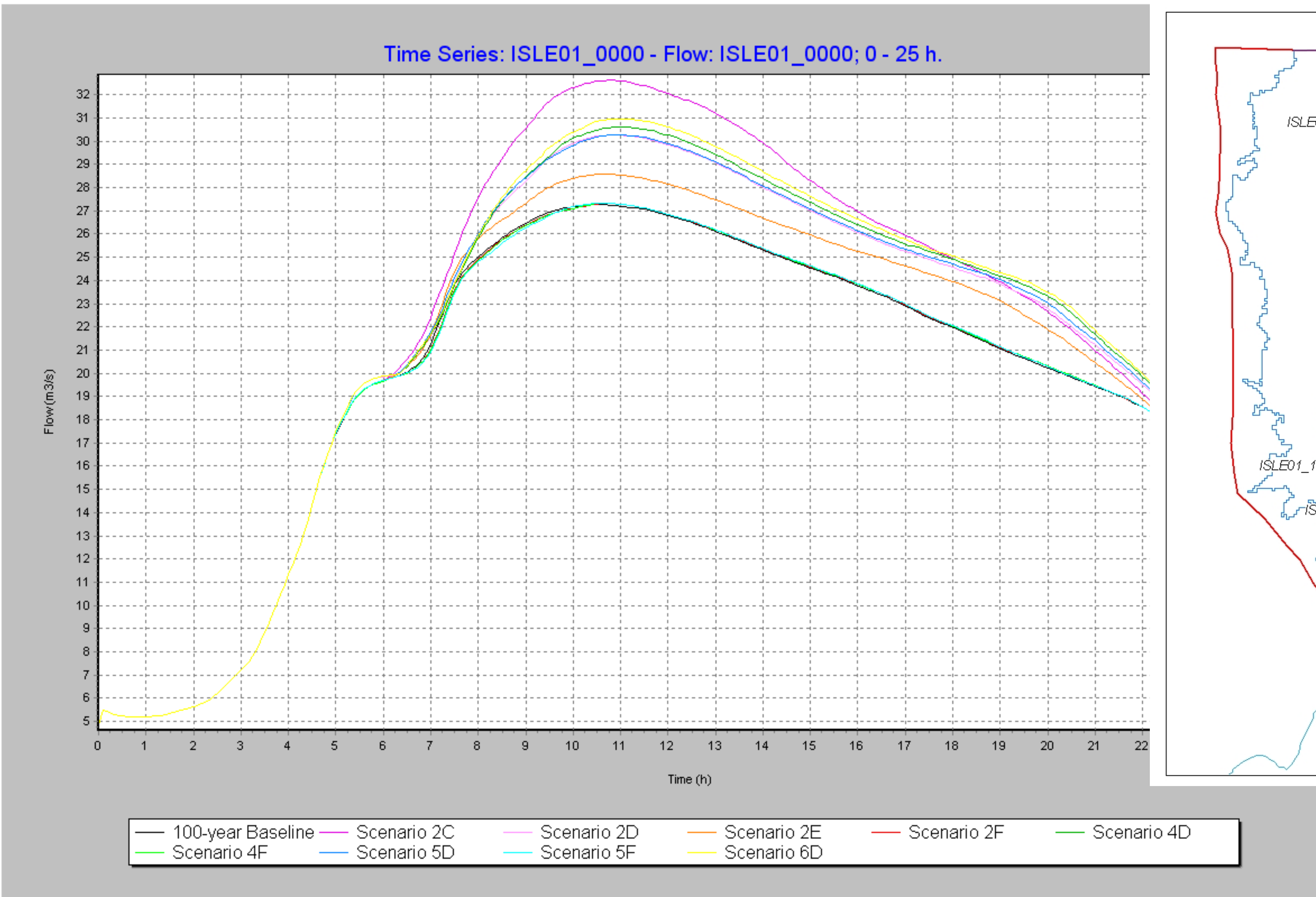
- Flood hydrographs in the downstream area (e.g. downstream of plantation)

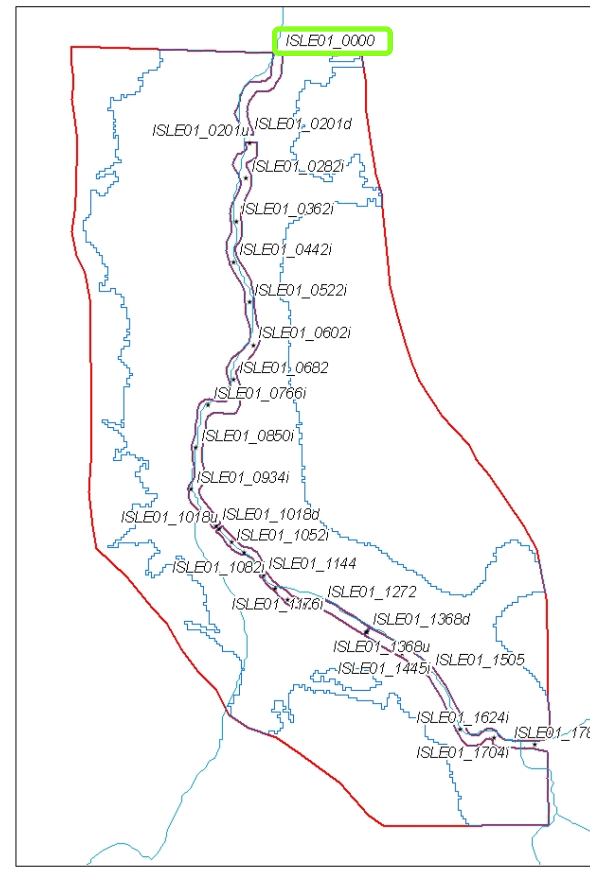




Model results – River Flow Hydrographs for Scenario 2, 4, 5 and 6 series (Miscanthus)

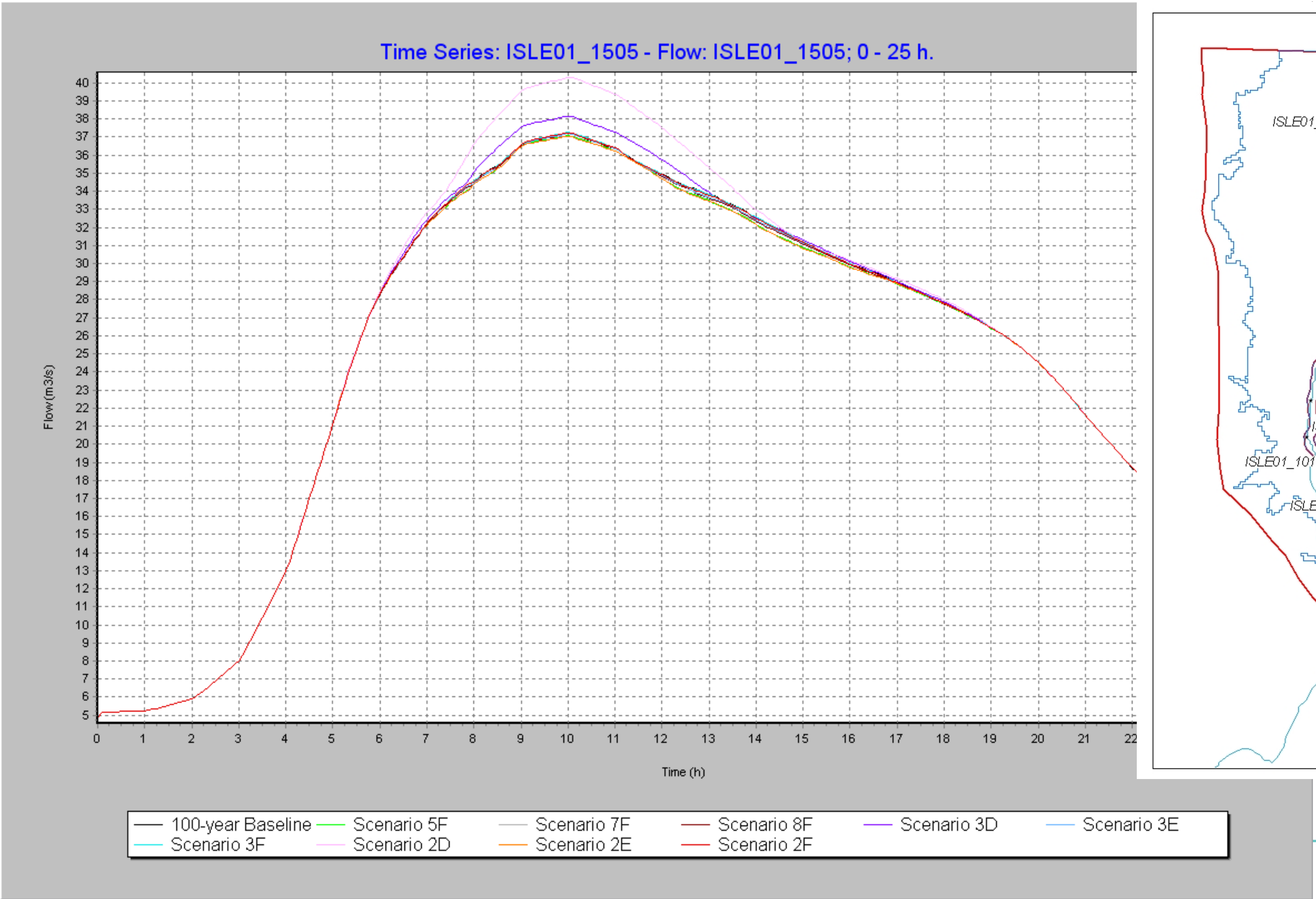
- Flood hydrographs at downstream end of the model domain

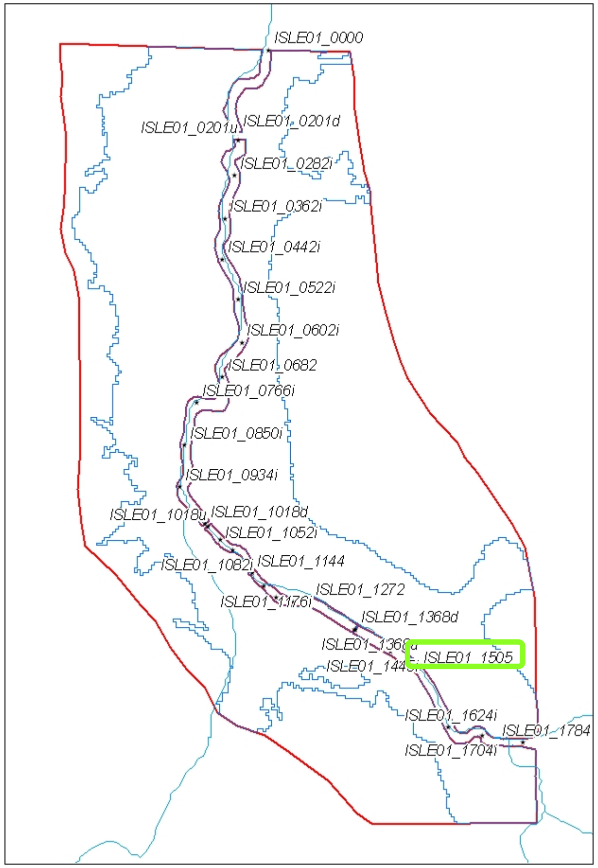




Model results – River Flow Hydrographs for Scenario 7, 8 (Miscanthus) and 3 series (SRC Willow)

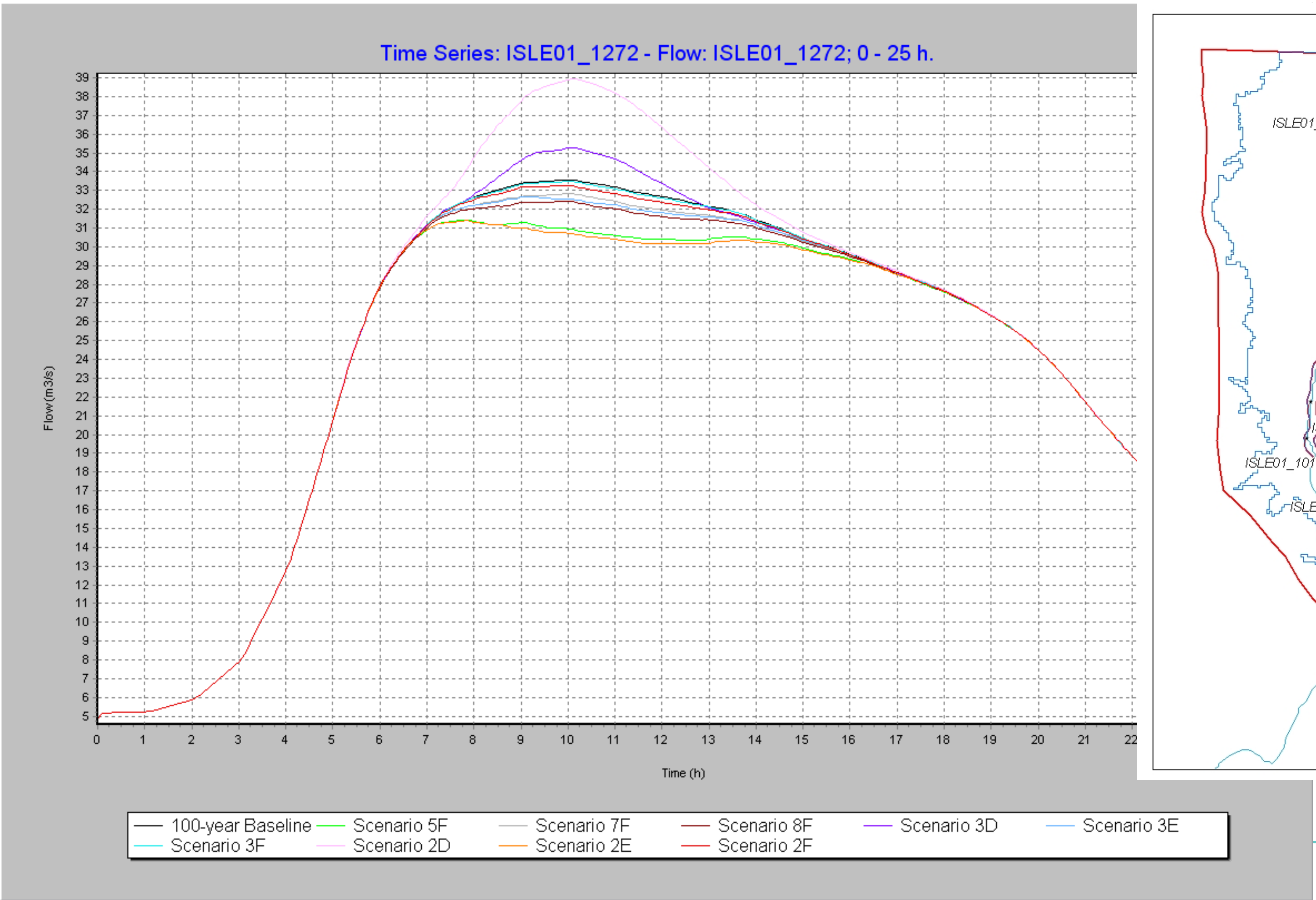
- Flood hydrographs in the upstream area (e.g. upstream of plantation)

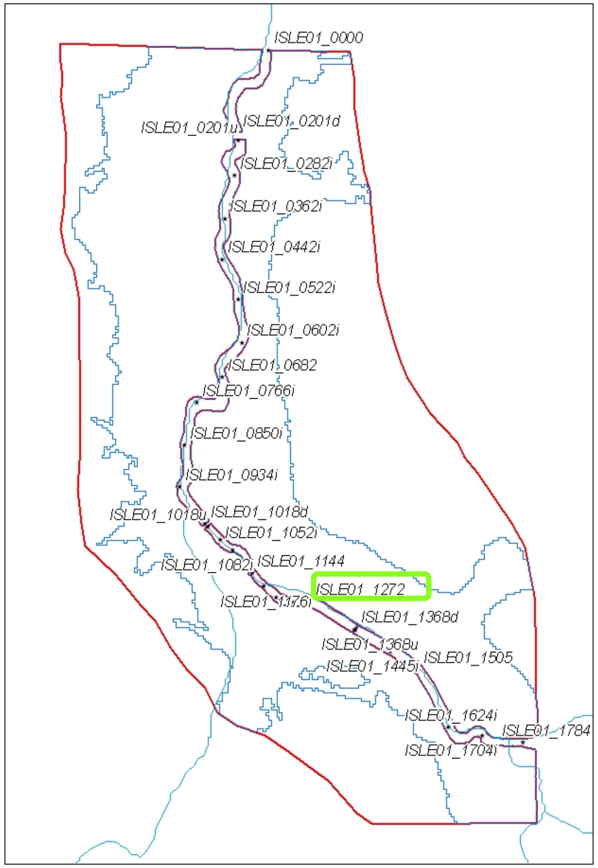




Model results – River Flow Hydrographs for Scenario 7, 8 (Miscanthus) and 3 series (SRC Willow)

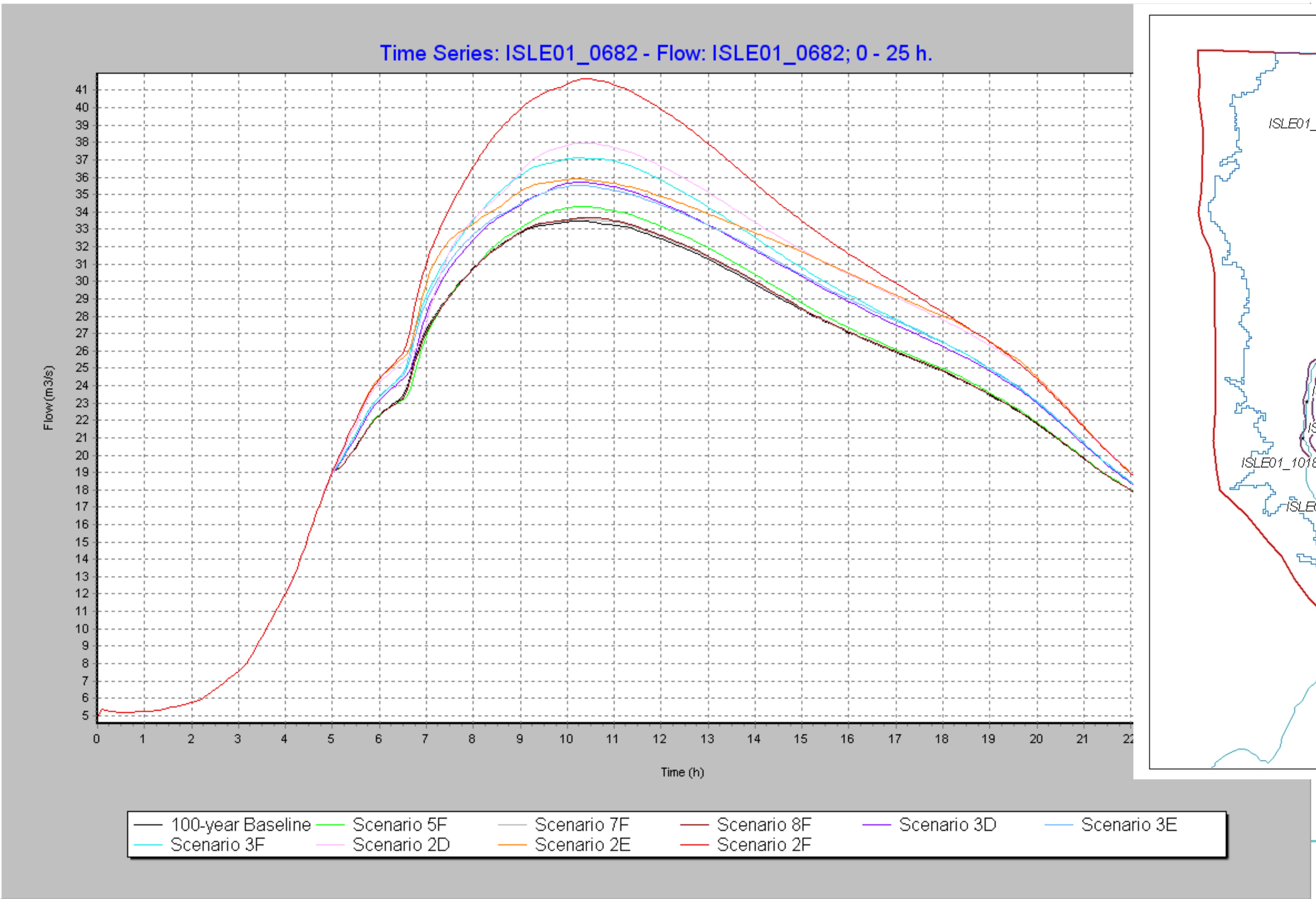
- Flood hydrographs in the upstream area (e.g. upstream of plantation)

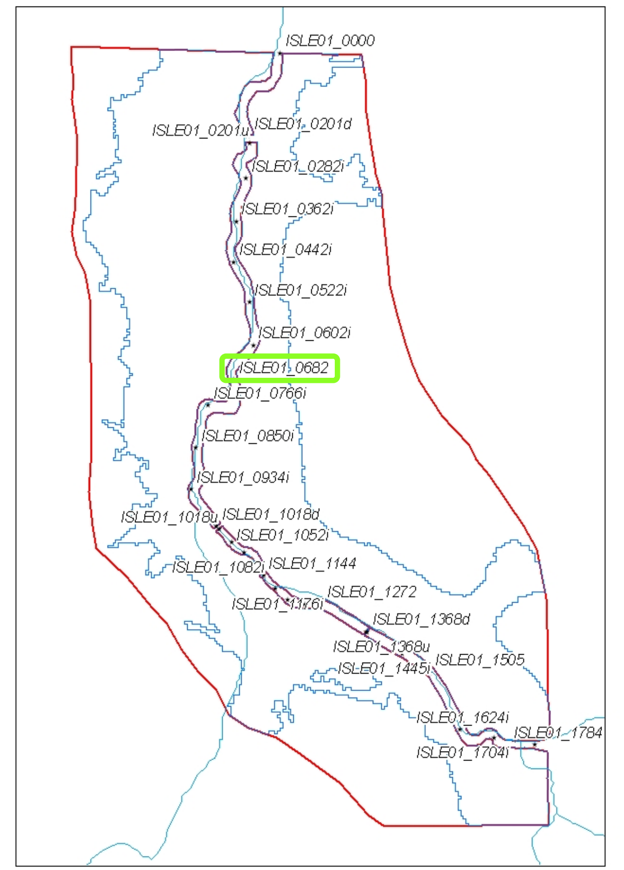




Model results – River Flow Hydrographs for Scenario 7, 8 (Miscanthus) and 3 series (SRC Willow)

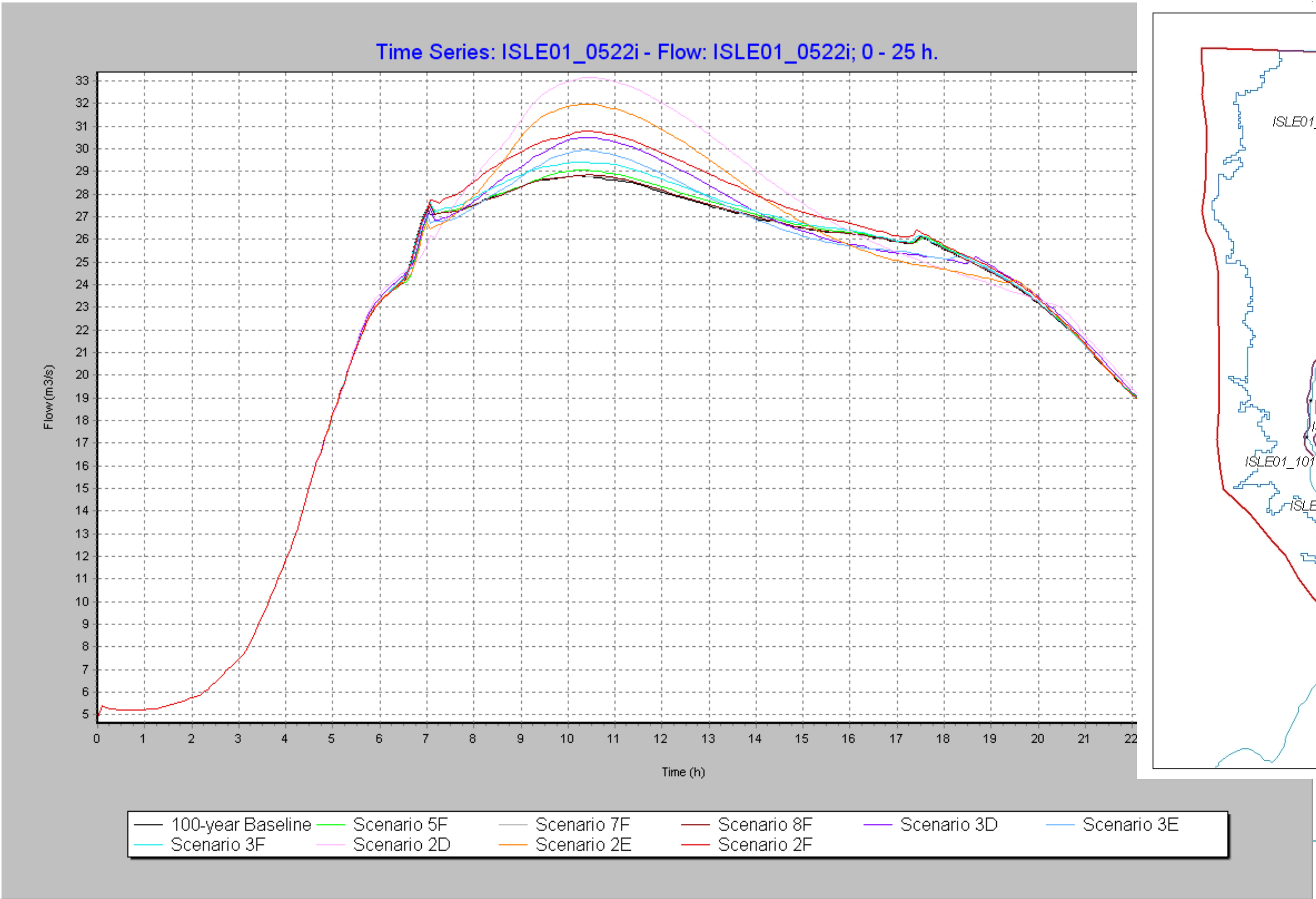
- Flood hydrographs in the middle area (e.g. at plantation)

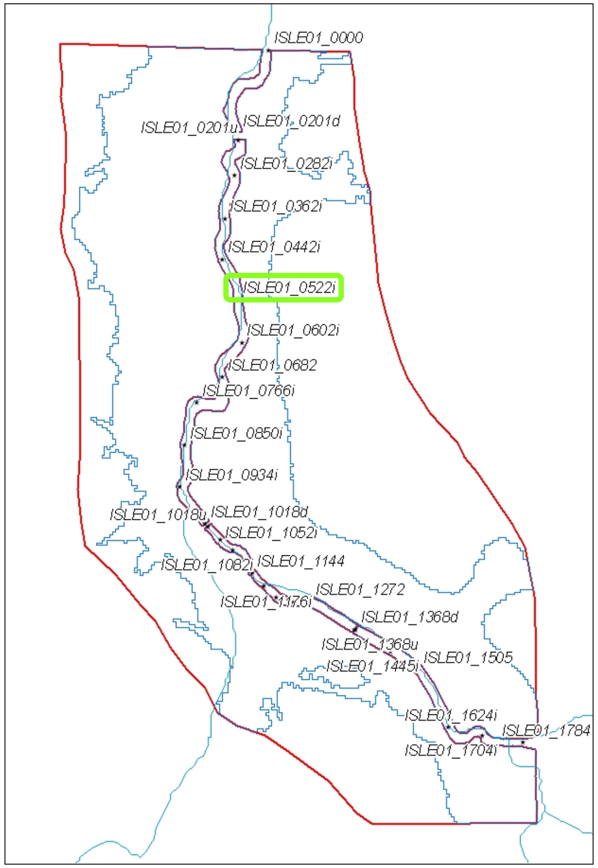




Model results – River Flow Hydrographs for Scenario 7, 8 (Miscanthus) and 3 series (SRC Willow)

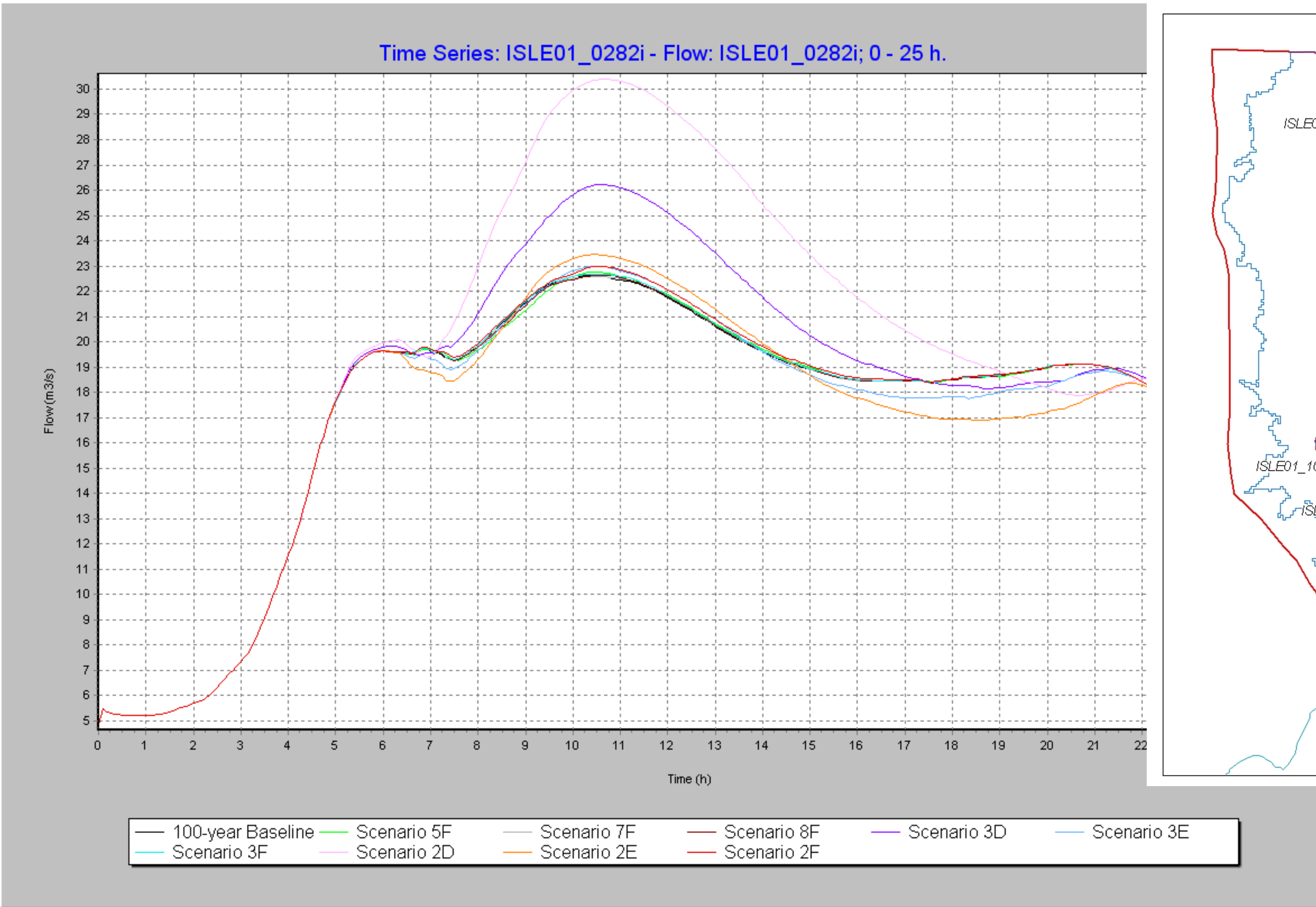
- Flood hydrographs in the middle area (e.g. just downstream of plantation)

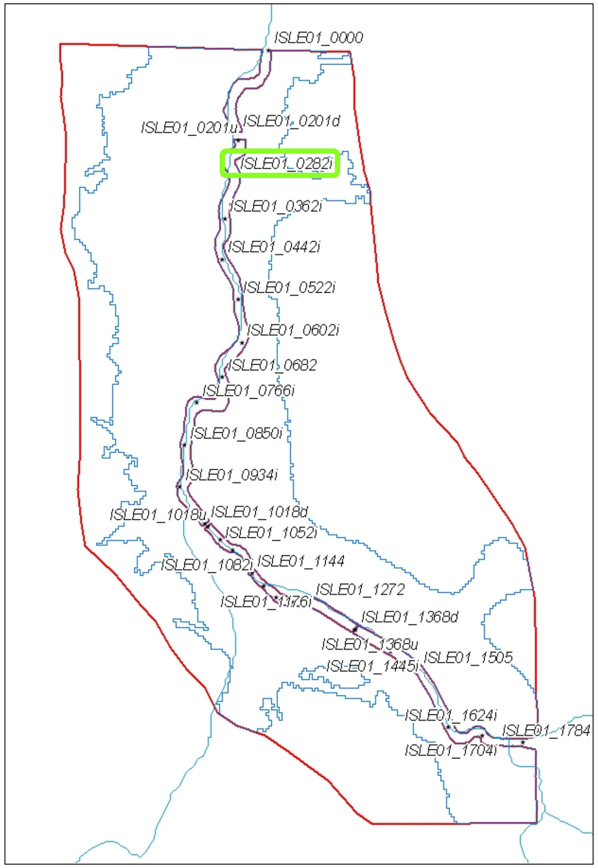




Model results – River Flow Hydrographs for Scenario 7, 8 (Miscanthus) and 3 series (SRC Willow)

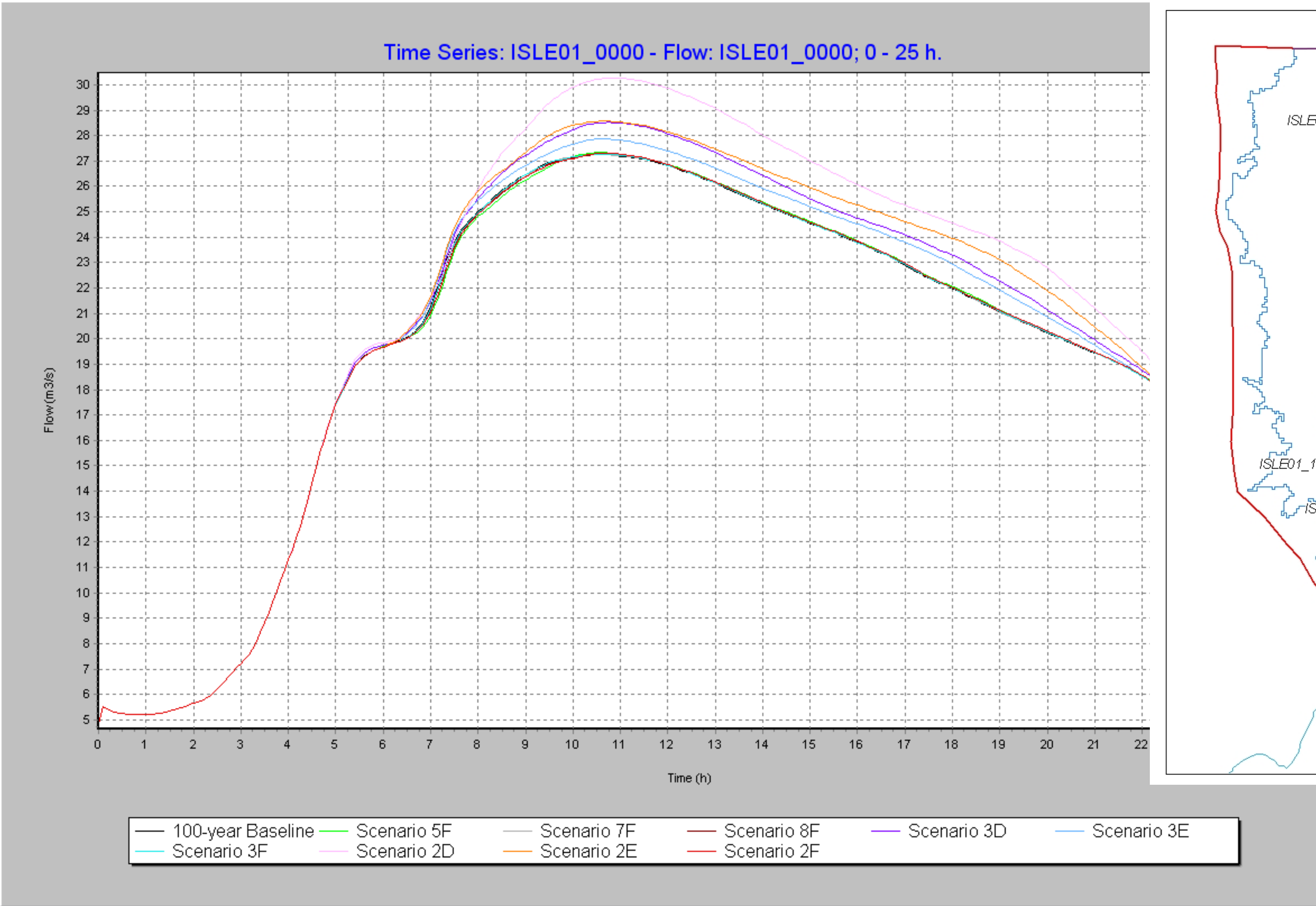
- Flood hydrographs in the downstream area (e.g. downstream of plantation)

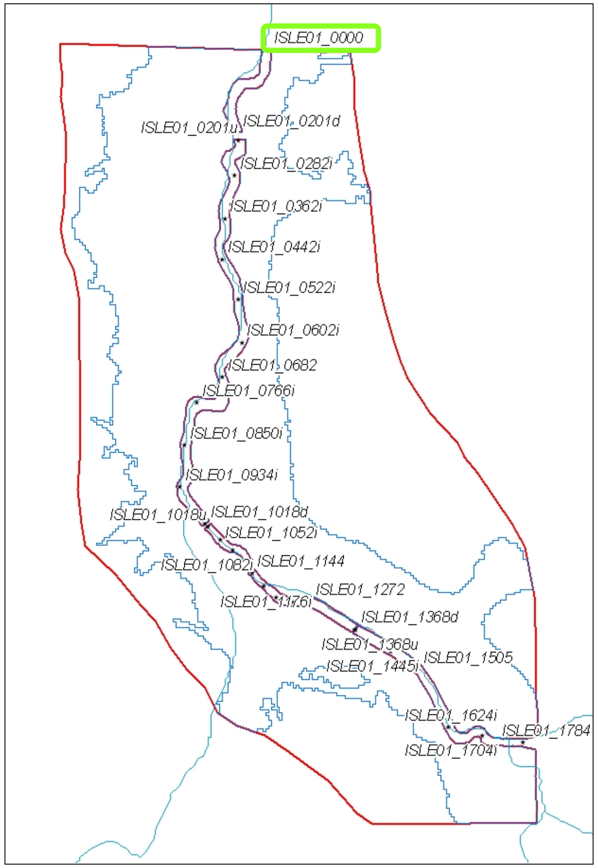




Model results – River Flow Hydrographs for Scenario 7, 8 (Miscanthus) and 3 series (SRC Willow)

- Flood hydrographs at downstream end of the model domain





JBA consulting

Energy Crops Project

2009s0426

Case Study 3

Modelled results for the Theoretical Model

Modelling approach and methodology

- Plantation type
    - Scenario 2, 4, 5, 6 and 9 series – Miscanthus
    - Scenario 3 series, 4 (Willow), 5 (Willow), 6 (Willow) and 9 (Willow) – SRC Willow (i.e. roughness changes with depth of inundation as follows: n=0.1 for 0 – 0.5m, n=0.34 for depth 2m or greater (the 2D model interpolates between these two)
- Plantation pattern
    - 3ha plots with 10m or 5m rides around
- Plantation coverage
    - 100% of floodplain
    - 30% of floodplain (both sides of the river) or less
- Modelled return period: 100years (1%AEP)
- The existing 1D-2D models details:

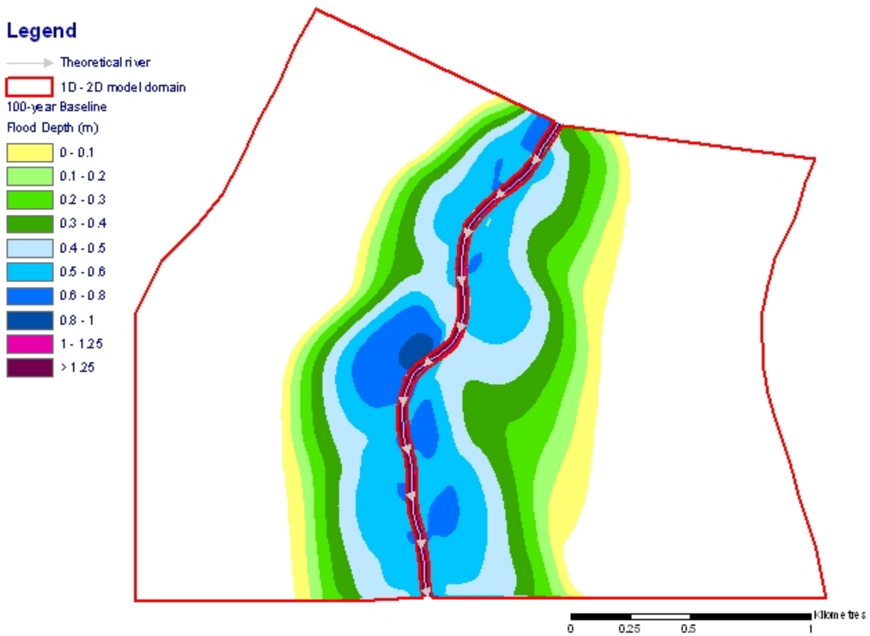
Modelled floodplain inundation (km^2)	100 year flood (m^3/s)	2D model domain resolution (cell size in m)	Simulation duration (hours)
2.3	409.8	4	8

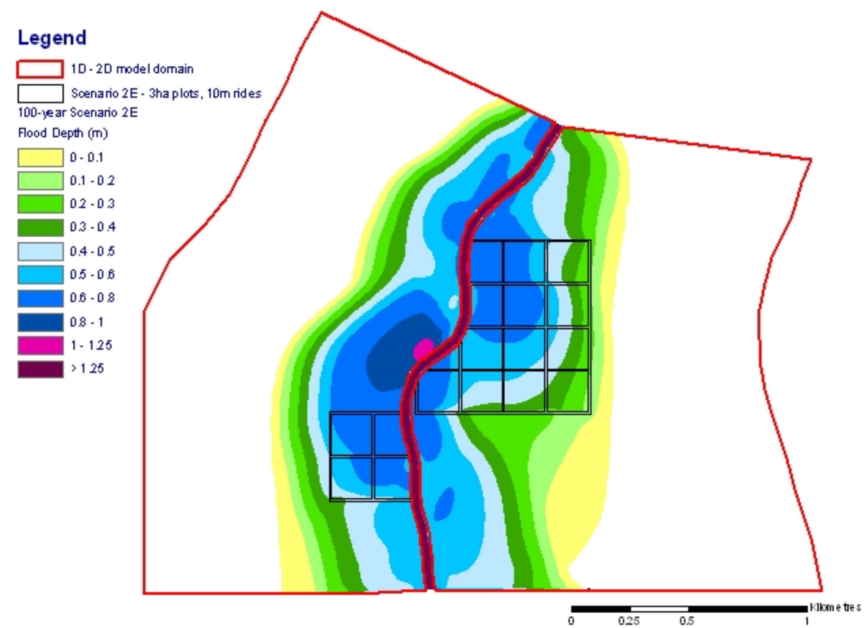
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 2 series (Miscanthus, 10m rides)

Baseline

Scenario 2E

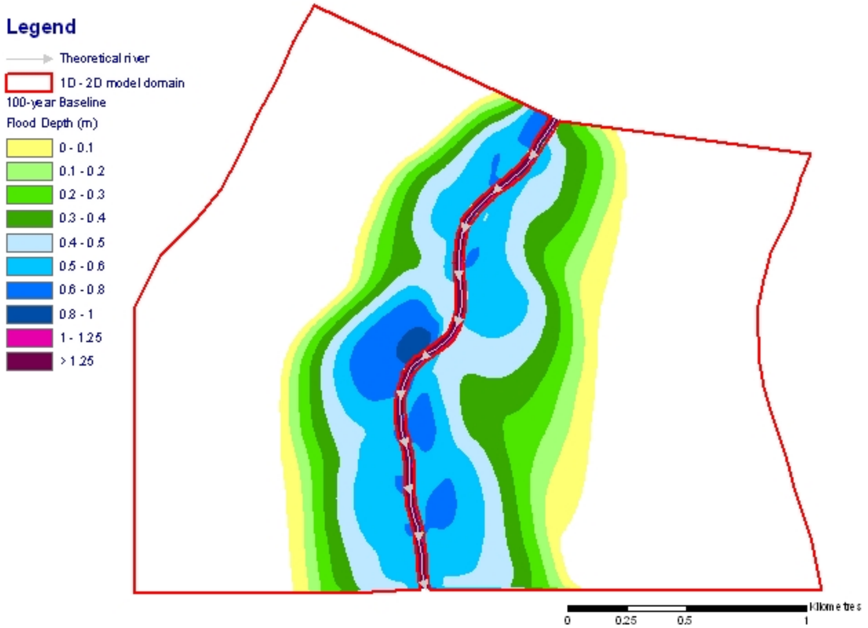




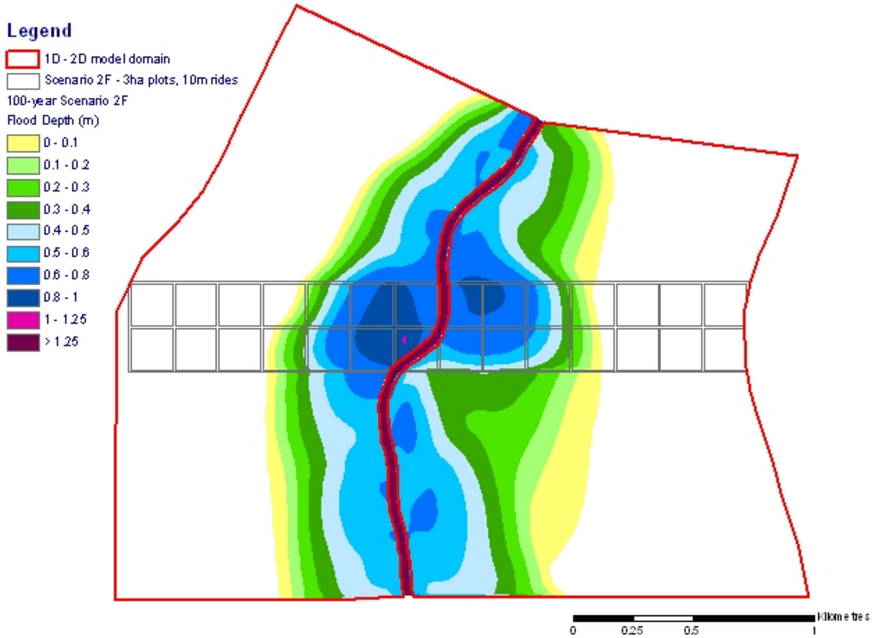
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 2 series (Miscanthus, 10m rides)

Baseline



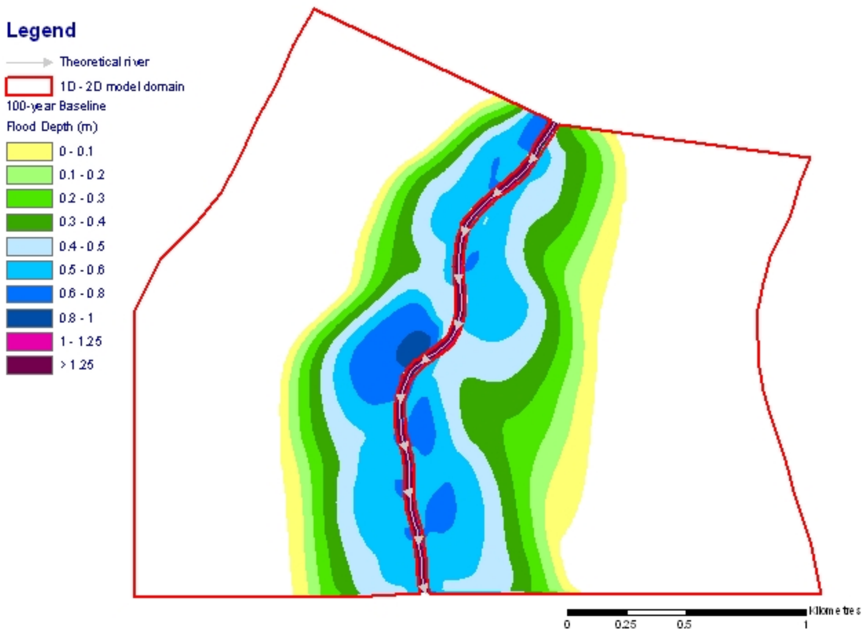
Scenario 2F



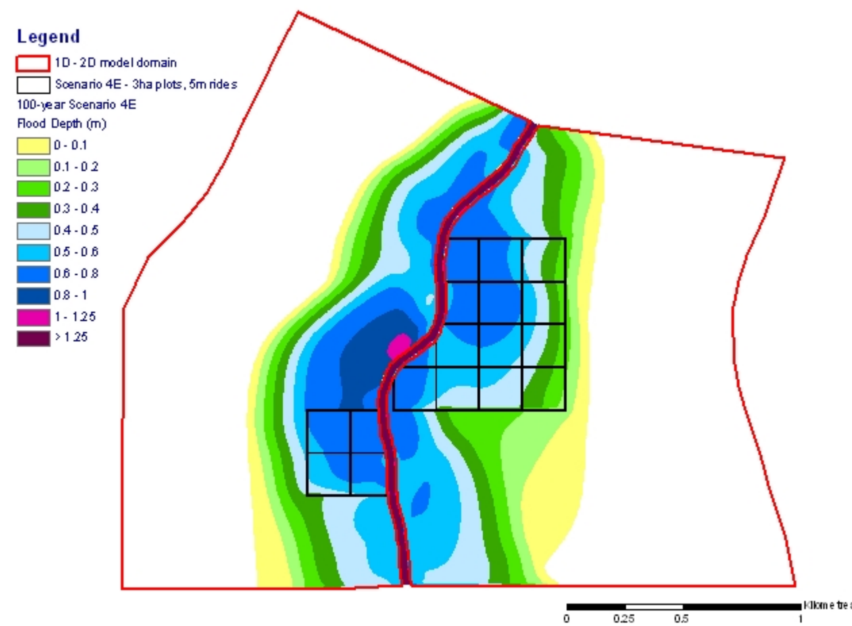
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 4 series (Miscanthus, 5m rides)

Baseline



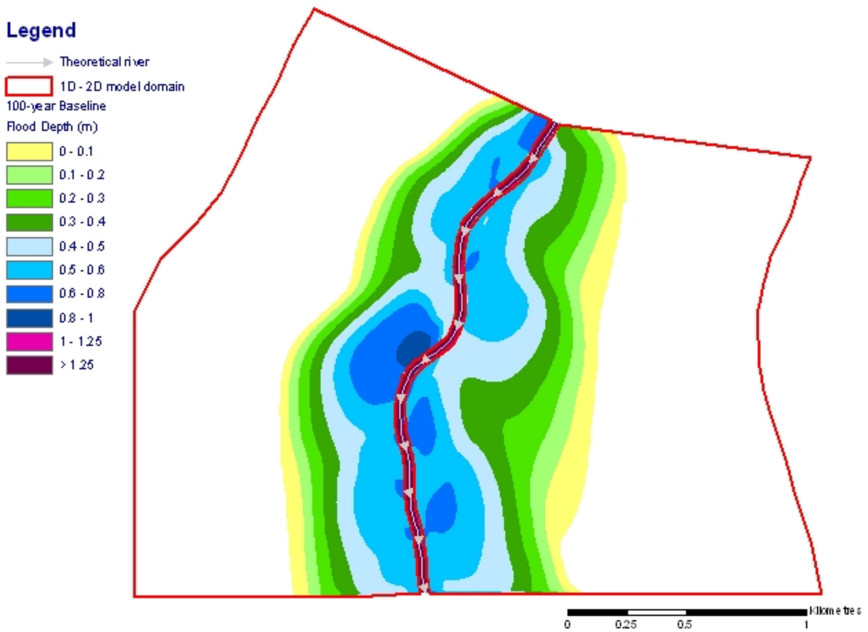
Scenario 4E



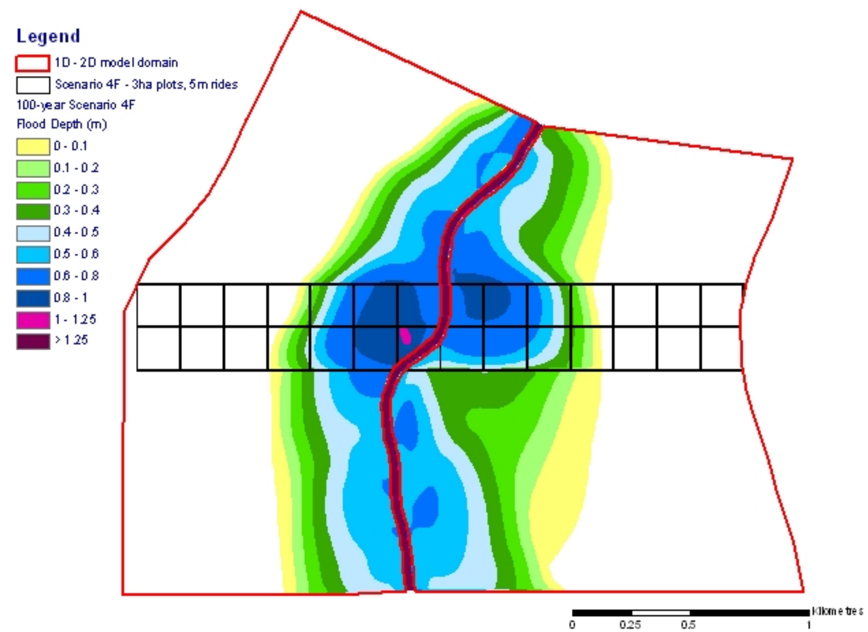
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 4 series (Miscanthus, 5m rides)

Baseline



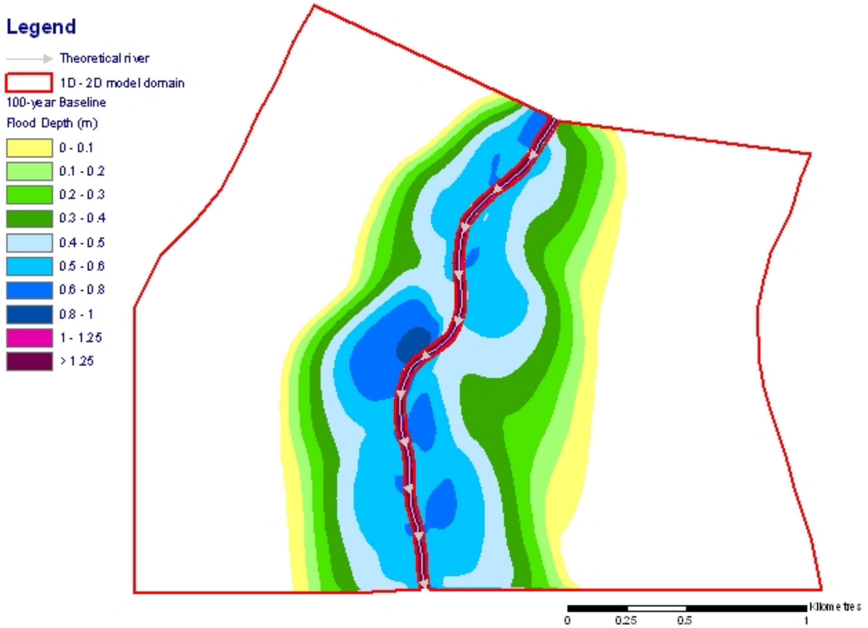
Scenario 4F



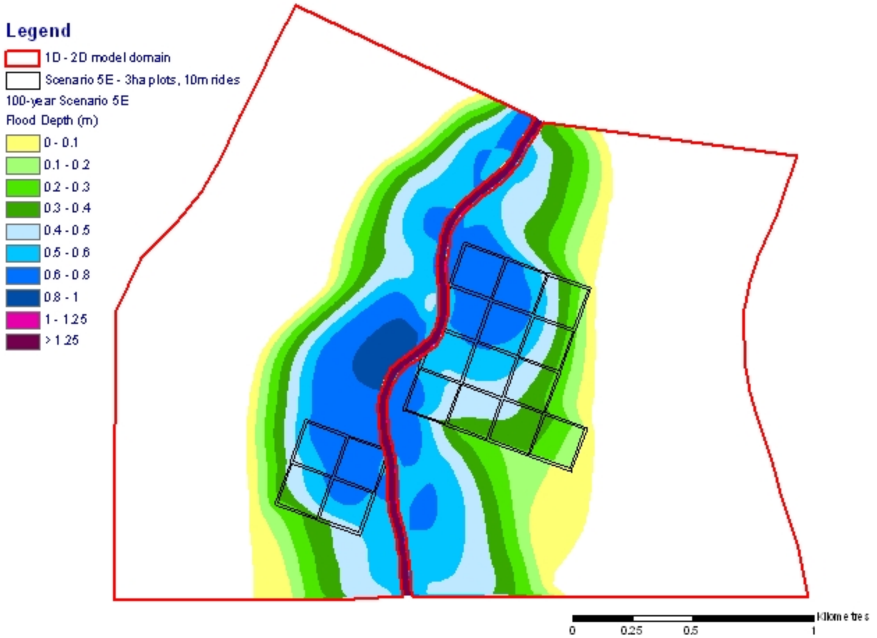
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 5 series (Miscanthus, 10m rides)

Baseline



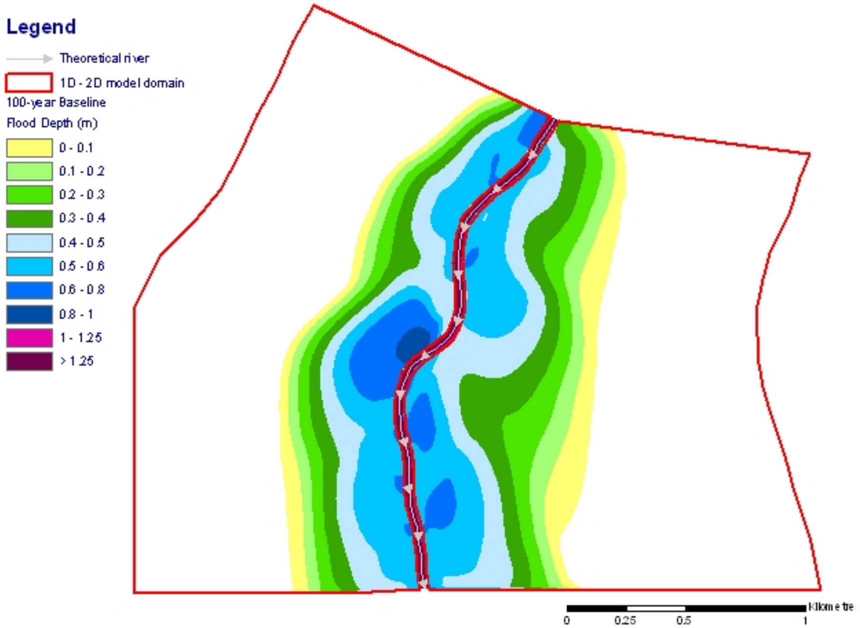
Scenario 5E



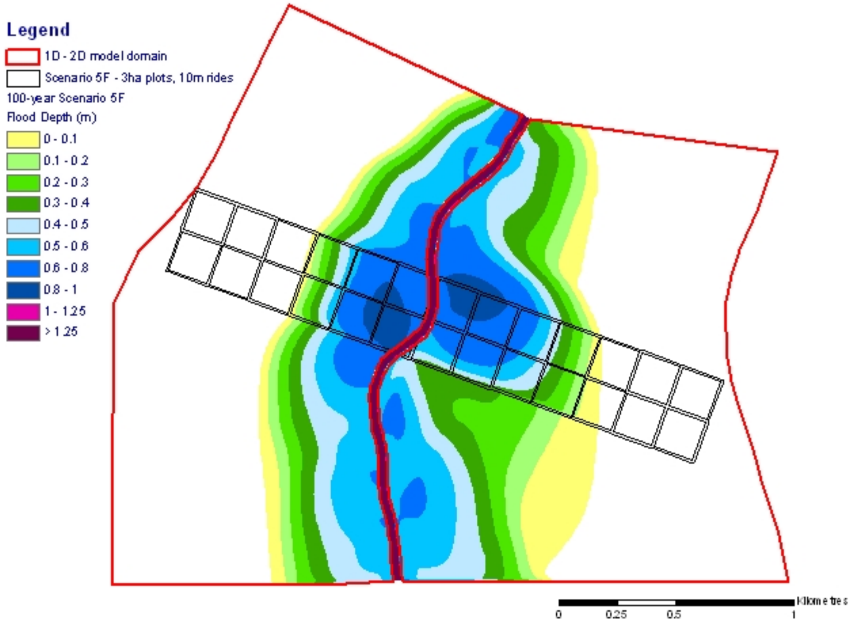
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 5 series (Miscanthus, 10m rides)

Baseline



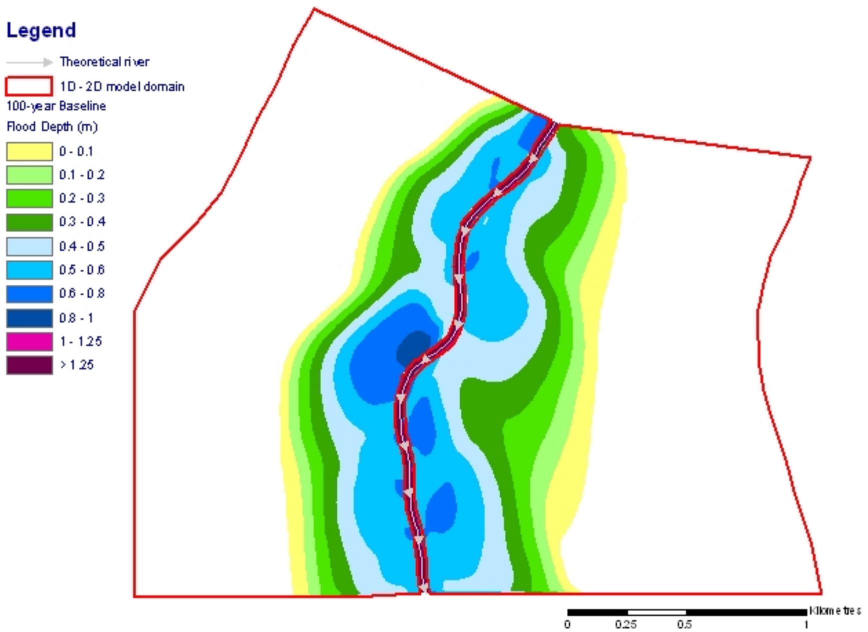
Scenario 5F



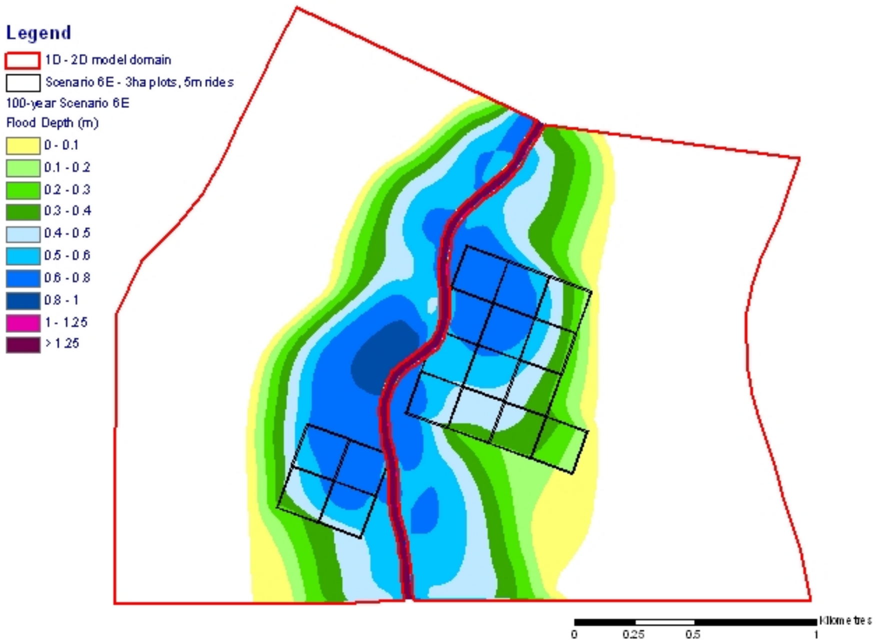
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 6 series (Miscanthus, 5m rides)

Baseline



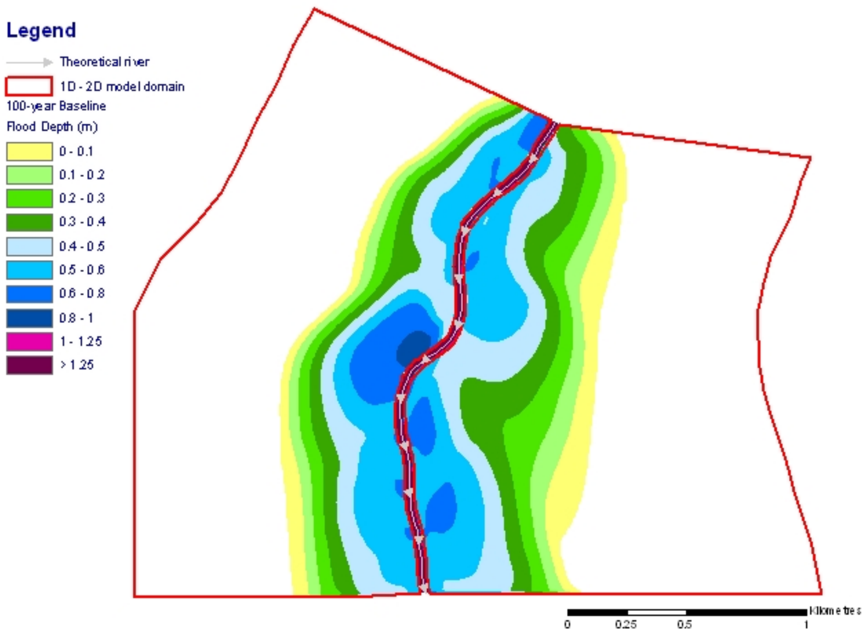
Scenario 6E



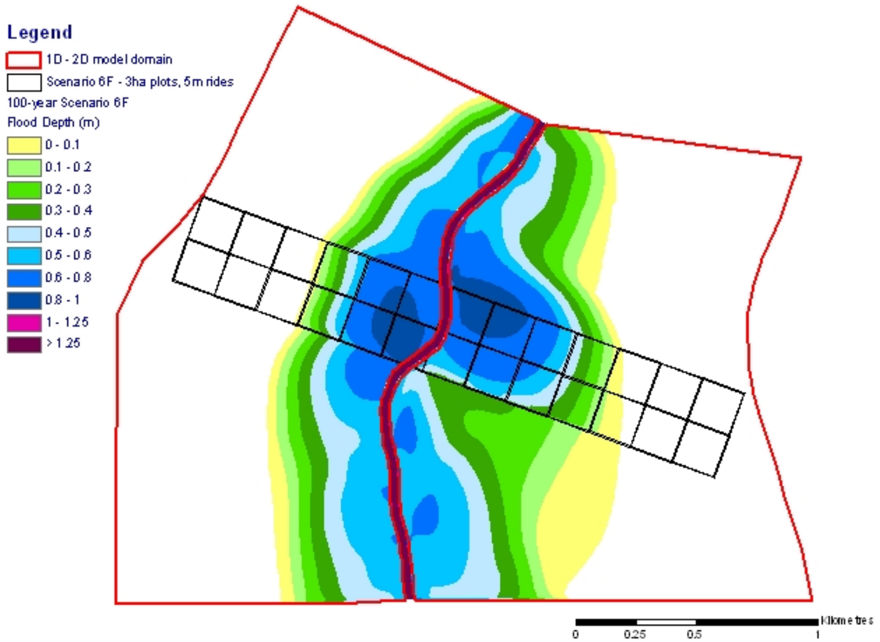
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 6 series (Miscanthus, 5m rides)

Baseline



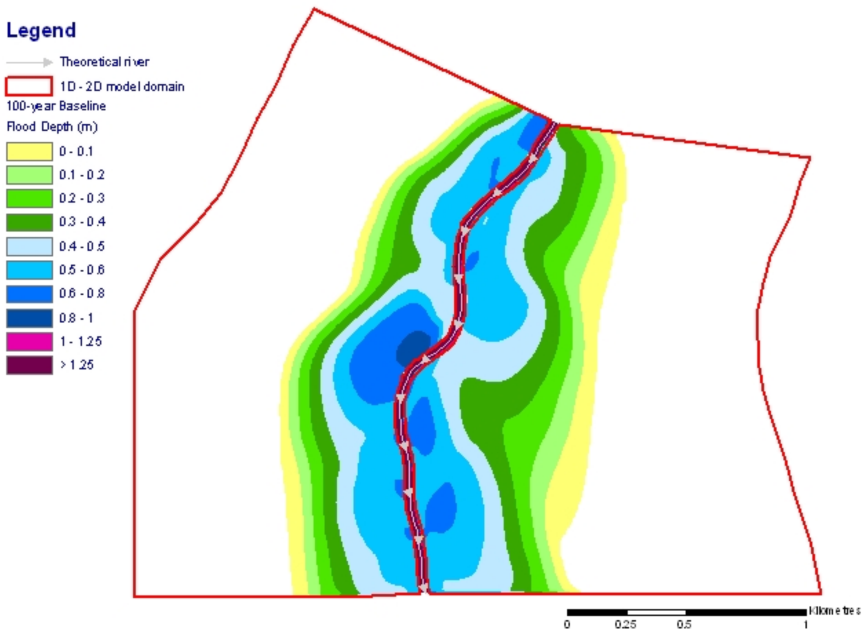
Scenario 6F



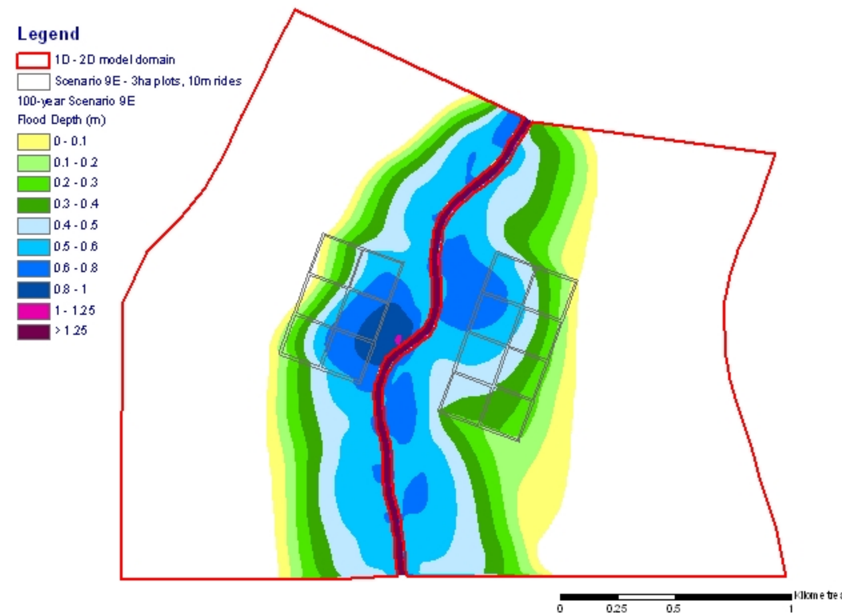
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 9 series (Miscanthus, 10m rides)

Baseline



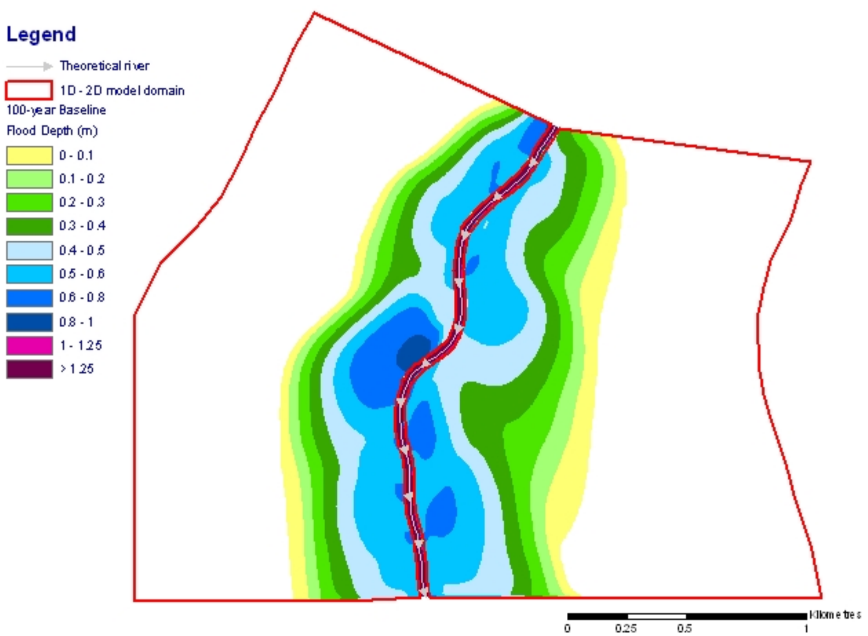
Scenario 9E



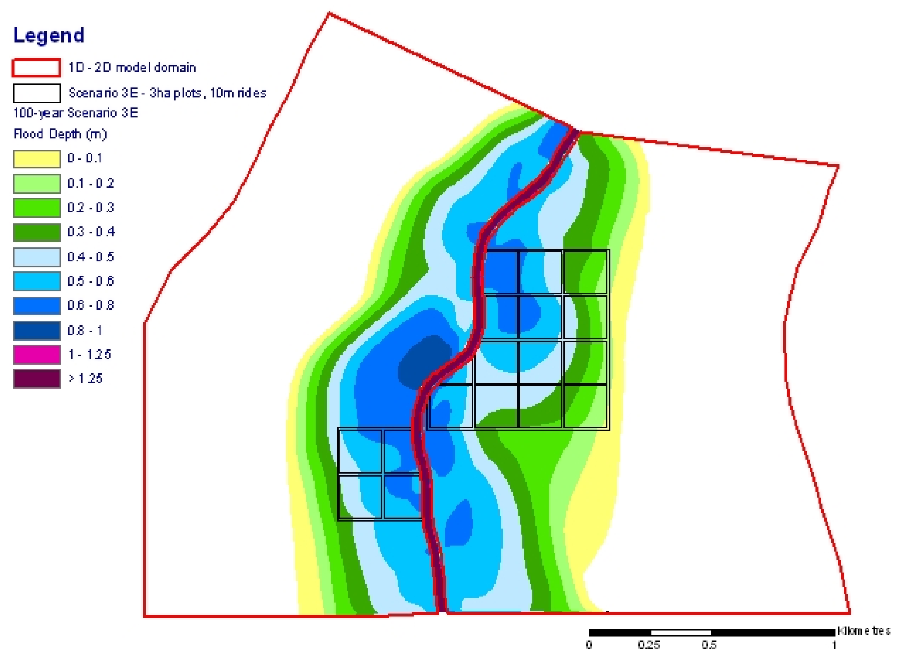
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 3 series (SRC Willow, 10m rides)

Baseline



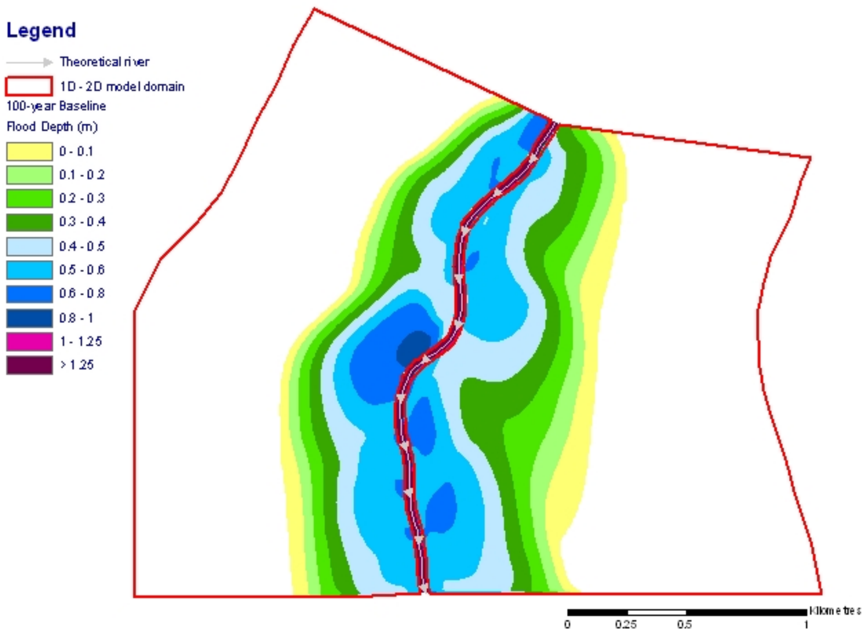
Scenario 3E



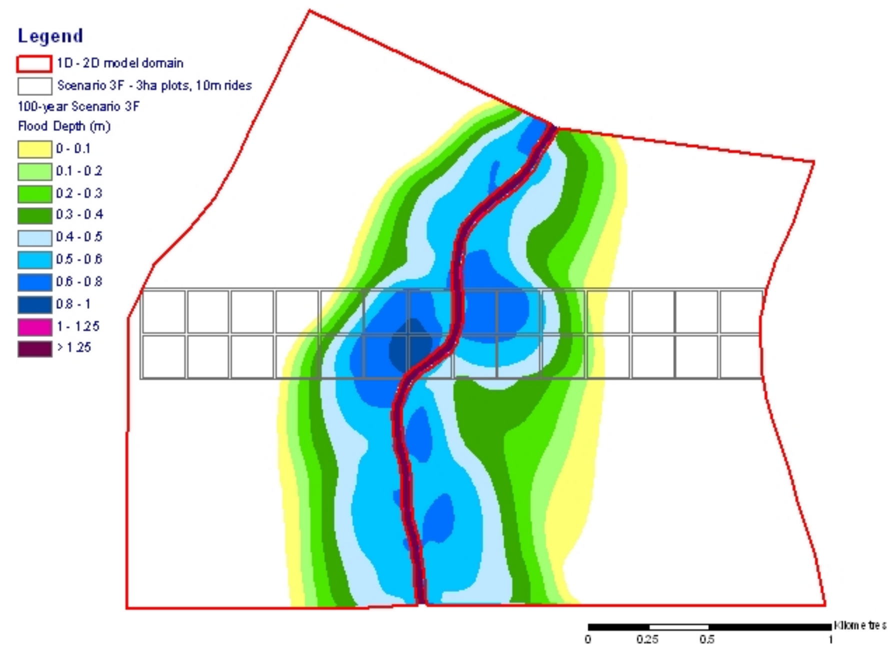
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 3 series (SRC Willow, 10m rides)

Baseline



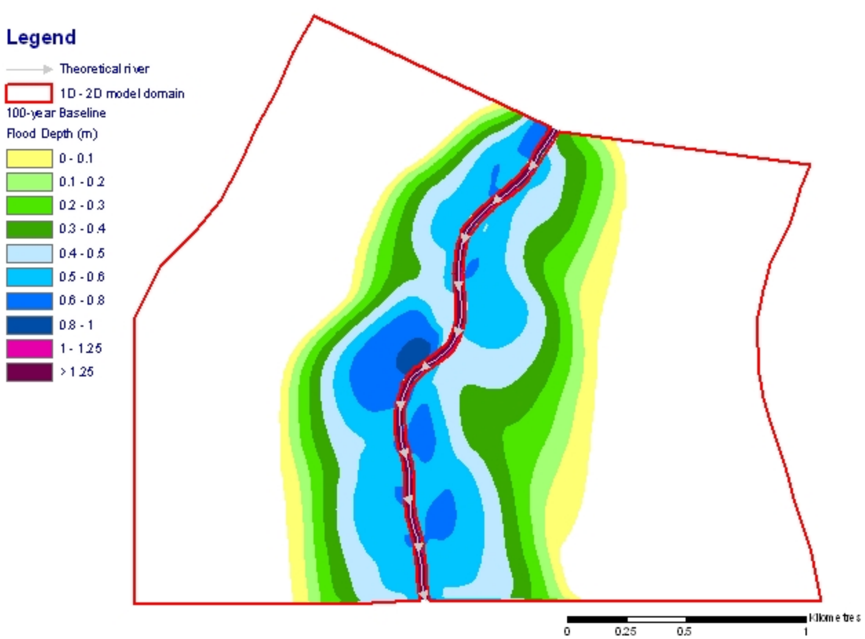
Scenario 3F



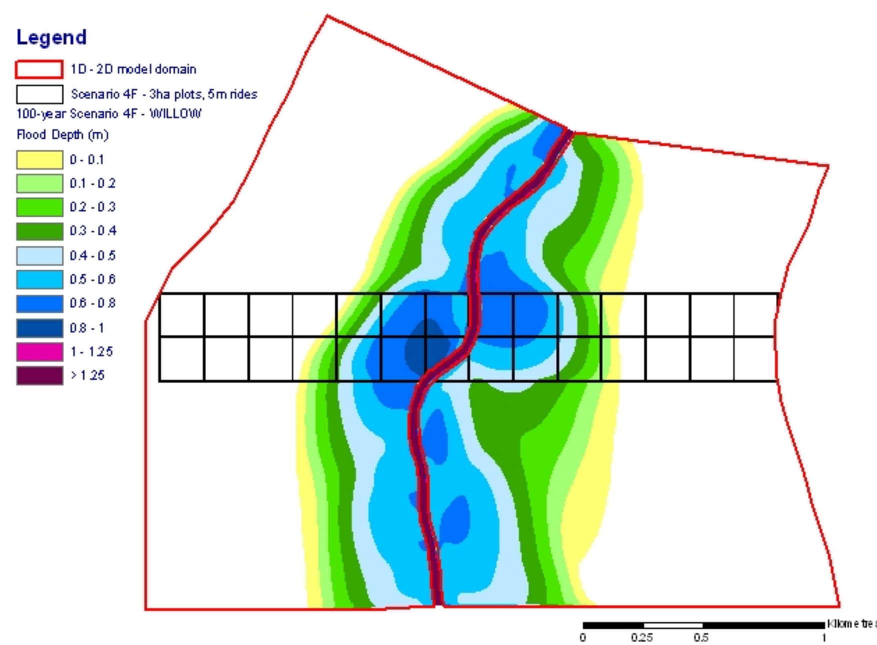
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 4 - WILLOW series (SRC Willow, 5m rides)

Baseline



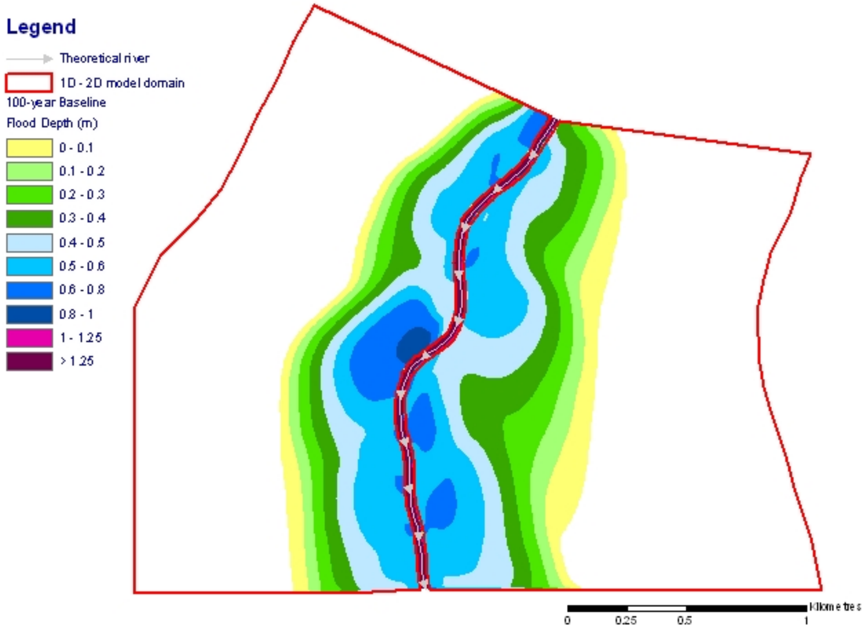
Scenario 4F - WILLOW



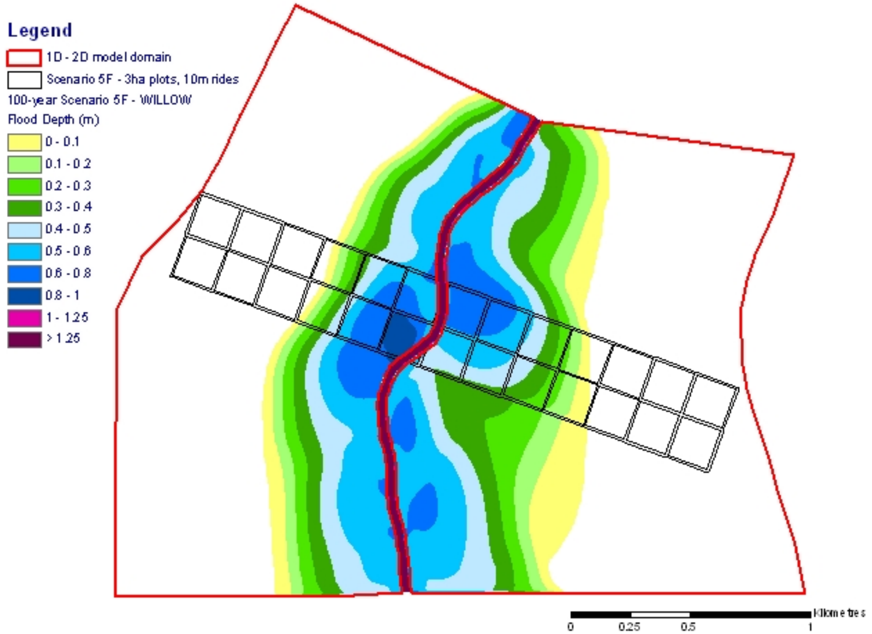
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 5 - WILLOW series (SRC Willow, 10m rides)

Baseline



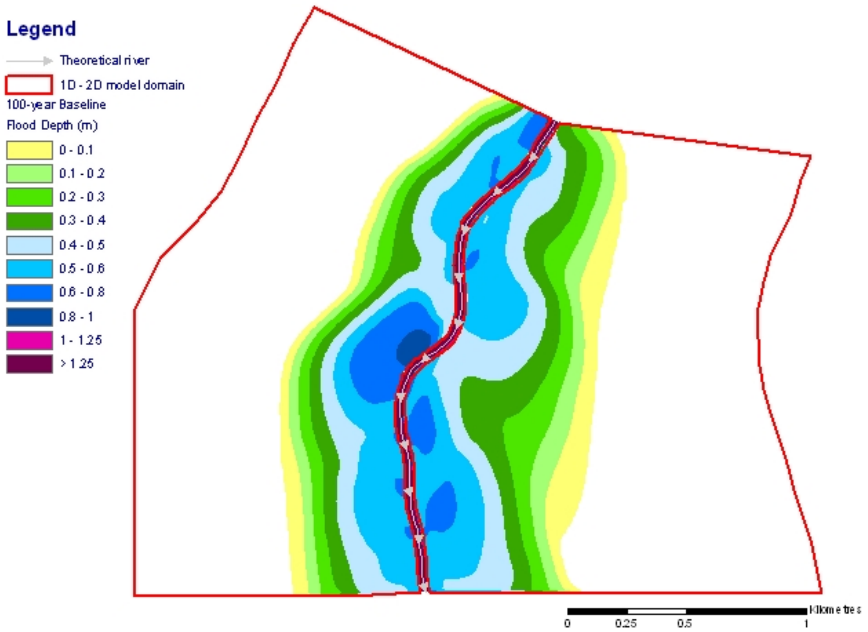
Scenario 5F - WILLOW



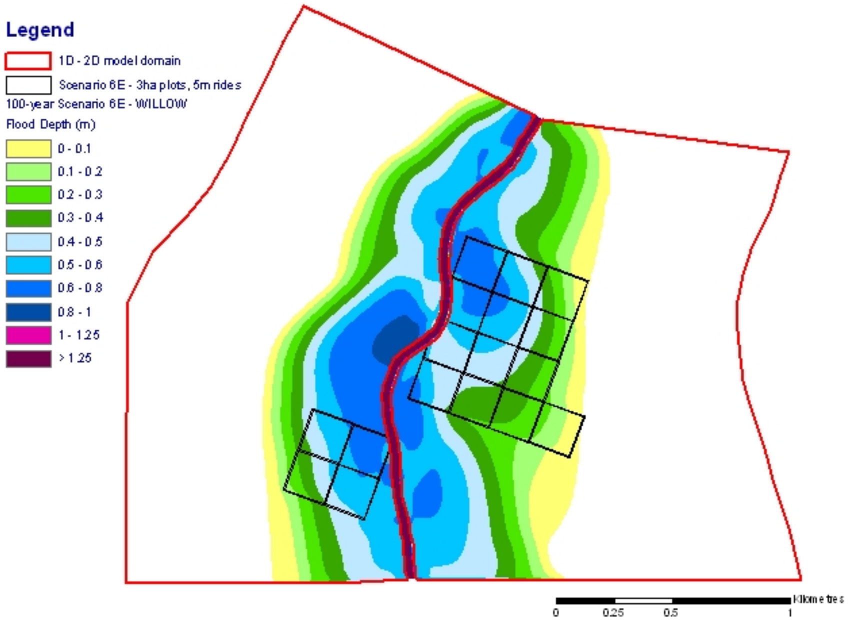
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 6 - WILLOW series (SRC Willow, 5m rides)

Baseline



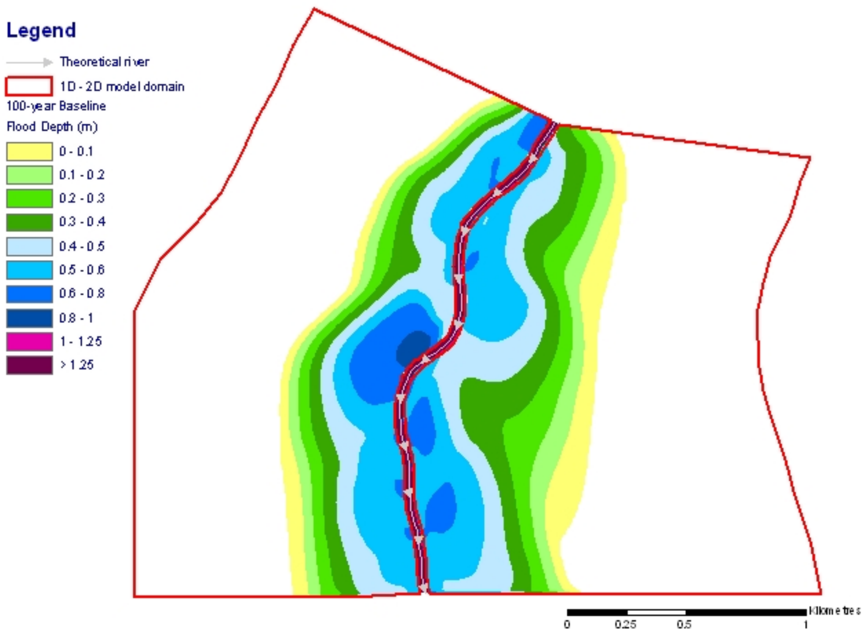
Scenario 6E - WILLOW



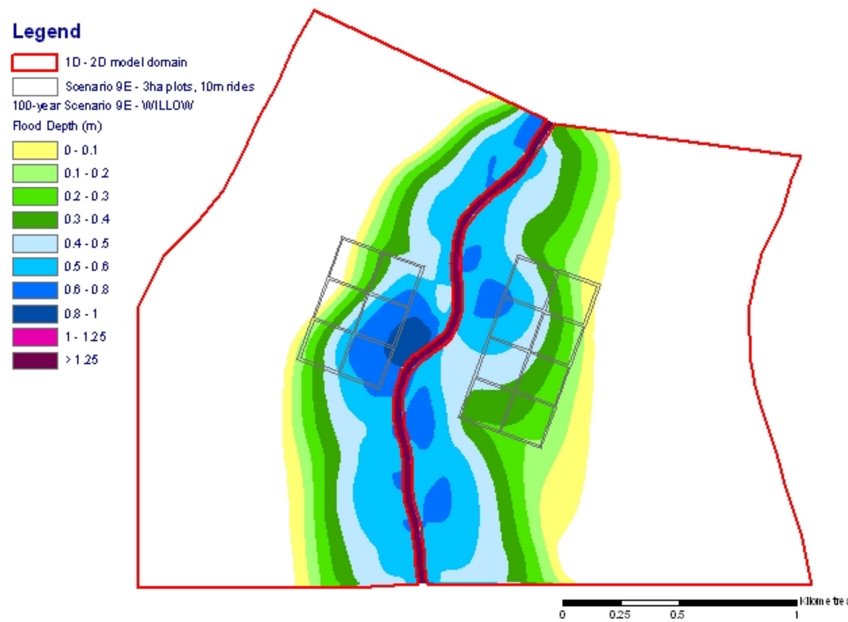
Model results – Floodplain Inundation

- Flood Depth (m) – Scenario 9 - WILLOW series (SRC Willow, 10m rides)

Baseline



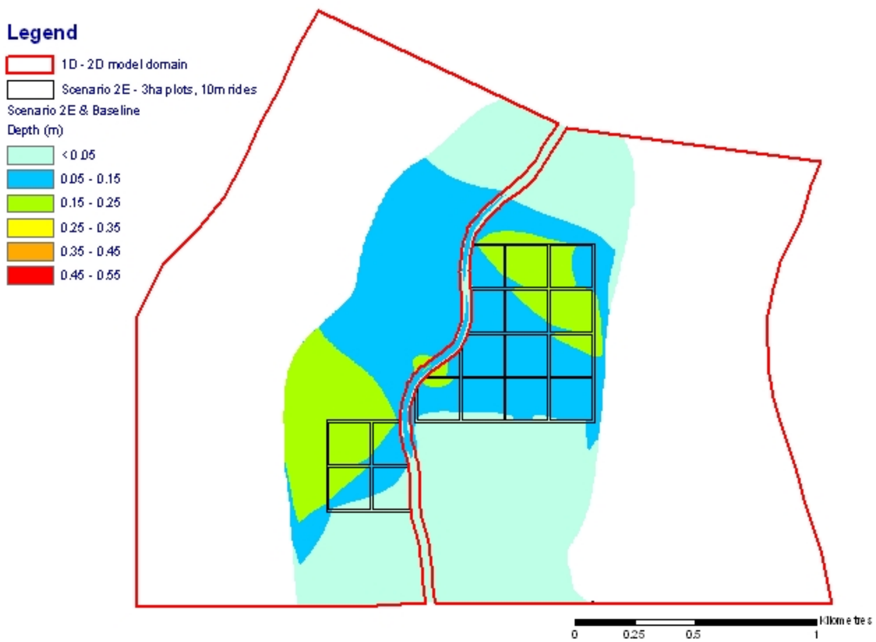
Scenario 9E - WILLOW



Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 2 series (Miscanthus, 10m rides)

Scenario 2E - Baseline



Scenario 2F – Baseline

Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 4 series (Miscanthus, 5m rides)

Scenario 4E - Baseline

Scenario 4F – Baseline

Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 5 series (Miscanthus, 10m rides)

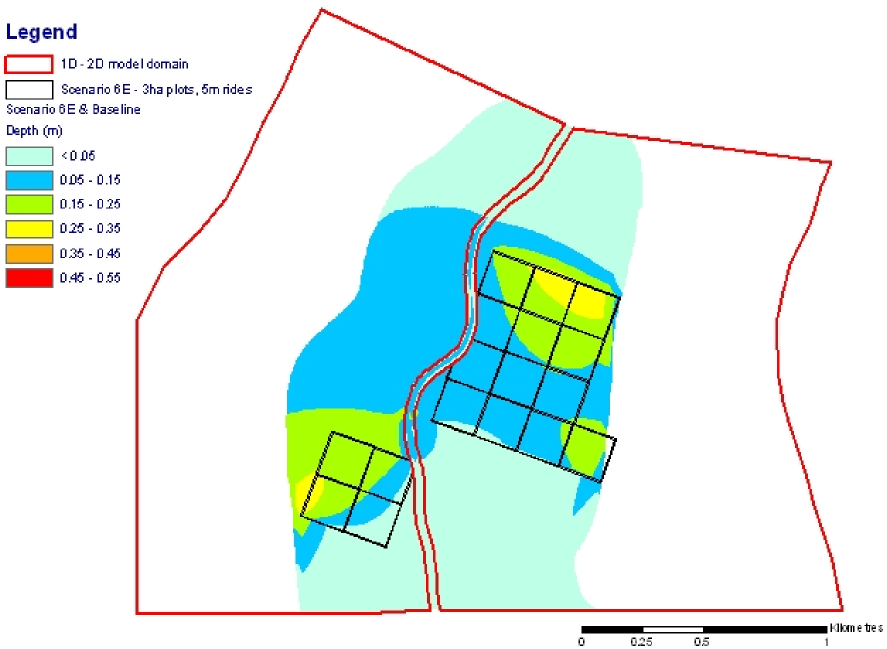
Scenario 5E - Baseline

Scenario 5F – Baseline

Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 6 series (Miscanthus, 5m rides)

Scenario 6E - Baseline

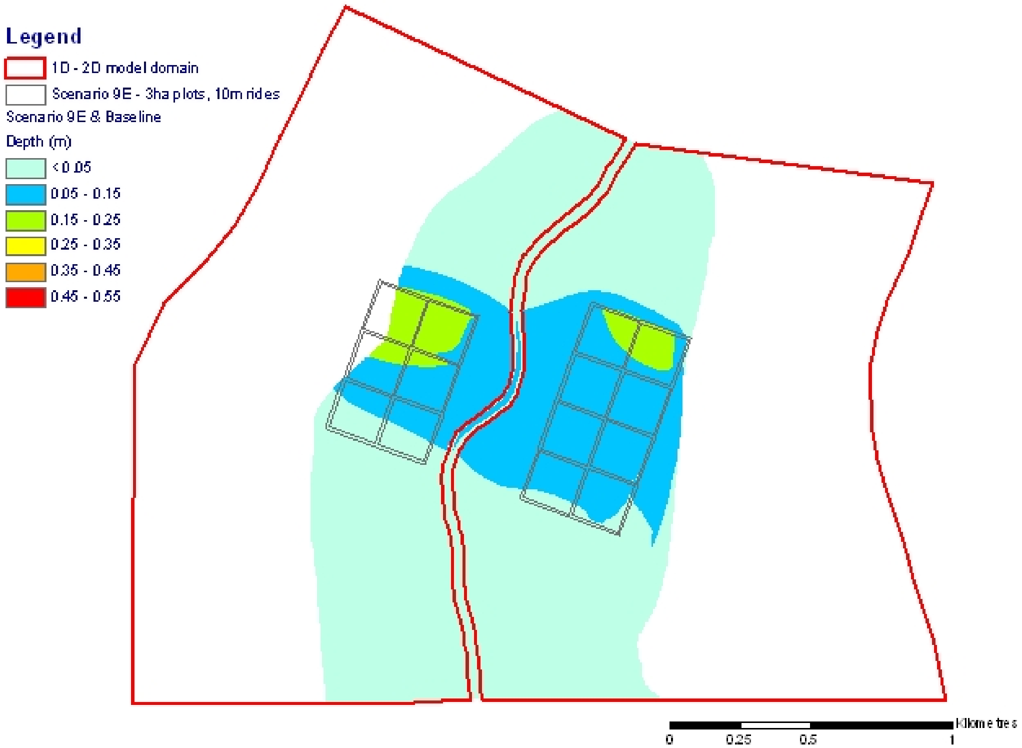


Scenario 6F – Baseline

Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 9 series (Miscanthus, 10m rides)

Scenario 9E - Baseline

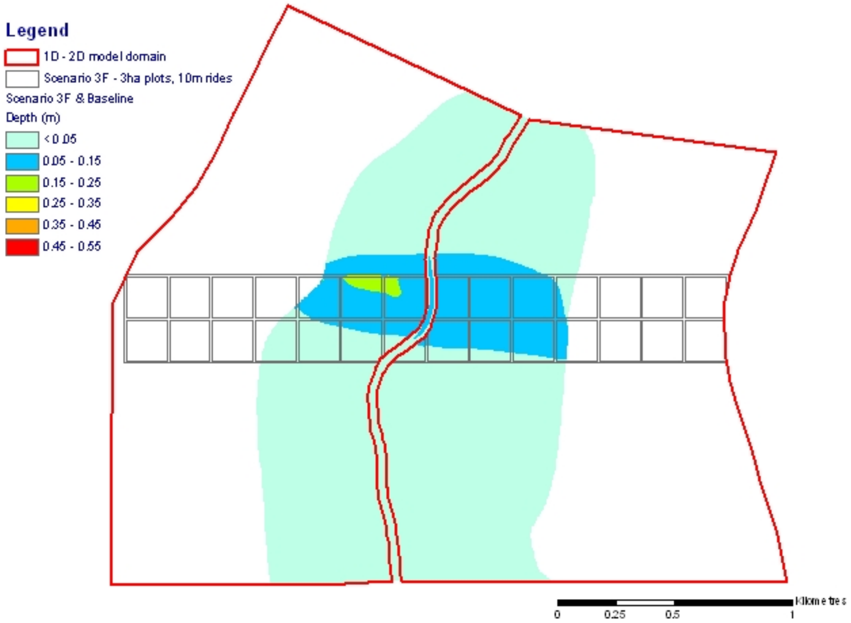


Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 3 series (SRC Willow, 10m rides)

Scenario 3E - Baseline

Scenario 3F – Baseline

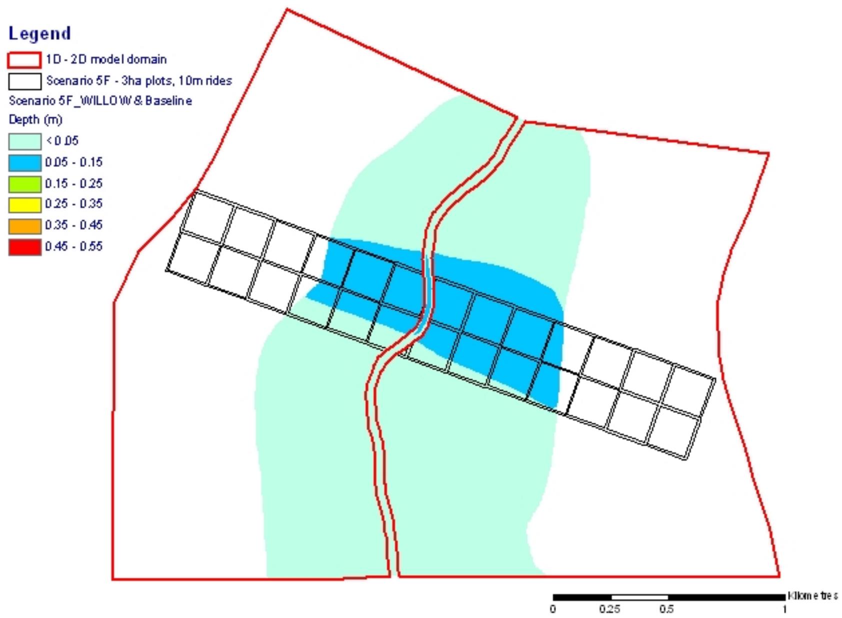


Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 4 – and 5 - WILLOW series (SRC Willow, 5 and 10m rides, respectively)

Scenario 4F (WILLOW) - Baseline

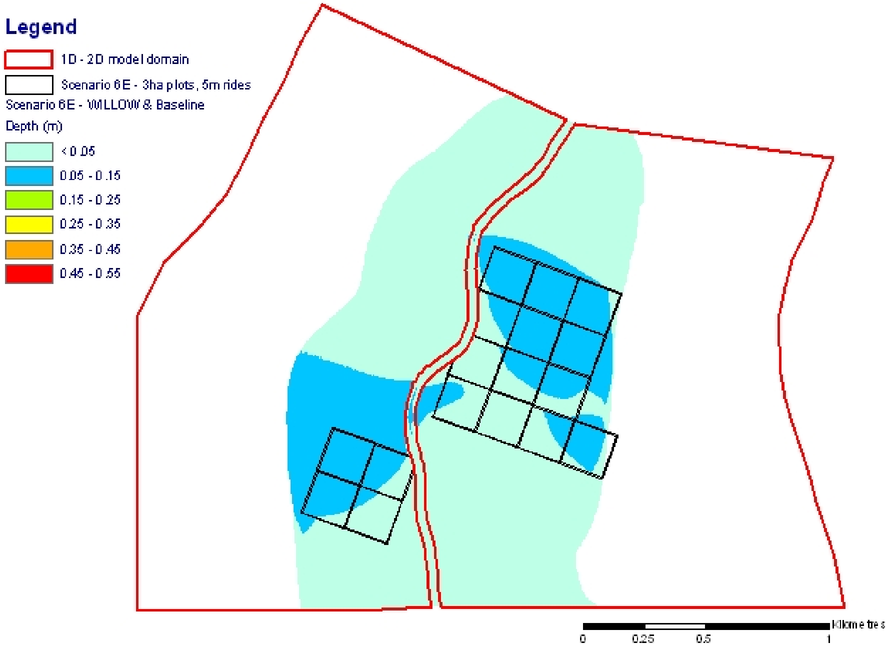
Scenario 5F (WILLOW) – Baseline



Model results – Floodplain Inundation (difference from Baseline depth)

- Flood Depth Difference (m) – Scenario 6 – and 9 - WILLOW series (SRC Willow, 5 and 10m rides, respectively)

Scenario 6E (WILLOW) - Baseline

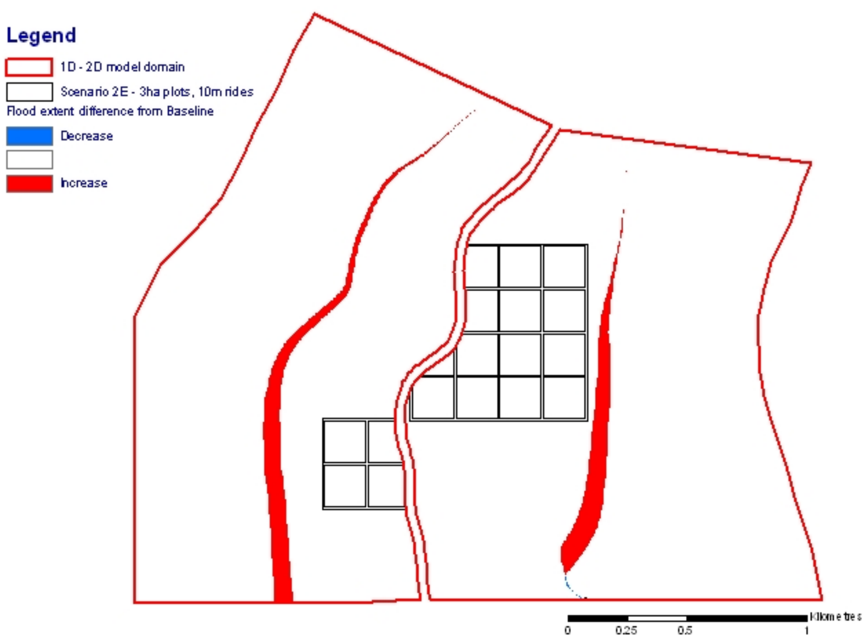


Scenario 9E (WILLOW) – Baseline

Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 2 series (Miscanthus, 10m rides)

Scenario 2E - Baseline



Scenario 2F – Baseline

Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 4 series (Miscanthus, 5m rides)

Scenario 4E - Baseline

Scenario 4F – Baseline

Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 5 series (Miscanthus, 10m rides)

Scenario 5E - Baseline

Scenario 5F – Baseline

Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 6 series (Miscanthus, 5m rides)

Scenario 6E - Baseline

Scenario 6F – Baseline

Model results – Change to flood extent (difference from Baseline)

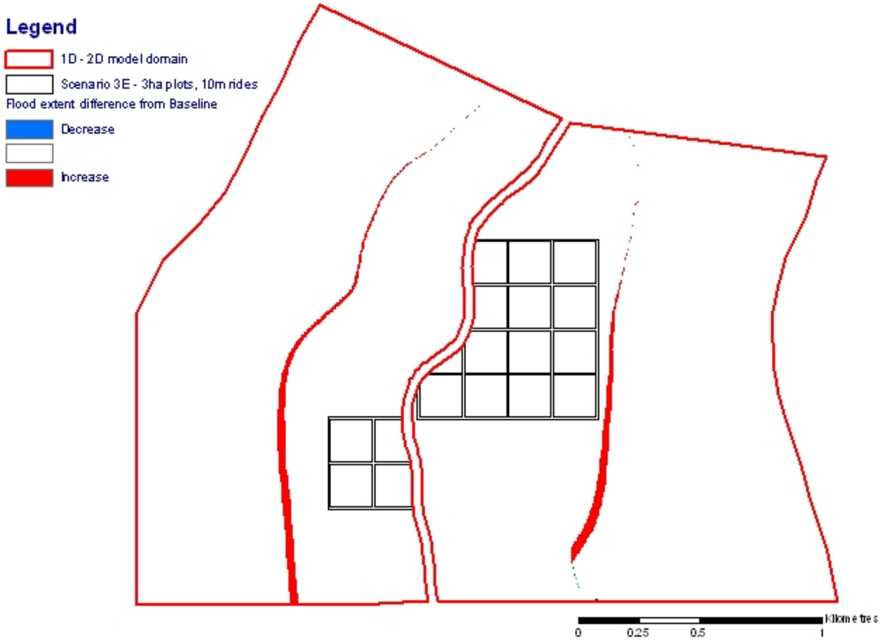
- Flood Extent Difference – Scenario 9 series (Miscanthus, 10m rides)

Scenario 9E - Baseline

Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 3 series (SRC Willow, 10m rides)

Scenario 3E - Baseline



Scenario 3F – Baseline

Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 4 – and 5 - WILLOW series (SRC Willow, 5 and 10m rides)

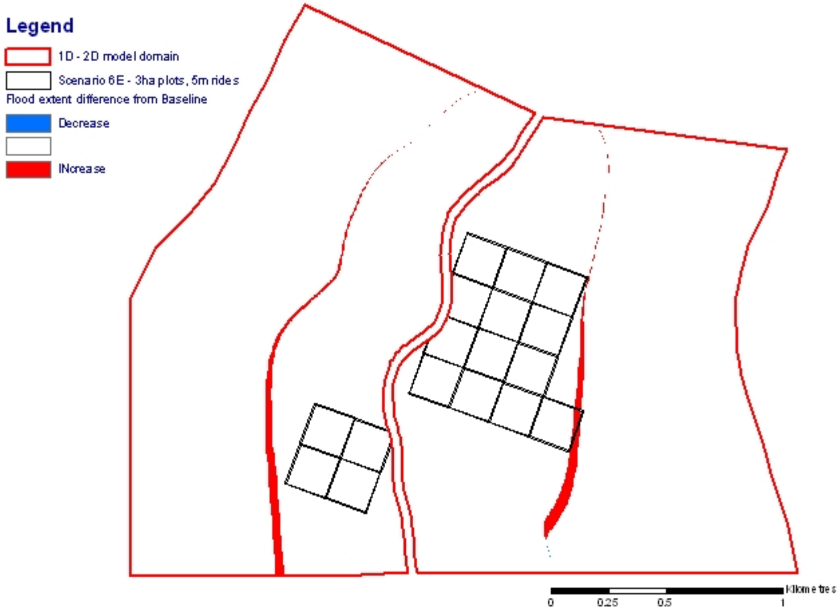
Scenario 4F (WILLOW) - Baseline

Scenario 5F (WILLOW) – Baseline

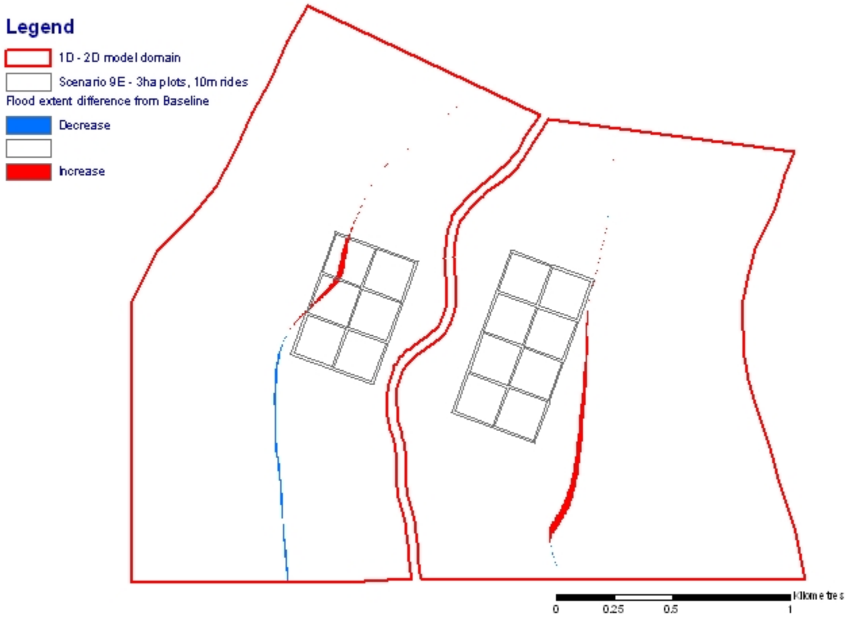
Model results – Change to flood extent (difference from Baseline)

- Flood Extent Difference – Scenario 6 – and 9 - WILLOW series (SRC Willow, 10 and 5m rides)

Scenario 6E (WILLOW) - Baseline



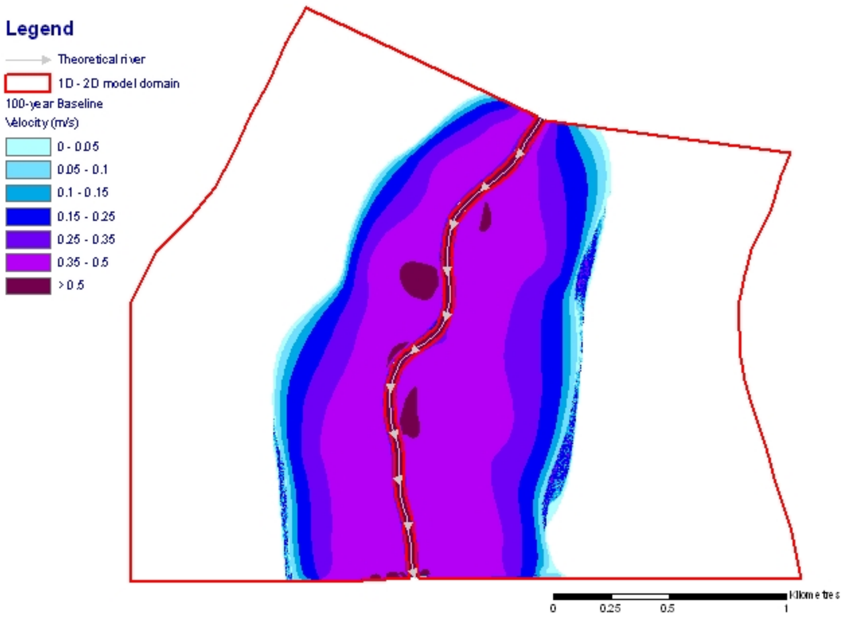
Scenario 9E (WILLOW) – Baseline



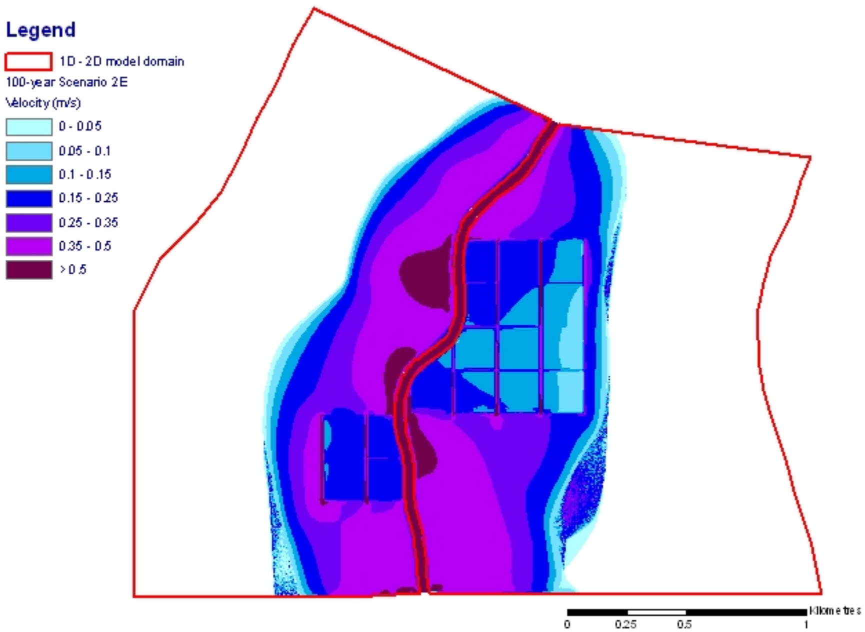
Model results – Velocities

- Flood Velocity (m/s) – Scenario 2 series (Miscanthus, 10m rides)

Baseline



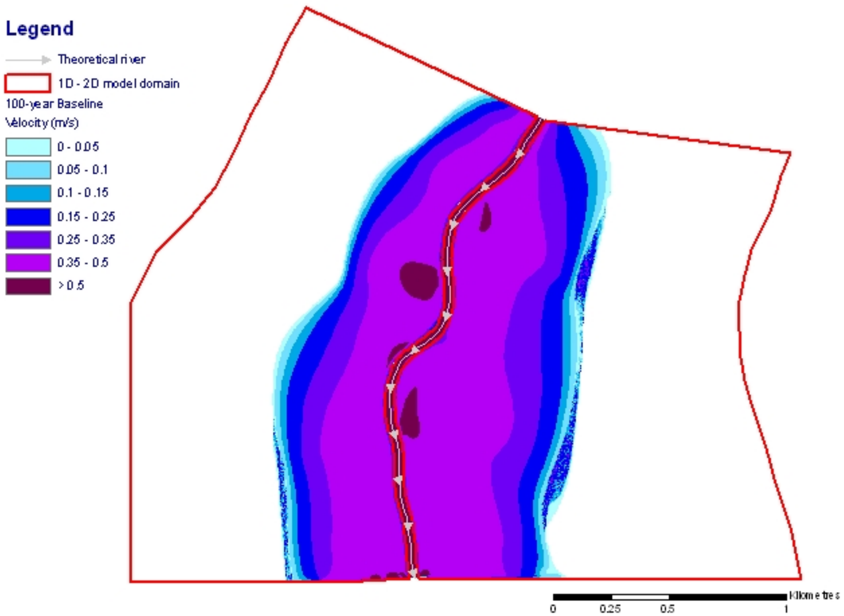
Scenario 2E



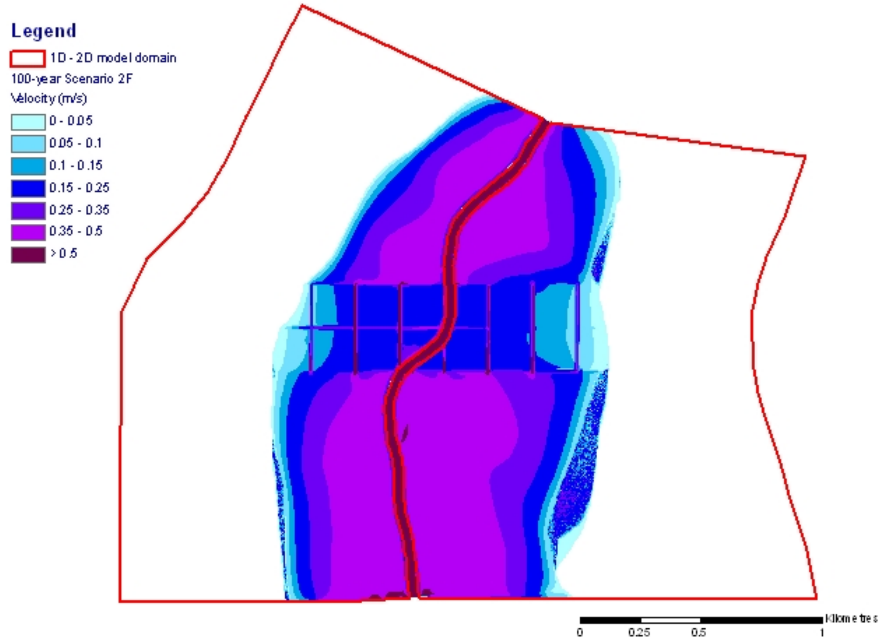
Model results – Velocities

- Flood Velocity (m/s) – Scenario 2 series (Miscanthus, 10m rides)

Baseline



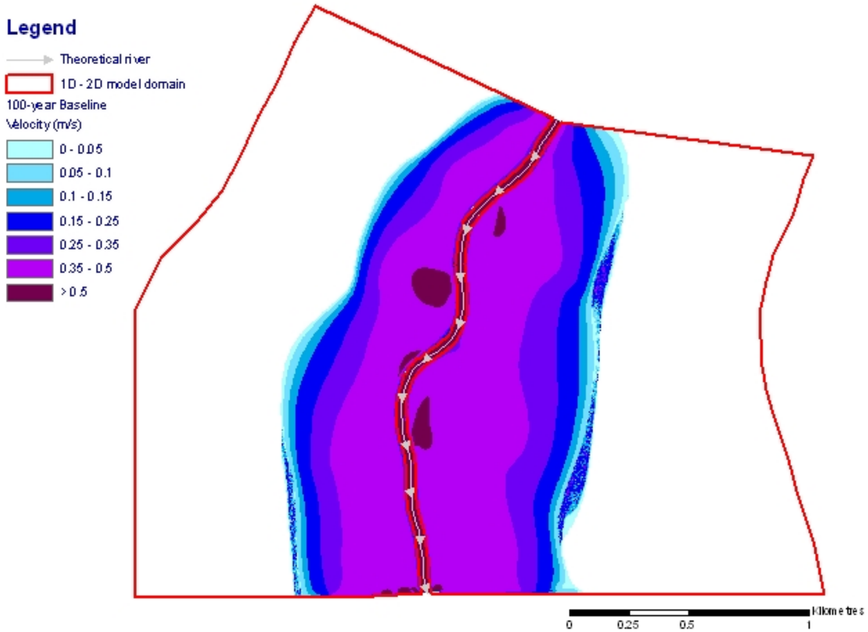
Scenario 2F



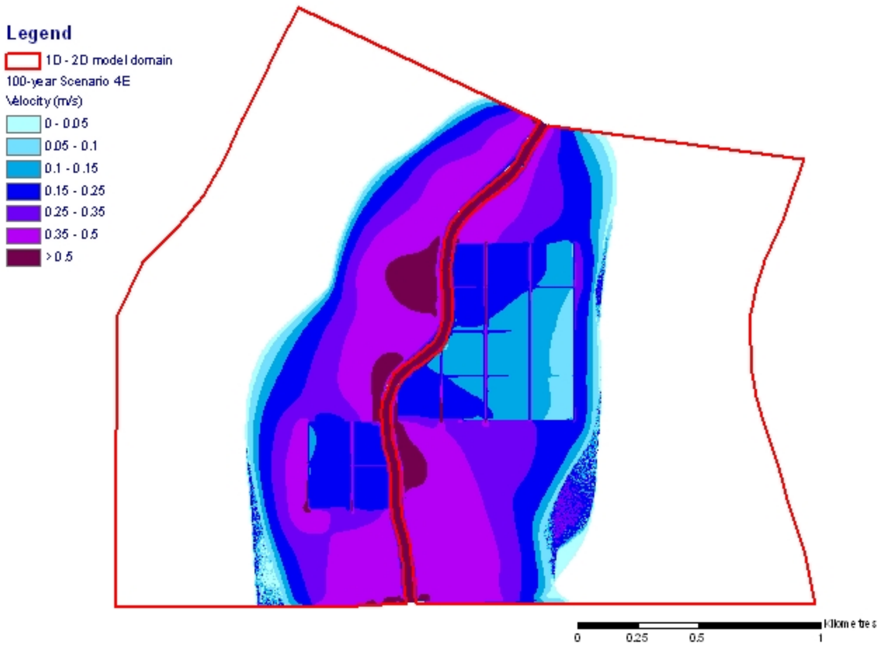
Model results – Velocities

- Flood Velocity (m/s) – Scenario 4 series (Miscanthus, 5m rides)

Baseline



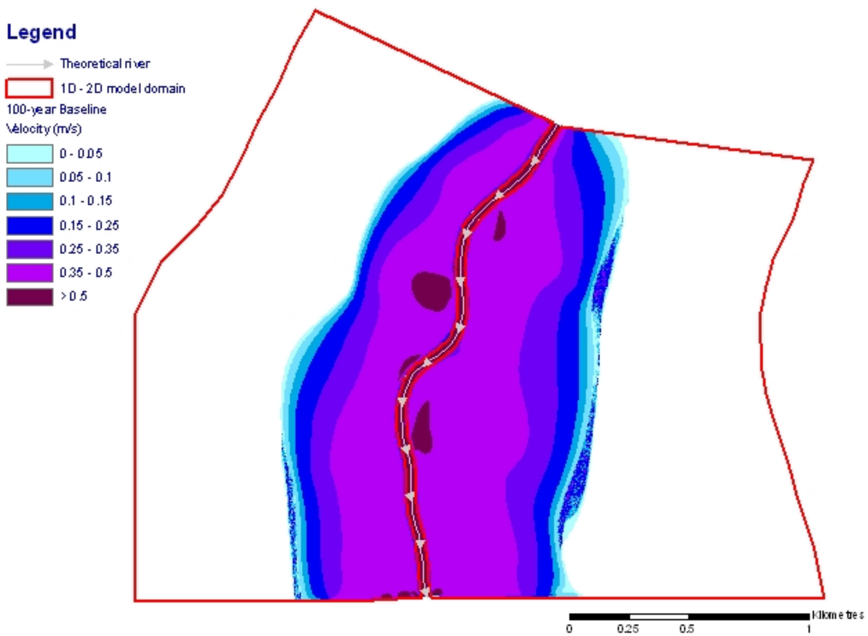
Scenario 4E



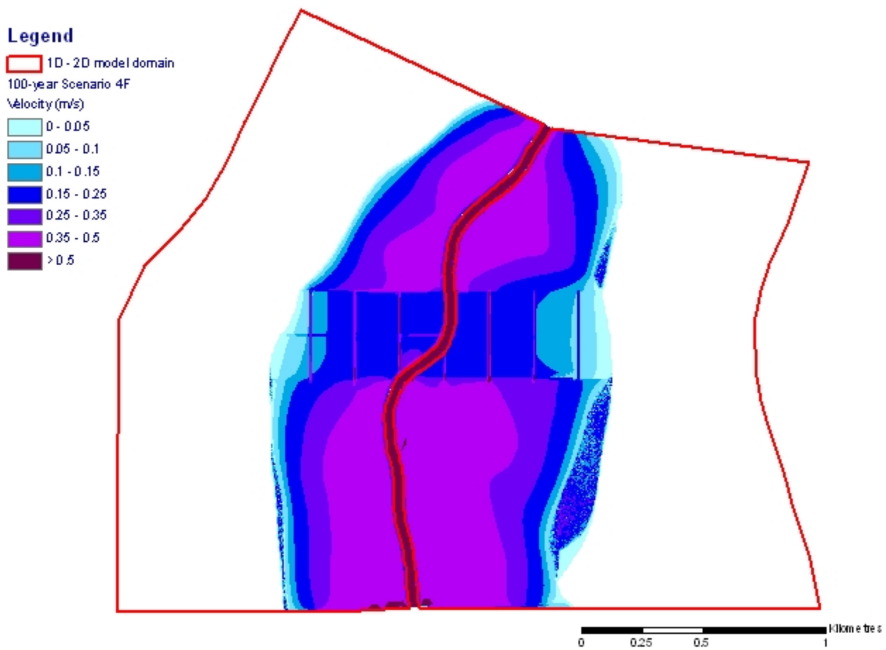
Model results – Velocities

- Flood Velocity (m/s) – Scenario 4 series (Miscanthus, 5m rides)

Baseline



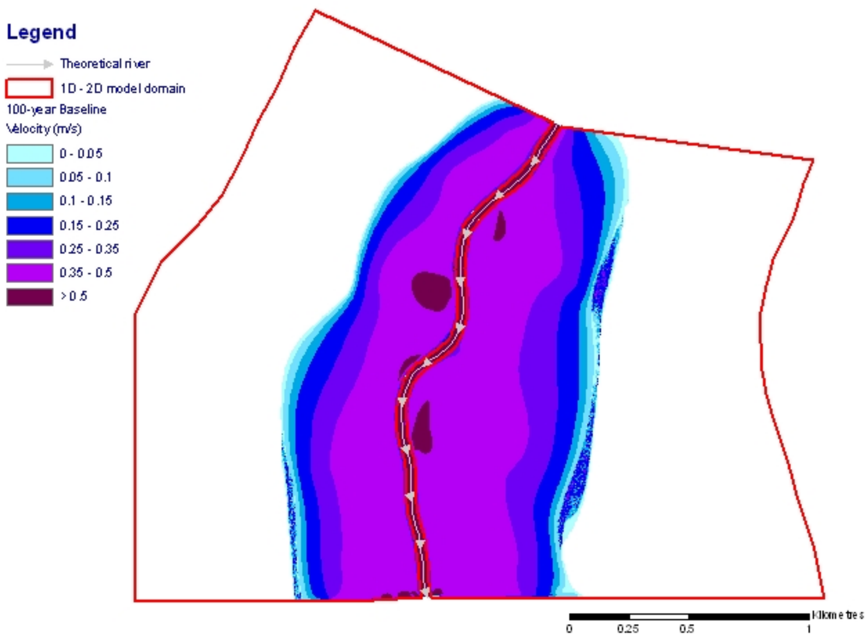
Scenario 4F



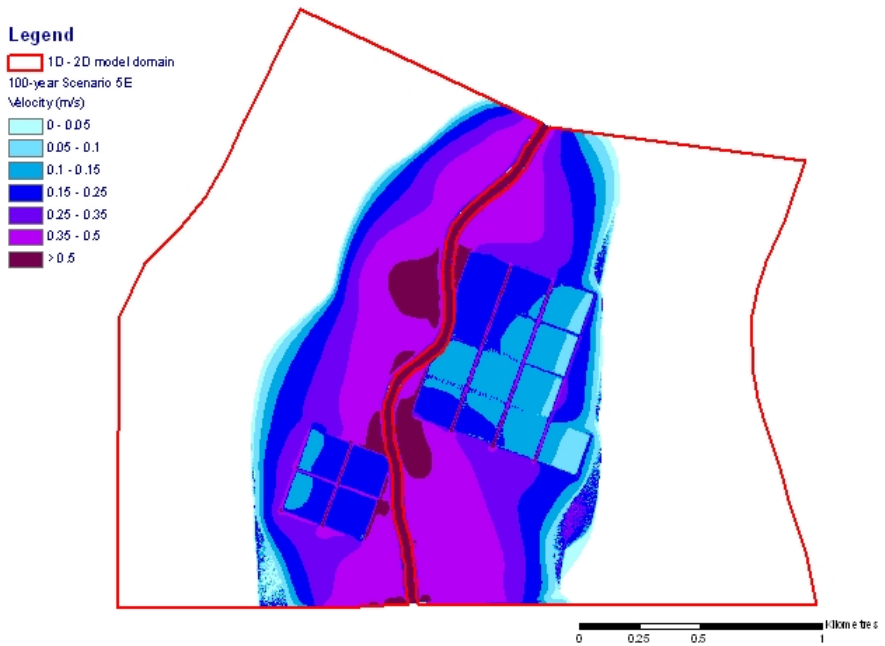
Model results – Velocities

- Flood Velocity (m/s) – Scenario 5 series (Miscanthus, 10m rides)

Baseline



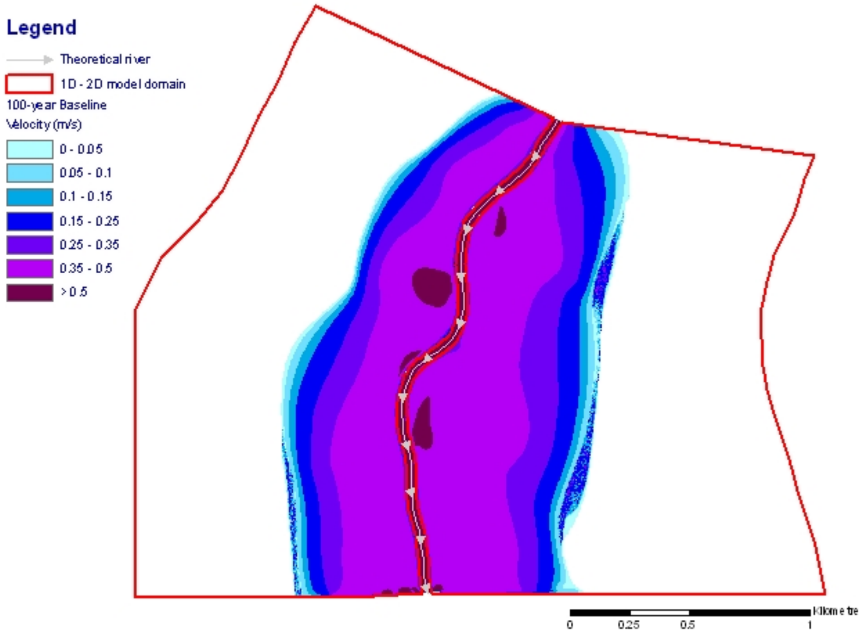
Scenario 5E



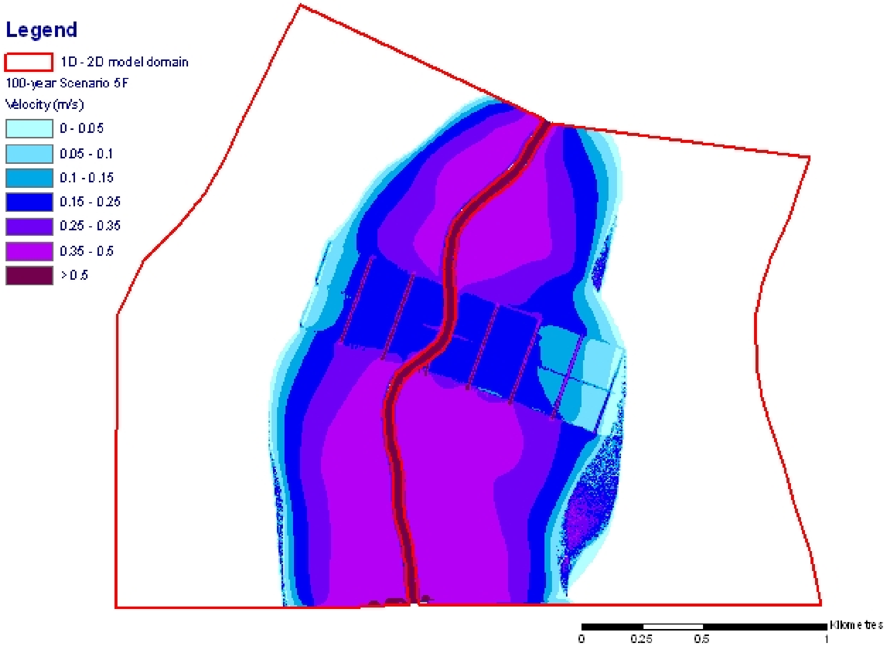
Model results – Velocities

- Flood Velocity (m/s) – Scenario 5 series (Miscanthus, 10m rides)

Baseline



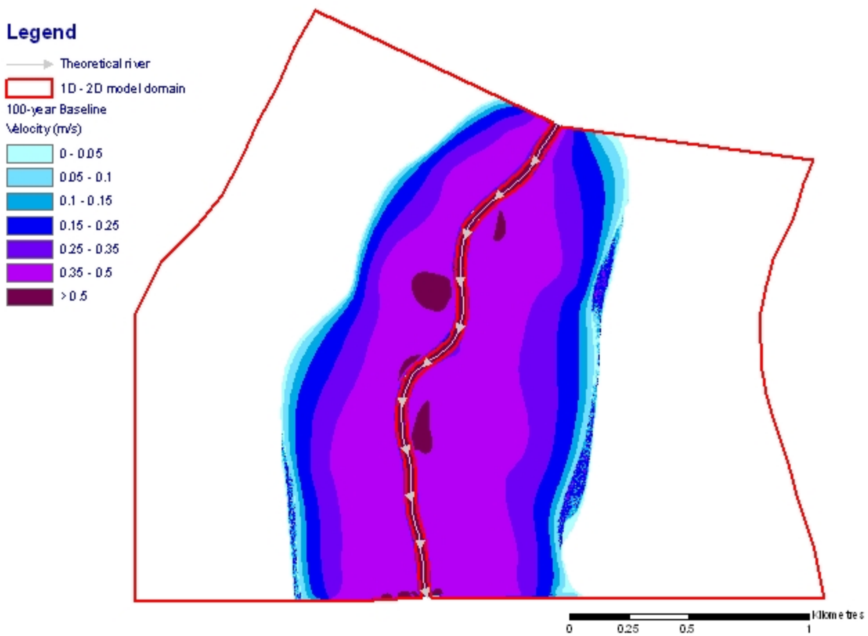
Scenario 5F



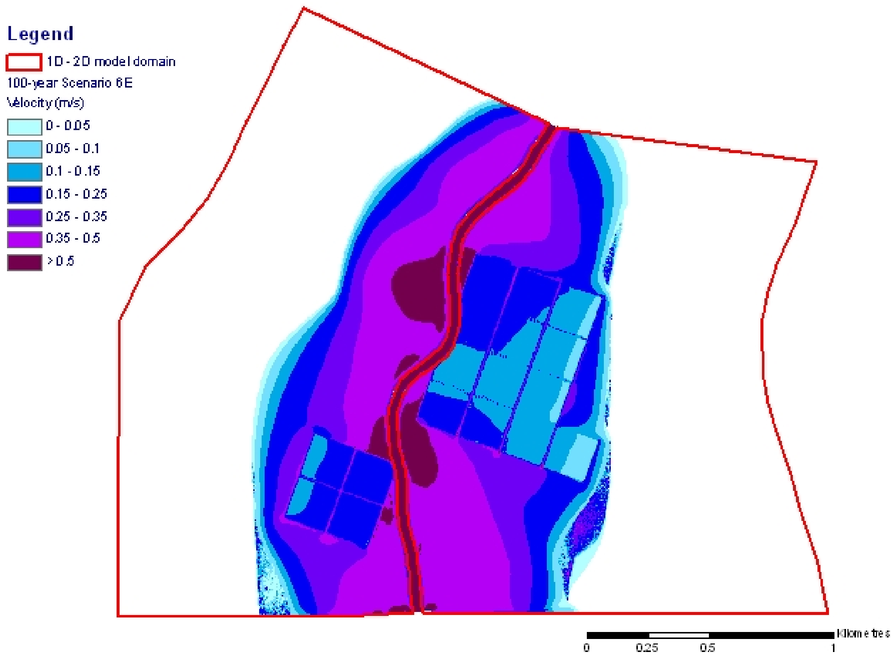
Model results – Velocities

- Flood Velocity (m/s) – Scenario 6 series (Miscanthus, 5m rides)

Baseline



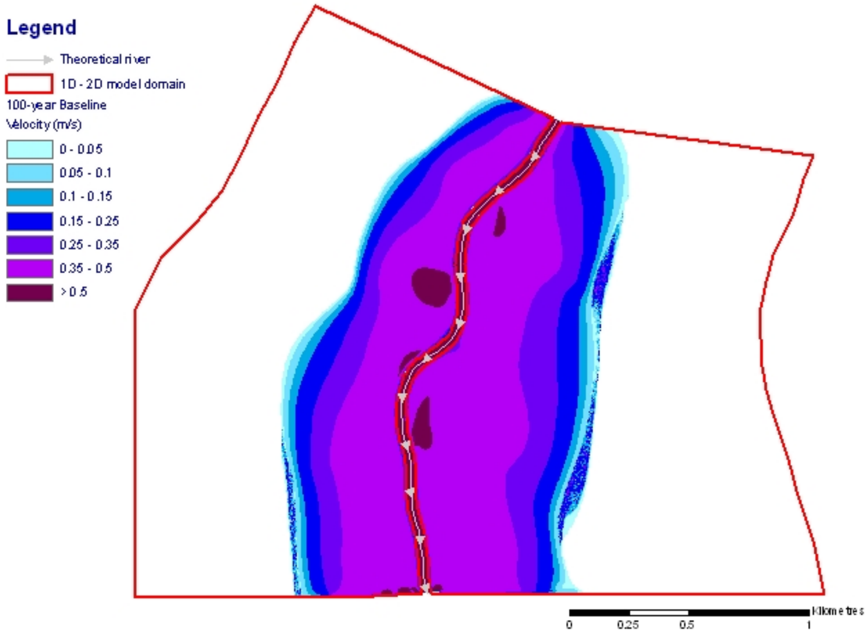
Scenario 6E



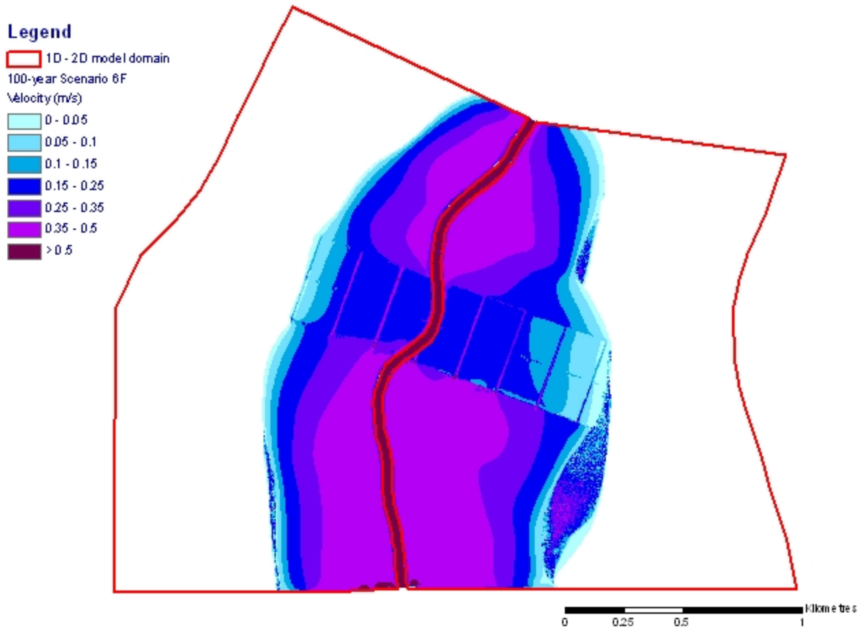
Model results – Velocities

- Flood Velocity (m/s) – Scenario 6 series (Miscanthus, 5m rides)

Baseline



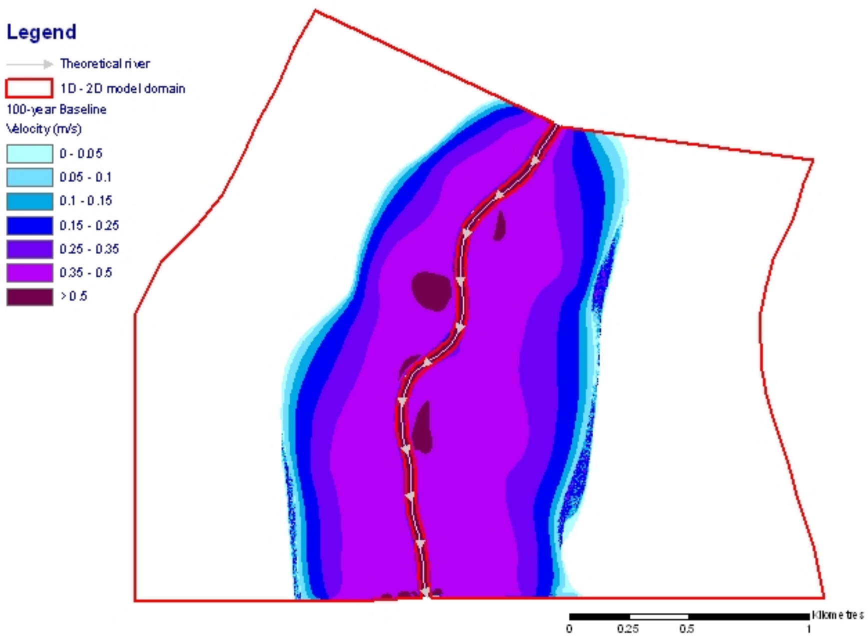
Scenario 6F



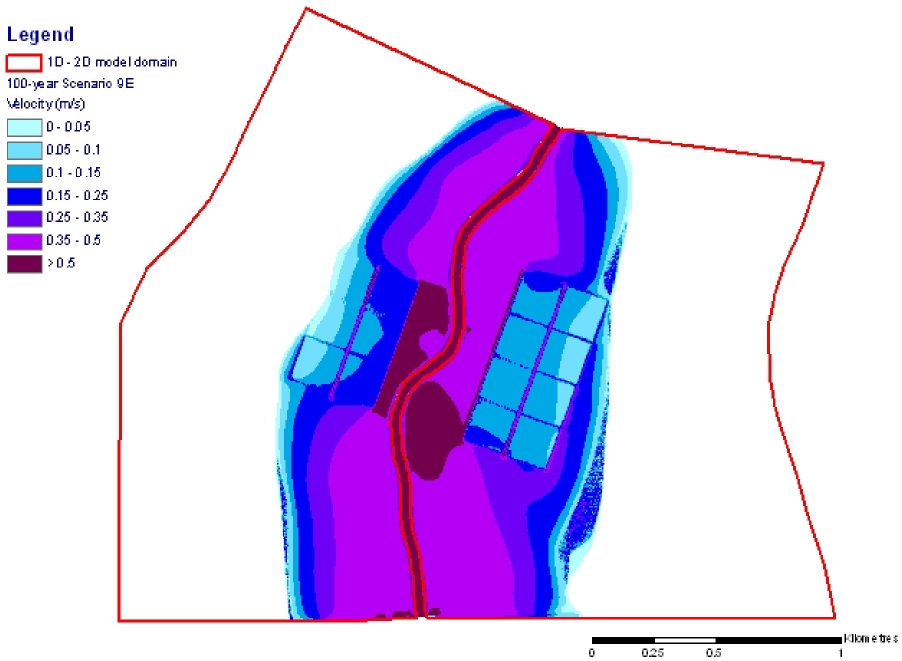
Model results – Velocities

- Flood Velocity (m/s) – Scenario 9 series (Miscanthus, 10m rides)

Baseline



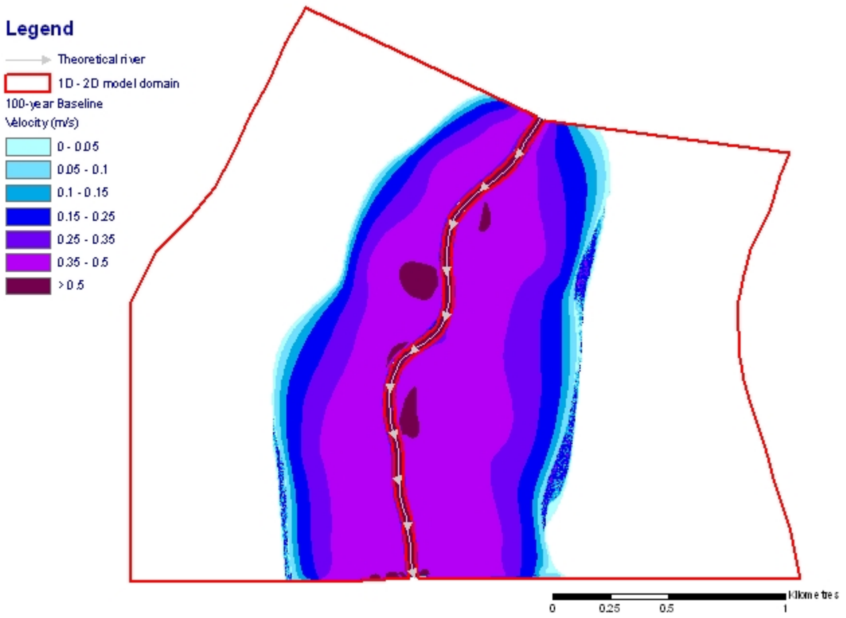
Scenario 9E



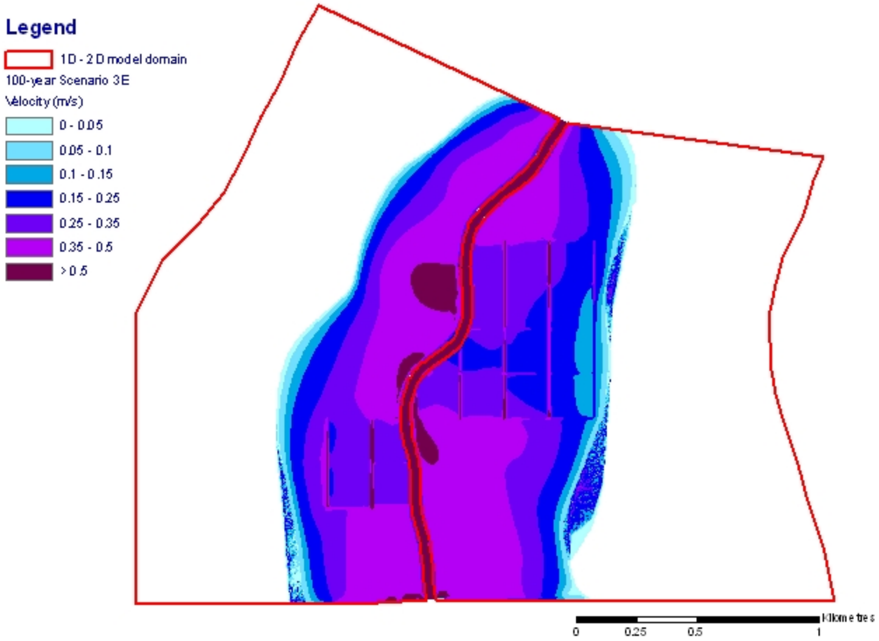
Model results – Velocities

- Flood Velocity (m/s) – Scenario 3 series (SRC Willow, 10m rides)

Baseline



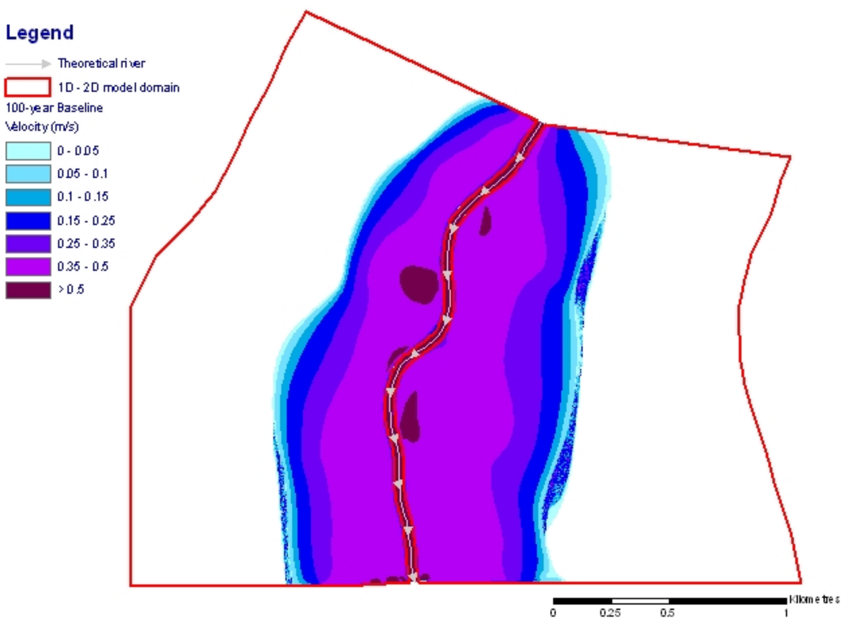
Scenario 3E



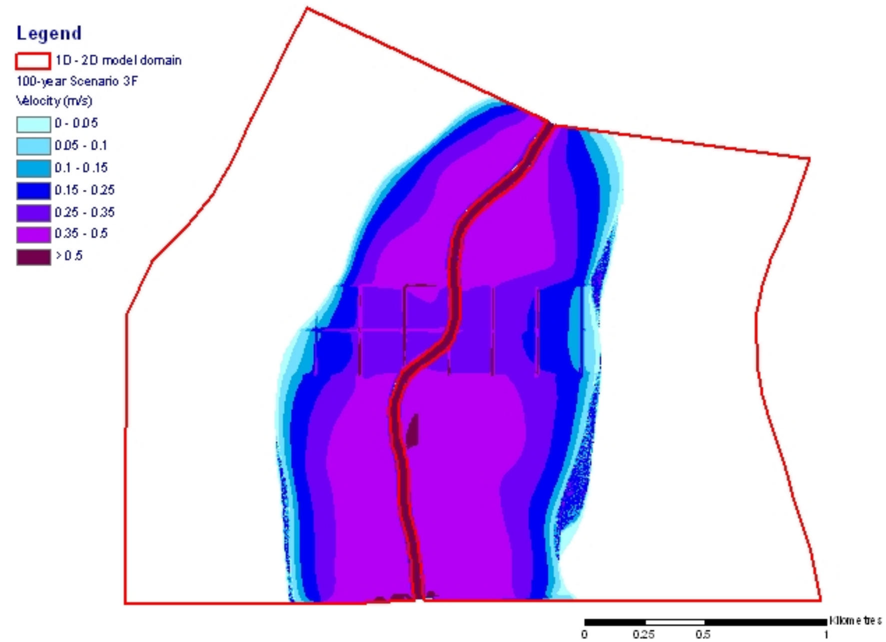
Model results – Velocities

- Flood Velocity (m/s) – Scenario 3 series (SRC Willow, 10m rides)

Baseline



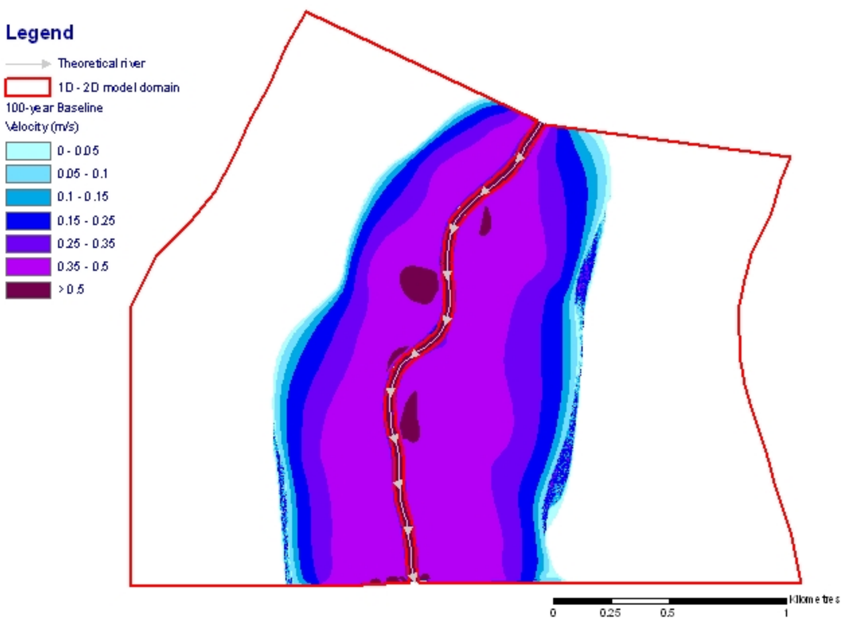
Scenario 3F



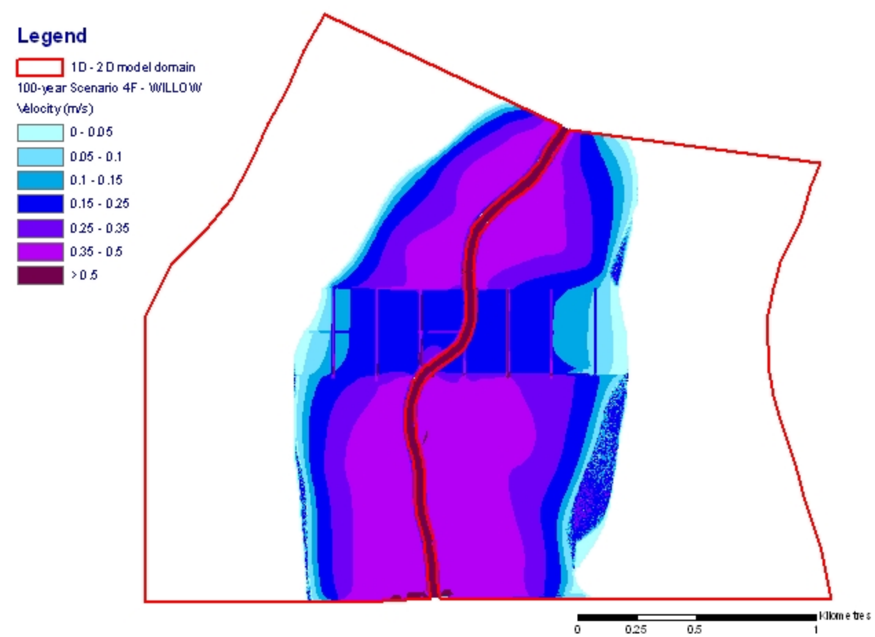
Model results – Velocities

- Flood Velocity (m/s) – Scenario 4 - WILLOW series (SRC Willow, 5m rides)

Baseline



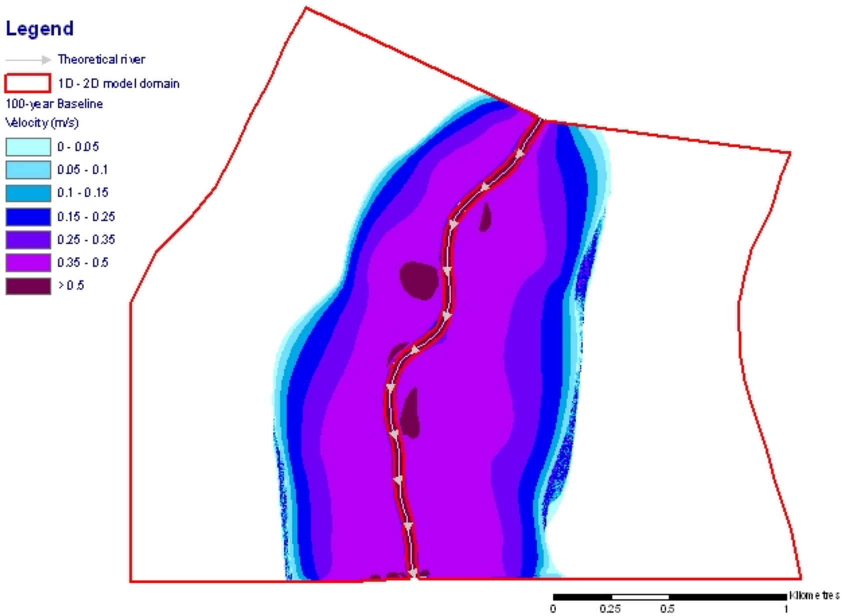
Scenario 4F - WILLOW



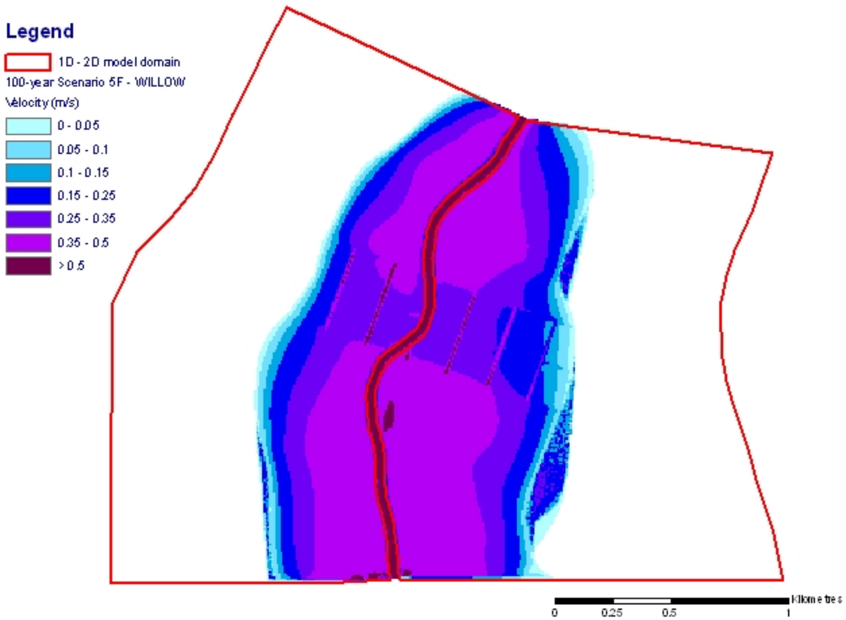
Model results – Velocities

- Flood Velocity (m/s) – Scenario 5 - WILLOW series (SRC Willow, 10m rides)

Baseline



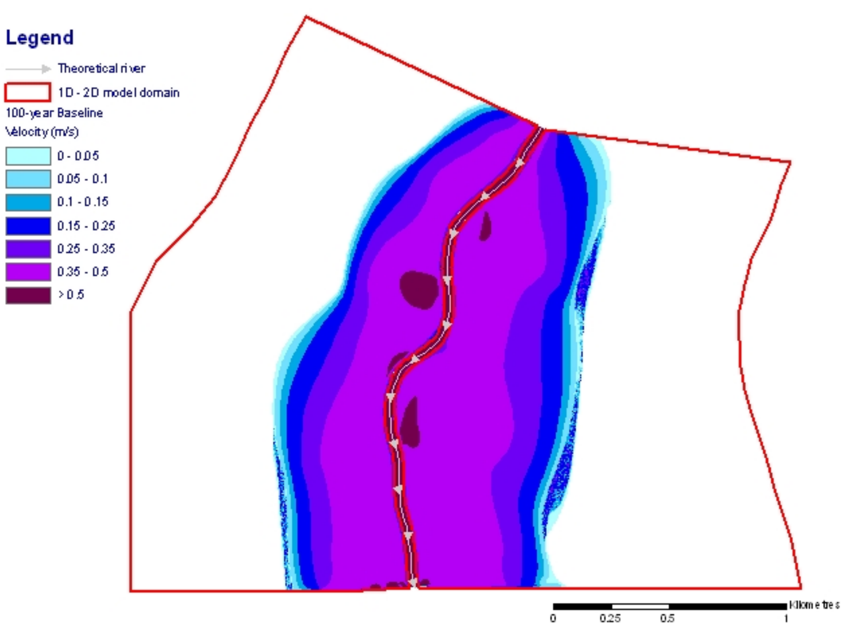
Scenario 5F - WILLOW



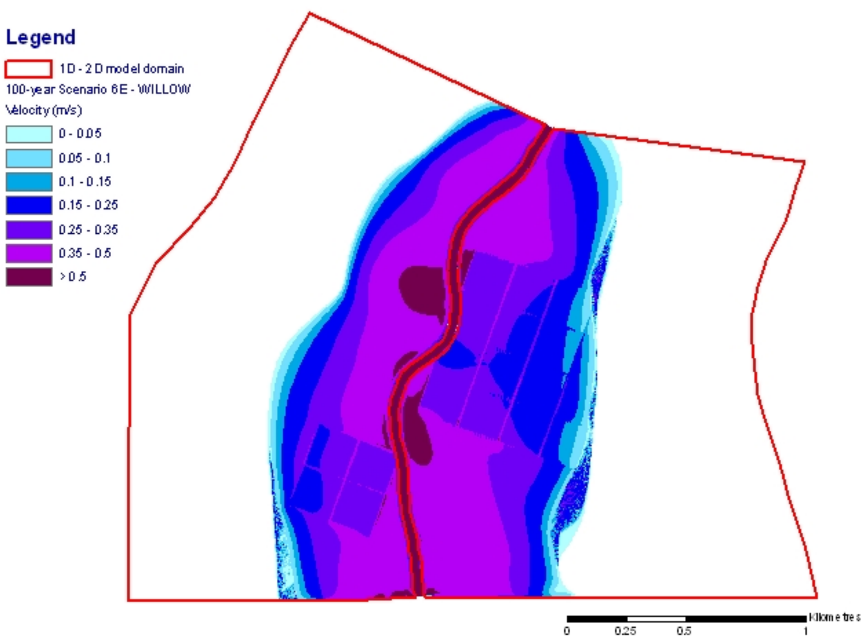
Model results – Velocities

- Flood Velocity (m/s) – Scenario 6 - WILLOW series (SRC Willow, 5m rides)

Baseline



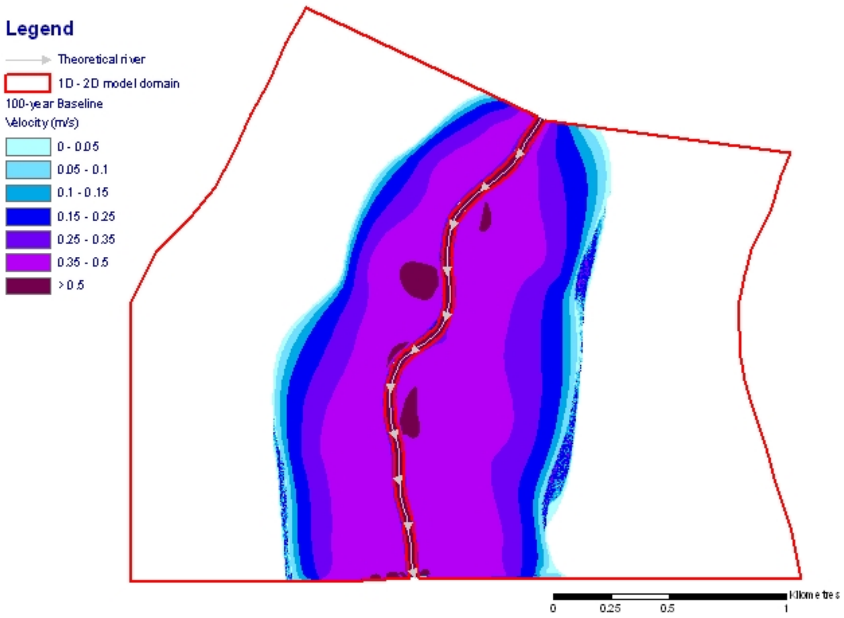
Scenario 6E - WILLOW



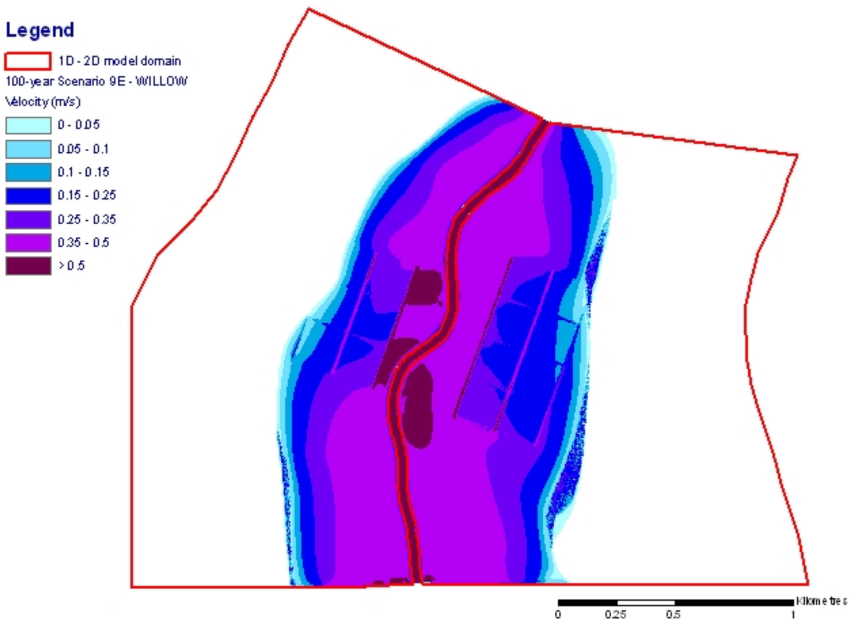
Model results – Velocities

- Flood Velocity (m/s) – Scenario 9 - WILLOW series (SRC Willow, 10m rides)

Baseline

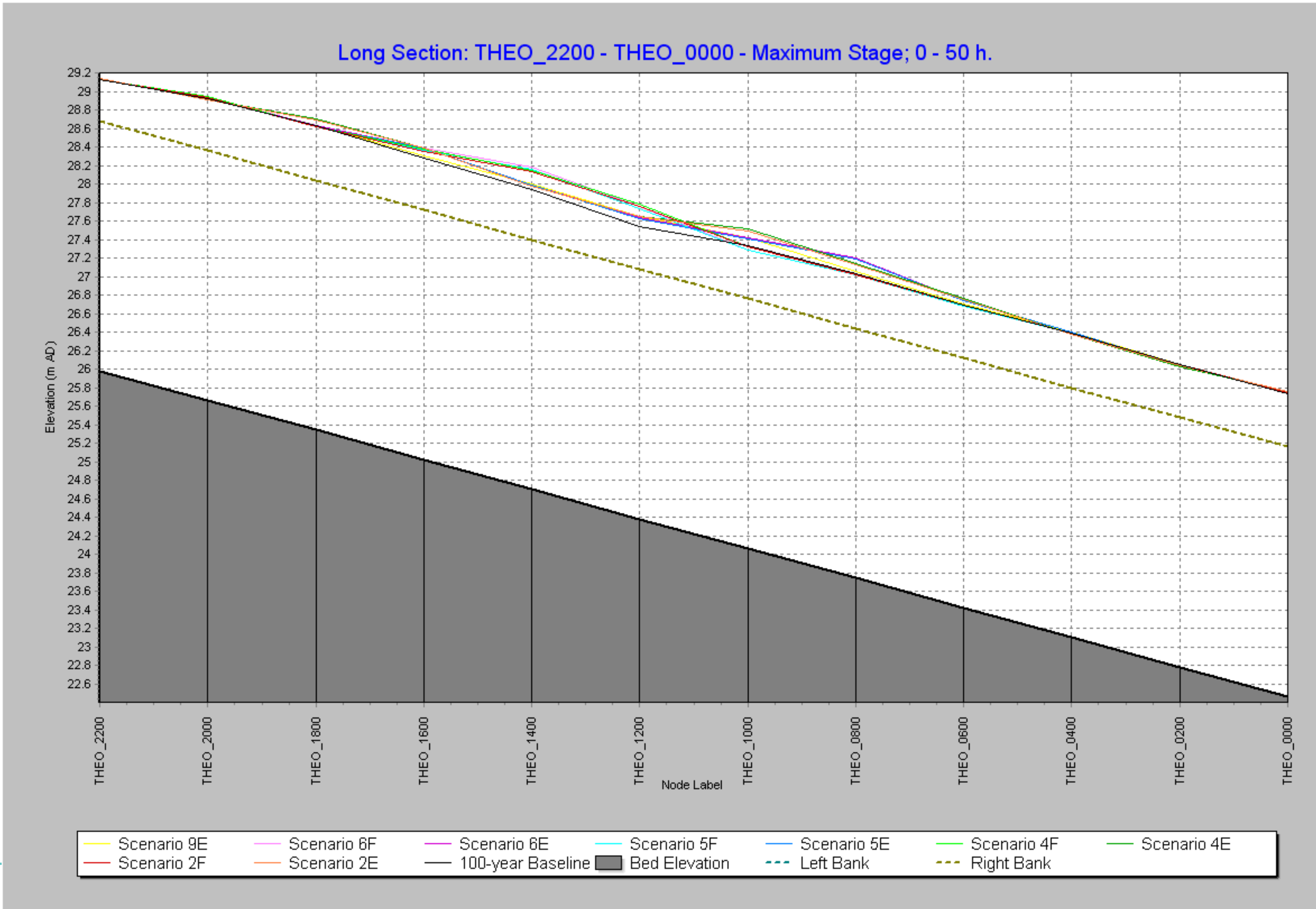


Scenario 9E - WILLOW



Model results – River Flow Hydrographs for Scenario 2, 4, 5, 6 and 9 series (Miscanthus)

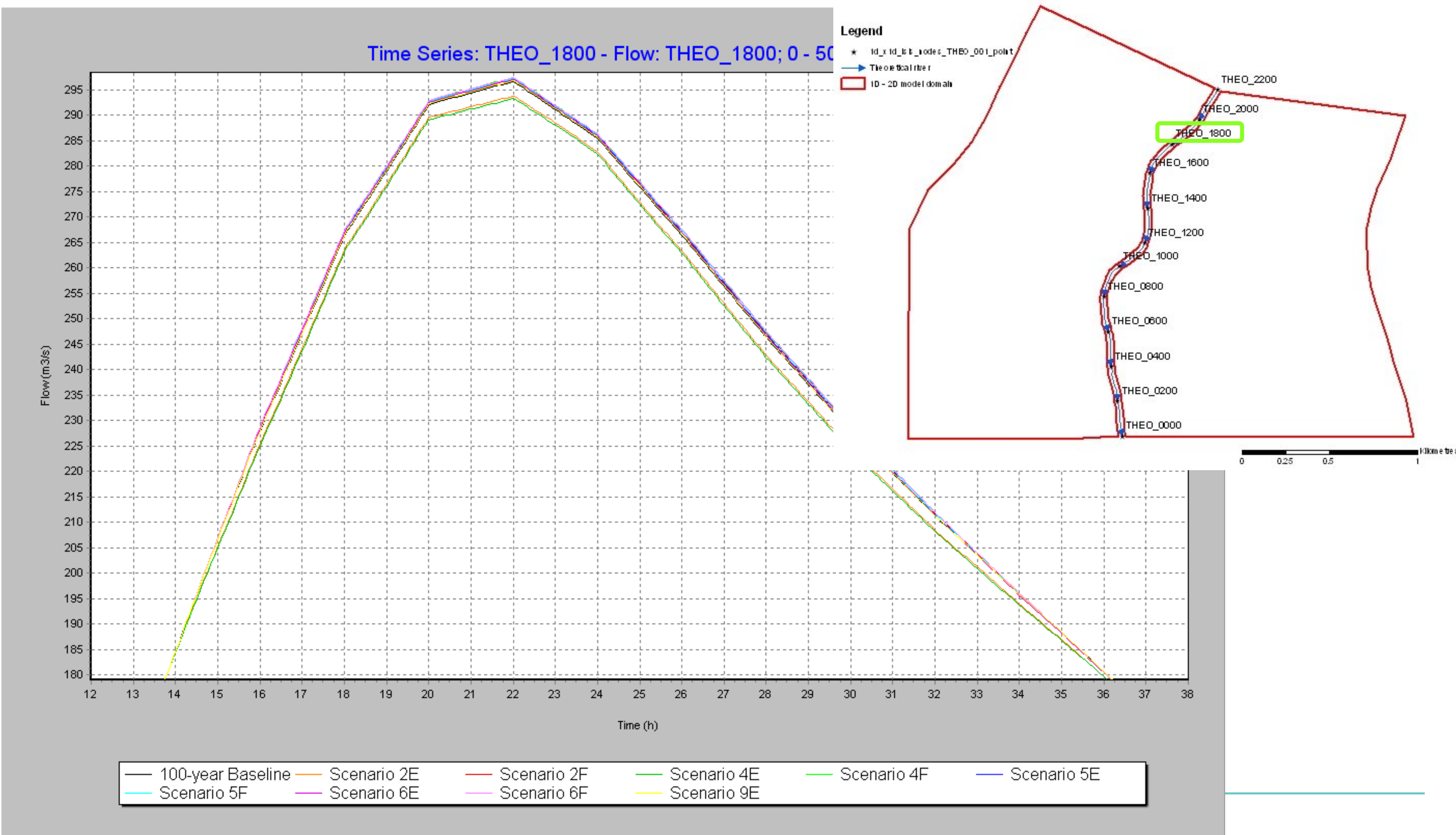
- Longitudinal profile – Modelled Maximum Stage



Model results – River Flow Hydrographs for Scenario 2, 4, 5, 6 and 9 series (Miscanthus)

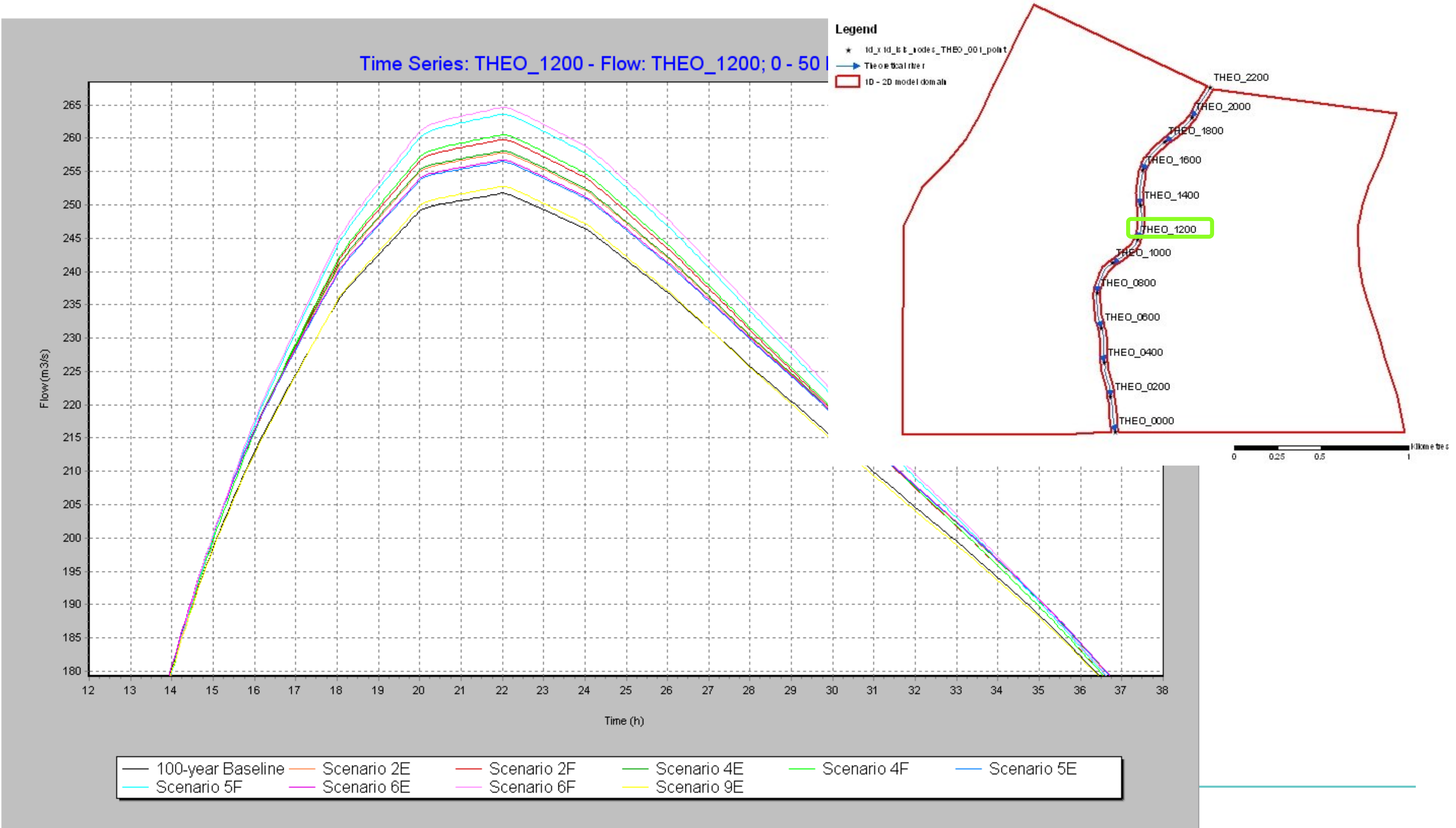
JBA consulting

- Flood hydrographs in the upstream area (e.g. upstream of plantation)



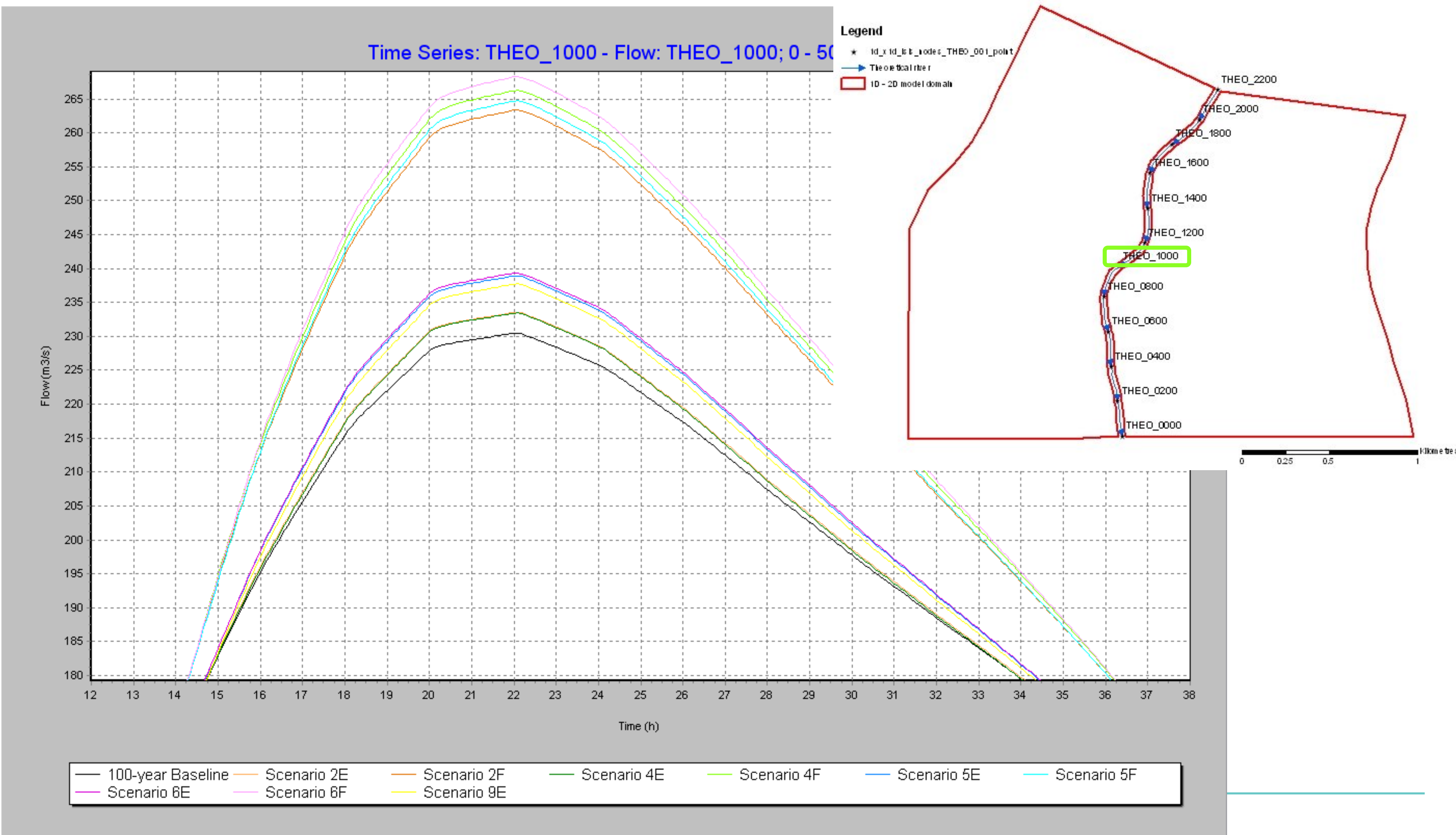
Model results – River Flow Hydrographs for Scenario 2, 4, 5, 6 and 9 series (Miscanthus)

- Flood hydrographs along the plantation



Model results – River Flow Hydrographs for Scenario 2, 4, 5, 6 and 9 series (Miscanthus)

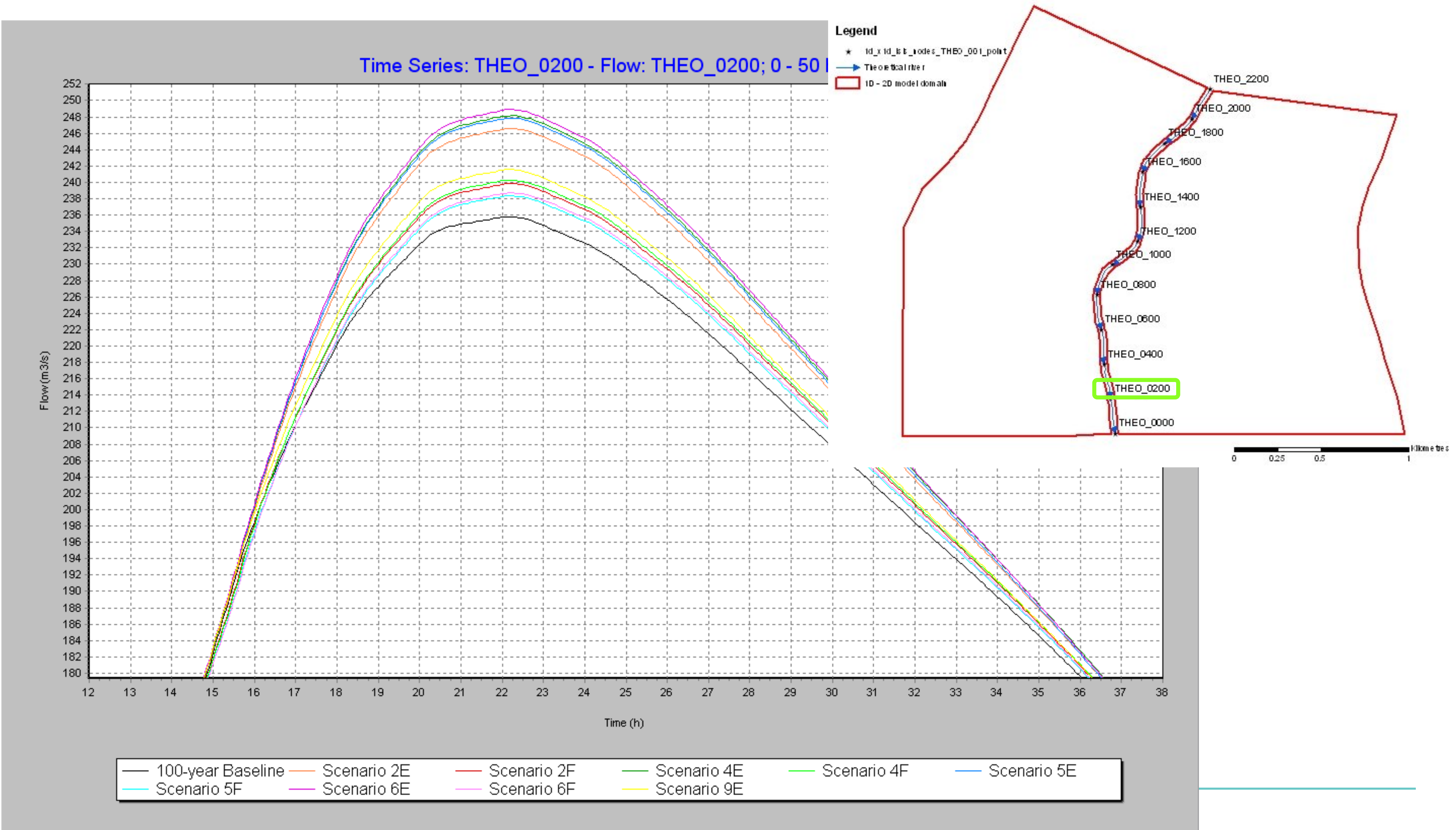
- Flood hydrographs along the plantation



Model results – River Flow Hydrographs for Scenario 2, 4, 5, 6 and 9 series (Miscanthus)

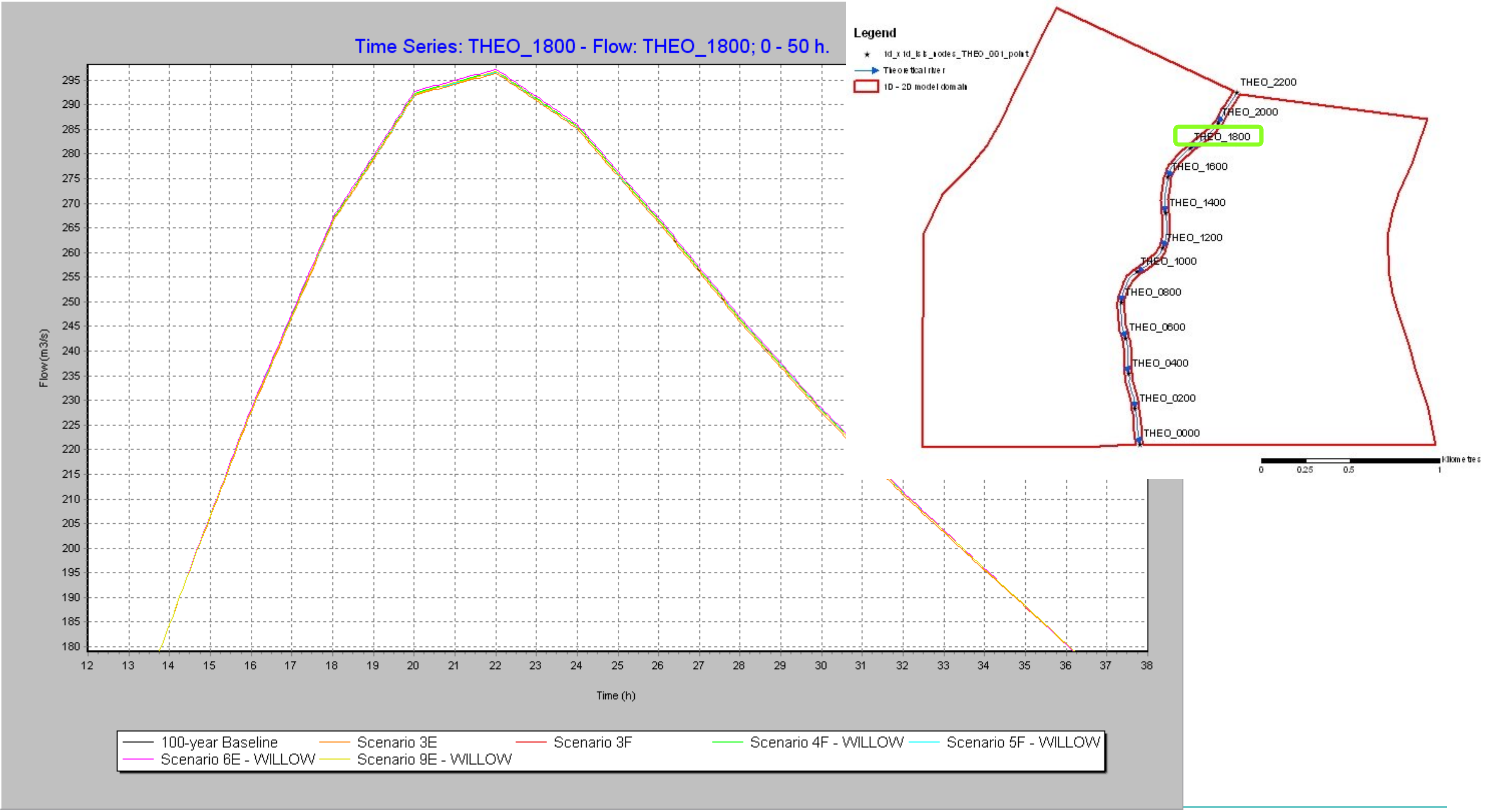
JBA consulting

- Flood hydrographs downstream of plantation



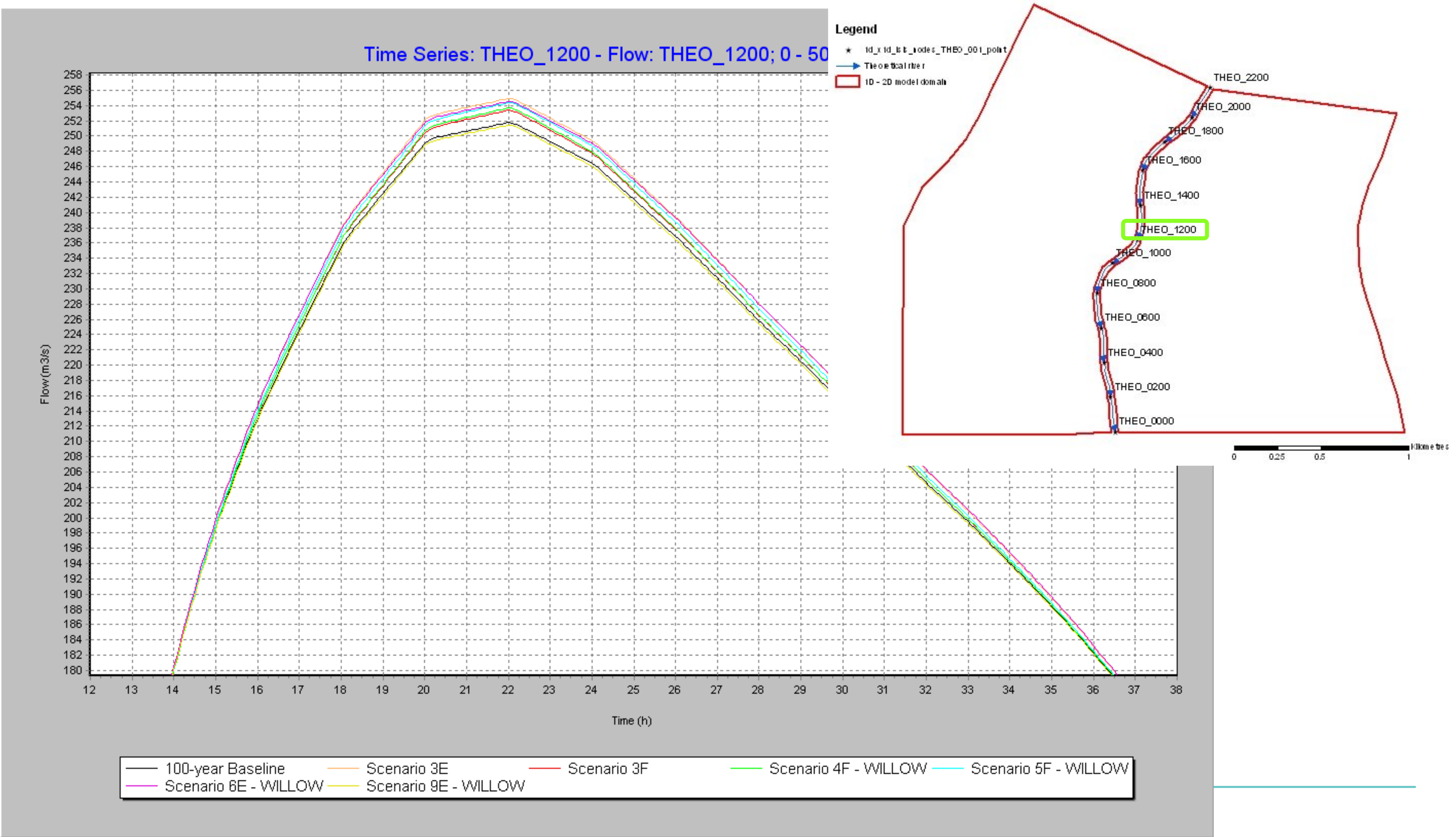
Model results – River Flow Hydrographs for Scenario 3, 4 - Willow, 5 - Willow, 6 - Willow and 9 - Willow series (SRC Willow)

- Flood hydrographs in the upstream area (e.g. upstream of plantation)



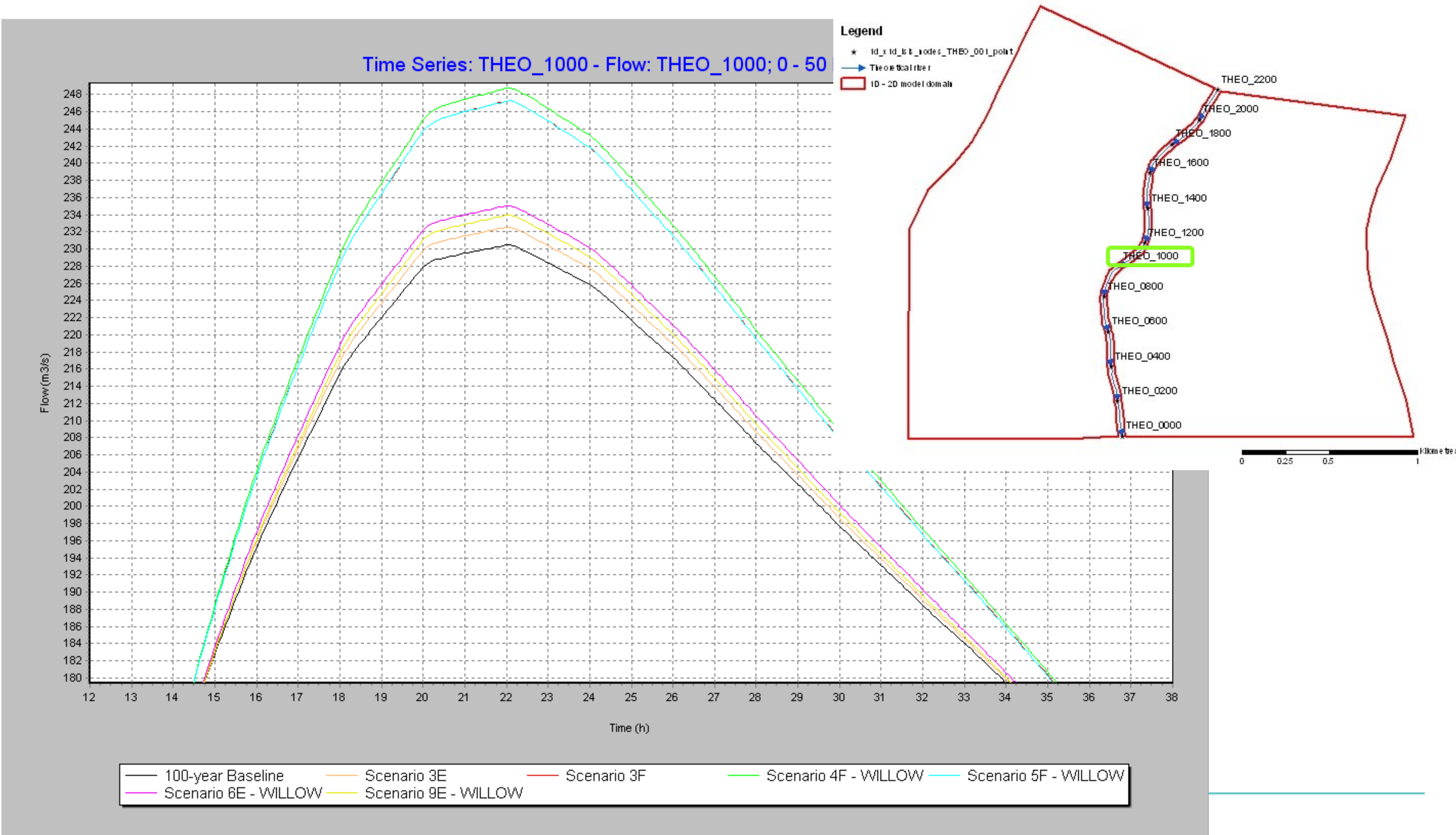
Model results – River Flow Hydrographs for Scenario 3, 4 - Willow, 5 - Willow, 6 - Willow and 9 - Willow series (SRC Willow)

- Flood hydrographs along the plantation



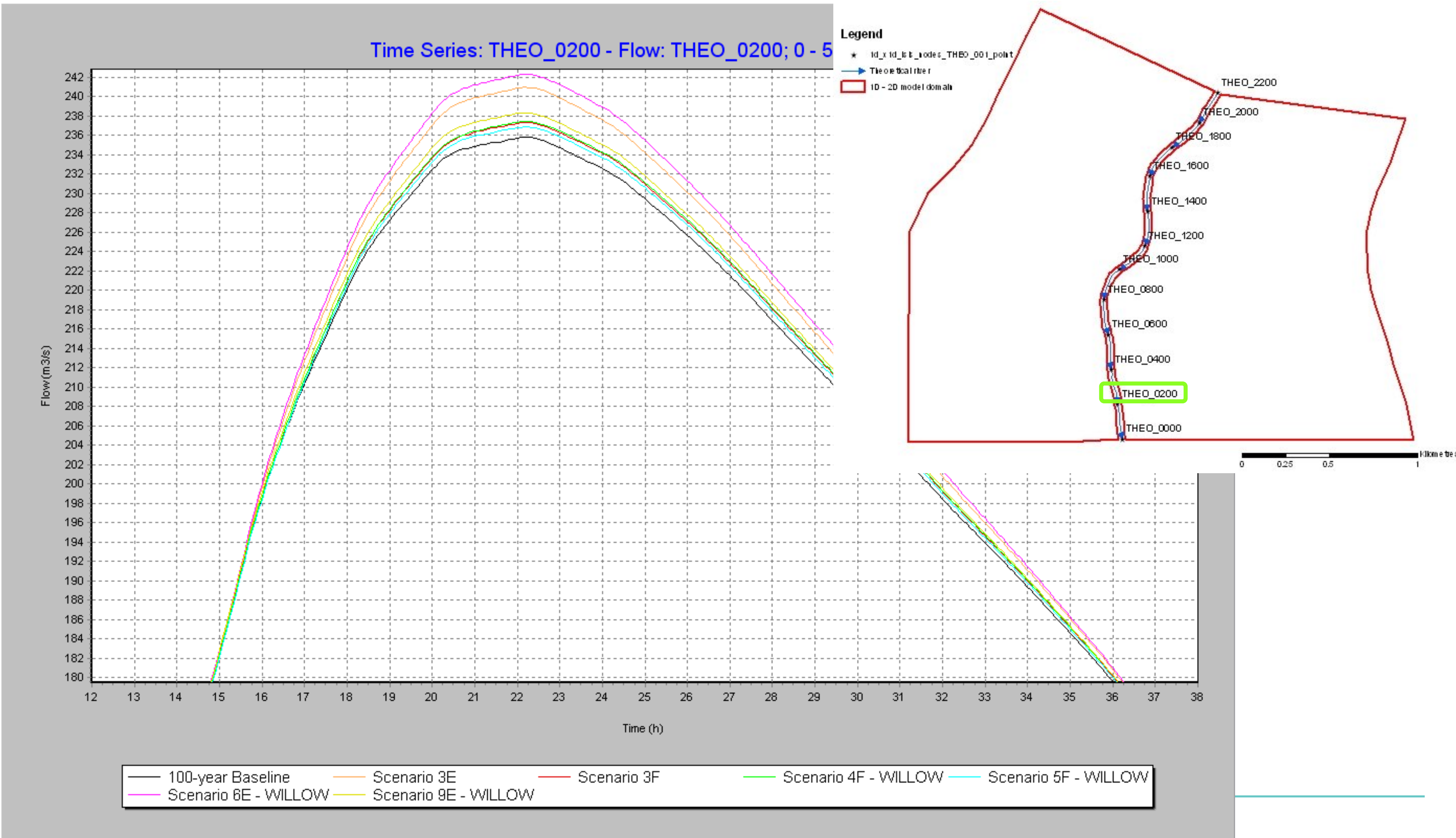
Model results – River Flow Hydrographs for Scenario 3, 4 - Willow, 5 - Willow, 6 - Willow and 9 - Willow series (SRC Willow)

- Flood hydrographs along the plantation



Model results – River Flow Hydrographs for Scenario 3, 4 - Willow, 5 - Willow, 6 - Willow and 9 - Willow series (SRC Willow)

- Flood hydrographs downstream of plantation



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