Castor fiber as a Natural Flood Management tool in a Sussex catchment

by Gareth Williams

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Queen Mary
University of London

Supervisor: Dr Gemma Harvey

Executive summary

Rationale

Natural Flood Management (NFM) is increasingly being looked at as an alternative to traditional methods of flood risk management. An approach which aims to protect, restore and emulate the natural function of catchments. One avenue of research highlighted by this work is understanding how beavers can be used to mitigate flood risk. Beavers have a positive influence on biodiversity, habitat heterogeneity and water quality, (Law *et al*, 2017), less is known about the benefits that can be realised in terms of mitigating flood risk, their dam structures specifically.

Aim

This research will identify the potential for reintroduced beaver to contribute to natural flood management in the headwaters of the Adur catchment in Sussex.

Objectives

1. Characterise the physical structure of *C. fiber* dams constructed by reintroduced beaver in catchments in southern England

2. Identify locations within the catchment where dam building may be most likely, using known beaver dam building requirements

3. Predict changes in stage and inundation extent arising from beaver dam

construction in different scenarios using a coupled 1D-2D hydraulic model

model

Method

Field work in Devon was carried out to validate known *C. fiber* dam building requirements from the literature. Data representing foraging resource, hydrology, topography and geomorphology parameters were mapped and modelled in GIS. Dam building locations were identified by combining modelled data and scoring stretches of watercourse on their suitability. Dams were built into a 1D/2D flood model to simulate the dams effect on stage and inundation in the Adur study area. Several flood event scenarios and dam configurations were run.

Conclusions

84% of the watercourses in the study area provided suitable habitat for dam building. Twelve dam locations were identified in areas most likely to attract *C. fiber.* Three of those were found in areas of optimal suitability. Simulations with dams in situ increased stage in the upper reaches of the study area, reducing the area of inundation downstream compared to simulations with no dams. These results were seen with both dam configurations but to a lesser extent with fewer dams in place.

Recommendations

Existing *C. fiber* dams can be mapped and modelled using the method described above and used to predict the likely impacts on stage and inundation in different flood events. The process could also be used to investigate potential impacts, positive and negative of proposed *C. fiber* reintroductions, helping to support feasibility and licence applications.

Acknowledgements

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1. Introduction

River catchments have a long history of modification. To the extent where small, straightened and uniform streams are ubiquitous in anthropogenically altered landscapes, (Law *et al* 2016). This has caused widespread physical and ecological degradation with the lack of depth variation, substrate diversity, velocity and poor lateral connectivity contributing to reductions in biodiversity and poor water quality. This degradation has led many government organisations to accept river restoration as an essential complement to conservation and natural resource management, (Wohl *et al* 2005). The increasing recognition of the limits of “hard engineering” approaches to river and flood risk management have highlighted the value river restoration can provide.

Despite considerable investment and legal mandates, river ecosystems around the world continue to deteriorate as a consequence of human interference, (Wohl *et al* 2005). Concepts of river ecology and morphology are often based on the assumption that rivers are stable, single-thread channels isolated from their floodplain, but this isn’t their natural condition, (Ward *et al* 2001). This misapprehension renders river restoration and management initiatives less effective. Most contemporary river restorations aim for a fixed point or benchmark but are hampered by poor knowledge of historical reference conditions and unrealistic objective setting. In answer to this, restoration practitioners are increasingly looking to the re-establishment of natural process as an alternative strategy. One way of harnessing natural processes is the introduction of ecosystem engineering species. Re-establishing species known for their ecosystem engineering can complement, if not, replace human efforts at restoring ecologically degraded systems. Byers *et al* (2006) argues that identifying and managing potential engineering species and responsive ecosystems should be a key priority for conservation, having the potential to necessitate a shift to a process-based understanding of the functioning of entire systems. In some cases, now absent engineering species would have been complicit in sustaining sought after undisturbed conditions that restorations aspire to reference, (Law *et al* 2017). To date, only a handful of species have been well documented as tools for restoration, with beaver, willow and macrophytes among the most popular, (Polvi and Sarneel 2017). Their potential for habitat restoration, and creation is well understood and used as an argument for reintroducing ecosystem engineers into a landscape, (Law *et al* 2017). The benefits that the Eurasian Beaver, (*C. fiber)* in particular can provide is becoming better evidenced. The discontinuity caused by their dams for example and the lateral heterogeneity they provide, is more commonly being used to restore habitats and natural process in the UK.

Reintroductions in the UK and Europe, motivated by the benefits their engineering can provide, particularly their influence on ecosystem structure and function, (Jakes *et al* 2007), are increasing. Wohl *et al* (2005), argue that river restoration should assist the establishment of improved hydrologic, geomorphic, and ecological processes within degraded river systems and look to replace lost, damaged or compromised elements of a natural system. Beavers have been a key component of that system in the past, through reintroductions their multiple benefits are starting to be realised. Their potential contributions to Natural Flood Management on the other hand are less understood. Natural Flood Management seeks to restore and enhance natural processes. Reducing flood hazard, whilst sustaining ecosystem services including enhanced biodiversity, improved soil and water quality, carbon sequestration, reduced soil erosion and public amenity, (Dadson *et al* 2017). The engineering abilities of beaver, in the form of dam building could offer a natural, cost effective mechanism for restoring degraded streams whilst providing flood relief, (Law *et al* 2017). An alternative solution to contemporary river restoration and flood management. Further research is required to predict and quantify these benefits. This study will examine the potential for reintroduced beaver (*C. fiber)* to contribute to natural flood management in the headwaters of the Adur catchment in Sussex.

2. Literature review

2.1 The rewilding concept

Rewilding is promoted as an alternative to traditional and contemporary approaches to nature conservation. It aims to restore locally extinct species and ecological process by maintaining and increasing biodiversity and reducing past and present human intervention, (Lorimer *et al* 2015). The reintroduction of extirpated species is encouraged by European Legislation (Article 22, EC Habitats and Species Directive, EC 92/43), this legislation has provided a platform for the movement, (Gaywood, 2017). The organisation rewilding Europe defines rewilding as a "progressive approach to conservation…letting nature take care of itself, enabling natural processes to …repair damaged ecosystems and restore degraded landscapes.". The concept has emerged as a promising strategy to enhance and restore biodiversity, increasing ecological resilience whilst offering essential ecosystem service provisioning, (Pettorelli *et al* 2017). It focuses on process-led conservation compared to the goal-orientated conservation of particular species and habitats that has dominated the past decades (Meech and Green 2017). As evidence mounts around the altering of key processes driven by species extinctions and the effect this is having on the productivity and sustainability of earths ecosystems, scientists and governments are increasingly referring to rewilding as a potentially cost-effective solution to the restoration of ecosystem function, (Pettorelli *et al* 2017).

The term rewilding was instigated through a collaboration between biologist Michael Soule and environmental activist David Foreman in the late 1980's, (Lorimer *et al* 2015). Their concept focused on the release of keystone species into large, well-connected landscapes and became known as the 3Cs approach; core area, corridors and carnivores (Lorimer *et al* 2015). It sought to combine the creation and protection of wilderness and biodiversity conservation into a single interlinked and complementary agenda. An alternative version is the rewilding of areas with proxy species for long extinct Pleistocene megafauna, (Lorimer *et al* 2015, Donlan 2005). Donlan (2005), argues the ecological structure of Pleistocene ecosystems should be the appropriate baseline for ecosystem restoration, achieved via the restoration of surrogate species (Exmoor ponies and Longhorn cattle) for megafauna (Tarpan and Aurochs) present over 13,000 years ago. In recent times the emphasis has taken a more novel approach, one that embraces historic baselines and the introduction of keystone species and focuses on the development of self-sustaining ecosystems via the restoration of natural ecological processes, (Navarro and Pereira 2012). Rewilding sets itself apart from traditional approaches to restoration, i.e. those that typically set benchmarks, often from relatively recent memory, to aspire to and or reference sites to mimic, (Lorimer *et al* 2017; Pettorelli *et al* 2017). It offers the opportunity for a rethink. Helping environmental managers struggling with the challenge of protecting and preserving biodiversity and landscapes and restoring them to previously observed levels in the face of economic, political and societal change, (Pettorelli *et al* 2017). Global environmental change is driving ecosystems beyond their limits, so much so that modern approximations of historical benchmarks may no longer be viable in any case, (Pettorelli *et al* 2017). Rewilding takes a different approach, focusing on the restoration of ecosystem function and process, (Sandom *et al* 2013). For example, Brown *et al* (2018) argue that the often idealised unembanked, sinuous, barrier-free form to which many rivers across Europe are restored to, chooses form over function, focusing on the structure of the river and not the processes which might sustain it long term. Studies of alluvial floodplains suggest that benchmarks should be more akin to the anabranching or anastomosing channel forms associated with vegetated floodplains present during the Carboniferous period, (Brown *et al* 2018). Pushing back the historical horizon through rewilding could allow conservationists to better comprehend the ecological dynamics of a pre-human planet, (Lorimer *et al* 2015). The notion that wild areas must be free of human influence however, is unnecessarily restrictive, (Pettorelli et al 2017). If rewilding is to be successful, then human intervention is essential, (Jorgenson, 2015). Natural processes will, in many situations, need a kick-start. Where seed sources no longer exist, trees may need planting and if ecosystem engineers are needed to restore natural process then these will need to be reintroduced. People have a role to play, particularly regarding ongoing management. Despite the term being coined in the 1980's the movement is still a relatively new concept. References to it in scientific literature have risen exponentially other the last 15 years, but there is little empirical evidence of the benefits. Despite the growing interest, it is still seen as a marginal conservation activity compared to more traditional approaches, (Lorimer *et al* 2015).

2.2 The rewilding movement in the UK and Europe

Despite the benefits of a rewilded landscape, as a management option, it has often been disregarded in favour of more traditional approaches to conservation. This is starting to change. Initiatives such as Rewilding Europe are bringing the agenda into focus, to the forefront of European conservation policy, (Navarro and Pereira 2012). Established in 2011 as an independent foundation operating on a European scale, Rewilding Europe works across 17 European countries, promoting policies for rewilding and developing tools to help advocate benefits. They encourage nature-based tourism and have set up a European Wildlife Bank loaning keystone species to projects across Europe. Their success is inspiring action in the UK, most notably Rewilding Britain. Launched as a charity in 2015, rewilding Britain, inspired by George Monbiot's book Feral, aspires to reverse the loss of biodiversity by restoring ecosystem function, securing a resilient environment that reignites passion for nature and revitalises local economies. The rewilding movement in the UK is stimulated by the lack of wild areas and the realisation that the UK is one of the most ecologically depleted nations in the world (Meech and Green 2017). Major changes to the landscape have taken place since the medieval times, with habitats lost during the Inclosure Acts of the 17th and 19th century and more recently World War II Agricultural Committees, (Colebourn and Kite 2017). Present day landscapes in the UK are fragmented and disconnected, often as a result of agricultural clearance and intensification. In total approximately 70% of land in the UK is in agricultural production (GOV.UK, 2011). It is hoped that rewilding may help to offset or reduce the impact of intensive agricultural practices, particularly soil degradation, greenhouse gas emissions and declines in pollinating insects, (POST note 537, 2016).

Rewilding compliments the "bigger, better, more joined up" approach exulted by Sir John Lawton in his review of England's Wildlife Sites "making space for nature", (Making space for nature, 2010). There still remains a lack of government policy and strategy to encompass it. In fact, many current policy frameworks in the UK and Europe work against it. Farm subsidies through the Common Agricultural Policy (CAP) incentivise landowners to keep their land in agricultural condition, preventing ecological restoration by disqualifying payments when land ceases to be farmed (Meech and Green 2017). CAP payments raise the market value of land, making its acquisition for rewilding prohibitively expensive, (POST note 537). A post Brexit Britain could allow the development of an alternative land management strategy. One that rewards farmers and land managers for the delivery of ecosystem services, (POST note 537). As yet there is no UK strategy for the agricultural industry following Brexit, but it is possible that successive UK governments will seek to reduce the levels of subsidies and ensure those that remain deliver public goods and environmental protection, (Miller 2016). Figure 1 summarises the value natural capital currently provides the UK. The decrease in value between 2007 and 2014 is largely attributable to the falling value of oil and gas, and diminishing recreational value, (ONS 2016). The list of natural capital assets is certainly not exhaustive and could certainly be expanded as ecosystem values are better understood. Rewilding Europe suggests that rewilding can provide these natural assets (Jepson and Schepers 2016). This will depend on the trade-off with benefits from other land-uses however, (POST note 537). As projects develop and the public become more engaged the recreational value could increase. DEFRA’s 25-year plan highlights the way land is

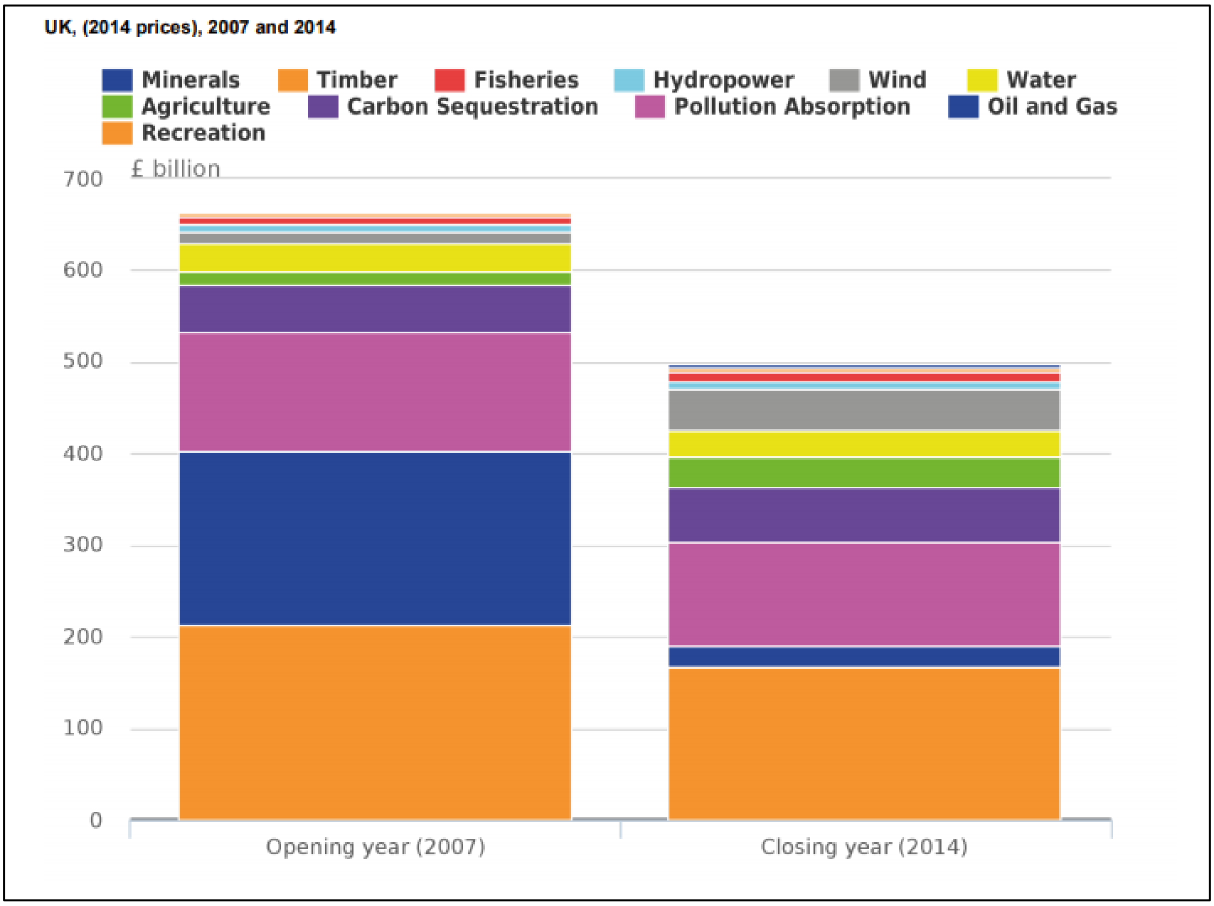

Figure 1: Partial estimation of the value of UK natural capital. £664.48 billion in 2007 and £497.0 billion in 2014. Source: Office for National Statistics.

currently managed in England, it recommends a Nature Recovery Network be developed to bring a wide range of benefits from: public enjoyment, pollination, carbon capture, water quality and flood management, (A Green Future 2018). It is not known how this will look, but the provision of up to 500,000 hectares of additional wildlife habitat could include the reintroduction of key species. Until tax incentives and innovative funding streams are common place however, it is likely that rewilding in the UK will remain a piecemeal exercise with only local benefits.

2.3 Ecosystem engineers as a component of rewilding projects

Ecosystem engineers create, modify and maintain habitats, directly or indirectly modulating the availability of resources to other species (Jones *et al* 1994). Keystone species are defined as having a disproportionately large impact on their environment, relative to their size and abundance, (Paine, 1995). Ecosystem services, biotic resources and processes which benefit humans, can be enhanced by both. Provision of clean air, pollination of crops, nutrient cycling and flood water storage are among the services they provide, (Brown *et al* 2011). The UK has lost all its large carnivores and many large herbivores, which, if still present could help create and maintain habitats, manipulate ecosystem function and contribute provisioning services. Reintroductions can provide a solution to this.

The first and most famous example of the reintroduction of a keystone species and the first flagship example of the 3Cs approach is the rewilding of Yellowstone National Park, (Lorimer *et al* 2015). Wolves (*Canis lupas*) were reintroduced after being eradicated in the early 20th Century, in part to combat the impact unchecked elk numbers were having on flora and fauna within the park, (Smith *et al* 2003). Following the Wolves reintroduction to Yellowstone in 1996, elk populations decreased, with both beaver (*Caster Canadensis*) and bison (*Bison Bison*) populations increasing due to the rise in woody species of willow, aspen, and cottonwood recovered from excessive grazing pressure, (Brown *et al* 2011; Lorimer *et al* 2015; Ripple and Beschta 2012). Yellowstone was the first of its kind to evidence ecosystem restructuring species can affect if reintroduced. It has provided the blueprint for many reintroductions since. Research has indicated substantial effects on both plants and animals, with unexpected benefits. Wolves in the park led to a decrease in riverbank erosion by Elk with recovering vegetation stabilising banks. Rivers are now meandering less, channels are deepening, and small pools are forming benefiting aquatic biodiversity. Yet Northern Yellowstone still appears to be in the early stages of ecosystem recovery, suggesting the effects have yet to be fully realised (Ripple and Beschta 2012).

Ecosystem engineers are being used to good effect in continental Europe, enhancing the diversity of freshwater environments with the reintroduction of large herbivores, (Brown *et al* 2018). The introduction of Konik horses (*Equus ferus caballus*) and Heck cattle (*Bos Taurus*) is increasing the heterogeneity of floodplain landscapes. The disturbance they cause having a positive ecological effect on habitat diversity, (Klink *et a*l 2016). The restoration of lost species comes with its own dangers. Thorough investigation is needed to assess population viability and capacity for growth. Sufficient resources, which may have been available in the past, are needed if long-term survival is to be achieved, (Macdonald *et al* 2000). In the absence of predators, herbivore numbers increase beyond the capacity of the environment to sustain them. A high-profile rewilding reserve in the Netherlands had to cull more than half of the 5,230-red deer (*Cervus elaphus*), Konik horses and Heck cattle at the 5,000 ha Oostvaardersplassen's reserve due to starvation. A special committee has called for a cap of 1,500 to prevent winter fatalities, (Guardian 2018). A key aim of rewilding is to maintain and increase biodiversity while reducing the impact of past and present human intervention. Rewilding needs to be mindful of how the public respond to situations like the Oostvaardersplassen. Despite the increasing reintroduction of ecosystem engineers globally, the concept has rarely been applied to the restoration of ecosystem function, particularly within degraded freshwater systems, (Law *et al* 2017). Recently, however studies are investigating the hydromorphological changes caused by beavers (*Castor fiber*), and how it can apply to the restoration of degraded river systems. A number of studies are taking place in the UK.

2.4 Beaver re-introductions in the UK – understanding the benefits

Beaver introductions initially focused on species conservation, but recent efforts and research are focusing on the multiple benefits they provide. Several ecosystem services are associated with beaver reintroductions. Sediment and carbon storage, water quality improvement, habitat heterogeneity, species diversity and the restoration of degraded river systems (Brown *et al* 2018; Law *et al* 2017; Gurnell 1998; Puttock *et al* 2017; Pollock *et al* 2014). Following widespread persecution, it was estimated that less than 1500 Eurasian beavers (*Castor fiber*) remained in the wild at the beginning of the 20th century. Reintroductions motivated by fur-harvesting and later by conservation began in 1922 when beavers were reintroduced to Sweden from Norway, (Halley and Rosell 2002). Existing populations were given legal protection and numbers across Europe increased. Over 150 reintroductions of beaver across 24 European countries have now taken place according to the Beaver Advisory Committee for England, (BACE 2017). The first formally approved non-enclosed reintroduction of beaver in the UK was announced in Scotland in November 2016, (Gaywood 2017). Individuals and organisations championing the benefits referenced the environmental advantages, amongst public appetite, socio-economic benefits and legal grounds for reintroducing them to the Scottish landscape, (Gaywood 2017). Following thorough investigation and public debate over several years, the Scottish government was minded to allow two trial populations to remain in Scotland, expand naturally, receiving legal protection.

This marked the first official return of the beaver in the UK for 400 years. Figure 2 illustrates the various reintroductions, enclosed and free roaming, authorised and unauthorised across the UK since early 2000.

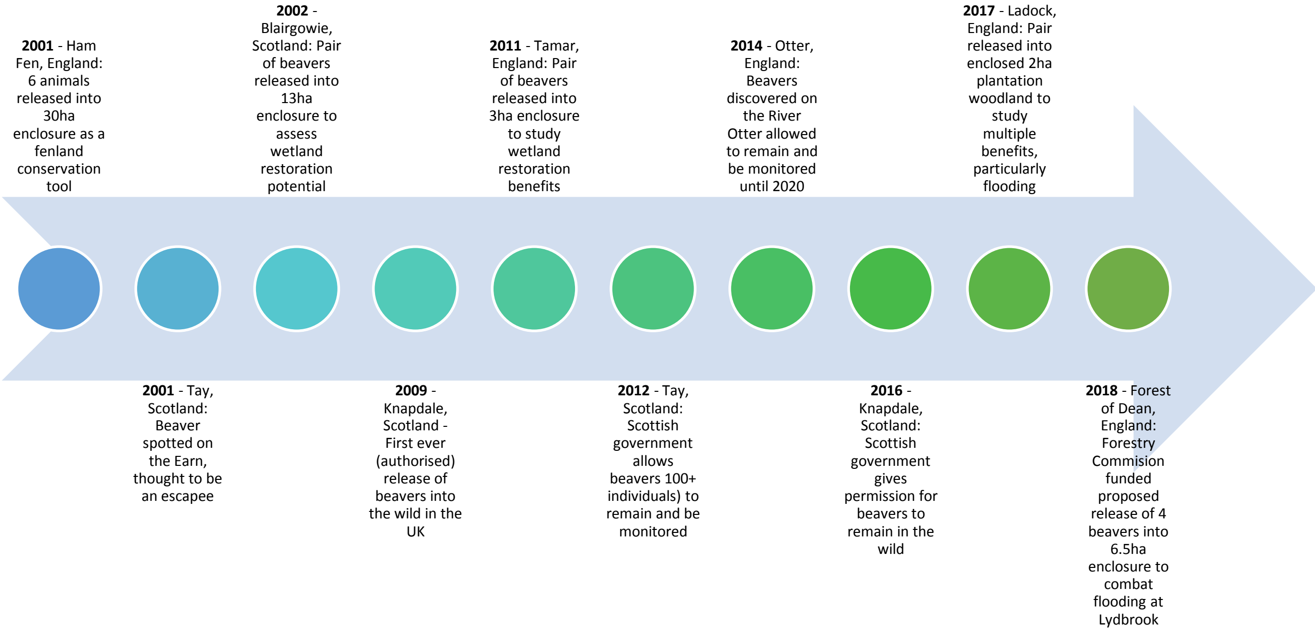

Figure 2: Timeline indicating beaver reintroductions in the UK over the last 18 years. Source: Personal collection

There are a growing number of drivers for the reintroduction of beaver into freshwater environments. Most early examples focused on the attributes beavers have for restoring habitat, advocated as a viable option for restoring ecologically degraded freshwaters, (Pollock *et al* 2014, Law *et al* 2016). The introduction of logjams and large woody obstructions for example has been commonplace in contemporary river restoration. Small-scale discontinuities formed by the accumulation of wood, have long been recognised as a key feature of functionality in streams promoting organic matter retention, increased habitat complexity and flow refugia, (Law *et a*l 2016). This offers a rather limited rewilding approach. A substitute for natural fluvial processes and a forested floodplain, (Brown *et al* 2018). Beaver on the other hand provide this function in the form of dam building, a natural mechanism for restoring degraded streams and wetlands (Law *et a*l 2016). Understanding these benefits triggered the first reintroduction in the UK at Ham Fen in Kent in 2001. Faced with the logistical and economic difficulties of restoring fen habitat with machinery, the Kent Wildlife Trust applied for a permit to release two families into the overgrown and inaccessible fen (Wildlife Trust, 2018). Since their introduction, the now 10 beavers, have created a self-maintaining landscape. The requirement for intervention and management are now almost non-existent, (Wildlife Trust, 2018). This experimental approach was repeated on the Blairgowrie estate in Scotland the following year. A pair of Beavers were introduced into an enclosed 13ha site, their behaviour and impacts monitored over a 12-year period. The study concluded that the hydromorphological changes occurring from their activity translated into beneficial biological response, see figure 3, in a landscape with a long history of degradation and contraction due to agricultural land use, (Law *et a*l 2016). The beavers at Blairgowrie created in-stream habitats which transformed sections of channel from erosional to depositional environments, acting as sinks for plant propagules, nutrient-rich sediment and organic matter, (Anderson *et al* 2014).

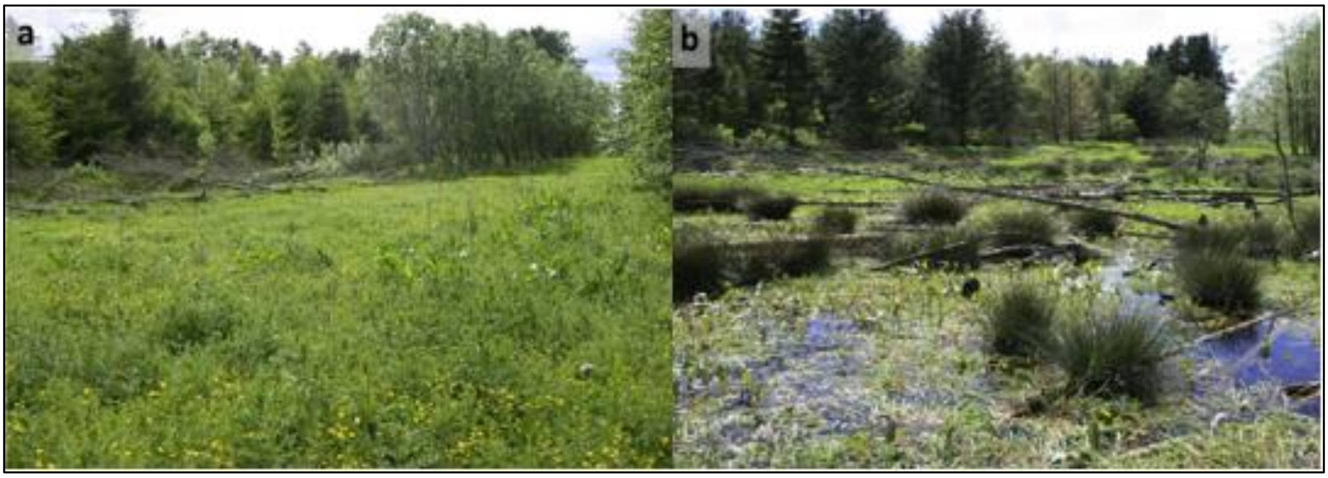

Figure 3: a) Blairgowrie study area year 1, b) study area after 12 years. Source: Adapted from Law *et al* 2017.

Concentrations of Phosphate and Nitrate were on average 49% and 43% lower respectively in front of beaver dams, (Law *et a*l 2016) with organic matter increasing 7-fold and aquatic plant biomass increasing 20-fold compared to unmodified channels. The Blairgowrie study was the first in the UK to demonstrate the services that *C. fiber* can promote. Many of which are difficult to replicate by conventional methods, (Law *et al* 2016). Examples of beaver presenting a cost-effective, more successful, alternative to human intervention is growing. Studies in America have demonstrated how the American beaver (*Castor canadensis*), who's behaviour and impacts are very similar to the Eurasian beaver, (Gaywood, 2017), can restore incised streams with their dam building. Channel incision is widespread around the globe, causing extensive ecosystem degradation, (Pollock *et al* 2014). Incised streams have a lower groundwater table, are disconnected from their floodplains, and have lower summer base flows and warmer temperatures which has consequences for habitat diversity, (Pollock *et al* 2014). The biological significance is a loss of riparian plant biomass and population declines in fish and other aquatic organisms, (Cluer and Thorne 2014). The study found that beaver dams increase roughness, reduce slope and increase channel width, boosting the retention of bed and suspended sediment, allowing streams to aggrade. In addition, submerged floodplains behind beaver dams encourage emergent vegetation to establish, providing additional flow resistance, increasing sediment storage, (Pollock *et al* 2014). Restoration in this manner can provide important ecosystem services such as flood control, groundwater recharge and carbon storage, (Pollock *et al* 2014). Beavers and their activities can offer a passive and innovative solution to the problem of habitat loss and degradation in freshwater environments, (Law *et al*

2017). Until now their role has largely been overlooked but now the beaver seems to be emerging as a key

component of successful restorations. A study by Exeter university at an enclosed beaver site in Devon has added to the evidence base. They examined the water quality benefits, alongside water attenuation *C. fiber* brings to freshwater environments. Monitoring has shown significantly lower concentrations of suspended sediment, phosphate and nitrogen, (Puttock *et al* 2017). Figure 4 Illustrates their findings. Excess phosphorous in freshwaters can lead to eutrophication, accelerating algal growth and causing adverse effects on water quality and ecology. 45% of river waterbodies in England are failing EU Water Framework Directive objectives due to excessive phosphorous, (POST note 477). Research is helping to develop understanding of how beavers can form a natural solution to land management and water resources in the UK.

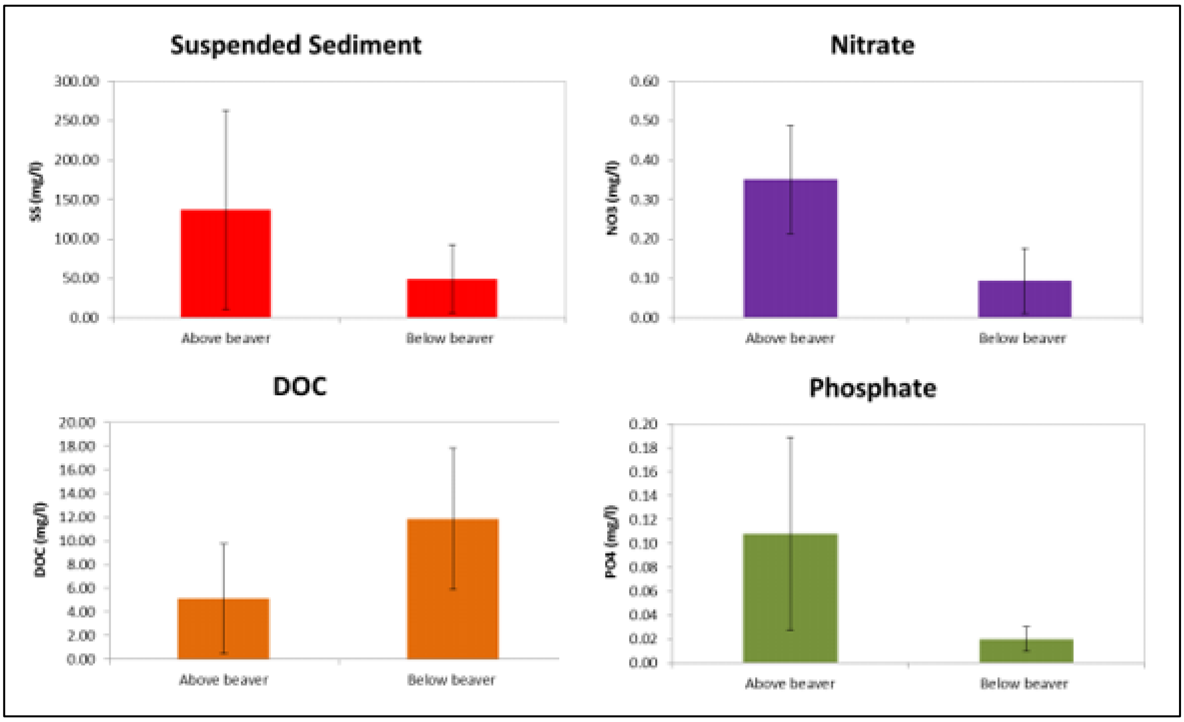

Figure 4: Suspended sediment, nitrate, phosphate and dissolved organic carbon were measured above and below beaver dam structures at the enclosed Devon beaver project. Source: Adapted from a slide in the Rivers Trust Autumn Conference 2016.

2.5 Working with natural processes – Natural Flood Management

Beavers engineer their environment to provide security from predators and access to food and building materials, (Puttock *et al* 2017). Where water levels are not sufficient they build dams, often in lower order streams. Dams dissipate stream energy and slow flow, extending hydraulic connectivity and reducing discharge, (Law *et al* 2016). NFM is advocated as a sustainable alternative to traditional flood management, (Lane 2017). Focusing on “natural” manipulation of river flow at the catchment-scale, reducing run-off and storing water during high flows. Natural infrastructure such as trees in the channel provide an alternative to hard engineered defences, increasing attenuation, (Lane 2017). Planting trees within or alongside rivers intercepts, stores and filters flood water. The issue with this strategy is the time it takes trees to establish and the effort needed to plant and or construct woody debris dams. Dixon *et al* (2016) found that riparian forest restoration at the sub-catchment scale, representing 20-40% of the total catchment area, would see reductions in peak magnitude of up to 19%. Peak reductions would not be seen until 25 years post restoration however, when trees are established enough to provide the function.

Beaver on the other hand, assuming that sufficient trees exist for dam building, could provide attenuation far quicker. Law *et al* (2017) commented on the potential for dams to contribute to natural flood management by enhancing storage and slowing the release of water but wasn’t a formal component of the Blairgowrie 12-year study. Gurnell’s (1998) review of beaver as a geomorphic agent commented on their ability to build dams which impede flow through ponding and the diversion of water. The review concluded that dams reduce the seasonal and storm event range in water levels by attenuating discharge through ponded areas, spreading flow across the dam crest which is wider than the original channel. Diffuse seepage through the floodplain part of the dam creates floodplain wetlands, where-as concentrated flow can result in the excavation of additional channels, all of which add to river corridor complexity and flood storage.

The first UK quantifiable study of beaver's ability to provide NFM was undertaken on the Tamar at the enclosed Devon beaver site. The study carried out by Exeter university investigated whether beaver constructed features significantly increased water storage and alter flow regimes resulting in attenuated storm flows, (Puttock *et al* 2017). 13 dams were constructed by *C. fiber* along 183m of a first order stream between 2011 and 2016. Figure 5 illustrates the impacts on water storage, ponded areas increasing from 90m^2 prior to release to 1800m^{2}in 2015. Approximately 1000m^3 of water is stored at any one time, with the largest pond holding 220,000 litres of water, (Puttock *et al* 2017).

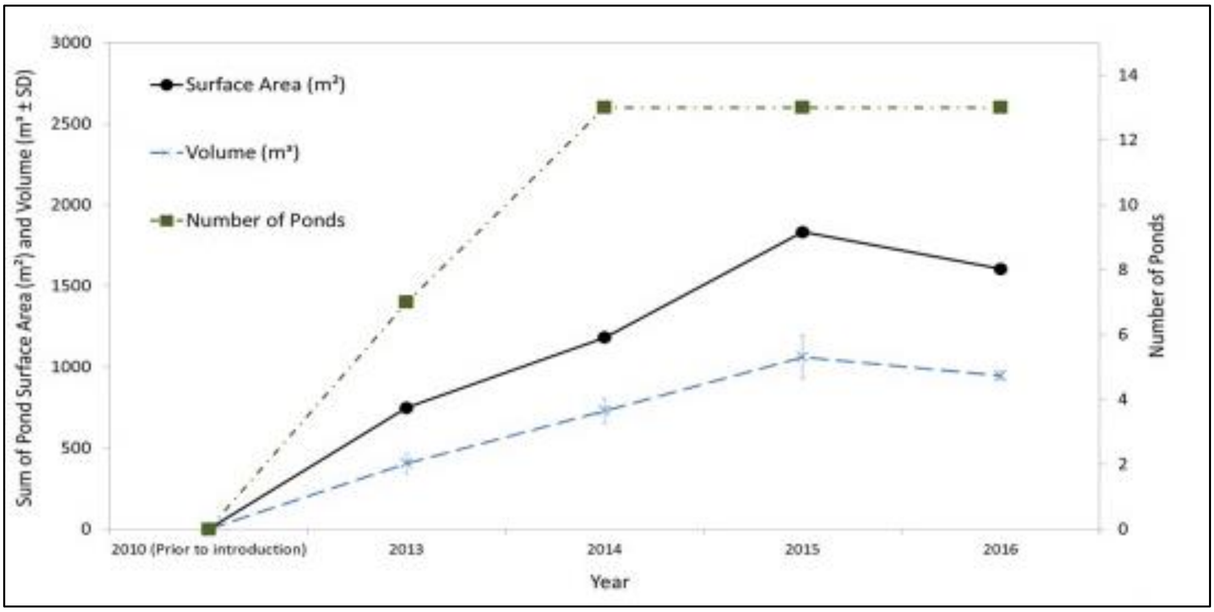

Figure 5: Graph illustrating the change in the number of ponds since beaver introduction and the corresponding increase in surface area and volume of storage. Source: Adapted from Puttock *et al* 2017.

The study concluded that beaver activity significantly increases water storage reinforcing the view that in small channels they will engineer freshwater habitat to create suitable conditions for themselves, (Gurnell, 1998, Puttock *et al* 2017). Dam complexes had an attenuating impact on flow, increasing the timing of peak rainfall to peak discharge, lowering peak discharge and total event discharge overall, (Puttock *et al* 2017). The findings align with studies carried out by Nyssen *et al* (2011) and Burns and Macdonald (1998) who observed a decrease in peak discharge at their study sites. The evidence presents a compelling argument for the role beavers could play in reducing flooding downstream. Figure 6 shows flow into the site, (blue line), increasing rapidly in response to rainfall as it travels through the farmed landscape, peaking at a higher flow rate, and falling more rapidly than flow leaving (red line).

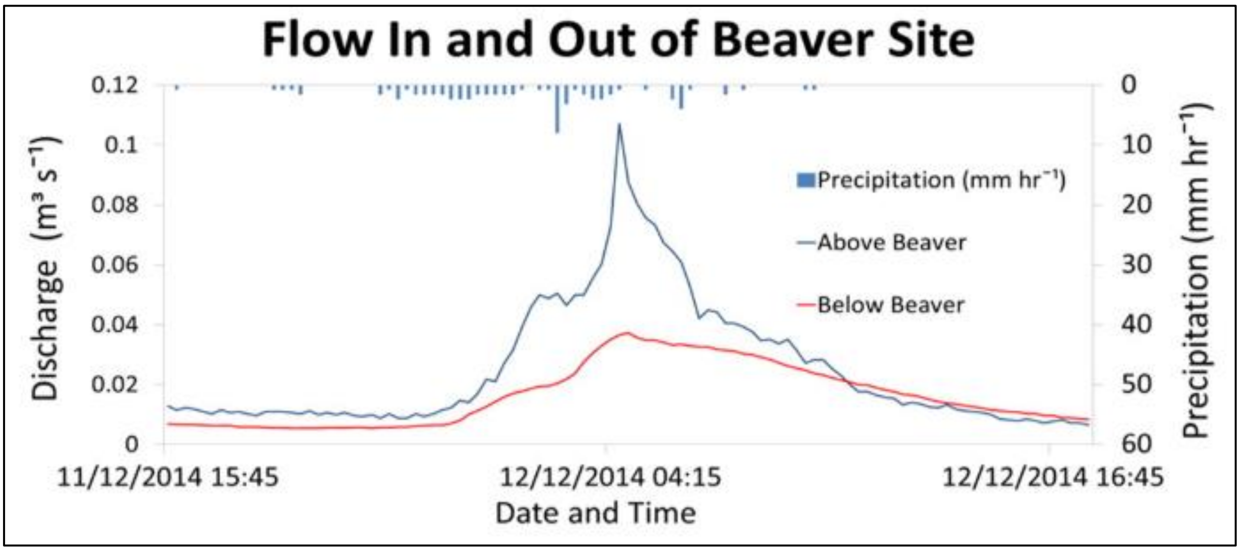

Figure 6: Graph illustrating water flow entering and leaving the enclosed beaver site during a high rainfall event in December 2014. Source: Adapted from Puttock *et al* 2017.

Flow leaving the site is attenuated, rising less rapidly and peaking at a lower rate, falling slowly as rainfall ceases. This effect is controlled by storage in each pond and the enhanced hydraulic roughness of the landscape within the enclosure, (Devon Wildlife Trust, 2018).

Despite the dams being relatively watertight some recharge can occur, freeing up storage for the next rainfall event, (Puttock *et al* 2017, Gurnell 1998). Holding water back and desynchronising peak flows from minor watercourses into larger river networks is a key principle in flood alleviation. This evidence suggests that beavers and their wetland complexes can contribute to NFM. Though more investigation is needed to quantify the benefits in different catchments and conditions.

3. Aims and objectives

This research will use a combination of field survey, GIS-based habitat suitability analysis and hydraulic modelling to identify the potential for reintroduced beaver to contribute to natural flood management in the headwaters of the Adur catchment in Sussex. This overall aim will be achieved by addressing three objectives:

1. Characterise the physical structure of *C. fiber* dams constructed by reintroduced beaver in catchments in southern England to inform model development (field survey).

2. Identify locations within the catchment where dam building may be most likely, using known beaver dam building requirements (GIS analysis).

3. Predict changes in stage and inundation extent arising from beaver dam construction in different scenarios using a coupled 1D-2D hydraulic model model that integrates information from objectives (1) and (2).

4. Methodology

4.1 Study area

The river Adur is fed by perennial springs emanating from the northern scarp slope of the Brighton chalk block providing a limited baseflow to some of its tributaries. The impermeable clay underlying it plays a significant part in the rivers hydrological characteristics, reacting quickly to rainfall events and affected by low summer flows, (Environment Agency, CAMS 2005). The main river is fed by two arms, the Adur East and Adur West arms meet at the tidal limit and follow nine miles of embankments to the estuary at Shoreham-by-sea. The Adur represents a typical lowland catchment in Sussex.

The study area falls within the Knepp estate on the Western arm of the Adur, see figure 7. The estate covers 3,500-acres south east of Horsham, West Sussex and contains a total of 30.2km of main river, tributaries and drains within its boundary. Until 2001 the estate combined a mix of arable and dairy farming but was running at a loss. The industrialisation of farming widened the gap in the 1990's and those losses became unsustainable, (Tree 2018). In an attempt to diversify the business, the estate turned to rewilding. Inspired by the restoration of parkland around the main house, which returned 140 hectares to permanent pasture (Tree 2018). The estate adopted the approach described by Donlan (2005). Introducing proxy species for extinct megafauna to manage the succession of species-poor closed canopy woodland, aiming to restore natural processes and increase biodiversity (Tree 2018). The estate aims to demonstrate the provision of ecosystem services such as carbon sequestration, water storage, air purification and a recreation resource to a wide range of users.

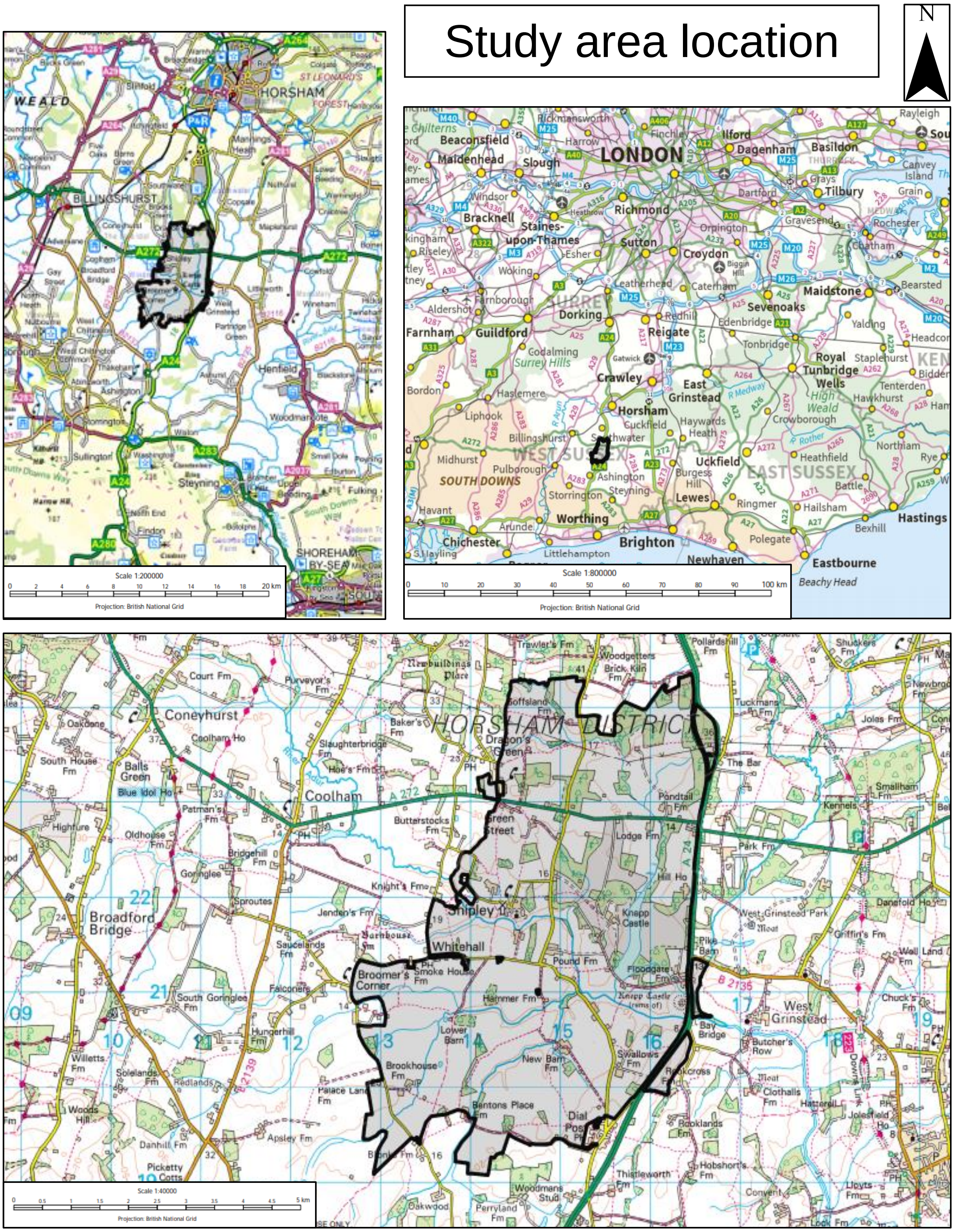

Figure 7: Map of study area at different scales

4.2 Knepp beaver re-introduction

Following findings from *C. fiber* re-introduction projects elsewhere in the UK, specifically the Devon projects in the South West, the estate plans to introduce a pair in 2019. A partnership between the Environment Agency, Natural England, Sussex Wildlife Trust and the Rivers trust have formed to progress the introduction of a trial population. Initially within the estate boundary but ultimately to the wider Adur catchment. The introduction aims to emulate the findings from recent studies, particularly how hydromorphological changes caused by beaver dams translate into desirable biological responses, (Jakes *et al* 2007). Specifically, those sites with a long history of degradation due to agricultural land use, (Law *et al* 2016). This study examines the potential flood attenuation and flood storage benefits that could be realised at Knepp if conditions are found to be suitable for dam building. This work will contribute to the feasibility needed to progress a successful beaver introduction application with Natural England.

4.3 Characterising existing *C. fiber* dams in Southern England to inform GIS model development

There are nine known beaver introductions currently effective in the UK, see figure 2. The majority established to demonstrate the benefits to water quality, habitat heterogeneity and species diversity. (Brown *et al* 2018; Law *et al* 2017; Gurnell 1998; Puttock *et al* 2017; Pollock *et al* 2014). To inform development of the model, two sites with reintroduced *C. fiber* in southern England were visited and surveyed. Two contrasting sites are available, the enclosed Devon beaver project and the Otter trial project, see figure 8.

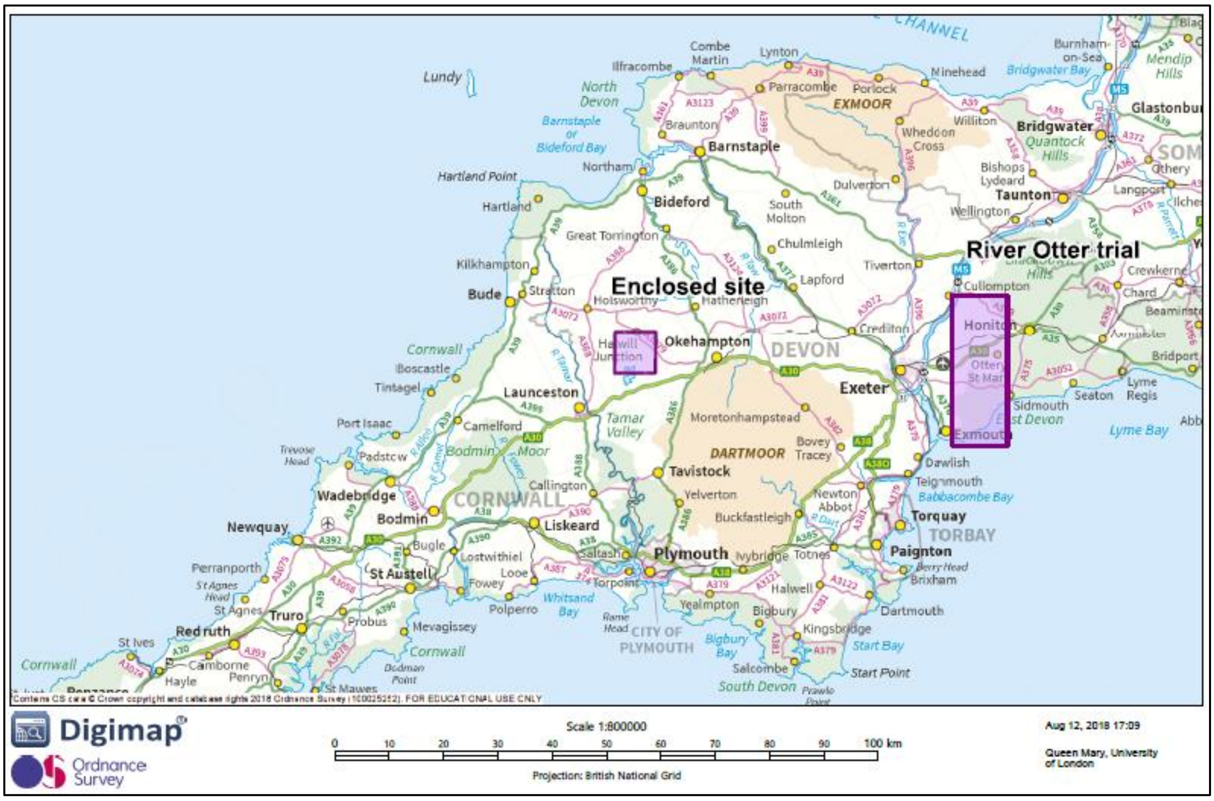

Figure 8: Location of the two Devon beaver projects. It was requested that the exact locations not be disclosed.

The enclosed Devon beaver project in the headwaters of the River Tamar is a 3ha fenced enclosure containing two adults and up to four young (Elliot, M J 2018, pers comm 14th June) the site represents the activity of *C. fiber* in the headwaters of a stream with no defined channel. A proportion of the 30.2km of watercourse within the Adur study area represents similar habitats.

The River Otter trial site holds approximately 30 beavers occupying several colonies within the 250km^2 catchment, (Chant, J 2018, pers comm 15th June). The beavers, of unknown origin, discovered in 2008 are being monitored under licence as part of a 5-year trial to study their behaviour and effects on the landscape. The relatively small numbers within the catchment and the availability of deep water has resulted in fewer dams being built compared to the enclosed site, (Elliot, M J 2018, pers comm

14th June). The Otter catchment represents dam structures on main watercourses with defined channels.

The enclosed beaver project was visited on the 14th June 2018 to contextualise the reports and papers researched during the review of literature and ground truth the dam building parameters informing the GIS modelling component of this study. Low flows following a very dry summer period made it difficult to define dams at the top of the enclosure, these were excluded from field survey. Length and height of beaver dams vary with topography, (Gurnell 1998), this was evident within the enclosure. Five of the thirteen dams were measured in total, these were considered to represent the scale and structure of the total. Compared to *C. canadensis, C. fiber* build smaller structures, (Gurnell, 1998). *C. fiber* dam lengths often measure as much as 20m, and dam heights are typically 1m, (Nyssen *et al* 2011). Taking these figures into account a 100m tape for dam length and a 5m telescopic measure pole for dam height was used, see figure 9. Height and length were measured at all five dams. Height was measured where dam height was greatest, in most cases at the mid-point of the downstream channel if one could be defined. Dam length was measured between the two laterally extreme points. Stream depth and width were measured on the downstream side of each dam to test the stream depth and width parameters where beaver would cease to construct dams, (Hatman and Tornlov, 2005). Stream depth was measured in the centre of the channel to reflect the maximum depth and where river topography was unaffected by the dam.

Figure 9: Width and height measured within the enclosed beaver site in the headwaters of the Tamar

Three dams were measured in the Otter catchment. One visually inspected on a drainage ditch north of Otterton St Mary and the other two by hand on the Tale, the largest tributary of the Otter, see figure 10.

Figure 10: Beaver dam on the River Tale, the largest tributary of the River Otter

4.4 Identifying potential beaver dam locations using GIS modelling

Using known dam building requirements of *C. fiber*, Geographical Information System (GIS) based modelling of hydrology, topography and vegetation parameters was undertaken to assess the suitability for dam building activity within the Adur study area. ArcMap 10.5.1 GIS software was used.

Several key factors are known to be important in determining the capacity of a catchment to support dam building activity, (Macfarlane *et al*, 2017). Beavers are semi-aquatic rodents so proximity to waterbodies is an essential requirement in the first instance. The nature of that waterbody and other properties of habitat play a role in governing the degree to which *C. fiber* may colonise and sustain a population, (Gurnell, 1998). The Devon fieldwork highlighted the importance of headwaters streams, wetlands and ditches as habitat for *C. fiber*. Width and depth of watercourses will influence *C. fiber* dam building behaviour, (Hartman and Tornlov, 2005). Habitat selection studies have shown that beaver prefer deeper water, meeting their demands without alteration, (Hartman, 1996). There is substantial cost involved in dam building, beaver would only be expected to build when absolutely necessary, (Hartman and Tornlov, 2005). Beavers build dams in small streams where sufficient depth does not exist, but there is an upper limit in the river size and gradient where the force of water will be too strong to allow construction, (Naiman *et al*, 1998). Dam presence is strongly associated with low stream gradient, (Macfarlane *et al*, 2017). Access to food and dam building materials is another contributing factor. Beavers will only inhabit areas with sufficient food resource, (Stringer *et al*, 2015). This resource needs to be in close proximity to water. Perhaps due to the cost of dragging food and building material large distances from the water's edge, but also the risk of predation when out of the water, (Baskin and

Novoselova, 1998). McComb *et al*, (1990) found that reaches with dams were shallower, had a lower gradient and greater tree canopy cover than those without dams, and avoided sites with a rock substrate. Table 1 lists the habitat requirements used in this study alongside the data sources and processing used in the GIS modelling. Despite the American beaver (*Castor canadensis*) and the Eurasian beaver (*Castor fiber*) having very similar ecology, (Gaywood, 2017), only references to *C. fiber* behaviour were used.

Habitat requirement	Data source	Data processing
Watercourse -	Datasets available from Edina Digi map did not include the minor watercourses that make up a significant proportion of the watercourse in the study area. The Environment Agency's Detailed River Network (DRN) has the required coverage but is not yet available through data.gov.uk. This was provided by the evidence and data team at the Environment Agency.	The DRN dataset included culverted sections and land drains which do not provide suitable habitat for *C. fiber*. These were removed from the shapefile using ArcMap editing tools to accurately represent the available resource.
Foraging habitat from the water's edge – Evidence from Germany, in an area with no predators, indicates the majority of foraging activity exists within 45m of watercourses (Baskin and Novoselova, 2008). The mean maximum foraging distance in Norway is 36m (Parker *et al*	The publicly available National Forest Inventory and CORINE land cover datasets were considered for this parameter but neither provided sufficient resolution or coverage to accurately map woodland availability within the study area boundary, see figure 12.	The Woodland Trust dataset was generated by selecting areas over 3m in height from a Digital Surface Model. Non-vegetation data such as buildings were removed, and remaining areas matched with aerial photography to determine vegetation over 3m in height. Flooding tools in GIS were used to break up large canopied areas into individual tree canopies to finish the

2001). For the purposes of this study a conservative 30m was chosen.	A dataset was provided by the Woodland Trust for the purpose of this dissertation only and is not publicly available. The Ouse and Adur Rivers Trust provided a polygon shapefile of the recently planted areas in the study area.	dataset. This dataset was compared to the latest aerial photography of the study area to verify its accuracy. The buffer wizard tool was used to create a 30m buffer from the detailed river network and a layer was created to display vegetation within foraging distance from all watercourses in the study area. A separate dataset was created to include areas of riverside planting carried out by the Ouse and Adur Rivers Trust.
Channel gradient – Habitat Suitability mapping for *C. fiber* in Austria used a maximum gradient threshold of 15% as the upper limit beyond which beavers would not build dams, (Maringer and Slotta-Bachmayr 2006). Stringer *et al* (2015) recommended a stricter threshold of <6% in his report to the Scottish Government. For the purposes of this study stream gradients of >15% have been rejected. Stream gradients between 0 and 6% have been classified	To calculate channel gradients a Digital Terrain Model with 1m resolution was downloaded from the gov.uk open data resource.	The adapted DRN was split into 100m sections throughout the study area using ArcMap editor tools. 3D analyst tools were then used to calculate the percentage slope for every 100m section using the DTM. Thresholds of 0-6, 6-15 and >15% gradient were assigned.

as optimal and gradients between 6-15% as sub-optimal.		
Channel width – Beaver dams studied in Sweden found that the majority if not all dams were built on watercourses no wider than 6m, (Hartman and Tornov 2006). A *C. fiber* dam surveyed on the River Tale measured 6.5m in width. A 7m channel width was used as the maximum width in this study	The OS Open Map Local data set was downloaded from Edina Digi map. The dataset includes a surface water polygon area which was used to calculate channel widths.	The surface water polygon did not include all areas identified by the merged DRN, editor tools were used to extend its coverage. The resulting shape file was split into 100m sections and the area of each calculated using ArcMap measuring tools. Widths were calculated by dividing the length by the area to get average width.
Channel depth - In a study of 100km of river in Sweden, Hartman and Tornlov (2006) concluded that depths of between 0.7 and 1m were sufficient for their requirements with no need to build a dam. 0.7m water depth will act as the threshold above which beavers will no longer need to build dams.	There are no datasets available that provide depth data along significant stretches of watercourse. Field measurements were carried out to gather this data.	Once the field survey data was collected these were imported into ArcMap and converted into a shapefile

Table 1: Table lists the habitat requirements for dam building activity and the data sources acquired and processing method used in the GIS modelling

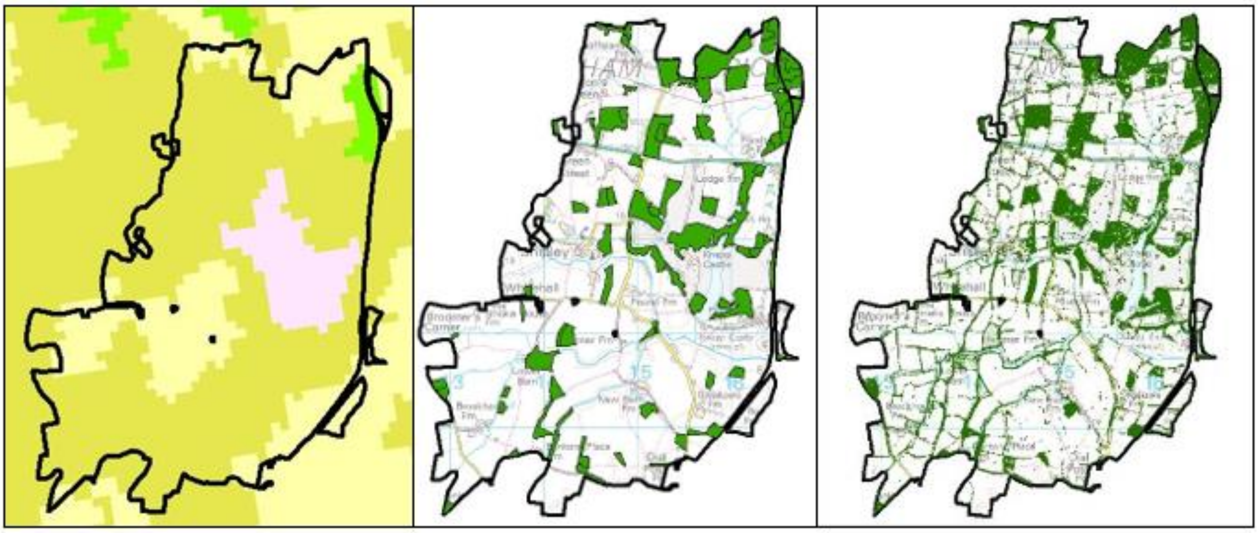

Figure 11: Left to right, CORINE landcover (poor resolution and very little woodland cover), National Forest Inventory (doesn't include woodland areas less than 0.5ha), Woodland Trust tree cover data (uses LiDAR data to define trees in the landscape). Source: Personal collection

Field measurements in the Adur study area were necessary where data didn't exist. Channel width and water depth were surveyed every 100m on the main channel from the downstream end of the study area to the upstream boundary covering a distance of 2.8km. The assumption was made that all other watercourses would be narrower and shallower than the main river and were not investigated. Width measurements were collected to validate the results from the GIS modelling. Stream depth was measured in the channel centre to reflect maximum depth, (Hartman and Tornlov, 2005), using a 5m measure pole. The same equipment was used to measure bank full width.

Three layers were created for woodland cover, average gradient and average width of channel following the processes described in table 1. The Detailed River Network (DRN) was split into 100m sections, 326 in total to cover the 30.2 km of watercourse within the Adur study area. For each of the 320 sections a figure for woodland (m^2), average gradient (%) and river width (m) was generated. The river width layer was found to underestimate channel width by almost 100% in most sections, so the layer was rejected with field measurements adopted in its place. Each 100m section had the potential to include a maximum of 6,000m^2 of woodland using a 30m buffer from each bank (100mx60m = 6000). Greater foraging habitat increases the likelihood of presence and dam building if other requirements are met, (Macdonald *et al* 2000). River sections with access to less than 500m^2 of woodland were considered unsuitable. Sections with between 500m^2 and 1500m^2 were seen as sub-optimal and areas between 1500m^2 and 6000m^2 as optimal. For average channel gradient, river sections with an average gradient over 15% were considered unsuitable, (Maringer and Slotta-Bachmayr, 2006). Gradients between 6 and 15% sub-optimal and those under 6% as optimal, (Stringer *et al 2015)*. Symbology functions within ArcMap were used to display the layers. River widths and water depths were considered optimal throughout the study area following the field measurements taken.

Once the layers had been categorised a scoring system was implemented. 0 for unsuitable, 1 for sub-optimal and 2 for optimal in each 100m section. These scores were combined to provide an overall suitability score. If any one category scored 0 for unsuitable the entire section was considered unsuitable regardless of the other scores. Suitability scores were imported into ArcMap from excel and the symbology function used to visualise them. The rivers trust had recently planted areas of riparian woodland along the main river bank, stretching approximately 1.5km. The scoring process was repeated to account for this planting, highlighting the increased foraging resource and increasing the suitability scores of some sections. Once the final layer had been created potential locations of dam structures in suitable locations were identified. The Devon Wildlife Trust found that *C. fiber* on the Otter seemed to preferentially build dams at the confluence of watercourses, presumably to increase the impact on the flooded area, (Chant, J Devon Wildlife Trust, pers comm 2018.) Zurowski (1992) found that all dams in the Masurian and Brodnica Lakelands in Poland were located on small watercourses or drainage ditches and appeared to be constructed primarily to provide access to new food areas. Preference was therefore given to areas below confluences and those near to areas of woodland that if flooded would provide both food and shelter. Dam building capacity doesn't directly equate to dams being built. Macfarlane *et al*, (2017) identified 52 dams in an area that had the capacity to support 5945 in the Fremont watershed in the United States. This could be related to previous hunting pressure and other factors, but it highlights the dangers in over predicting the number of dams that can be built in a catchment. With this in mind a conservative number of potential dam sites were identified.

4.5 Modelling dam-driven changes in stage and inundation extent

Suitable dam locations within the study area were built into a flood model to explore the differences between stage and floodplain inundation. Three scenarios were tested:

Scenario one – No dams

Scenario two – Dams in locations with optimal suitability only.

Scenario three – Dams in both sub-optimal and optimal suitability.

Beaver dams increase lateral connectivity by linking stream channels and floodplains, (Burchsted *et al* 2010). Flood Modeller Pro (FMP) software visualises inundation and creates flow, velocity, depth and water level data, (CH2MHILL, 1D user guide). 1D/2D combined modelling creates hydrodynamic simulations of flow and water levels within river channels, floodplains and through hydraulic structures, CH2MHILL (2018). 1D flood modelling solves 1D equations of flow within a channel, providing a single water level, velocity and flowrate calculation for each river-section (node) defined within the model boundary (study area). The 1D element represents point features such as weirs, bridges and sluices, or in this case beaver dams. The 2D element solves the 2D equations of flow and calculates water depth and velocity on a grid representing the floodplain. This requires a Digital Terrain Model (DTM) and/or the bathymetry of the river channel, (ch2m webinar 2015). The 1D element projects the channel and structures accurately and the 2D element provides the detail for the floodplain. 1D/2D modelling is best used for flood mapping purposes (ch2m webinar 2015). This method represented the best option for illustrating differences in stage and inundation with and without *C. fiber* dams in the study area.

Data for bridges and structures within the study area and most of the river sections were taken from the 1D Adur Flood Mapping Study commissioned by the Environment Agency and completed by Atkins consultancy in 2005. Table 2 presents the data type and source/method used in the flood modelling.

Data type	Source/method
Channel cross-section and point features	Topographic survey of the restored reach using a Leica 1200 smart-rover GPS. Cross-sections and point feature data (weirs and bridges) from the River Adur Flood Mapping Study
Topography	1m Digital Terrain Model
Channel and floodplain roughness	Manning’s roughness coefficient (Chow 1956) and site survey
Boundary conditions	Stage and discharge data from Hatterels gauging weir, situated downstream of the study area and flow data from the Adur Flood Model return periods

Table 2: Data requirements for 1D/2D hydrodynamic modelling and methods to source them

The Adur Flood Mapping Study is a hydrodynamic model of the Adur catchment capable of accurately predicting inundation of the floodplain for extreme fluvial and tidal flooding, (Atkins, 2005). The Atkins model simulates a range of flood scenarios with return periods of 1in2 year, 1in5 year, 1in10 year, 1in25 year, 1in50 year, 1in100 year and 1in100 year with climate change predictions. Between 2010 and 2011 the Knepp estate, in partnership with Natural England and the Environment Agency, restored the main river channel for 2km. Constructing a new channel through the floodplain, thought to be the relic route of the river. The Adur Flood Mapping Study no longer accurately represents the river, new cross-sections were therefore necessary to update the model, see figure 12. Cross sections were surveyed using a Leica 1200 GPS smart-rover. Surveys were conducted in the new

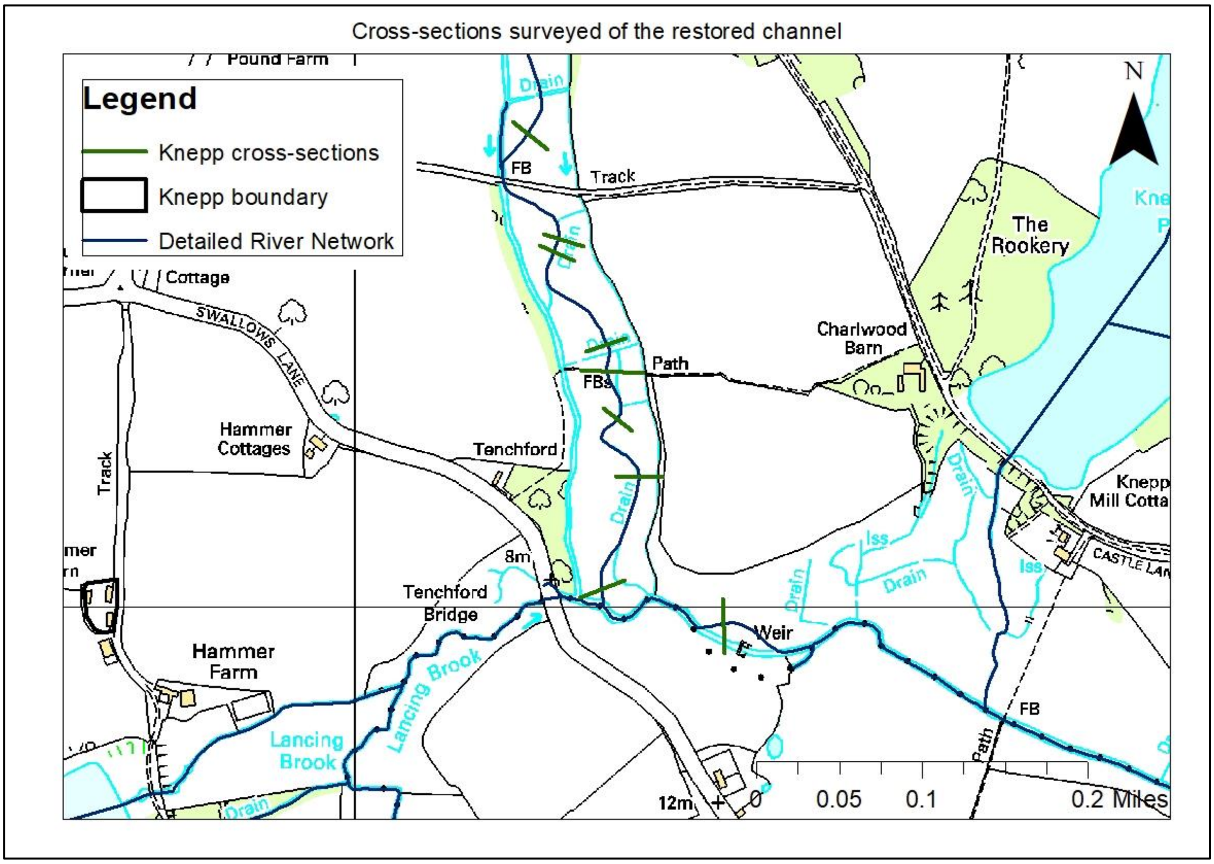

Figure 12: Map created using ArcGIS showing the locations of the additional cross-sections surveyed from the restored channel

channel and where changes in channel profile occurred. Nine new cross-sections were recorded in total.

The Adur study area boundary was imported into FMP as a shapefile. All cross-sections (nodes) outside of the boundary and those representing the old channel were removed. The new cross-sections were imported and georeferenced into the model network. The Adur Model was developed with an extended 1D set-up to represent the floodplain. These floodplain points were deactivated to align with those surveyed. Boundary conditions were created as entry and exit points for the model, allowing water in and out. A flow time boundary (discharge versus time) was applied at the upstream end of the network, with a value of 1.2 m^3/s representing mean flow. This value was provided by the Environment Agency, with data from Hatterels gauging weir downstream. The downstream end was represented by normal depth, calculated using section data to generate a flow-head relationship, (CH2MHILL, 1D user guide). Once the network was constructed 1D simulations were run with 1in2 year, 1in5 year, 1in10 year and 1in25 year return periods from the Atkins model. Initial values of flow are required at each node before commencing 1D simulations, (CH2MHILL, 1D user guide). Mean flow (1.2 m^3/s) was used to create these initial conditions. Once all 1D simulations ran successfully the 2D component was built. An active area was created to represent the floodplain and link lines were built to instruct the model where to flood the active area, moving water from the 1D component to the 2D. A general weir configuration was used to represent *C. fiber* dams in the network. Gurnell, (1998) compares well maintained beaver dams to low weirs, watertight by nature. This provided the justification for the general weir configuration. Further research could potentially investigate alternative options. 2D simulations ran successfully for 1in2 year, 1in5 year, 1in10 year and 1in25 year with no dams in the network. Instabilities in the model when introducing dam structures caused the model to fail repeatedly at higher return periods. Despite many alterations to the active area, link lines, manning's roughness and nodes, no simulations ran successfully above the 1 in 2-year return period.

5. Results

5.1 Characterising existing *C. fiber* dams in Southern England

Fieldwork carried out at the two Devon beaver projects highlighted different dam structures in relation to their position in each catchment defined by local topography, hydrology and vegetation composition.

The enclosed site is situated on a small first order stream in the headwaters of the Tamar, North West Devon. A watercourse springs at the top of the enclosure, supplemented by a number of field drains. The watercourse flows via multiple anastomosing channels through an area of wet woodland. Figure 13 identifies the channel as it comes in and out of the enclosure.

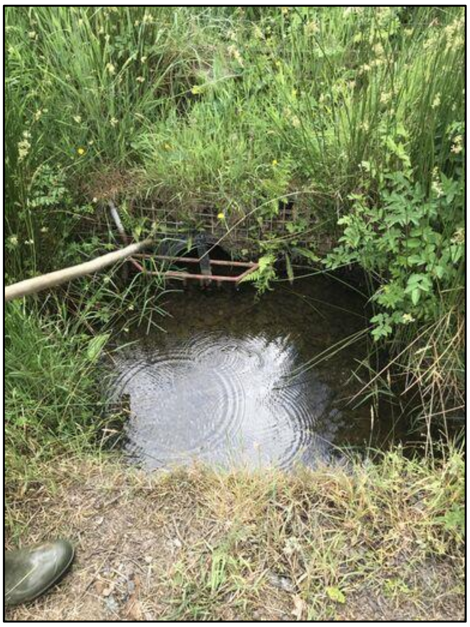

Figure 13 Left sided picture shows the watercourse at the top of the site. Right sided photo is the downstream watercourse as it leaves the enclosure, the v-notch weir was used by Exeter university to measure flows leaving the site. The channel is no wider than a 1m at both locations.

The channels stepped longitudinal profile is created by 13 dams positioned along the183m length of the watercourse, with a head-loss of approximately 10m, (Elliot, M J 2018, pers comm 14th June), see figure14. Calculated slope gradient is 5.46%, towards the upper end of the optimal gradient parameter used in this study.

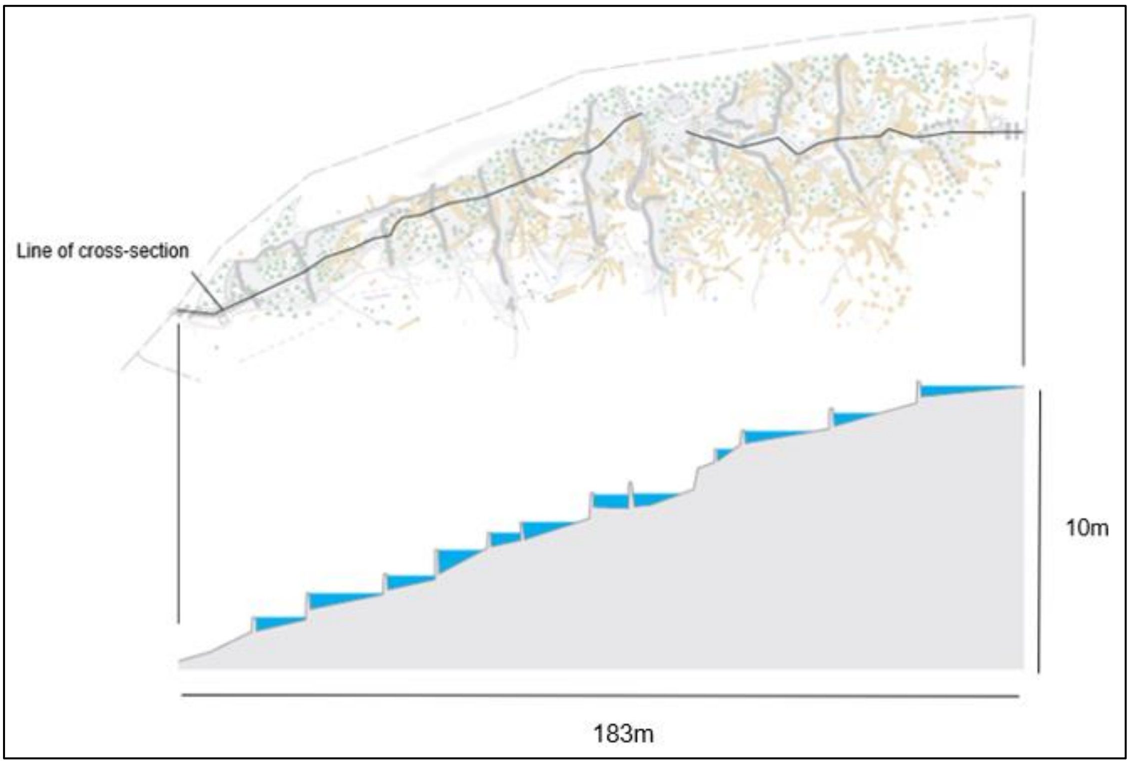

Figure 14: Beaver enclosure cross-section. 13 dams have been built over a distance of 183m. Source: Adapted from material supplied by the Devon Wildlife Trust.

Visual observations established the dams were constructed predominantly from silt and root balls, with *Juncus sp* a common building material. *C. fiber* dredge the area surrounding the dam, moving sediment and material into position, (Elliot, M J 2018, pers comm 14th June). The structure is supported with short lengths of woody material, branches and small trunks, used to fill gaps and breaches. Preferred species are hazel and willow providing flexibility, but larger tree and hedgerow species are used when required. In some locations *C. fiber* made use of fallen trees to start construction, using them as an anchor point to improve structural integrity, reducing building effort. Once established the dams vegetated, contributing to their stability, figure 15 provides two examples of *C. fiber* dams within the site.

Figure 15: Beaver dams within the enclosure. The materials used in building the dam are evident in the picture on the left, the picture on the right shows established vegetation atop completed dams. The blue arrow is showing the location of the dam.

Five of the thirteen dams were measured to define their dimensions and compare them to those found in the Otter catchment, see table 3.

Dam	Dam length (m)	Dam height (m)	D/S channel depth (m)	D/S channel width (m)
1	49.8	1.58	0.38	0.77
2	19.8	0.86	n/a	n/a
3	17.1	1.58	0.28	0.59
4	18.1	0.93	0.3	1.25
5	16.9	0.80	0.1	0.37

Table 3: Beaver dam dimensions within the enclosed site

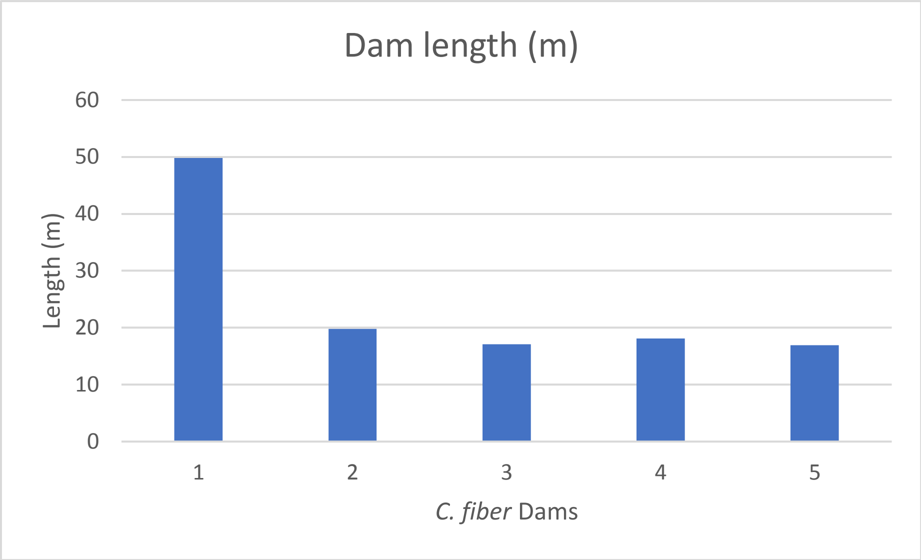

Figure 16: Bar graph showing the length of *C. fiber* dams in the enclosed site

The mean length of dams in the enclosure was 24.34m with a standard deviation of 14.2788. The range of values is high at 32.9m, skewed by the length of dam 1 in comparison to the other four dams, see figure 16.

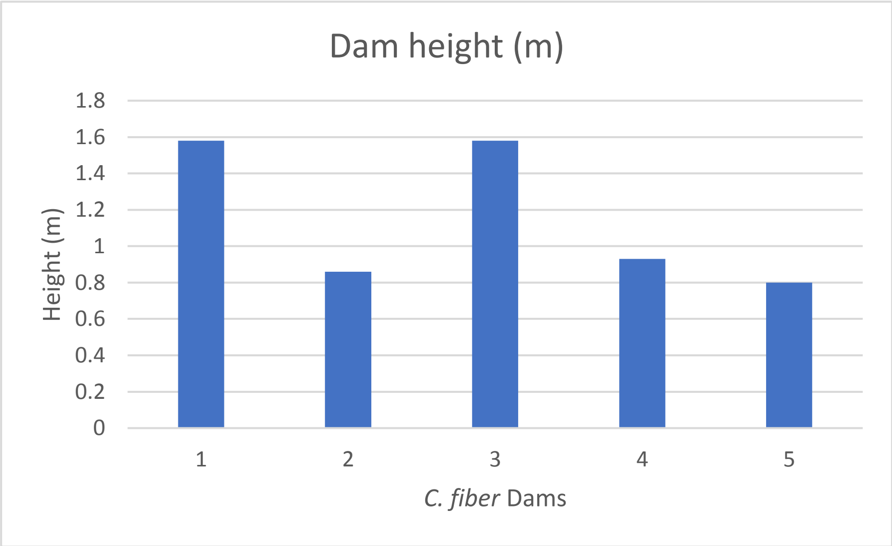

Figure 17: Bar graph showing the heights of *C. fiber* dams in the enclosed site

Mean height of dams was 1.15m with a standard deviation of 0.39. The range of heights indicates some variability with a difference of 0.78m, see figure 17. Mean downstream channel depth was 0.22m with a standard deviation of 0.13740. The range between depths equalled 0.32m. Mean downstream channel width was 0.74m with a standard deviation of 0.37. The range between widths equalled 0.88m. Dam 2 had no identifiable downstream channel to measure.

C. fiber on the River Otter are not restricted in the areas they build their dams. Many watercourses provide sufficient depth to forgo dam building. On the main river below Otterton St Mary, for example *C. fiber* have burrowed into the river bank, where water depth meets their requirements without dam building. Figure 18 shows two examples of where *C. fiber* have built dams in the catchment.

Figure 18: Two beaver dams on the river Otter. The one on the left is on a drainage ditch which enters the main river just above Otterton. The second is on the River Tale, the largest tributary of the Otter.

Figure 19 shows the third dam observed on the River Tale. The structure had been abandoned when it failed in high flows. All three dams were measured in total, see table 4.

Figure 19: Failed dam on the River Tale. Blue arrow highlights the remains of the dam

Dam location	Dam length (m)	Dam height (m)	D/S channel depth (m)	D/S channel width (m)
Drain	3	1	0.3	3
River Tale - failed	8	0.75	0.15	8
River Tale	6.5	0.75	0.15	6.5

Table 4: Dimensions of three dams measured on the Otter

Mean length of dams in the Otter catchment were 76% smaller than those in the enclosure at 5.833m. Standard deviation = 2.5658. The range between lengths was 5m, considerably lower than the 32.9m range between dams in the enclosure, see figure 20.

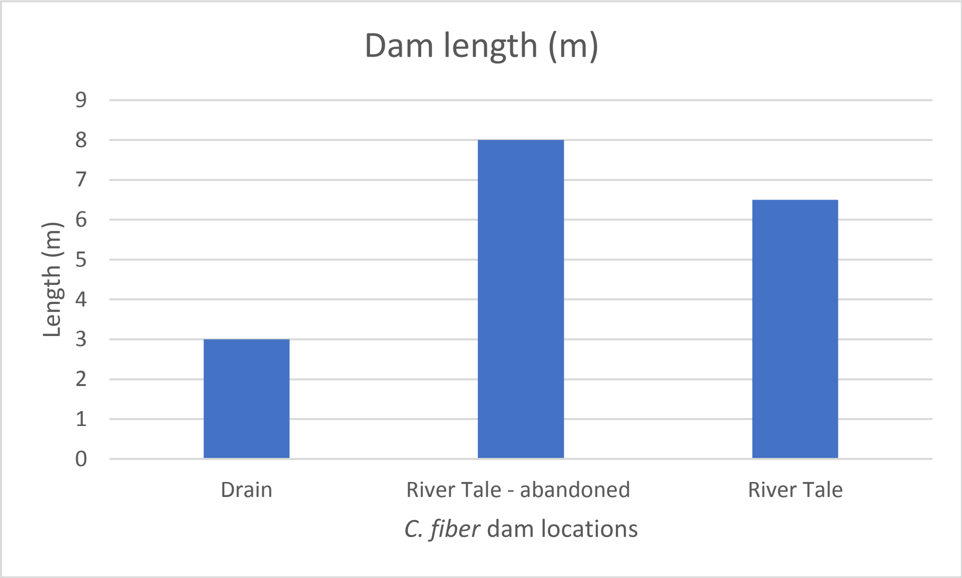

Figure 20: Bar graph showing the length of *C. fiber* dams in the Otter catchment

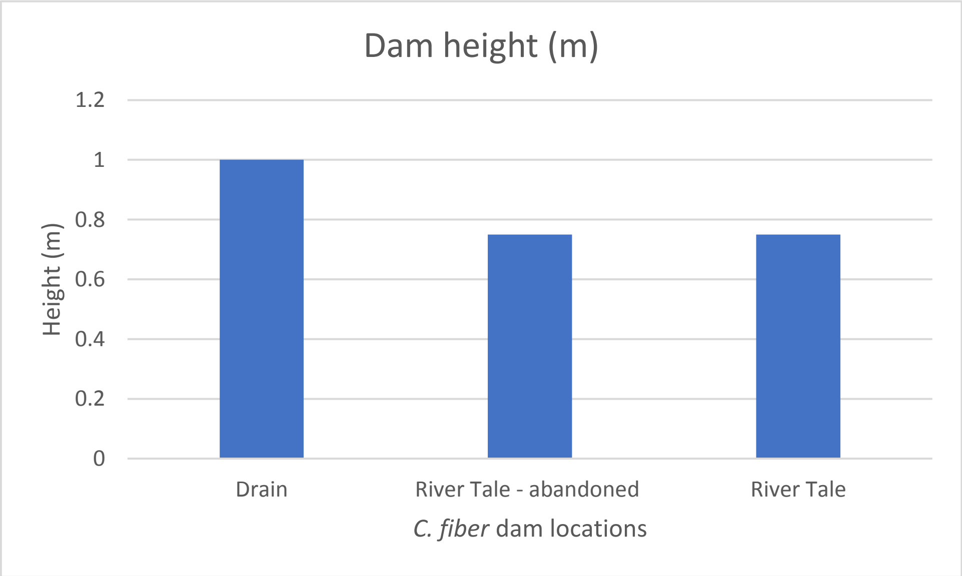

Figure 21: Bar graph showing the height of *C. fiber* dams in the Otter catchment

Mean height of dams measured was 0.83m with a standard deviation of 0.114434. 28% lower in height than those on the Tamar. The range of heights indicates less variability than those in the enclosure with a difference of 0.25m between them.

Mean downstream channel depth was 0.2m with a standard deviation of 0.08660. 11% shallower than mean depth on the Tamar. The range between depths equalled 0.15m. Mean downstream channel width was considerably higher in the Otter at 5.83m, 682% wider than the Tamar. Standard deviation equalling 0.37. The range between widths was 5m.

The dam structures show dimensional and compositional differences between sites. Woody material was observed to be more prevalent on the Otter, presumably due to the lack of available sediment and silt in each of the channels and the need for further stability. Vegetation had again colonised the tops of the Otter structures. More so on the drainage ditch due to the open canopy, see figure 18. Excluding the abandoned structure on the River Tale, all dams at both sites can be characterised as active. They all extended across the channel width and induced a step in the water surface profile, even in low flows. The data acquired during the Devon field work informed the building of the GIS model, particularly the validation of parameters used. Meeting these parameters highlights suitable areas for dam building within the River Adur study area.

5.2 Identifying potential beaver dam locations using GIS modelling

There are 30.2 km of watercourse in the Adur study area. 15.4km have an average gradient of less than 6%. 14.6km have an average gradient between 6 and 15% and only 110m have gradients over 15%. Over half the total watercourse length within the study area has the optimal gradient for dam building. Figure 22 shows the non-suitable, sub-optimal and optimal areas on a map. 4.6km of the watercourses do not provide sufficient woodland cover for foraging, 8.1km is sub-optimal and 17.4km are classified as optimal with extensive foraging habitat available, see figure 23. Out of the 28 locations surveyed for water depth and channel width, only 5 were found to be deeper than 0.7m, with an average of 0.47m. Measurements were taken during low summer flows, flows which generally dictate whether *C. fiber* require dams or not. 4 out of the 28 survey locations had river channel widths over 7m with an average width of 5.86m. Beaver dams were located in areas where width and depth fell within the parameters set. Figure 24 shows a suitability map with all parameters scored, illustrating all potential watercourse stretches were *C. fiber* can build dams. 4.6km was found to be unsuitable, 17.7km was found to be sub-optimal and 7.8km optimal in total.

Gradient suitability map

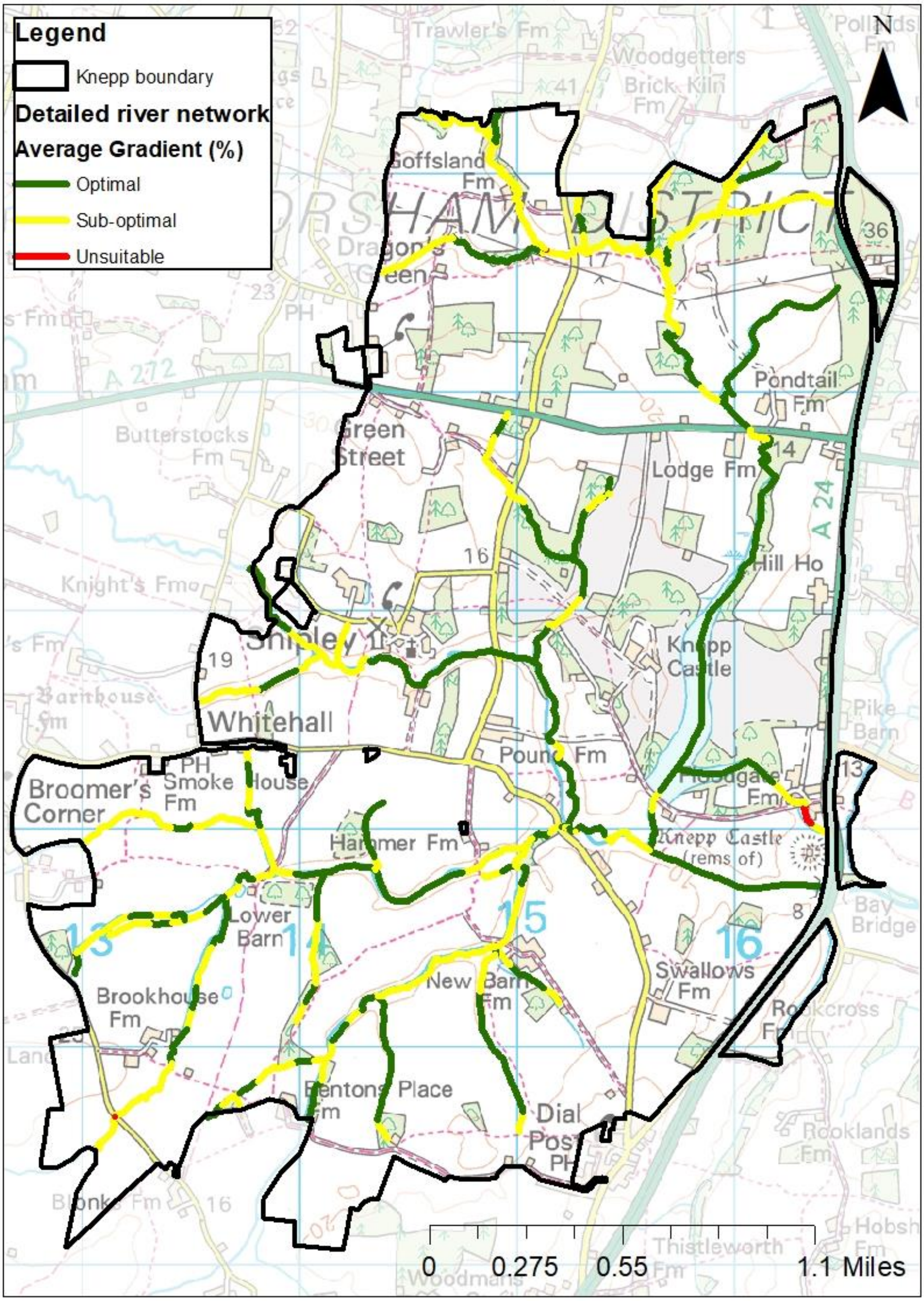

Figure 22: Map showing gradient suitability. Unsuitable = >15%, Sub-optimal = 6-15% and Optimal = <6%

Foraging habitat suitability map

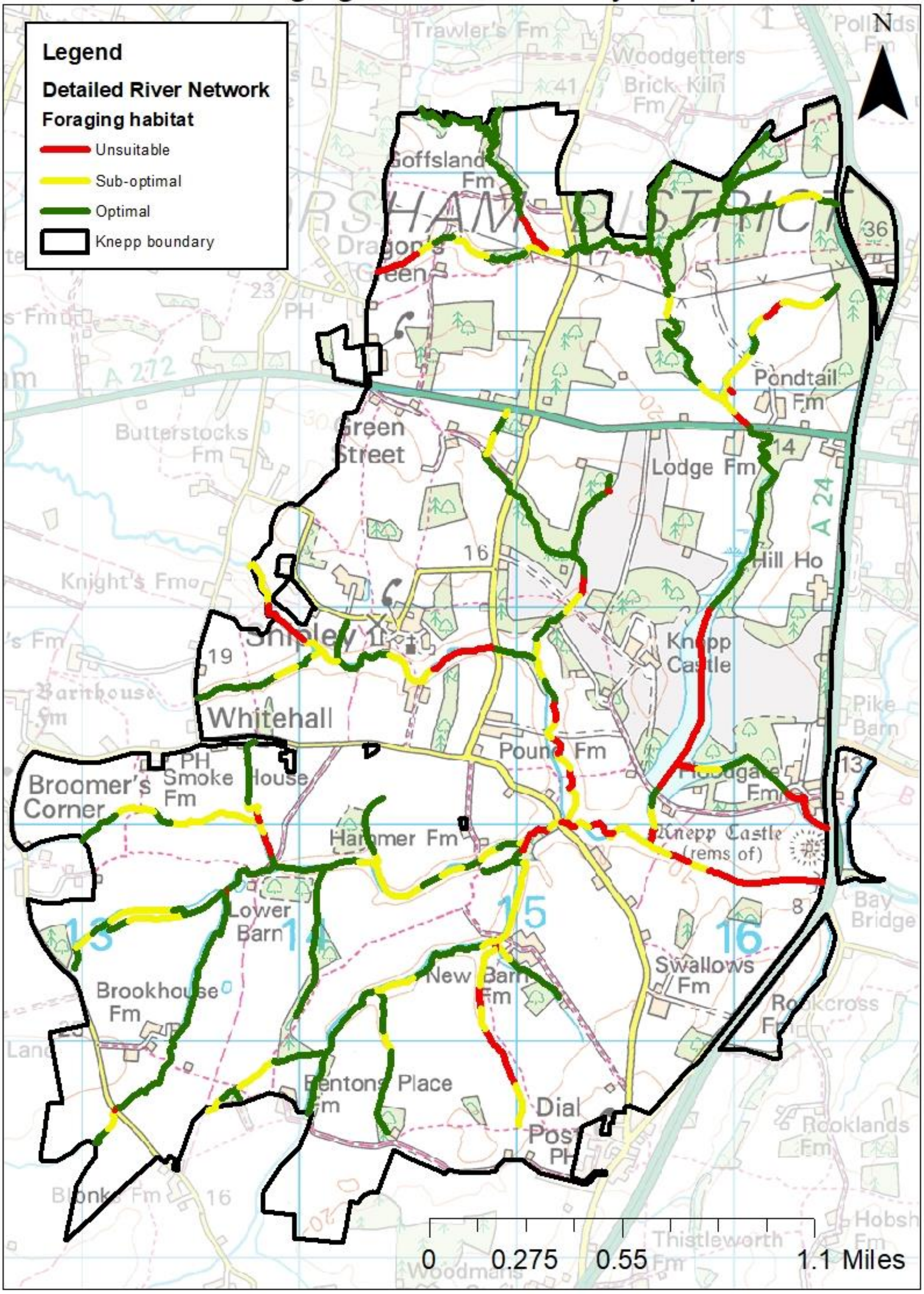

Figure 23: Map showing foraging habitat suitability. Unsuitable = <500m^2, Sub-optimal = 500-1500m^2 and Optimal = 1500-6000m^2

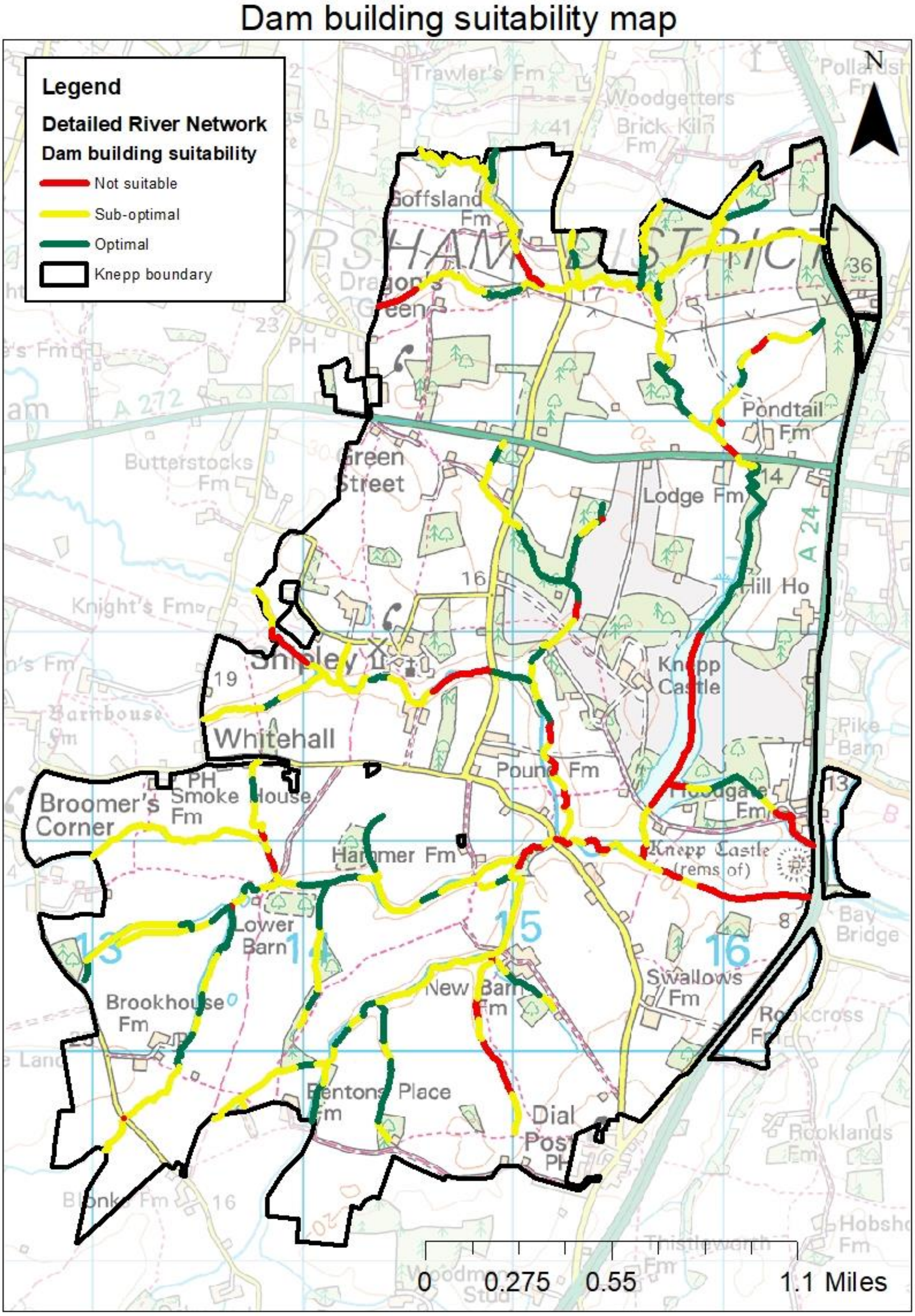

Figure 24: Map showing dam building suitability. Red = Unsuitable, Yellow = Sub-optimal, Green = Optimal

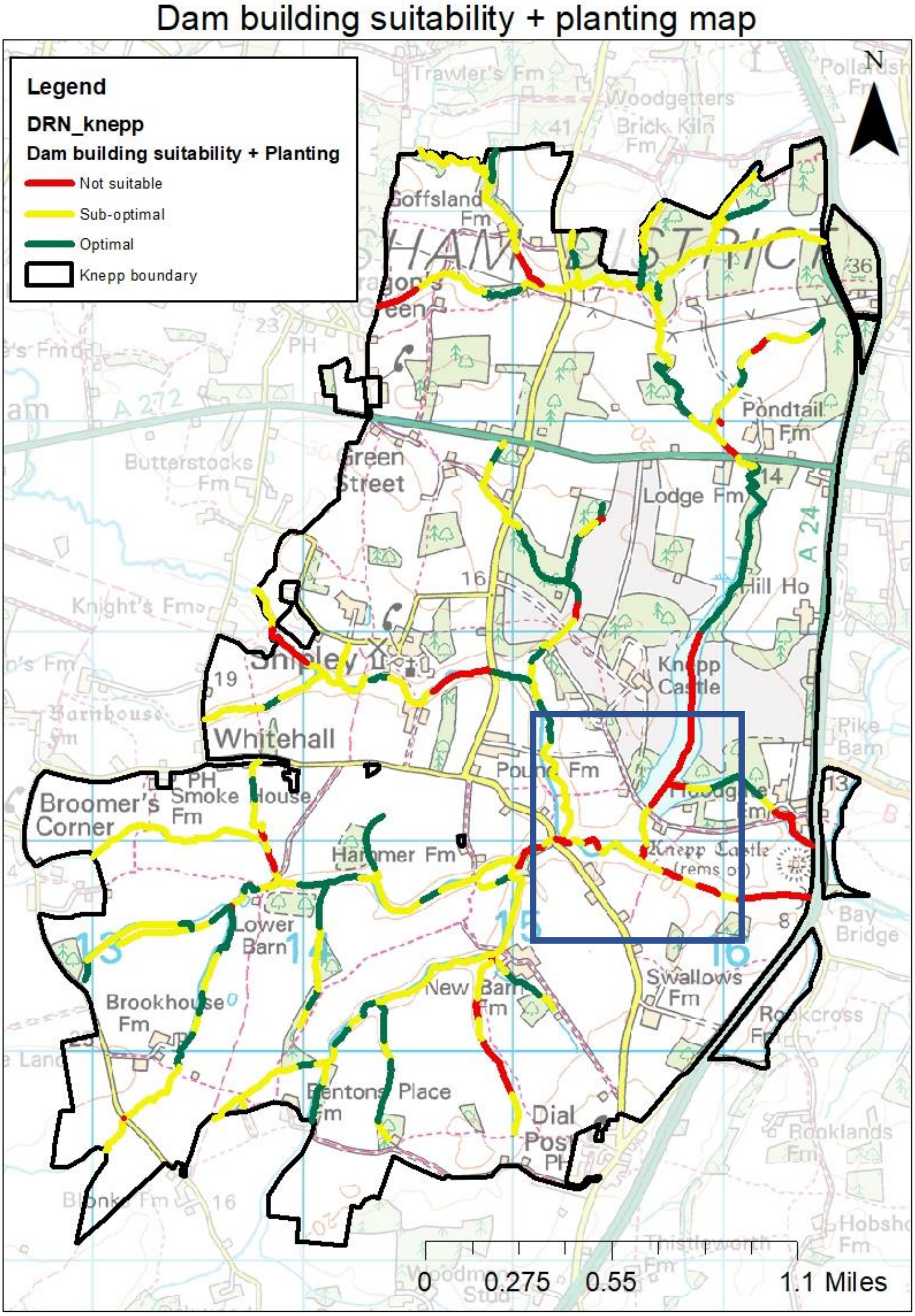

Figure 25: Map showing dam building suitability with rivers trust planting. Red = Unsuitable, Yellow = Sub-optimal, Green = Optimal. Blue box highlights areas that have changed score with the addition of rivers trust planting

Figure 25 shows dam building sutiability with rivers trust planting accounted for. The planting should be established enough to provide foraging resource by the time *C. fiber* reach sufficient numbers to extend onto the main river. The inclusion of the planting extends the sub-optimal resource by 351m from unsuitable to sub-optimal and a further 100m from sub-optimal to optimal.

12 viable dam locations were identified following the GIS modelling, see figure 26. The justification for these can be found in the method section, they represent scenario three in the flood modelling analysis. Viable dam locations were mapped on the main river only. It was not possible to model the effects of dams located outiside of this area due to the lack of flow data.

Location of beaver dams - scenario 3

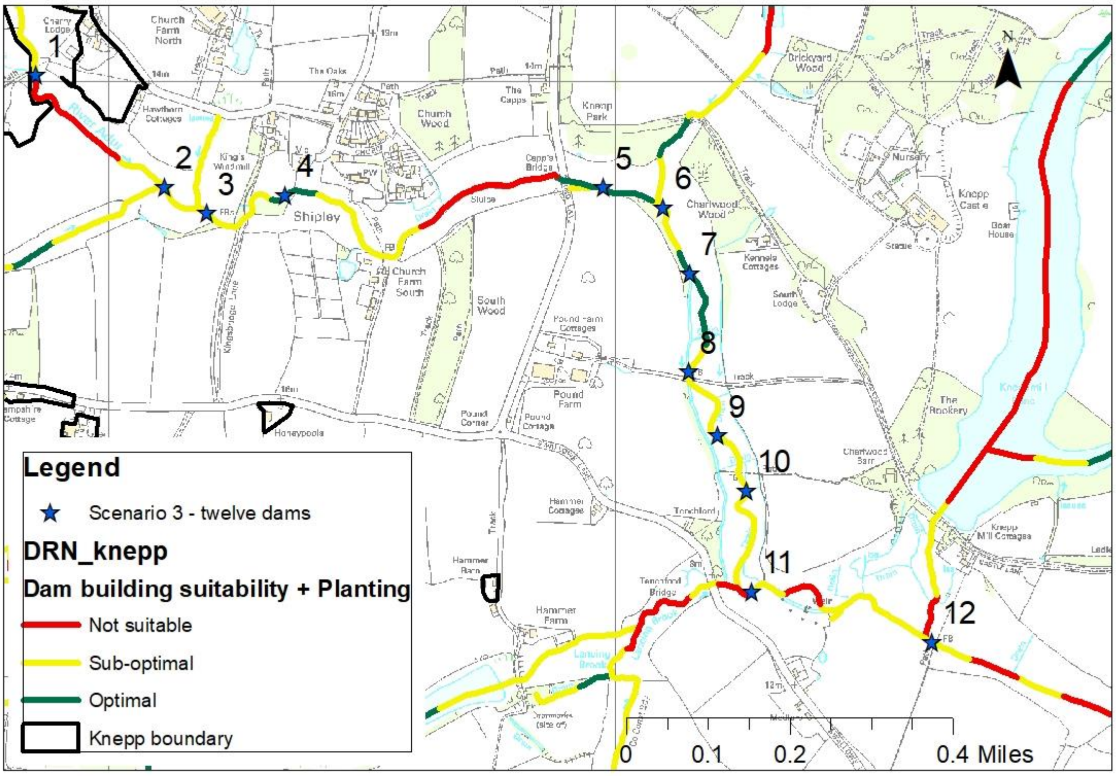

Figure 26: Map showing 12 viable dam locations on the main river in the Adur study area

Figure 27 shows viable dams in optimal suitability locations only, representing scenario 2 in the flood modelling analysis.

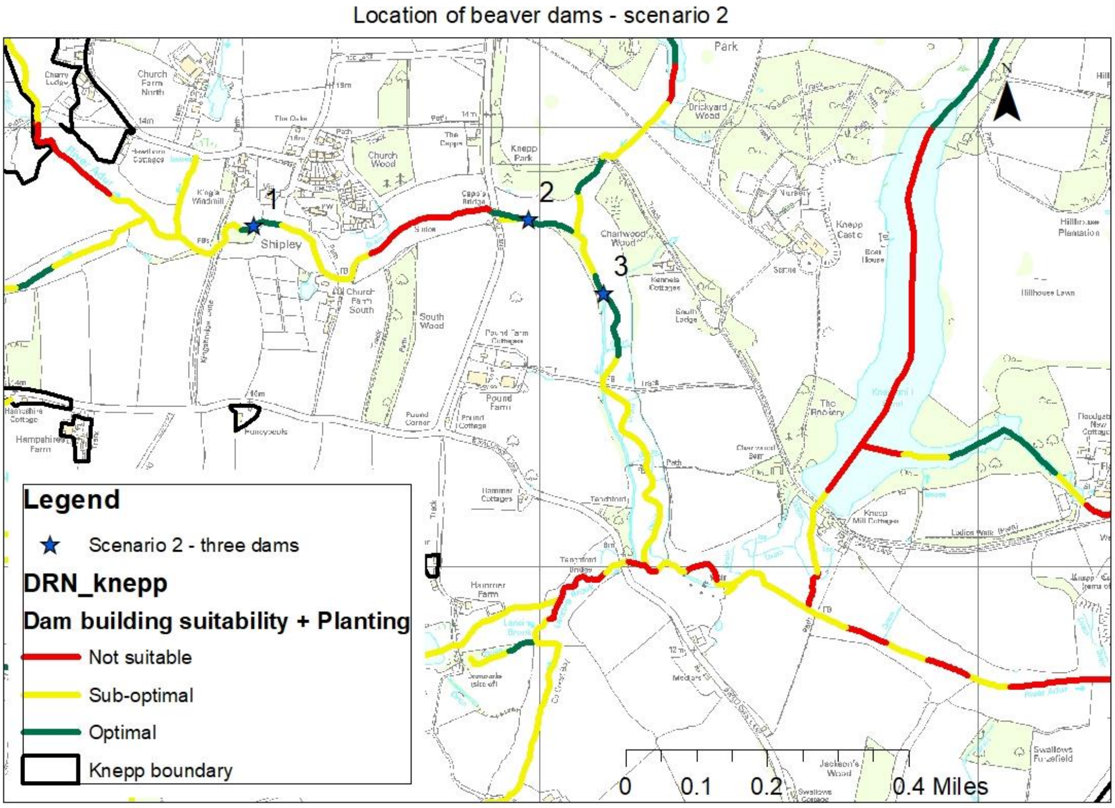

Figure 27: Map showing 3 viable dam locations on the main river in the Adur study area

5.3 Predicting changes in stage and inundation extent arising from *C. fiber* dam construction in different scenarios using a coupled 1D-2D hydraulic model

The three scenarios described in the methods section were run using a 1D/2D coupled flood model to predict changes in stage and inundation extent.

1D modelling was simulated for four return periods, 1 in 2 year, 1in 5 year, 1in 10 year and 1 in 25 year, to investigate differences in stage (river level) within the main channel. Figure 28 shows maximum stage longitudinally at each return period over 50 hours with no dams. Figure 29 shows the same return periods with all 12 dams in situ. The average increase in maximum stage between the two scenarios is 24cm in the 1in2 year, 55cm in the 1in5 year, 22cm in the 1in10 year and 26cm in the 1in25 year. Statistical analysis was carried out to test the significance of differences in maximum stage between the four return periods. The data was normally distributed so the Kruskal Wallis test was used. Maximum stage values were compared between no dams, 3 dams and 12 dam scenarios for each return period. The test revealed no significant difference between maximum stage on any of the four return periods. 1in2 (KW = 0.93, p> 0.05), 1in5 (KW = 2.595, p>0.05), 1in10 (KW = 0.104, p>0.05) and 1in25 (KW – 0.224 p>0.05). Post-hoc tests revealed no significant differences between the groups.

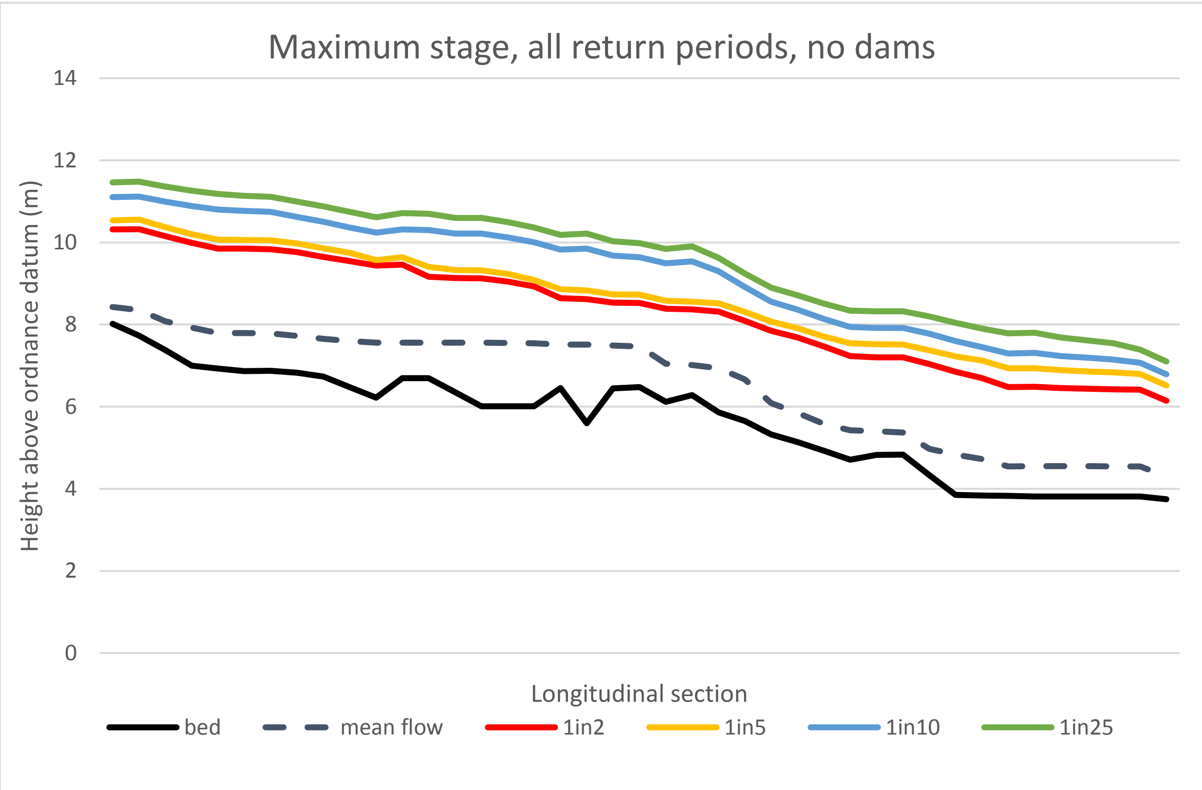

Figure 28: Maximum stage without beaver dams during four return periods, 1in2, 1in5, 1in10 and 1in25 year.

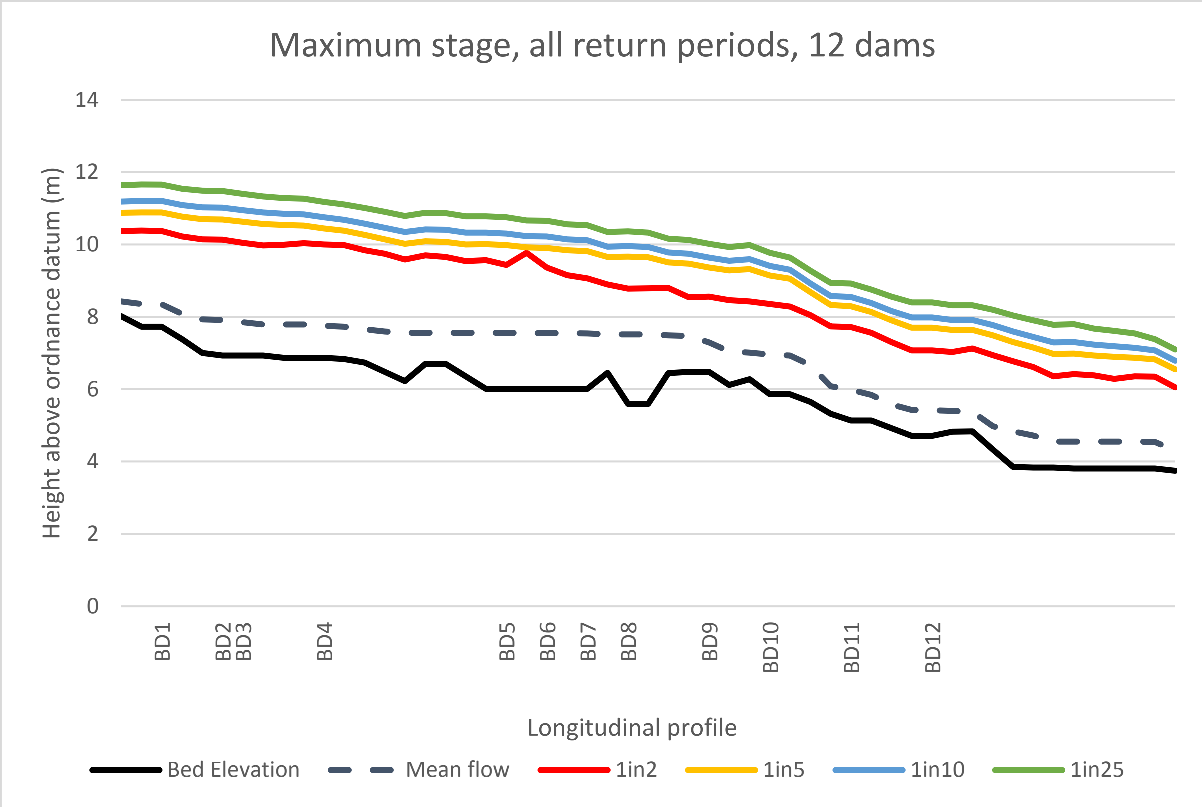

Figure 29: Maximum stage with 12 beaver dams during four return periods, 1in2, 1in5, 1in10 and 1in25 year.

Reductions in channel capacity caused by increased stage will lead to overbank flooding. When flow increases a tipping point occurs, with water entering the 2D domain. The 2D element considers differences in the inundation of the floodplain between scenarios. Figures 30, 31, 32 and 33 show the maximum areas of inundation. At the peak 24,878 cells were inundated with no dams, covering a total area of 223,902m^2. 21,384 cells were inundated with three dams, covering an area of 192,456m^2, and a total of 19,503 cells were inundated with twelve dams, covering an area of 175,527m^2. An additional 48,375m^2 of floodplain is inundated with no dams, compared to that inundated with twelve *C. fiber* dams, an increase of 27.5%. Despite scenario 2 only containing three dams there is still a decrease in the wetted area, see figure 34. An additional 31,446m^2 of floodplain is inundated with no-dams, compared to that inundated with three *C. fiber* dams, an increase of 16.3%.

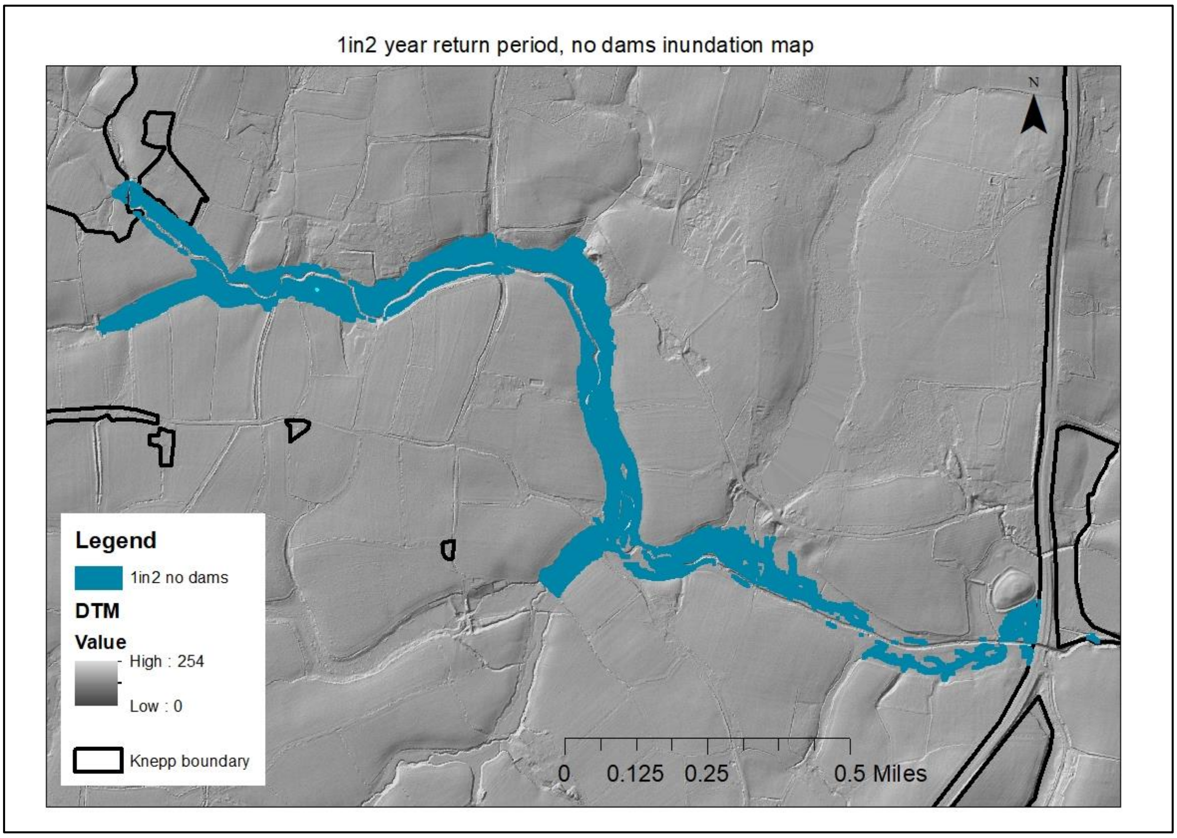

Figure 30: Maximum inundation for 1in2 year return period, scenario 1

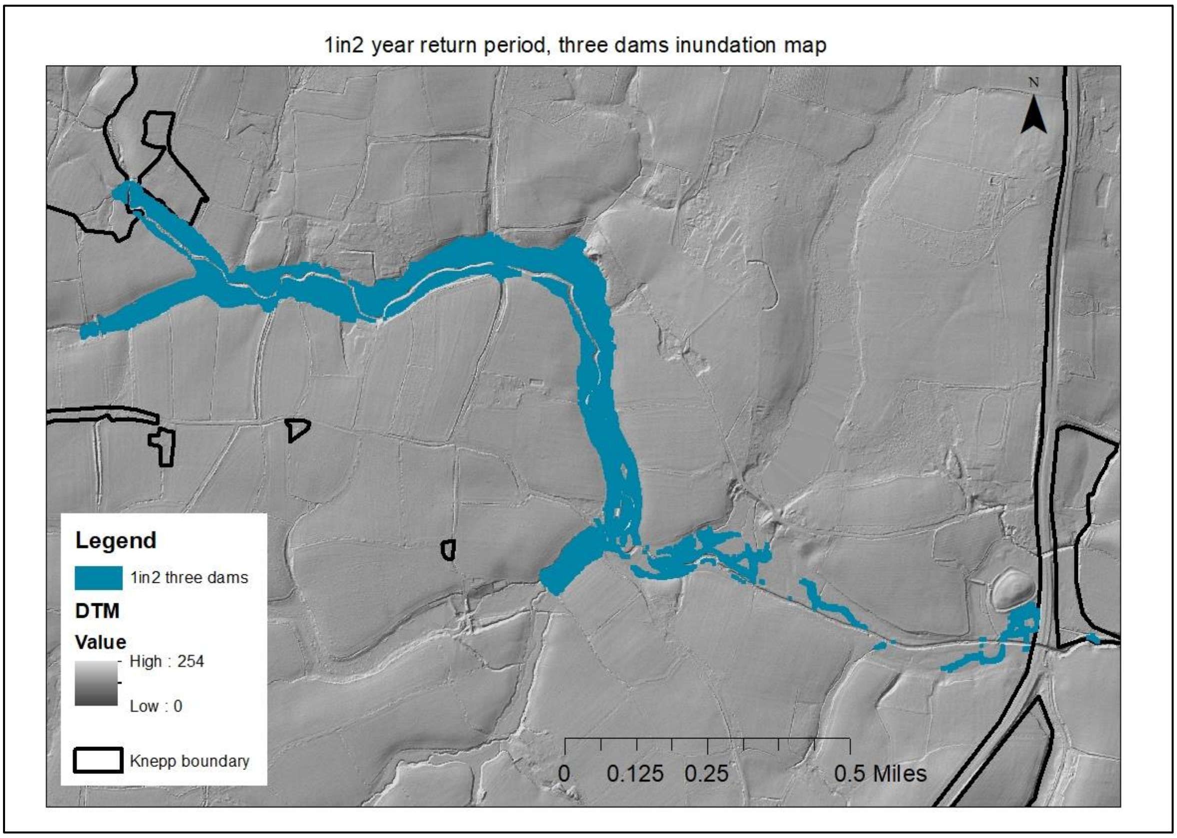

Figure 31: Maximum inundation for 1in2 year return period, scenario 2

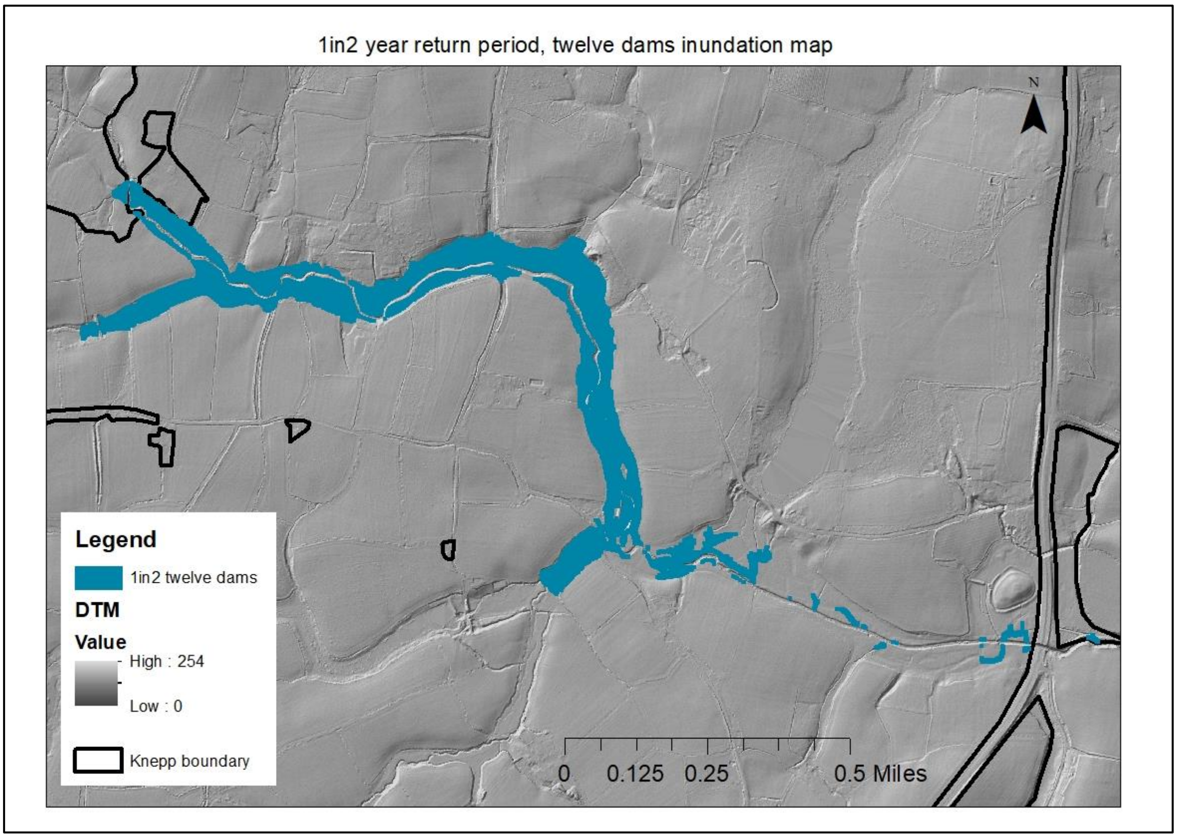

Figure 32: Maximum inundation for 1in2 year return period, scenario 3

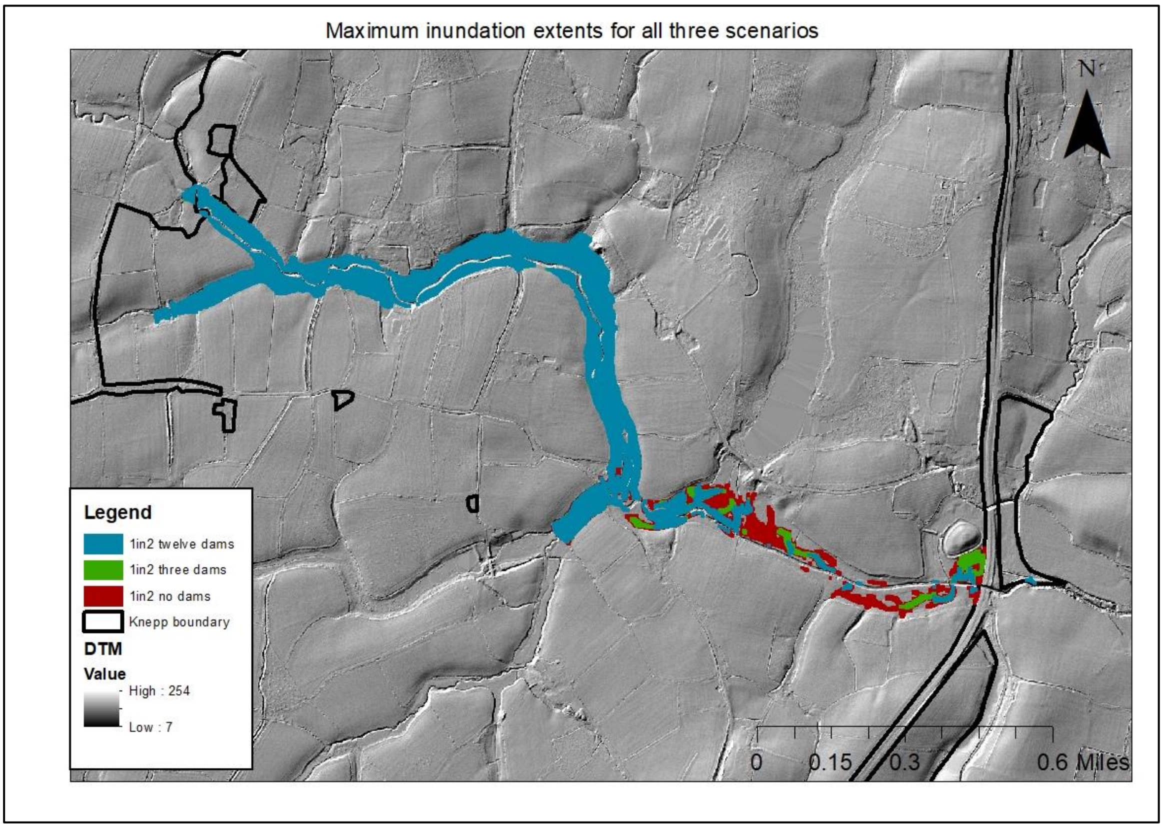

Figure 33: Maximum inundation for 1in2 year return period, scenario 3

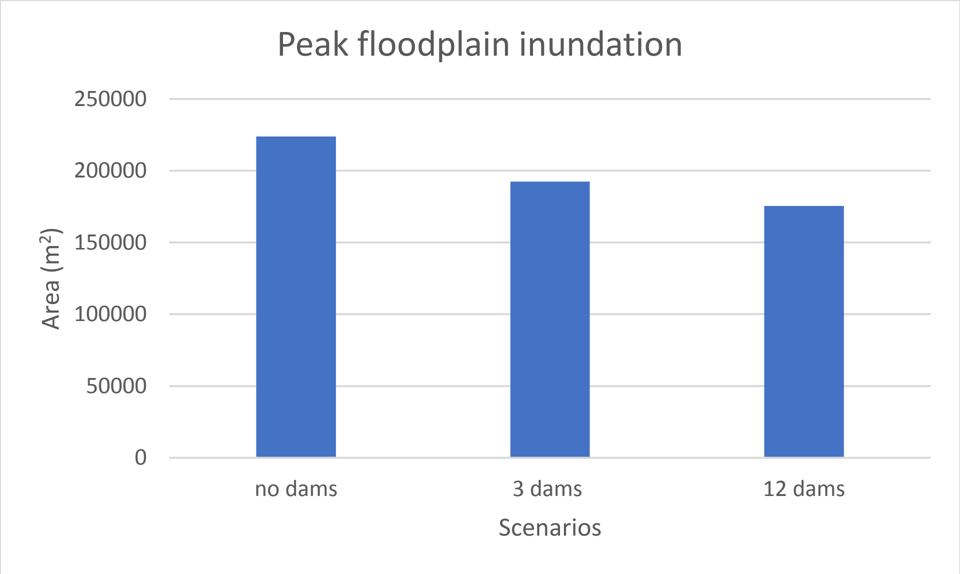

Figure 34: Maximum inundation for each scenario

Flood water is stored further up the catchment with *C. fiber* dams in situ. In the first thirteen hours the 12-dam scenario inundates the floodplain to a larger extent than the other two. This is repeated between no-dams and 3-dams but only for the first four hours, see figure 35. Inundation peaks at 23 hrs with 12-dams, the number of wet cells decreasing steadily from then on. No dams and 3-dams both peak at 26 hrs, but the number of wet cells with 3-dams is less.

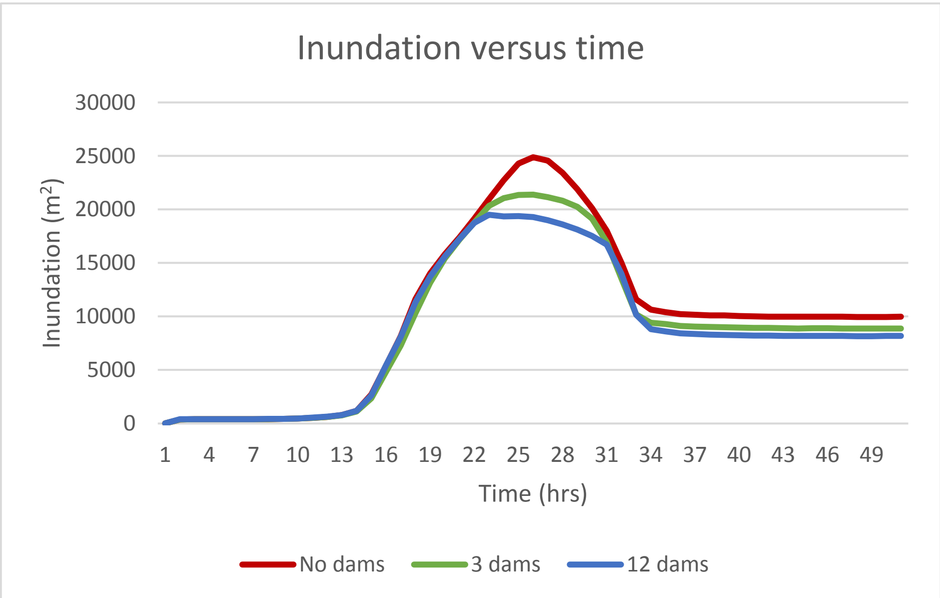

Figure 35: Inundation over time for all three scenarios

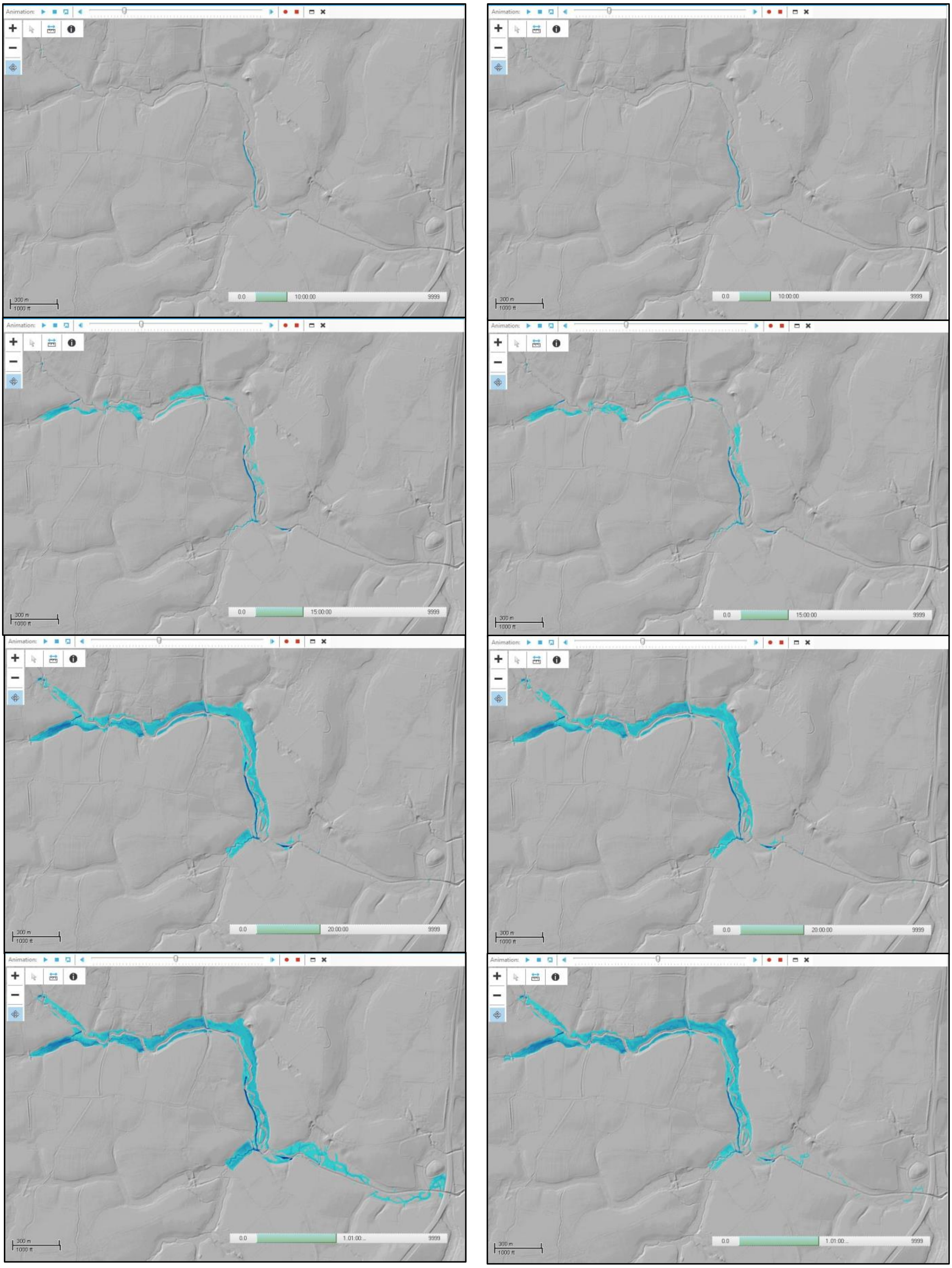

Figure 36: Inundation at four time-steps, 10hrs, 15hrs, 20hrs and 25hrs for no dam and 12 dam scenarios

Figure 36 shows the area of inundation for four-time steps for the no dams and 12 dam scenarios. At 15 hrs the 12-dam scenario has inundated more of the floodplain as water is pushed out of bank, this happens to a lesser extent in the no-dams' scenario with volumes moving further downstream. Analysing stage within the study reach helps to illustrate the increased storage in the upper reaches. Data was abstracted from the model at six cross-sections along the study reach, see figure 37.

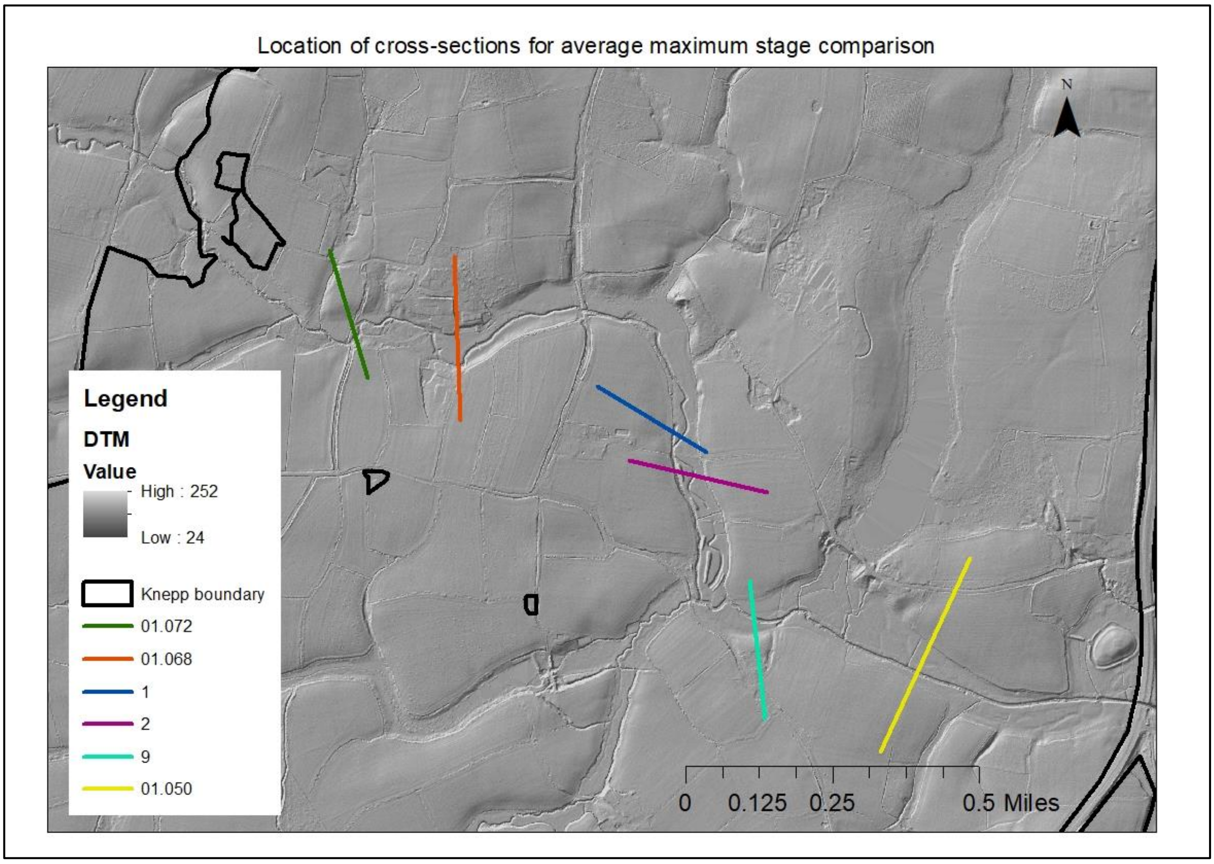

Figure 37: Position of cross-sections for maximum stage comparisons between scenarios within the reach.

Maximum stage at each cross-section was calculated and plotted in a scatter graph, see figure 38. The first four cross-sections, representing the top two thirds of the reach show that the 12-dam scenario has the highest maximum stage of the three. At the lower end of the reach, represented by cross-sections 9 and 1.05, the no-dam scenario has the highest maximum stage. This data matches the inundation map in figure 33. As flood water moves down the reach it hits the dams and inundates the

2D domain. By the time the flood water reaches the lower end of the reach (cross-section 1.05) there is no longer enough flow to inundate the floodplain in the 12-dam scenario. The increased storage upstream and the lack of inundation downstream demonstrate the benefit of *C. fiber* dams in the test reach. Increases in stage and flood storage can be seen with the increase in *C. fiber* activity in the 12-dam scenario compared to the other two. Location of dams is likely to be significant however. Less dams could have more benefit if situated in areas where water can more readily access the floodplain or in locations with higher flood storage capacity. At approximately 2.5km downstream average maximum stage is the same across all three scenarios, see figure 38. After this point maximum average stage drops in the 12 dam and 3 dam scenarios.

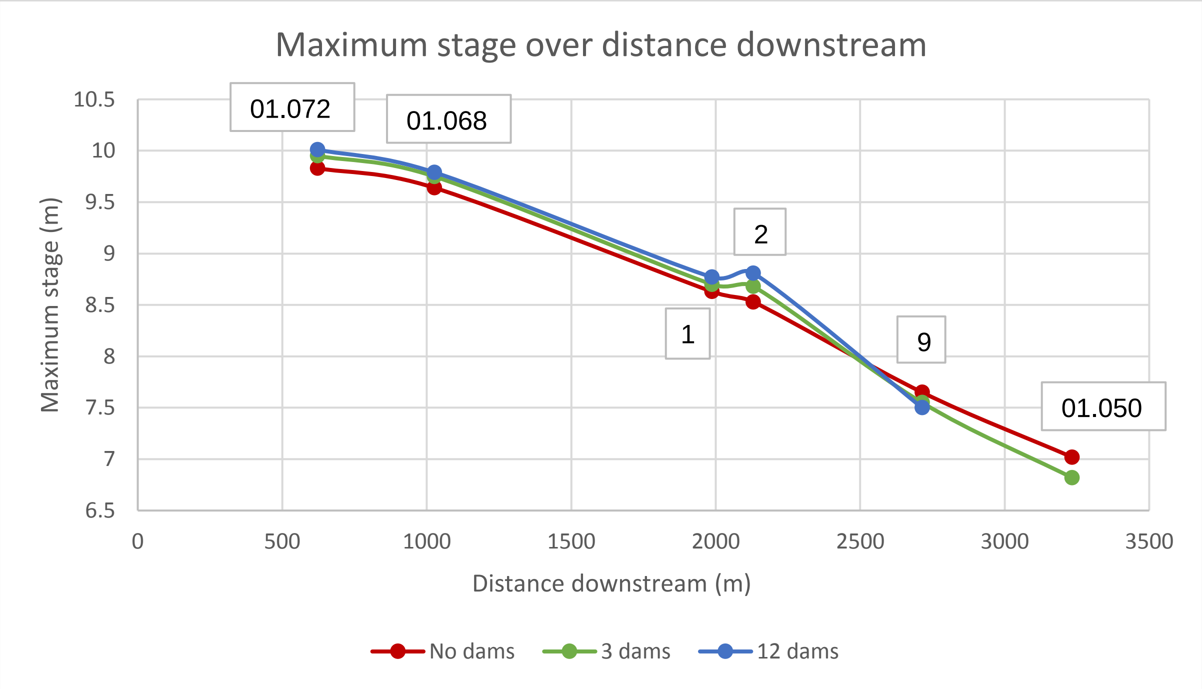

Figure 38: Maximum stage over distance downstream for all three scenarios

Pearson's correlation analysis shows there is a strong positive correlation between distance downstream and maximum average stage. This correlation can be seen between no dams and 12 dams ($r = 0.992$, $p<0.001$) and no dams and 3 dams ($r =$

0.998, p<0.001). The correlation between no dams and 3 dams is stronger due to the smaller difference in stage between the two.

6. Discussion

Beavers greatly affect their environment by constructing dams, canals and lodges. The activity of *C. canadensis* for example, can influence as much as 20-40% of the total of 2nd and 5th order streams, (Naiman *et al*, 1986). *C. fiber* in comparison appear to undertake dam building less frequently, (Gurnell, 1998). Though, when they do, extensive alteration of the local landscape can occur. This was particularly evident at the enclosed Devon beaver project where the construction of 13 dams impounded significant amounts of water. Dams typically consist of tree trunks, branches, twigs, earth, mud and stone, (Gurnell, 1998). Those in the enclosed site comprised mainly of silt and root balls. As watercourse size increases and flows become more powerful, larger woody material is used to strengthen the structure, as was observed on the Otter catchment. *C. fiber* in the enclosed site appeared to purposefully introduce live vegetation such as *Juncus*, sp to stabilise their dams, utilising the binding behaviour of its root systems. This behaviour is dependent on suitable vegetation existing nearby, but highlights the effort taken to strengthen the structures. *C. fiber* typically construct smaller structures than *C. canadensis,* (Gurnell, 1998), but topography and channel size will ultimately dictate length and height. *C. fiber* dams found in Sweden, rarely exceed 15m in length and 1m in height, (Curry-Lindahl, 1967). Medwecka-Kornas and Hawro (1993) reported dams in the Saspowka brook in Poland ranging between 2.5 and 24m in length. It is useful to compare the lengths and widths of those in the enclosed site with these figures.

The mean length of the 5 dams measured in the enclosure was 24.34m, somewhat skewed by the longest dam spanning 49.8m. Topography seeming to define these dimensions. Where the valley is narrower and gradients steeper, dam lengths were more consistent. Where the valley broadened out and the gradient reduced a bigger structure was necessary to acquire the optimal depth of water. Substantial cost is involved in dam building, they would only be expected to build when absolutely necessary, (Hartman and Tornlov, 2005). It is unclear whether *C. fiber,* would expend such effort if free to choose their habitat. It would be pragmatic to bear this in mind when applying the potential storage and attenuation benefits observed in enclosures elsewhere. The few dams investigated in the Otter catchment conformed to the parameters used in the study which was useful for validation purposes. Dams measured at both sites do however, highlight their variability. Making accurate predictions of scale, if not the composition of dams is therefore difficult. Structures within the enclosure for example, are likely to be skewed by the enclosure itself. Whilst it is useful to make comparisons between dam structures and analyse their composition it is difficult to specify a particular analogue for *C. fiber* dams more broadly. It may be more useful to classify their hydraulic impact. This would align with approaches used to determine the influence of Large Woody Debris, (Linstead and Gurnell, 1999). Determining the hydraulic effects of *C. fiber* dams could highlight beneficial geomorphological and ecological feedbacks, (Jakes et al 2017, Naiman et al, 1986). Characterising in-channel beaver dams, where the dam is limited only to the bank full width, does provide a range of dimensions that can be used as a proxy for dam structures, however. Vanderhoof and Clifton, (2018) have applied this theory in Missouri for example, creating Beaver Dam Analogues to aggrade incised streams. An alternative option could be the definition of reach types which could support beaver dam construction instead. Burchsted *et al* (2014), Introduced the concept of beaver-modified reach types in comparison to free-flowing channel reaches. The appraisal of topography, hydrology and vegetation in an area would offer an indication of its suitability for dam building without attempting to predict dam specifications. Modelling carried out in this study highlights the dam building suitability of headwater streams, for example. Predicting the flood storage and attenuation benefits in these areas would be difficult due to the lack of hydrological data for flood modelling and the greater variability in dam structure that would likely occur in these locations. Unless purposefully introduced, *C. fiber* occupy smaller headwater tributaries a lot later in a colonizing process, (Gorshkov *et al*, 2002), in any case.

The frequency, density and size of beaver dams rather than the population density, drive the positive hydrologic, geomorphic and biotic feedbacks (Johnston and Naiman, 1990). When attempting to predict these benefits, it is essential to concentrate on the requirements that necessitate dam building and not the habitat suitability of the animal. *C. fiber* will gravitate towards deeper water which meets their needs without modification, (Beier and Barret, 1987). There are considerable areas of deep water within the study area. Not until the most suitable areas are occupied will *C. fiber* colonise smaller watercourses where dam building is necessary, (Hartman and Tornlov, 2005). With this in mind flood storage and attenuation benefits may take time to realise. Investigating the potential in the mean-time can help support reintroduction bids and evidence the advantages of *C. fiber* in the landscape. Combining several parameters, as was done in this study, identifies available habitat suitable for dam building. Optimal suitability was found in 7.8km of a total of 30.2km of watercourse. A further 17.7km was found to provide sub-optimal habitat, well within the parameters set for this study. Beaver dams located on streams in constricted, steep, upland valleys are more restricted in area. The topography of upland river corridors does not favour the construction of dams or canals. In contrast, wider, lower gradient valleys, support extensive, complex pond and canal systems, (Gurnell, 1998). The study area represents a typical lowland catchment in Sussex. The results from the modelling appear to follow this evidence, with more than 84% classed as suitable for dam building activity. Creating models based on known parameters from existing populations of a species still recovering its former range can be problematic, (Cianfrani *et al*, 2010). It is feasible that the full extent of its potential niche has not yet been recorded, caution therefore needs to be given to predictability models, as some assumptions will inevitably be made. Assuming *C. fiber* will exhibit the same preferences and behaviour as it does elsewhere in Europe has potential flaws. Species reflect the different ecologies in which they evolved, perhaps accentuated by the bottlenecks caused by their mass decline, (Durka *et al*, 2005). Using the enclosed beavers as a guide for example could be unreliable as their behaviour may not mimic that observed in the wild. Data availability at the scale used for this study can be restrictive. The availability of environmental variables and resolution of maps affect the predictive power of suitability models, (Rondinini, *et al* 2011). The woodland data used for example is not a widely available dataset, those available don't provide the required resolution to make accurate calculations of foraging habitat availability. If sufficient data doesn't exist, substantial field data collection will be necessary. This may make the process potentially difficult to repeat on other catchments, particularly those on a larger scale. Regardless of the difficulties, predicting where *C. fiber* might dam is a useful exercise, assuming any reintroduction, (Gaywood, 2017). In the absence of stream depth data, Stringer et al, (2015) created a data set predicting where beavers were less likely to dam in their assessment of potential *C. fiber* colonisation in Scotland. Mapping watercourses without core woodland and more than 6m in width they estimated that a minimum of 87% of watercourse length on mainland Scotland is less likely to provide dam building suitability, (Gaywood, 2017). A similar study in the United States looked at the capacity of riverscapes to support beaver dams, but on a much larger scale, modelling potential dam locations per kilometre, (Macfarlane *et al*, 2017). They were able to validate their results with existing *C. canadensis* dams in the landscape. Macfarlane *et al* (2017) observed no dams in areas where the model predicted none but it over estimated the number of dams considerably. Partly due to inaccuracies in the vegetation classification. Using more detailed data at a local scale, as was done in this study can eliminate some of these accuracies, potentially providing more accurate predictions.

The Environment Agency's 'Working with Natural Processes' Evidence Directory highlights the need to understand how beavers could be used to mitigate flood risk, (Environment Agency, 2018). The multiple benefits beavers bring to a landscape are well evidenced in the literature, their value to flood water storage and attenuation less so. The biggest hydrological impact of beaver's results from their dam building and the impoundment of large volumes of water, (Butler and Malanson, 2005). Beaver dams increase lateral connectivity by linking stream channels, floodplains, and adjacent uplands, increasing longitudinal discontinuities downstream, (Burchsted *et al* 2010). Increased lateral connectivity was evident with *C. fiber* dam scenarios in the flood modelling exercise. When dam building occurs, it increases the area of lentic habitat in a system, particularly those dominated by lotic habitats, (Hering, *et al* 2001). An increase in ponded areas above dam's results in a stepped profile channel, (Giriat *et al* 2016), enhancing lateral connectivity, (Law *et al* 2016), forcing water sideways out of bank and onto the floodplain. This was observed in the results from the flood modelling. Stage and distance downstream affected total inundation in all three scenarios. Linking the channel with the floodplain earlier in the event made use of available storage capacity, demonstrated by the increased maximum stage at the top of the reach with both dam scenarios. Apart from the no-dam scenario, lateral connectivity diminished as flood water moved down the catchment, a result of the attenuated flow. With 12 beaver dams in situ a reduction in wetted cells was attained, a total area of 48,375m^2 of floodplain failed to be inundated compared to simulations with no dams. The benefit being, increased floodplain storage availability in larger or more prolonged events. Benefits will depend on where and how much inundation occurs. *C. fiber* dams located near property could cause local flooding even if benefits are observed downstream. One may expect to have seen a far greater difference in inundation between the 3 dam and 12 dam scenarios, considering the difference in the number of dams. This could indicate the importance of location over number of structures. The Environment Agency's Working with Natural Processes Guidance (2018), finds the benefit of woody dams for example tend to be site specific. Differences in stage throughout the study reach demonstrated the increased capacity for flood water storage in the upper reaches with *C. fiber* dams in situ. The results demonstrate that *C. fiber* can provide a Natural Flood Management function. It was not possible to establish whether this benefit remains with higher return periods as model instabilities prevented these simulations from running. It is assumed that in very large events, such as 1 in 100-year return period the benefits are not as obvious or seen at all. Research by the forestry commission showed that leaky barriers delayed the flood peak in a 1 in 100-

year event by a few minutes, but in larger events features are submerged and their effects less pronounced, (Forestry Research, 2008). Wood placement measures have been shown to slow the progression of flood water, not necessarily reducing peak magnitude, (Thomas and Nisbet 2012). This could be due to water moving onto the floodplain, round the structure and back into the channel. Riparian roughness created by *C. fiber* dams could mitigate this. The storage and attenuation benefits of *C. fiber* dams could increase over time as the wetland behind each dam evolves. Beaver alter plant communities by building dams, (Westbrook *et al*, 2011). Plant propagules are deposited behind structures and extensions to the wetted area encourage wetland vegetation to establish, increasing surface roughness. This was evident at the enclosed site in Devon where *C. fiber* activity opened up the canopy and encouraged ground flora to increase, (Elliot, M J 2018, pers comm 14th June). Even when the dams themselves are saturated and their storage function is diminished, landscape roughness will still provide benefit in terms of attenuating flows. Beaver dams could also combat incision in lowland catchments. Channel incision is part of denudation, drainage-network development and landscape evolution, (Simon and Rinaldi, 2006). Many lowland catchments have been subject to historic navigation and dredging activity to improve conveyance. The resulting incision has led to watercourses losing connectivity with its floodplain. Beaver dams can substantially accelerate the recovery of incised streams by raising bed levels, aiding deposition of sediment behind dam structures, (Pollock *et al*, 2014). As incised reaches recover, sediment supplies decrease, at some point in the recovery sediment inputs and outputs will reach equilibrium. Over time heavily vegetated, multithread channels with slow moving water, undefined banks and no clear transition between bank edge and riparian vegetation can occur, (Walter and Merrits, 2008). This type of watercourse could have the capacity to provide substantial amounts of flood storage, and the complex nature of it, with its innate roughness would slow water down considerably. Evidence suggests such streams were once common throughout the world, (Polvi and Wohl, 2012), created, perhaps, in part by healthy populations of beaver.

7. Conclusion

C. fiber reintroductions are providing valuable evidence into the benefits of rewilding in the UK. The provision of flood storage and the attenuation of flows could result in rewilding projects offering an alternative process led alternative to traditional conservation and river management approaches in the future. The recently published evidence directory on Working with Natural Processes makes multiple references to beaver and their potential to provide wide ranging ecosystem services, flood relief among them, (Environment Agency, 2018). Highlighting these services can help generate support among the public, policy makers and funding bodies. The £2.5 billion investment programme the UK has committed to flood defence between 2015-2021, (Elliot, 2018) could fund further investigations into the benefits *C. fiber* can provide in mitigating flood risk in the UK (Environment Agency, 2018). The flood modelling exercise carried out in this study demonstrates the value of *C. fiber* in the landscape during small flood events. The position and number of the dams in the model however are theoretical. It remains to be seen whether *C. fiber* will colonise and build in these areas if the Knepp beaver introduction is permitted. The approach used in this study could be used to map and measure *C. fiber* dams already in existence in the UK, simulating them in flood models to investigate potential impacts, positive and negative. This could provide data on flood storage provision and inundation before the event occurs. Highlighting areas where problems could arise so that affective mitigation can be implemented.

Evidence has shown enhanced recharge of the riparian aquifer adjacent to beaver ponds in comparison with un-ponded reaches, (Gurnell, 1998). *C. fiber* dams not only attenuate channel flows but modify the hydrology of the riparian zone, driving seepage into the banks, bed and riparian zone and releasing water during dry periods (Giriat et al. 2016). This highlights a particular benefit *C. fiber* could provide in the study area, the Adur suffering from low summer flows. Further research could investigate the benefit of water stored behind beaver dams on helping to maintain base flows and how this might alleviate the impacts of drought.

The value *C. fiber* can provide to Natural Flood Management will take time to be realised due to the lag between initial colonisation and occupying those areas where flood storage and attenuation benefits can be or want to be realised. This can be managed to a certain extent by enclosing *C. fiber* in areas where that benefit is needed most, as is the case above Lydbrook in the Forest of Dean, (Guardian, 2018). It can be argued however, that a rewilding approach, truly allowing natural processes to take place provides the most gains in the long term.

8. References

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Castor fiber as a Natural Flood Management tool in a Sussex Catchment

Author: Gareth Williams (gareth.williams @environment-agency.gov.uk)

Queen Mary University of London

MSc Environmental Science: Integrated Management of Freshwater Environments

Introduction

Natural Flood Management (NFM) is increasingly being looked at as an alternative to traditional methods of flood risk management. *C. fiber* reintroductions in the UK, motivated initially by conservation are starting to see the benefits to flood storage and attenuation. This study examines the potential to predict dam building locations in a Sussex catchment and what influence *C. fiber* dams have on stage and inundation in different flood events.

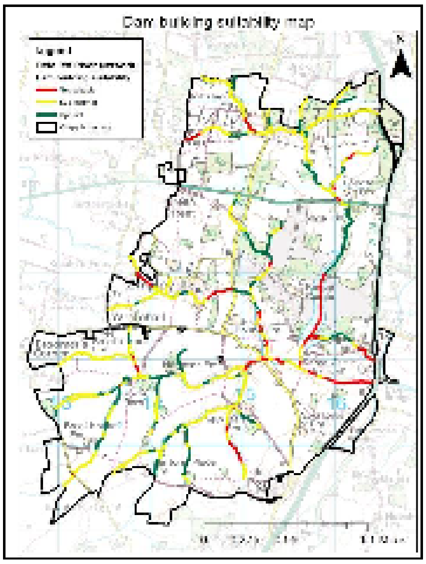

Figure 1: Dam building suitability map

Method

GIS modelling using researched parameters was carried out to identify suitable dam locations. These were built into a 1D/2D flood model to examine the differences in stage and inundation in different flood event and dam configuration scenarios.

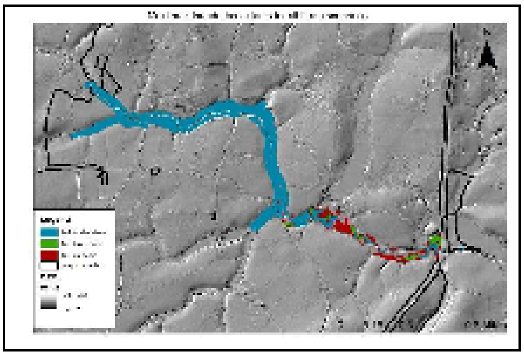

Figure 2: Floodplain inundation map

Results

- 25.6km of watercourse were found to provide suitable conditions for dam building
- 48,375m^2 less floodplain was inundated with 12 *C. fiber* dams in place
- Stage is higher in the upper reach as water is pushed onto the floodplain earlier by dam structures

Conclusion

C. fiber can provide a Natural Flood Management ecosystem service. This can be predicted using GIS and flood modeller systems. This method can be used to predict the impacts, positive and negative of *C. fiber* dams in existence

Supervisor(s) Dr. Gemma Harvey (g.l.Harvey@qmul.ac.uk)
School of Geography
Queen Mary, University of London
www.geog.qmul.ac.uk