An assessment of the potential for Eurasian beavers to naturally colonise the Cairngorms National Park

Risks and opportunities associated with their presence

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Cover photo: River Luineag in Cairngorms National park © Alan Puttock

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Overview and Scope

The scope of this project was designed in collaboration with Cairngorms National Park (CNP) to assess the potential for Eurasian beavers (*Castor fiber*) to recolonise the CNP from existing populations, in the catchments of the River Tay and Forth. This document also reviews the predictable impacts this species is likely to have on the landscape, ecology and land use practices within the CNP. It is based on extensive field experience of beavers in Scotland gained by Dr Roisin Campbell-Palmer, including information gained from the most recent survey of beaver territories within Tayside. This information has been combined with modelling systems developed by the University of Exeter to define both habitat suitability and beaver dam capacity.

This assessment investigates how beaver activity could enhance and complement existing habitat, land use, ecological, socio-economic and species-specific management considerations. It assesses the potential routes of natural colonisation and makes recommendations regarding the forward planning requirements for beavers.

Status of Beavers in Scotland

Britain represents the very western extent of the Eurasian beaver range. Archaeological evidence of their former presence such as gnawed timber and bones in combinations with trade records, illustrations and other historic references, testifies to their former widespread occurrence throughout Britain (Coles, 2006; Manning et al., 2014). By the 15th century, the trade in Scottish beaver furs was no longer economically viable due to over-exploitation. While oral tradition recalls their presence in and around Lochaber until the late 1700's, there is no further mention of their presence after this time (Coles, 2006). The Eurasian beaver is therefore believed to have become generally extinct in Scotland, by the 16th century (Kitchener & Conroy, 1997).

The case for reintroducing the Eurasian beaver to Scotland has been debated for over 20 years. Beavers and beaver reintroduction issues are summarised in the Scottish Natural Heritage (SNH) 'Beavers in Scotland' report (Gaywood, 2015). In May 2009 five Norwegian beaver families were released into the Knapdale Forest of Argyll, as part of the officially sanctioned Scottish Beaver Trial (SBT). Although this official beaver trial concluded in 2014 by then beavers resulting from further unauthorised releases or escapes in the east of Scotland had extensively colonised the River Tay. In 2016, the Scottish Government stated that they were minded to allow both populations to remain. In 2019, European Protected Species (EPS) was accorded to beaver populations in Knapdale, Argyll and the Tayside and Forth catchments which extended to any populations naturally colonising other areas from these core zones. The Scottish Government made it clear at that time that no further unauthorised releases would be tolerated or permitted and a NatureScot Beaver Mitigation Scheme was established to provide practical advice and support to landowners and interest groups. A management framework has been developed in which a range of beaver mitigation tools and interventions can be provisioned including tree protection and dam management. Under specific criteria landowners may apply for a licence for lethal control. In the first year of protection, 39 lethal control licences were issued and a reported 87 beavers were culled as a result. A cull of a further 115 was recorded in the second year of this schemes operation (NatureScot 2020, 2021). While government policy currently allows the translocation of beavers in Scotland within their current range the only recent applications to do so occurred as part of the population augmentation exercise for the Knapdale population and more recently to move a family into a series of pool systems at the Argaty Red Kite Centre, near Doune. This last project represents the first successfully permitted translocation of beavers within a catchment where the species is otherwise free-living. Other unauthorised releases of beavers have also resulted in the establishment of populations in other parts of Scotland, England and Wales. While this wider restoration has generated much excitement in the nature conservation community (Brazier et al., 2020; Law et al., 2016, 2017; Stringer & Gaywood, 2016) certain land interest groups have expressed strong concerns regarding the species ability to modify landscapes in a manner unfavourable to their interests. NatueScot are hosting a workshop to develop the National Beaver Strategy which may be in place and help steer decision making later this year.

The SBT, Tayside Beaver Study Group, Beaver-Salmonid Working Groups have all published their findings, and along with ongoing data collection, landowner and interest group engagement through the Scottish Beaver Forum and the NatureScot Beaver Mitigation Scheme significant data and experience informed the decision-making process regarding beaver presence and management in Scotland. In 2019, the Scottish Government gave European Protected Species (EPS) to beaver populations in Knapdale, Argyll and the Tayside and Forth catchments (referred to as Tayside beavers in this report) which extended to animals naturally colonising from these zones, but that further unauthorised releases would be an offence and not permitted at present. The NatureScot Beaver Mitigation Scheme was established to provide mitigation advice and support to various landowners and interest groups. A management framework has been developed in which a range of beaver mitigation tools and interventions can be provisioned including tree protection and dam management. Under specific criteria landowners may apply for a licence for lethal control. In the first year of protection, 39 lethal control licences were issued and a reported 87 animals dispatched, and a further 115 in the second year (NatureScot 2020, 2021). Note that government policy currently allows the translocation of beavers in Scotland within their current range, this has only occurred as part of the population augmentation of Knapdale beaver population and most recently a family to the Argaty Red Kite Centre, near Doune. This represented the first successfully applied and permitted within catchment translocation of beavers in Scotland. Beavers colonising the Tayside and Forth catchments form the largest population currently in Britain, with other wild breeding populations originating from unauthorised releases existing in Kent, Devon and Avon areas. DEFRA/ NE have recently held a consultation process to develop future beaver strategies in England. An announcement on the future legal status of beavers in England is expected this year.

As the bulk of the beaver population which now inhabits Britain developed from unauthorised sources its precise initial composition (e.g. numbers and sex ratios) is unknown. This paucity of information also applies to a broad range of other issues impacting its status such survival data and the impact of random culling. In Scotland the SBT, Tayside Beaver Study Group and Beaver-Salmonid Working Group have all published their findings. These studies in combination with ongoing research projects, stakeholder involvement and wider engagement through the Scottish Beaver Forum and the NatureScot Beaver Mitigation Scheme are all assisting the decision-making process regarding beavers in Scotland.

The Beaver and its Recovery

Modern beavers exist only in the northern hemisphere and are represented by two extant species; the Eurasian *C. fiber* and the North American/ Canadian *C. canadensis*. Though highly similar in appearance, behaviour, ecology and biology, they diverged from a common ancestor ~7.5 million years ago and possess different chromosome numbers and cannot hybridise (Horn et al., 2014). Both are large, semi-aquatic highly territorial rodents which live in family units, and exhibit specialised behaviours such as tree felling and damming. They are a highly adaptable species and can modify many types of natural, cultivated and urban habitats to suit their needs (Campbell-Palmer et al., 2016; Pachinger & Hulik, 1999).

Overhunting for its castoreum glands, fur and meat in historic times meant that Eurasian beaver by the end of the 19th century was on the verge of extinction with an estimated ~1,200 individuals remaining in a scattering of isolated populations (Nolet & Rosell, 1998). While the species has recovered its existence in part throughout much of its former range due to hunting regulation, protective legislation, natural expansion and proactive translocations and is now believed to number in excess of 1.5 million, a fraction of its former status (Halley et al., 2020). The first known beaver translocations, from Norway to Sweden, occurred in 1922, and since then, there have been more than 205 recorded translocations which have restored beavers to 25 nations where they were formerly extinct (Halley et al., 2012). Overtime this process incorporated a mix of official and more unorthodox returns such as that undertaken in Belgium (Verbeylen, 2003). Large viable populations of North American beavers are also now well established on a Eurasian scale as a historic lack of initial knowledge that the two species were not the same. In more recent times further escapes of this form from zoos or game parks have also occurred. Though both species function the same ecologically, as a non-native removal and sterilisation programmes exist particularly in Finland and parts of Germany, they are thought to have been successfully removed from parts of France and Luxenberg (Halley et al., 2020).

Review of Beaver Environmental and Socio-Economic Impacts

Beavers have the ability to modify ecosystems profoundly to meet their ecological needs, with significant associated hydrological, geomorphological, ecological and societal impacts. While this report principally reviews current state-of-the-art scientific understanding of the beavers role as a quintessential ecosystem engineer from a European perspective it also incorporates North American research.

Appendix 1 adapts and updates a recent comprehensive and peer reviewed literature review (Brazier et al., 2021) which summarises how beaver impact:

- Ecosystem structure and geomorphology
- Hydrology and water resources
- Water quality
- Freshwater ecology
- Humans and society

It concludes by examining future considerations that may need to be resolved as beavers further expand in the northern hemisphere with an emphasis upon the ecosystem services that they can provide and the associated management that will be necessary to maximise the benefits and minimise the conflicts arising from their behavioural activities.

In addition to the information presented in the appendix, since its publication additional beaver and fish interactional work has been published. Globally, freshwaters are the most degraded and threatened of all ecosystems. In northern temperate regions, beaver (Castor spp.) reintroductions are increasingly being used as a low-cost and self-sustaining means to restore river corridors. River modification by beavers has been well documented to increase availability of suitable habitat for fish, including salmonids. The key benefits of beaver activity for salmonids that are commonly cited include increased habitat heterogeneity and quality. Ponds created upstream of beaver dams provide juvenile overwintering and rearing habitat and can be a critical refuge for larger fish. The beneficial response from a fisheries perspective is usually quantified in terms of increased fish abundance, condition and growth, and overall productivity. Conversely, the principal negative consequence of beaver activity often cited is the potential for dams to impede or delay salmonid migration, particularly for upstream moving adults during their migration to the spawning grounds.

The modification of fluvial habitats due to beaver activity may influence the availability of suitable habitat for fish, including Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*), which in Scotland are species of high economic value. Increases in the size and geographical extent of Scottish beaver populations as a result of successful recruitment, further reintroductions, escapes, and illegal releases has caused concern in relation to their potential impact on salmonid fisheries. A recent study by Needham et al., (2021) investigated the response of young brown trout to habitat modification by beavers. By modifying fluvial habitat, beavers had profound effects on a local brown trout population through the creation of impounded reaches that promoted a higher abundance of larger size classes. Invertebrate abundance was higher in the modified stream and community composition differed between the modified and control streams. This study provides important insight into the possible future effect of beavers on British freshwater ecosystems.

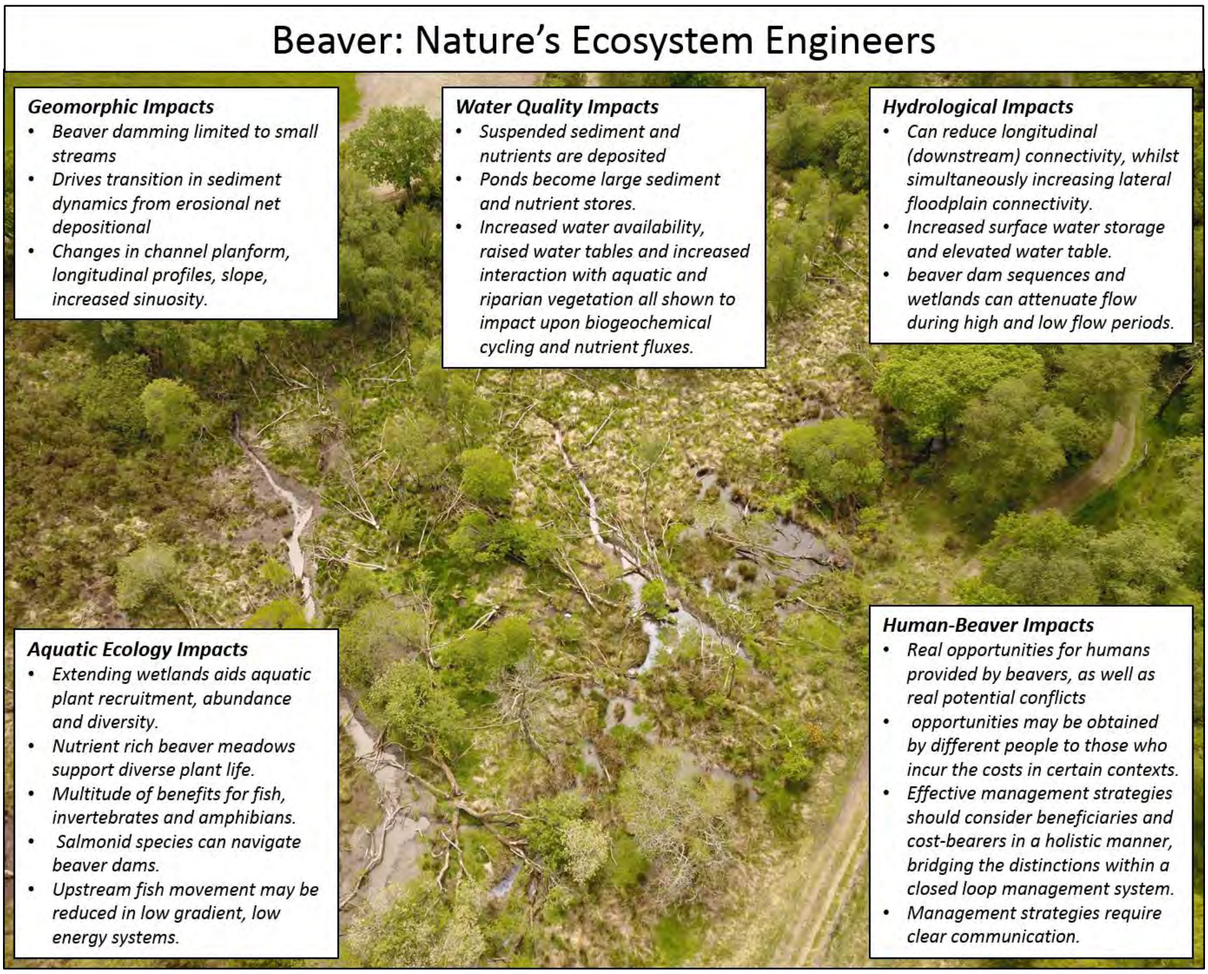

Figure 1. A visual summary of beavers impacts as ecosystem engineers.

Desktop Analysis of Beaver Habitat and Dam Capacity in Cairngorms National Park

Desktop analysis prepared by Dr Alan Puttock to provide understanding of beaver habitat and dam capacity prior to field visits.

Summary

The habitat suitability and the capacity for beavers to dam channels within the study areas was assessed using beaver modelling tools developed by researchers at the University of Exeter (Graham *et al*., 2020). These modelling tools consist of a Beaver Habitat Index (BHI) model and a Beaver Dam capacity (BDC) model.

There is a requirement to complete an analysis of rivers catchments to assess their suitability for supporting populations of beaver. Beaver habitat suitability is determined primarily by vegetation suitability which has been classified nationally using a Beaver Vegetation Index (BVI) as well as access to water bodies. Together these two factors have been incorporated into a Beaver habitat Index model (BHI). BHI has been run nationally to develop a high resolution (5m) continuous raster product that can inform local decision making with regard to beaver reintroduction. BHI classifies habitat suitability from 0 (No access to vegetation - not suitable) to 5 (Highly Suitable)

Beavers are also well known as ecosystem engineers, having the capacity to change environments to suit their needs. The beaver engineering activity that has the greatest capacity to modify ecosystems is dam building. Dam building and the creation of ponded surface water has the ability to bring benefits (i.e. for biodiversity, water storage, flow attenuation) but also potentially management and conflict (i.e. localised inundation of land, blocking of critical infrastructure). BDC classifies reaches from no capacity for dam building to a pervasive capacity for damming.

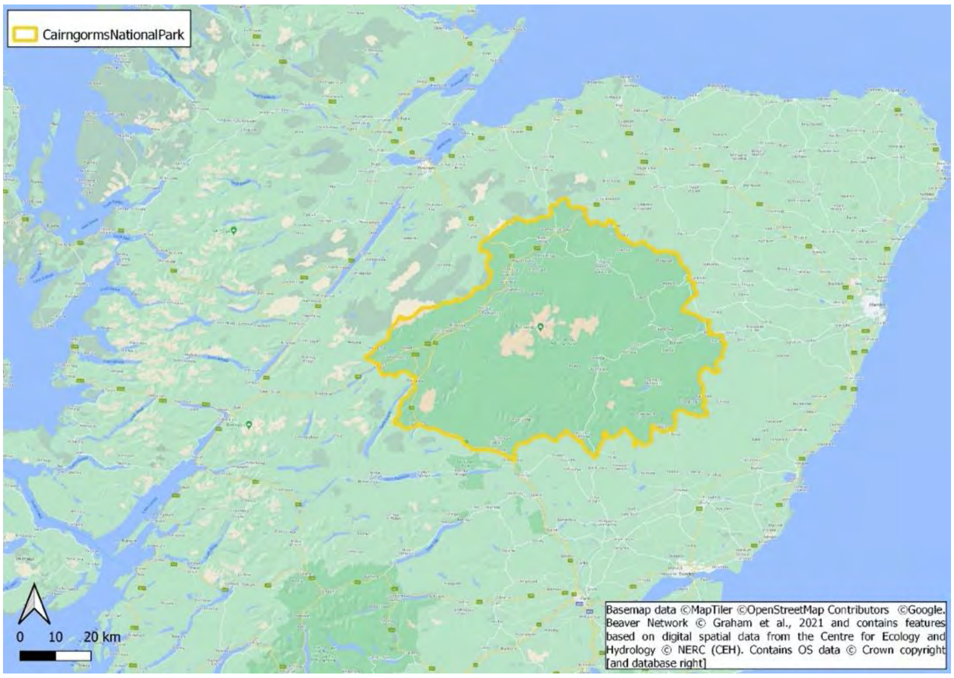

Figure 2. Cairngorms National Park boundary.

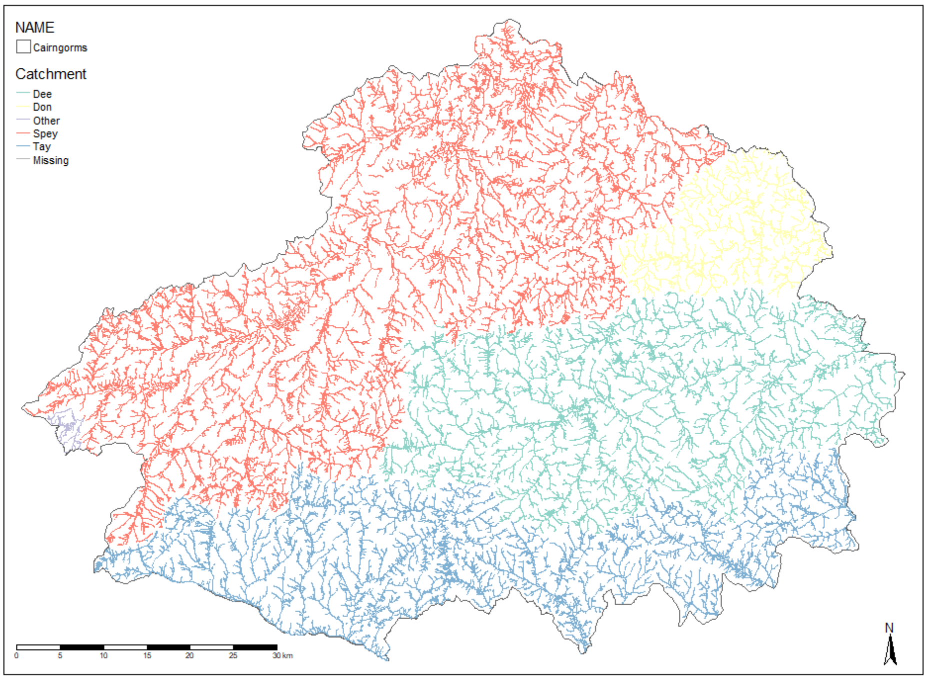

Figure 3. Main river systems in Cairngorms National Park

Modelling of beaver habitat suitability

Beaver Habitat Suitability Modelling

Summary Description: Production of a continuous description of habitat suitability for beaver. First a vegetation suitability index is created using multiple high-resolution spatial datasets from Ordnance Survey, CEH and Copernicus will be combined to provide detailed land cover/vegetation information which is classified based on empirical field observation of beaver habitat and preference. Vegetation suitability is combined with additional parameters describing stream networks and water bodies. Whilst beaver habitat suitability is primarily defined by vegetation suitability, beavers also require water for security and movement. Therefore, accessibility to water bodies (i.e. channels, ponds, and lakes) will also determine the viability of beaver occupancy and therefore are required to classify habitat accurately.

Outputs: This product provides a high-resolution (5m cell size) resource (raster Tiff format) for describing habitat suitability for beaver. This dataset can allow the user to explore which landscapes were most (or least) suite to beaver reintroduction and also to understand where habitat enhancement might be useful to support future reintroduction.

Beaver Vegetation Index (BVI –prerequisite for BHI modelling)

Vegetation is important for classifying beaver habitat (Hartman, 1996; John et al., 2010; Pinto et al., 2009; St-Pierre et al., 2017). It was therefore critical to establish a reliable Beaver Vegetation Index (BVI) using nationally-available spatial datasets. No single dataset contained the detail required to depict all key vegetation types. Therefore, a composite dataset was created from: OS VectorMap data (Ordnance Survey, 2018), The Centre for Ecology and Hydrology (CEH) 2015 land cover map (LCM) (Rowland et al., 2017), Copernicus 2015 20 m tree cover density (TCD) (Copernicus, 2017) and the CEH woody linear features framework (Scholefield et al., 2016).

Vegetation datasets were assigned suitability values (zero to five). Zero values were assigned to areas of no vegetation i.e. buildings and values of five were assigned to favourable habitat i.e. deciduous woodland. Values were assigned based on a review of relevant literature (Haarberg & Rosell, 2006; Jenkins, 1979; Nolet et al., 1994; O'Connell et al., 2008), field observation and comparison with satellite imagery. Vector data were converted to raster format (resolution of 5 m). TCD data were resampled to 5m and aligned with converted vector layers. An inference system was used to combine these four raster datasets to create the BVI. The workflow prioritises the reliability followed by the highest value data.

Examples of highly suitable land (graded 5) include broad-leaf woodland, mixed woodland and shrub; examples of suitable vegetation (graded 4) include shrub and marsh; examples of moderately suitable (graded 3) include coniferous woodland, marsh, shrub and unimproved grassland; examples of barely suitable (graded 2) include reeds, shrub and heathland and boulders, neutral grassland; examples of unsuitable (graded 1) include heather, acid grassland, unimproved grass and boulders, bog; examples of no accessible vegetation (graded 0) include shingle and sand, buildings, rock, urban, freshwater and saltwater.

2.3. Beaver Habitat Index model (BHI)

Whilst vegetation is a dominant factor in determining habitat suitability for beaver, so is proximity to a water body (Gurnell et al., 2008), with beavers being strong swimmers, using water bodies both to provide security, as a means of escaping predators and to access foraging areas. It is thought that most foraging occurs 10 m of a watercourse/body (Haarberg & Rosell, 2006), and rarely above 50 m (Stringer et al., 2018). However, greater foraging distances have on occasion been observed and as in Macfarlane et al., 2015 it has been accepted as a maximum distance in which the vast majority of foraging occurs. Therefore, to determine suitable habitat for beaver incorporating both BVI vegetation suitability and water accessibility a 100m buffer was applied to water bodies. To do this the OS mastermap river network and OS vector in land water bodies were combined to get the best readily available national waterbody and water course coverage.

Whilst BVI was run nationally on a 5m scale it is best viewed as a preparatory step for BHI (and later BDC) modelling and is superseded in usefulness by the BHI dataset. It is strongly recommended that most analysis and management applications use BHI i.e. if there is an area of preferred vegetation such as willow woodland, more than 100m from a waterbody it is thought inaccessible to beaver and therefore does not form suitable habitat.

Both BVI and BHI use a scoring system of zero to five (Table 1). Scores of five represent vegetation that is highly suitable or preferred by beavers and that also lies within 100 m of a waterbody. Zero scores are given to areas that contain no vegetation or are greater than 100 m from a waterbody. It is important to note that the habitat model considers terrestrial habitat where foraging primarily occurs and that watercourses themselves are also scored zero. It is also important to note that all scores above 1 contain suitable vegetation.

Table 1. BVI and BHI value definitions. It is critical to note that all values above 1 are suitable for beaver.

BVI and BHI Values	Definition
0	Not suitable (no accessible vegetation)
1	Not suitable (unsuitable vegetation)
2	Barely Suitable
3	Moderately Suitable
4	Suitable
5	Highly Suitable

Beaver Habitat Index maps and summary statistics for study area

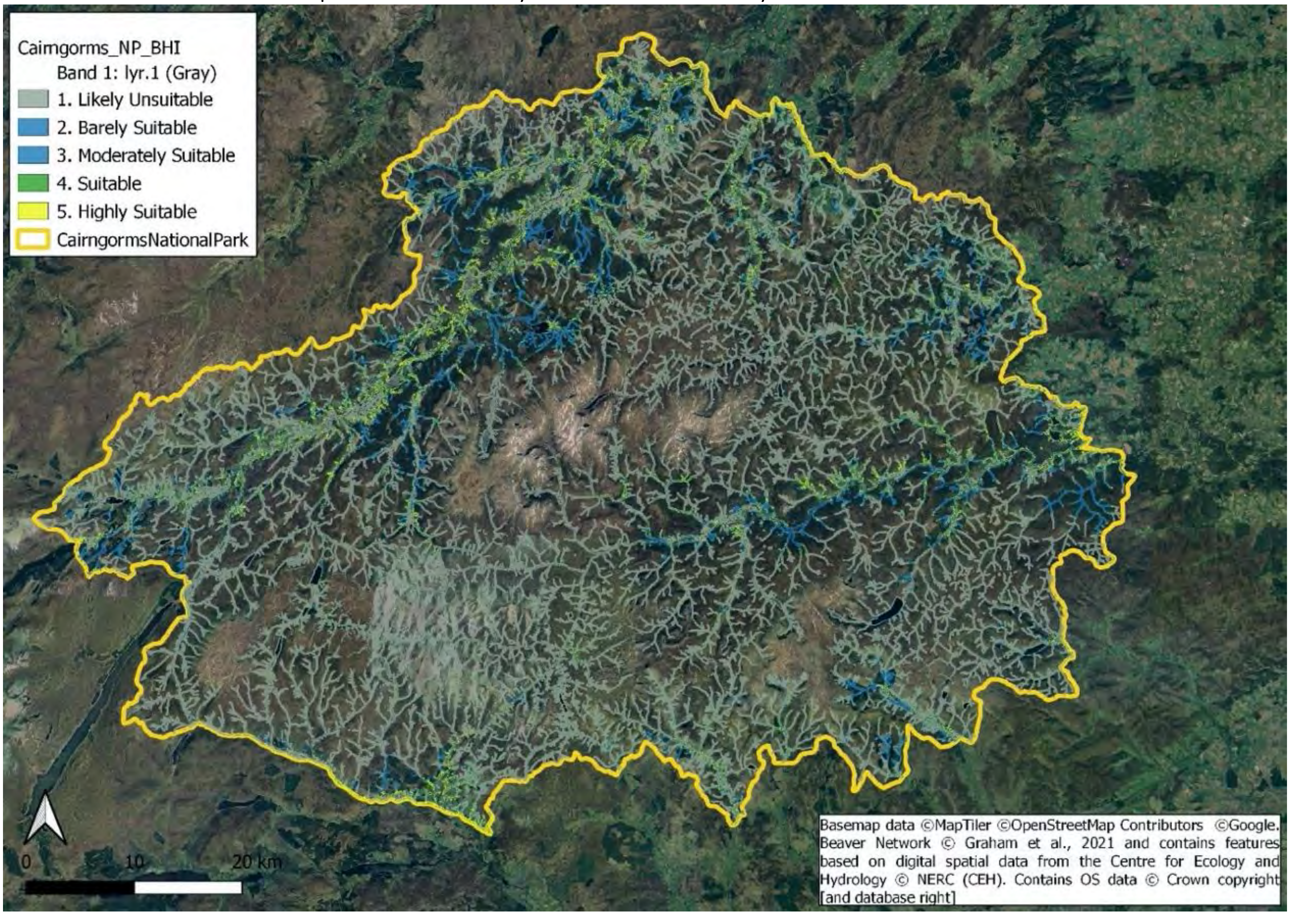

Figure 4. Beaver Habitat Index at a 5m resolution across entire National Park. Contains Ordnance Survey data © Crown Copyright 2007 and some features of this map are based on digital spatial data licensed from the Centre for Ecology & Hydrology, © NERC (CEH). Aerial imagery: Open-Source Google imagery © OpenStreetmap (and) contributors CC-BY-SA.

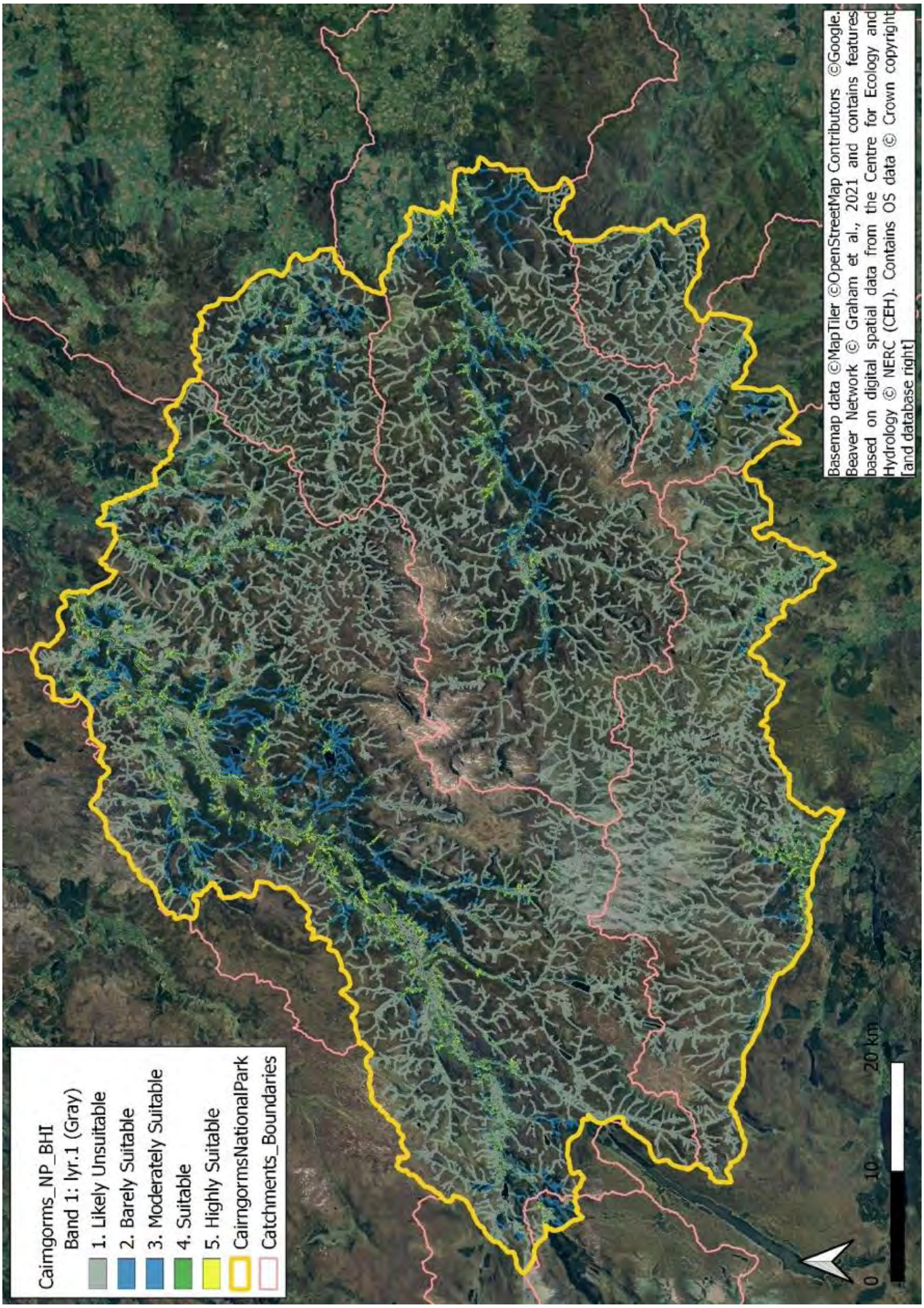

Figure 5. Beaver Habitat Index for National Park with SEPA catchment boundaries Highlighted. Contains Ordnance Survey data © Crown Copyright 2007 and some features of this map are based on digital spatial data licensed from the Centre for Ecology & Hydrology, © NERC (CEH). Aerial imagery: Open-Source Google imagery © OpenStreetmap (and) contributors CC-BY-SA.

Table 2. Beaver Habitat Index summary statistics for riparian vegetation along channels in Cairngorms National Park.

Beaver Habitat Index Category	Total (km)	Percentage (%)
Highly Suitable	1053.5	10.7
Suitable	952.9	9.7
Moderately Suitable	789.7	8.0
Barely Suitable	1158.1	11.8
Likely Unsuitable	5858.7	59.7

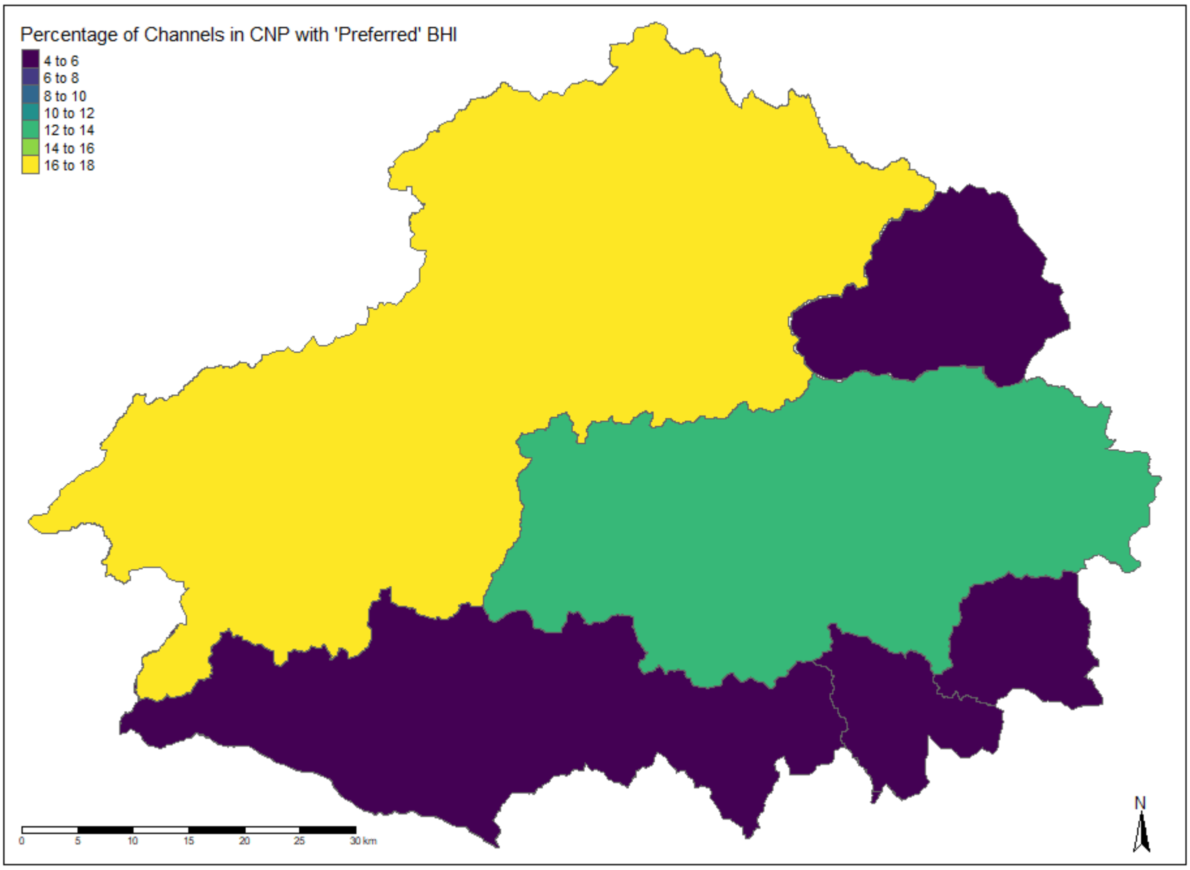

Figure 6. Percentage of channels ineach of the main catchments, with 'prefferred' beaver habitat along their banks. Illustrates habitat is most suitable in the Spey followed by the Dee.

Table 3. Beaver Habitat Index summary statistics for riparian vegetation along channels in Cairngorms National Park separated by catchment.

Catchment	Beaver Habitat Index	Total (km)	Percentage (%)
Dee	Highly Suitable	261.9	11.7
Dee	Suitable	188.9	8.4
Dee	Moderately Suitable	127.5	5.7
Dee	Barely Suitable	171.0	7.6
Dee	Likely Unsuitable	1488.0	66.5
Don	Highly Suitable	21.8	3.7
Don	Suitable	107.6	18.1
Don	Moderately Suitable	93.3	15.7
Don	Barely Suitable	125.0	21.1
Don	Likely Unsuitable	245.4	41.4
Spey	Highly Suitable	670.6	14.8
Spey	Suitable	539.2	11.9
Spey	Moderately Suitable	439.7	9.7
Spey	Barely Suitable	650.6	14.3
Spey	Likely Unsuitable	2245.6	49.4
Tay	Highly Suitable	91.8	3.8
Tay	Suitable	107.0	4.5
Tay	Moderately Suitable	120.2	5.0
Tay	Barely Suitable	206.6	8.6
Tay	Likely Unsuitable	1870.5	78.1
Other	Highly Suitable	7.3	17.9
Other	Suitable	10.2	24.8
Other	Moderately Suitable	8.9	21.8
Other	Barely Suitable	4.7	11.4
Other	Likely Unsuitable	9.9	24.1

Beaver Dam Capacity modelling

Beaver Dam Capacity (BDC) model summary

The Beaver restoration assessment tool (BRAT) was developed in North America (Macfarlane et al., 2014, 2015) to determine the capacity for river systems to support Beaver dams. The BRAT model has been further deployed in a range of different river systems to aid both Beaver recolonisation and beaver dam analogue led restoration. The BRAT model not only provides an invaluable tool for designing effective, empirically based, restoration strategies but it also indicates where Beaver dams might be constructed and therefore where they may cause potential management/conflict issues. The BRAT model structures the framework of the model around the river network itself and using a fuzzy logic approach which builds in the considerable uncertainty that is associated with beaver habitat/dammable reaches. Furthermore, it provides a range of output values to predict the dam capacity which has implications for beaver preference towards a given location. We have therefore used the BRAT framework to develop an optimised beaver dam capacity (BDC) model for Great Britain.

The BDC model estimates the capacity of river systems to support dams at the reach-scale (c.a. 150m). The model also highlights reaches that are more likely to be dammed by beaver and estimates the number of beaver dams that could occur for a catchment at population carrying capacity. As such, this highly detailed tool would provide understanding of where dams are most likely to occur and in what densities, supporting future work on the conflicts and opportunities that might accrue from beaver reintroduction.

The model infers the density of dams that can be supported by stream reaches (111.1m ± 52.5) across a catchment. Using low-cost and open-source datasets, the following attributes are calculated for each reach: (i) stream gradient, (ii) low (Q80) and high flow (Q2) stream power, (iii) bankfull width, (iv) stream order, and (v) the suitability of vegetation, within 10m and 40m of the bank, for beaver dam construction. These controlling variables are combined using a sequence of inference and fuzzy inference systems which follow an expert-defined rules system that allows for the considerable uncertainty often associated with these types of complex ecological processes.

Each reach was classified for damming capacity using five categories from none, defined as no capacity for damming to pervasive where a maximum capacity of 16-30 dams could theoretically be constructed in a km of channel. It is important to note that the model assumes both reach and catchment population carrying capacity for beaver. Therefore, in reality the maximum number of dams indicated in a category class is unlikely to occur. A full list of BDC classifications is included in Table 3.

Table 4. BDC classifications and definitions.

BDC Classification	Definition
None	No capacity for damming
Rare	Max capacity for 0-1 dams/km
Occasional	Max capacity for 1-4 dams/km
Frequent	Max capacity for 5-15 dams/km
Pervasive	Max capacity for 16-30dams/km

Beaver Dam Capacity Model maps for the study area

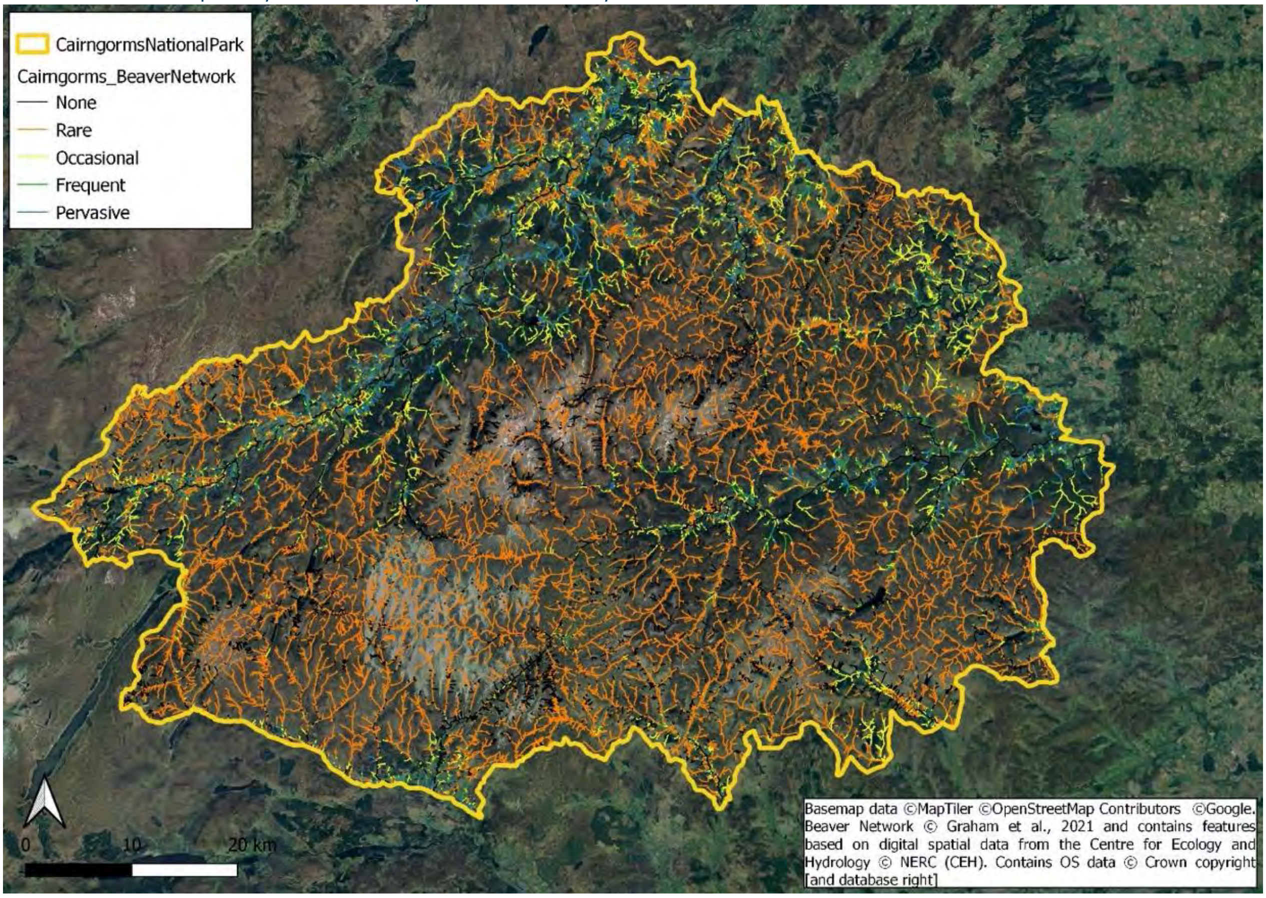

Figure 6. Beaver Dam Capacity model results for National Park. Contains Ordnance Survey data © Crown Copyright 2007, and some features of this map are based on digital spatial data licensed from the Centre for Ecology & Hydrology, © NERC (CEH). Aerial imagery: Open-Source Google imagery © OpenStreetmap (and) contributors CC-BY-SA.

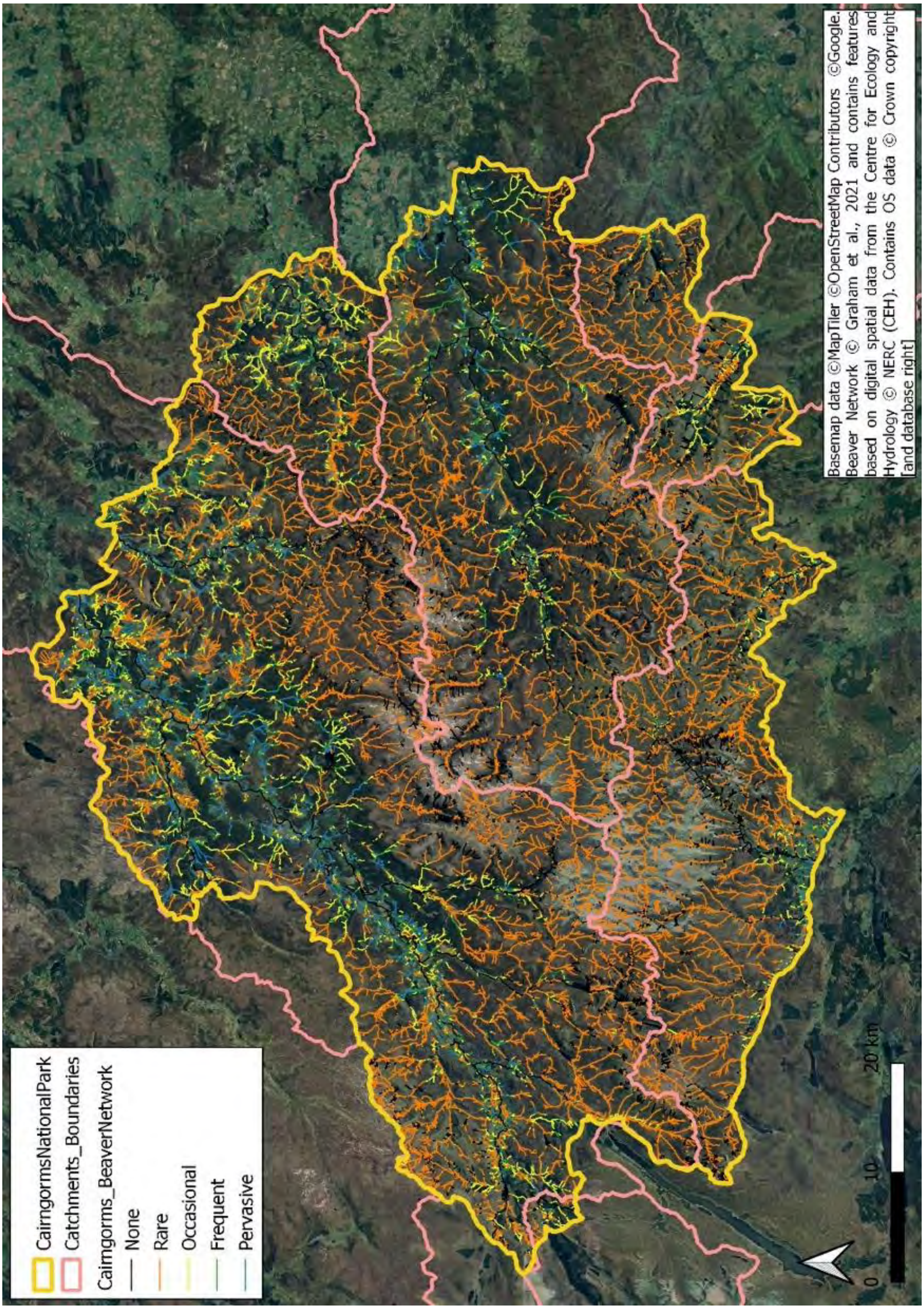

Figure 7. Beaver Dam Capacity model results and catchment boundaries. Contains Ordnance Survey data © Crown Copyright 2007, Licence number 100017572 and some features of this map are based on digital spatial data licensed from the Centre for Ecology & Hydrology, © NERC (CEH). Aerial imagery: Open-Source Google imagery © OpenStreetmap (and) contributors CC-BY-SA.

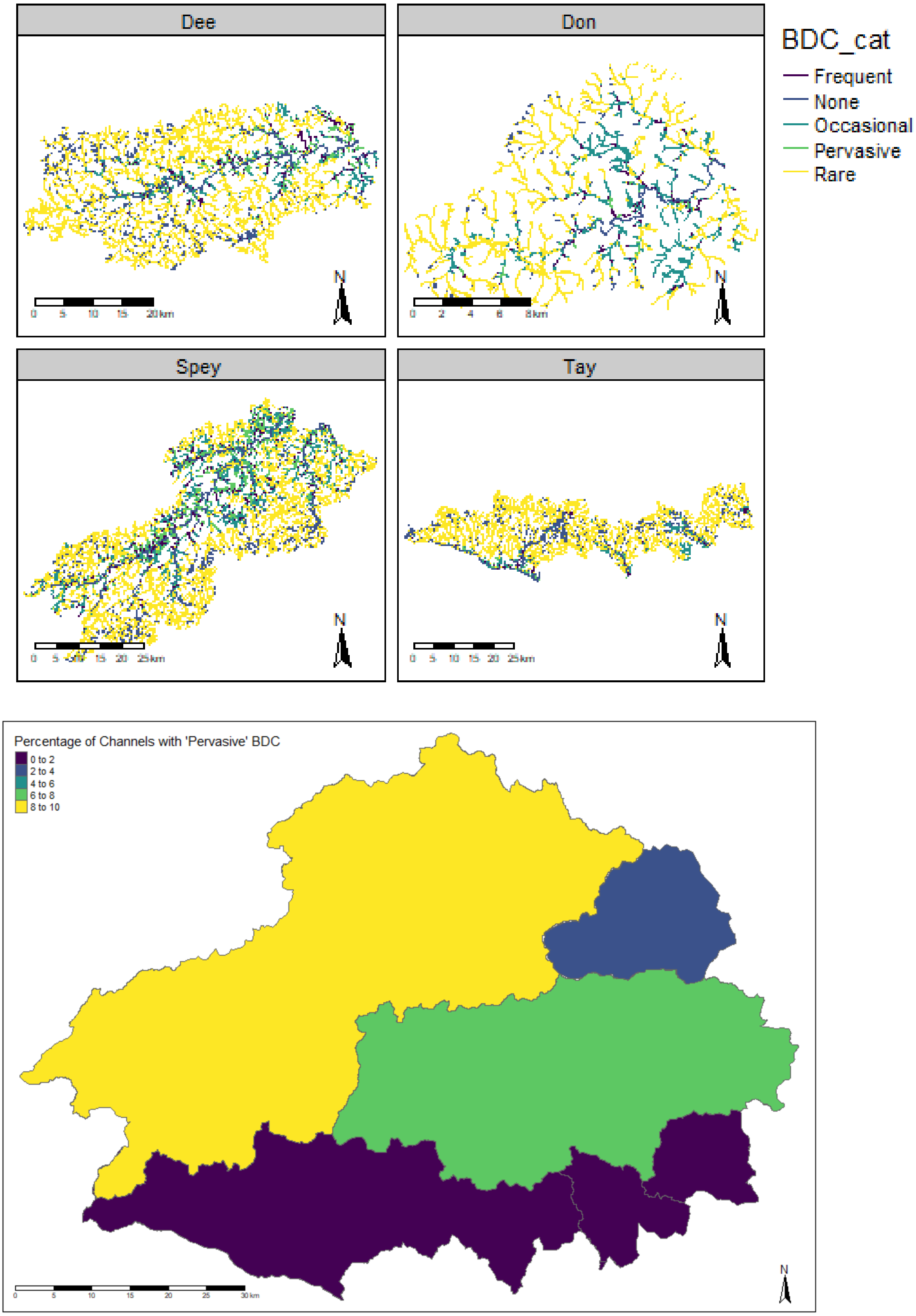

Figure 8. Summary BDC figures. Top BDC for each of the main river catchments, bottom % of channels in each catchment with 'Pervasive' dam capacity. Illustrating this is highest in Spey.

Table 5. Beaver Dam Capacity Summary Statistics for Cairngorms National Park.

BDC Category	Total (km)	Percentage (%)
None	1695.4	17.3
Rare	5884.5	60.0
Occasional	1238.4	12.6
Frequent	429.1	4.4
Pervasive	565.3	5.8

Table 6. Beaver Dam capacity summary statistics separated by river catchment.

Catchment	BDC_cat	Total (km)	Percentage (%)
Dee	None	408.3	18.2
Dee	Rare	1393.1	62.3
Dee	Occasional	208.6	9.3
Dee	Frequent	102.3	4.6
Dee	Pervasive	124.9	5.6
Don	None	51.1	8.6
Don	Rare	345.8	58.3
Don	Occasional	155.3	26.2
Don	Frequent	29.0	4.9
Don	Pervasive	11.9	2.0
Spey	None	718.9	15.8
Spey	Rare	2456.9	54.0
Spey	Occasional	711.7	15.7
Spey	Frequent	261.3	5.7
Spey	Pervasive	396.9	8.7
Tay	None	507.6	21.2
Tay	Rare	1674.9	69.9
Tay	Occasional	150.4	6.3
Tay	Frequent	33.2	1.4
Tay	Pervasive	30.2	1.3
Other	None	10.9	26.5
Other	Rare	12.9	31.6
Other	Occasional	12.4	30.3
Other	Frequent	3.3	8.0
Other	Pervasive	1.5	3.6

Beaver habitat and dam capacity model conclusions and next steps

As may be expected of a British upland, the majority of watercourses within the CNP were deemed to be most likely unsuitable or at most barely suitable for beaver habitation (71.5 % of all CNP watercourses). This primarily reflects a lack of suitable vegetation but also in many areas their steep, rocky characteristics of upland streams. However, as summarised in Table 2, there was still 20.4 % of watercourses, approximating 2000km where habitat was classified as 'Highly Suitable' or 'Suitable'. Along with an additional 8% (789.7km) of watercourses classified as moderately suitable these figures show that there are extensive within the National Park that would support a sizeable wild beaver population. Spatially the model maps and summary statistics illustrate that suitable areas are clustered primarily in the relatively low lying and well vegetated sections of the Spey and to a lesser extent the Dee, Don and Avon.

Modelled trends in the capacity for beavers to dam rivers within the National park (and thus have greatest impact both positive and negative) closely mirror those of the habitat index. With 77.3 % of the parks watercourses being deemed unsuitable or only very rarely going to support beaver dams. Most steep mountainous streams within the park did not have the habitat to support beaver territories and with a steep gradient and high stream power wouldn't support frequent or pervasive creation of dam sequences. The greatest dam capacity was as with habitat exhibited in the lower gradient and better vegetated lowland sections of the Spey, Dee, Don and Avon. However, it is also critical to note that beavers can only typically dam relatively small streams (typically 1-4 order) before stream power becomes too high. Thus, as illustrated in model results the main river sections of i.e. the Spey, whilst exhibiting high quality habitat which could support beaver territories, the main channels would be too powerful to dam.

Summary of Field Based Assessment

Fieldwork was undertaken in the week commencing 28h July by Dr Róisín Campbell-Palmer, Prof Richard Brazier and Dr Alan Puttock. Fieldwork had two main aims

1) Assess the viability of identified theoretical routes by which the wild Tay population could potentially naturally spread into Cairngorms National Park
2) Assess the suitability of habitat and watercourses within Cairngorms National Park for beaver. Thus providing a starting point for understanding if beavers were in the National Park where there impacts (both positive and negative) may occur.

Desk and Field Based Assessment of the Ability of Beavers to Naturally Spread from Existing Areas

Beavers are known in Scotland from 3 distinct areas, representing different origins and populations status;

- Knapdale, Argyll - Official reintroduction, augmented population of Norwegian and Tayside animals, breeding population situated in a relatively closed catchment with no evidence of colonisation outside released area (confirmed by field survey).
- Beauly, Inverness – Unofficial release / accidental escapes at two separated clusters, Bavarian origin, some animal removal but presence and breeding still evident, low numbers in a relatively closed system, no evidence of colonisation spread.
- Tayside and Forth, Perthshire & Stirlingshire – Unofficial release / accidental escapes at multiple locations, predominantly Bavarian with eastern European origin, breeding and rapidly expanding population on open linear systems.

Therefore, for the purpose of this study, only the Tayside population was investigated as a potential population source for beavers naturally colonising the CNP.

Summary of 2021 beaver activity in Tayside and Forth catchments

In 2020 and 2021 a comprehensive survey was undertaken (with NatureScot funding) to provide an updated picture of the state and spatial extent of the wild beaver population (Campbell-Palmer et al., 2021). The full report can be accessed at [NatureScot Research Report 1274 - Survey of the Tayside Area Beaver Population 2020-2021 | NatureScot] and a brief summary of key findings is included below:

- Beaver activity was recorded throughout large parts of Tayside, and to a lesser extent, the Forth catchments. Colonisation of new catchments was not observed, despite sightings of individuals, although range has expanded.
- 251 active beaver territories were identified. This estimate is based on the mapping of field signs with territory boundaries determined through a combination of modelling and expert judgement. Given the close proximity and densities of some families in some river sections, it is possible that more than one family is present in some identified territories, leading to an underestimation of the number of beaver territories in those sections.
- The growth in territory number represents a 120 % (more than doubling) increase compared to the minimum of 114 territories reported in 2017/2018.
- Up to 20 % of a breeding beaver population can be comprised of singletons, which act as potentially large-distance dispersers. Such pioneer dispersers, especially those living on minor watercourses on the fringes and outside of the main surveyed area, may not be captured in these survey results as they can live relatively unobtrusively.
- Furthermore, some additional active territories are likely to exist within Tayside, especially on minor watercourses which were not covered in this survey given the considerable extent of such areas, many of which would not have held beavers.
- The beaver range had expanded from that recorded in the 2017-2018 survey although there was considerable variability in this in part due to some areas being abandoned, potentially due to licensed control.

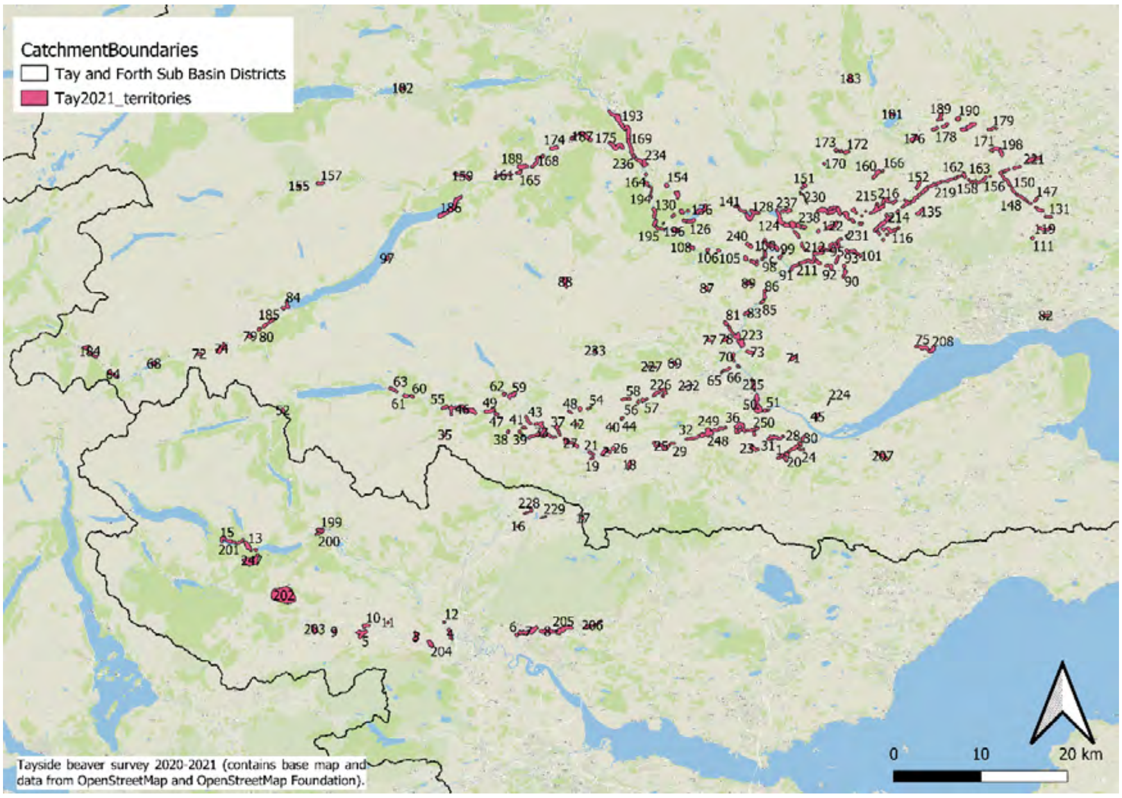

Figure 9. Tay & Forth estimated territories 2021 (adapted from Campbell-Palmer et al., 2021).

Main potential access routes into Cairngorms considered

Based upon mapping analysis and local knowledge, multiple theoretical routes by which the current Tayside population of beavers could naturally spread to the Cairngorms were considered and are summarised spatially in Figure 9. A key focus of fieldwork was further assessing the viability of these theoretical routes which are discussed individually in more detail below.

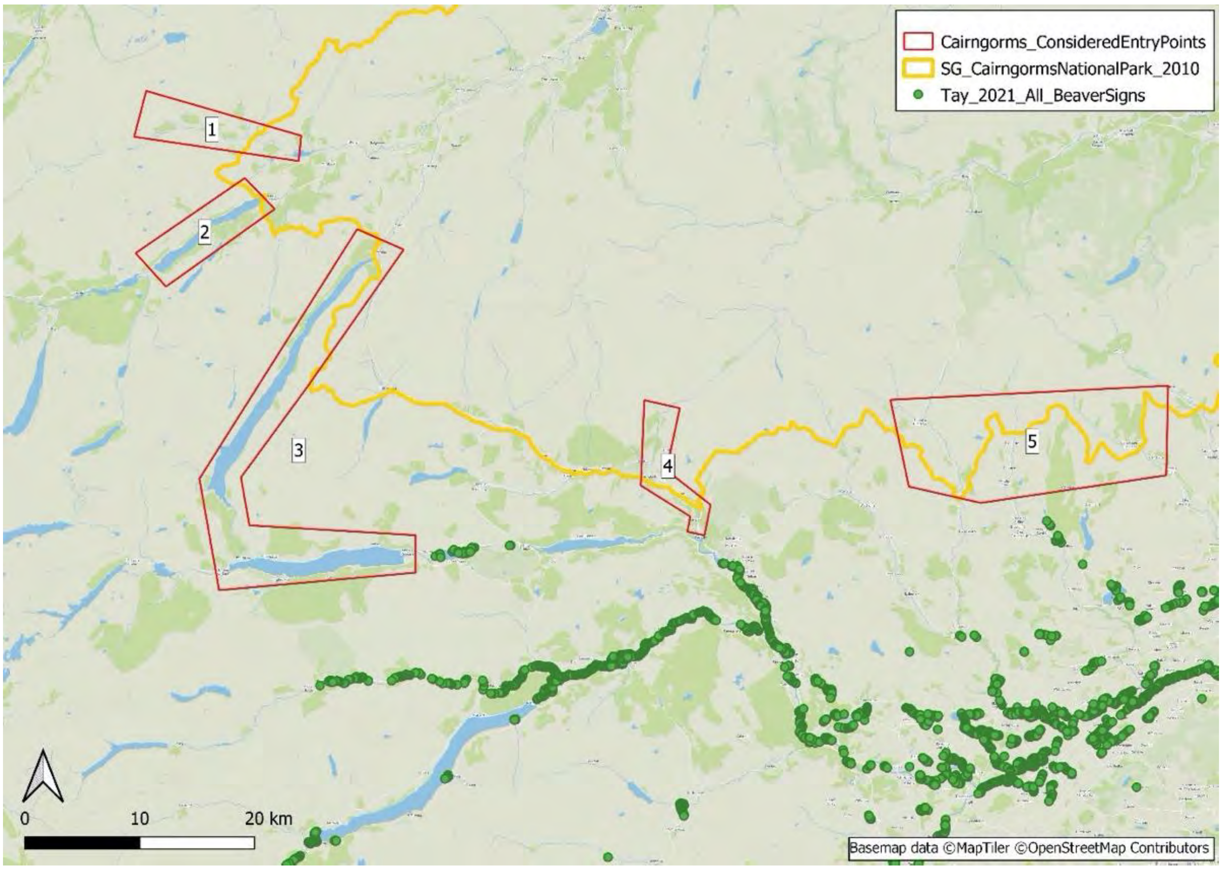

Figure 10. The location of nearby Tayside beavers (Campbell-Palmer et al., 2021) and theoretical routes into Tay considered.

1. Via headwaters of River Spey

Given the River Spey is one of the significant rivers in CNP, its head waters, situated in the west were investigated for their likely connectivity, habitat suitability and nearest known beaver presence. Though not directly connected, the known breeding Tayside beaver distribution extends as far west as the River Fillian, approaching Tyndrum and Glen Lyon for example. Direct accessibility given water course connectivity and topography is unlikely, though as multiple headwaters and lochs exist throughout this area some investigation was warranted. The nearest known beaver presence is south at Dunalastair Water, with no direct water dispersal route to the Spey headwaters, unless most likely via Loch Rannoch and then Loch Ericht (see below).

Field survey confirmed the terrain of the upper Spey to be very challenging for beaver colonisation, and no signs of their presence were recorded. The habitat in these upper areas are generally unsuitable given its lack of vegetation, suitable bank structure, general hydrology and exposed climatic conditions. Although there are limited patches of suitable woodland but general hydrology and climatic conditions makes it highly unlikely beavers would utilise this area unless significant population pressure existed downstream. Even then this would probably only ever represent beavers living at the edge of their range. Overall though is seems very unlikely beavers could disperse into CNP via the River Spey headwaters.

Figure 11. River Spey above Garvamore. Very open terrain, sandy based substrate makes it unlikely beavers would reside in this area due to lack of forage and more challenging burrow construction opportunities. Beavers could readily use as a dispersal route.

Figure 12. River Spey above Laggan. Similarly lack of immediately riparian vegetation and shelter construction may be challenging. Beavers are likely to use as a dispersal route.

Figure 13. River Spey at Laggan. Parts of the upper Spey do have significant stretches of woodland which would be readily utilized by beavers and most likely where beavers would be found should they colonise the river.

2. Via Loch Laggan

In a similar fashion to reasons presented above, the ability of beavers to disperse via Loch Laggan was considered. The nearest known beaver presence is on Dunalastair Water (though see discussion below). There is no direct water dispersal route through water and this route would appear to therefore be an unlikely access option into the Cairngorms from existing populations elsewhere. Loch Laggan was briefly checked for beaver field signs but nothing was recorded. As a colonisation route it offers entirely suitable habitat. The top of the loch has a low artificial dam but this would be no obstacle to dispersing beavers. Although the loch shoreline is stony and sandy in many parts, there are dense pockets of natural regen along its banks which would afford a plentiful food supply. Water fluctuations and low gradient bank slopes on this loch would lead to varying distances for beavers to access forage and are less favourable for burrow and lodge construction.

Figures 14. Loch Laggan, inflow end with extended low gradient stony and sandy shoreline, trees set well back and example of broadleaf woodland pockets.

3. Via Loch Ericht, Loch Rannoch and Loch Tummel

The Tayside beaver population has been present on the lower River Tummel (connecting directly to the River Tay) for many years, with recorded annual breeding and evident dispersal. Active territories exist in close proximity (see Figure 9). While theoretically the River Tummel and its tributaries such as the River Garry and Tilt, represents the most direct riverine routes into the CNP it is evident that the Pitlochry Dam (Figure 13) is a significant and effective barrier to their dispersal. Although an active territory has been recorded below Dunalastair Water for many years with at least two individuals recorded on camera traps previously, there is no evidence that they have ever bred or expanded out from this area even though there is plenty of highly suitable habitat. Visual observations this summer which were not conclusive only recorded a single adult present. It is therefore extremely unlikely that beavers will disperse into the Cairngorms via this route without an active release on either Loch Rannoch, Dunalastair Water and/or upper River Tummel. Any dispersing beaver from a project of this sort would still have to navigate multiple artificial dams, including the structure at Loch Rannoch (Figure 16). In the event that they manage to bypass this and then access Loch Ericht (Figure 15) this water body is also governed by another significant dam complex.

Figure 14. Pitlochry Dam is acting as the significant barrier to main Tay populations spreading into Cairngorms.

Figure 15. Loch Tummel and the connecting waters represent suitable beaver habitat. Breeding animals here are likely to rapidly expand and could be a source of dispersing individuals for future colonisation.

Figure 16. Dam below Loch Rannoch representing a further challenge to dispersing individuals.

Figure 17. Bridge of Gaur above Loch Rannoch where habitat suitability drops though low density populations could be supported.

Figure 18. River Erict, Rannoch represents a potential dispersal route though highly challenging and unlikely significant numbers of animals would successfully disperse regularly which would be required to realistically realise viable future populations in the Cairngorms.

Figures 19. Ericht dam again representing fairly hostile and challenging dispersal routes.

4. River Tilt

The River Tilt is in close proximity to existing beaver populations on the River Tummel. Without the obstruction of the Pitlochry dam this water course would have quite readily been colonised by beavers in its lower reaches. Other obstacles beyond this are that any dispersing beavers would have to travel to the headwaters of the River Tilt, cross open upland and then drop down into the River Dee. The Tilts headwaters have a generally steep and rocky aspect with a powerful central channel. Although there are dispersed stands of broad-leafed trees along its banks colonising its current environment would be a challenging exercise for even a robust beaver population which was present in an immediately adjacent environment.

Figure 15. River Tilt has patches of suitable forage but banks are steep and rocky, long-term residential population seems unlikely here unless at the very lower end.

Figure 21. Headwaters of River Tilt is not suitable habitat for beavers, though they could disperse through it but any beavers entering this river are most likely to seek habitat downstream. The chances of population density here ever producing enough pressure to push beavers into the head water and to the headwaters of the River Dee.

5. River Isla and Neighbouring Channels/Burns

The River Isla offers perhaps the most realistic option for beavers to technically enter the CNP given the proximity and increasing northerly colonisation of the Tayside beaver population as recorded in the last two surveys (Campbell-Palmer et al., 2018, 2021). The River Isla, especially nearing its head waters offers a challenging landscape for beavers, especially given its increasingly rocky banks and powerful water flows. Tributaries of the River Dee, such as Clunie Water, lay geographically close (no direct connection) to the Isla headwaters which in time may be successfully navigated by a disperser but this cannot be relied on as a realistic route for significant numbers to establish any sort of viable population. The South Esk, with its associated River Dee tributaries laying in close proximity should be treated similarly. This system currently remains beaver-free however it seems highly likely current Tayside populations will colonise this river system in the next few years.

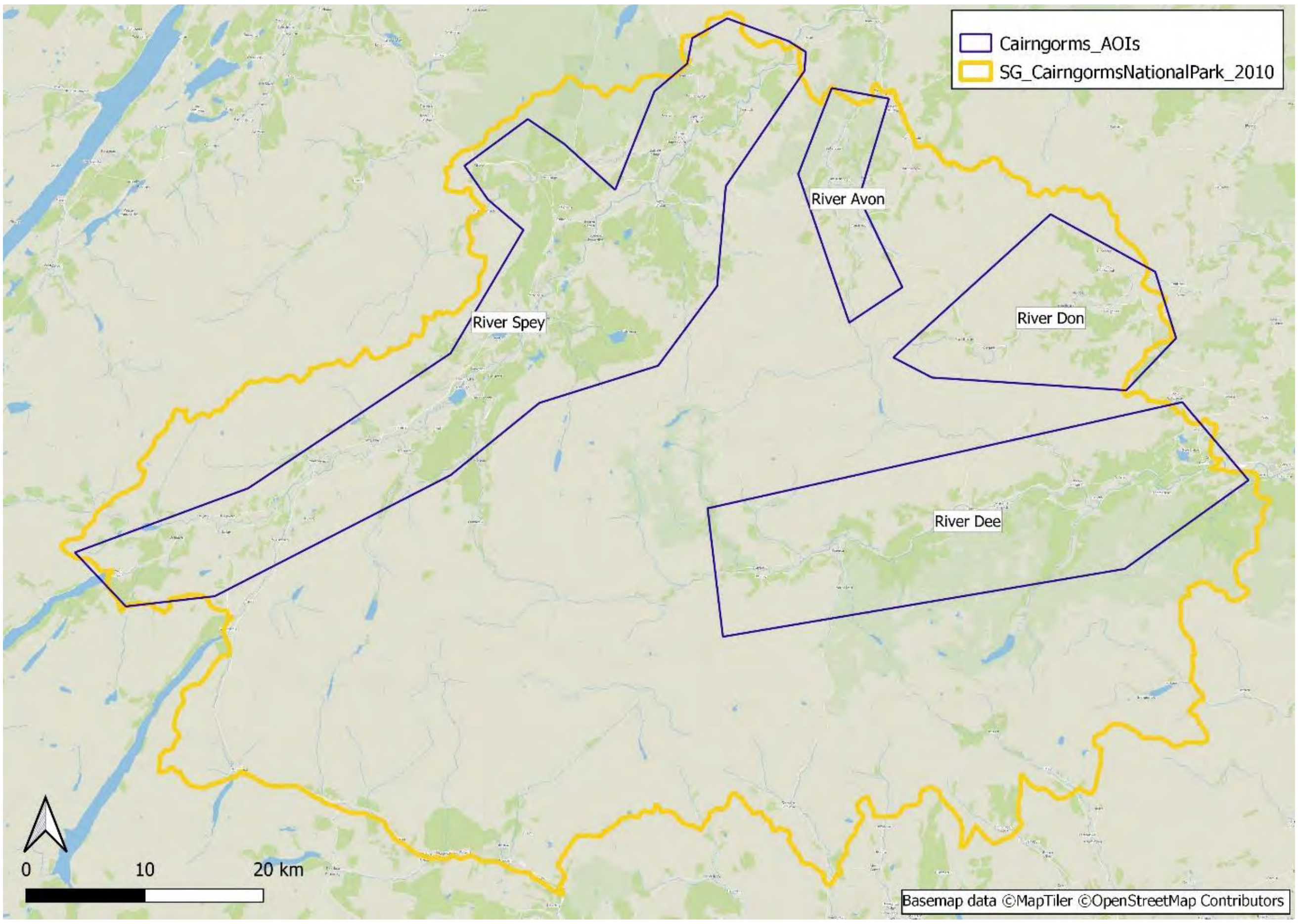

Figure 22. Main Rivers assessed as part of this CNP feasibility report.

River Spey

Main River Spey

The River Spey is the largest river within the Cairngorms. At around 109 miles long it has multiple large lochs associated with its course including Loch Garten, Loch Insh and Loch Morlich. Both the desk based modelling and field sign survey confirm large sections of native broadleaf and typical Scottish riparian vegetation. Although coniferous forests are the dominant woodland type much of the immediate riparian tree community is composed of alder (*Alnus glutinosa*) and birch (*Betula pendula*) with willow (*Salix spp*) to a lesser extent. The banks of the river are commonly high and friable and as a result afford suitable burrowing opportunities. Lodges could also be readily constructed in many areas. Though the water levels fluctuate and can rise quickly the gradients of the bankside are sufficient to ensure that chambers at different levels could be constructed with ease to afford variable levels of refuge throughout the year. Field experience gained from many European reintroductions demonstrates that beavers will readily select topographies of this sort.

Extensive areas of 'improved' grassland are also present along much of this rivers course. Where this is grazed by domestic livestock at high densities it either affords an entirely short, cropped environment or one in the case of cattle that is trampled and disturbed. These sections are typically associated with sandier and or stony banks which render burrowing more challenging and would be less likely in any case to afford living space for beavers. Some low-level conflicts may be expected with burrowing activities in these areas (See Management section below).

Figures 23. Spey at Granton on Spey and Boat of Garten, mix of mature native broadleaf with open grassland (amenity and improved). Beavers could readily utilise these areas though regenerative capacity of woodland crucial, especially if felling of mature specimens generates conflict. .

Figure 24. Spey at Rothiemurchus with more mixed woodland.

RSPB Insh Marshes

RSPB Insh Marshes is a significant flood plain wetland/fen associated with the River Spey. It is an important site for wading birds which is managed by the RSPB. Parts of this reserve have been designated as SSSI, SPA, SAC and Ramsar. This large marsh system is bisected by the River Spey, open lochs (including part of Loch Insh), smaller lochans and oxbows. A complex of smaller water courses and drainage canals interconnect throughout. Its dominant vegetation type is tall herb fen and marshy grassland. Scrub and wet woodland areas are mainly associated with the northern part of the reserve. The seasonal water levels within the marsh fluctuate greatly, with prolonged periods of high water.

However, as highly adaptable wetland animal this area is entirely within the habitat capacity for this species.

This area offers highly suitable beaver habitat with extensive food resources, open pools and manipulative substrate. It is entirely predictable that beavers in such an environment would generate an extensive series of canals, multiple open pools of different depths and interconnection flows.

Figure 25. Looking down over Insh Marshes.

River Luineag to Above Loch Morlich

This length of riparian habitat is a well wooded lower gradient river system, fringed with native broadleaf and coniferous tree species. Areas of semi-emergent riparian vegetation are intermittently present throughout this environment. The understory vegetation provides a foraging resource of seedlings and low shrubs. While the root systems of the trees will provide a mantle for beaver burrowing in locations where adjacent, deep pools exist much of the water course is shallow with a rocky bed. Though permanent dam creation is unlikely during low flows in the summer months woody weirs could well be erected across the narrower river sections. These features which may well not prove tenable during winter provide the beavers with deeper pools to navigate throughout a territorial range. High flows are likely to ensure that more permanent territories are likely to fulcrum around available off-line pool systems and backwaters. Foraging on the banksides is predictable where suitable areas of browse or food plants occur. The creation of canal systems back into damp fen environments where these occur with any resultant complexes of beaver dams creating further open water bodies would likewise be expected. Beavers would reside with ease on Loch Morlich and once established use the river as a foraging and dispersal route.

Figure 26. River Luineag more conifer dominated woodland with scrubby broadleaf and emergent vegetation throughout. Seasonal water flow can be powerful but back channels and multiple threads exist in parts offering retreat areas.

Figure 27. Loch Morlich provides suitable habitat in current state and could act as a positive public engagement site for further education and ecotourism opportunities.

Loch Morlich provides suitable beaver habitat. It is a popular area for visitors and could afford excellent public engagement and educational opportunities. Its open water character might render beaver viewing more practicable than tighter river or more complex, dammed environments and even if actual sightings were elusive the lochs extensive character would ensure a complete compatibility between their needs and high visitor usage.

Guided kayaking tours could be organised in time to visit established lodges and areas of identified beaver activity.

Loch Garten

Loch Garten is a large loch which is also popular with visitors as a walking and birdwatching location. Its main shoreline is predominantly rocky and lined with coniferous woodland with an understory of heather (*Calluna vulgaris*), blaeberry (*Vaccinium myrtillus*) and mosses. Although this water body could be utilised by beavers at low densities any emphasis of their colonisation would focus on the abundance of broadleaves in its area of interconnection with Loch Mallachie and any smaller side streams or wetlands within the surrounding landscape where a suitable vegetative community otherwise exists.

Figure 16. Loch Garten

River Avon

The River Avon in its upper reaches affords very limited beaver living space. Although there are riparian trees scattered or present in small woodlands along its length its predominant historic use as a grazing area for sheep and red deer (*Cervus elaphus*) limits its current suitability for beavers. While this situation improves in the lower reaches the main river is still a far from ideal environment and any beaver population colonising the wider riparian landscape would only exist on this water course in accord with areas of habitat which were suitable. It may be that these would more commonly exist in side streams or offline water bodies.

Figure 17. Near Bridge of Brown looking down on River Avon

Figure 18. River Avon near Fodderletter

River Don

The River Don is around 81 miles in length. While much of the woodland in its upper reaches is coniferous plantation its banks where grazing is light are in part well lined with tall grass and herb communities. Some broadleaves exist throughout its wider environment and it may be that where if palatable species which are capable of colonising swiftly along narrow forestry ditch systems such as silver birch and willow are present in abundance then locations of this sort would provide footholds for beaver wetland creation.

Figure 19. River Don near Cock Bridge

Figure 20. River Don near Candacraig

Figures 21. River Don and side channel to Don (Burn of Deochry evidence of some tree planting and suitable habitat on side channels).

River Dee

The River Dee is around 87 miles long. In its main channel the water course presents a challenging environment for beavers. While it is likely that some colonisable locations will exist where deep pools exist in association with good stands of broad-leafed trees and accessible communities of tall herbs and grasses the territorial occupancy of this river by beavers will be otherwise low. It may be that where if palatable species which are capable of colonising swiftly along narrow forestry ditch systems such as silver birch and willow are present in abundance then locations of this sort would provide footholds for beaver wetland creation.

Figure 22. River Dee near Linn of Dee.

Figure 23. River Dee near Mar Lodge typically woodland is set back from river which is highly stoney, understorey is generally lacking throughout with livestock grazing immediately along the riparian zone being a potential management consideration. Typical spates are alos likely to be beaver colonization on the main stem challenging, with beavers more likely to colonise this area after population densities rise.

Figure 24. River Dee near Corriemulzie represents challenging habitat for beavers, see following photos.

Figure 25. Clunie Water at Braemar

Figure 26. River Dee near Balmoral

Figure 27. River Dee at Oldhall

Loch Kinord

Figure 28. Loch Kinord has suitable habitat to support beaver

Figure 29. Banks of Loch Kinord

Figure 30. Wet woodland between Loch Kinord and Loch Davan

This length of riparian habitat is a well wooded lower gradient river system, fringed with native broadleaf and coniferous tree species. Areas of semi-emergent riparian vegetation are intermittently present throughout this environment. The understory vegetation provides a foraging resource of seedlings and low shrubs. While the root systems of the trees will provide a mantle for beaver burrowing in locations where adjacent, deep pools exist much of the water course is shallow with a rocky bed. Though permanent dam creation is unlikely during low flows in the summer months woody weirs could well be erected across the narrower river sections. These features which may well not prove tenable during winter provide the beavers with deeper pools to navigate throughout a territorial range. High flows are likely to ensure that more permanent territories are likely to fulcrum around available off-line pool systems and backwaters. Foraging on the banksides is predictable where suitable areas of browse or food plants occur. The creation of canal systems back into damp fen environments where these occur with any resultant complexes of beaver dams creating further open water bodies would likewise be expected. Beavers would reside with ease on Loch Kinord and once established use the river as a foraging and dispersal route.

Management and Mitigation Opportunities

Beaver mitigation techniques have been developed and widely practised across Europe and North America. The Beaver Mitigation Scheme, overseen by NatureScot has been in operation predominantly in the Tayside catchment for the last few years, supported with ScotGov funding. Effective and appropriate management actions are key in increasing the acceptance and tolerability of beavers. Any site may have several sources of conflict and/or require a combination of management solutions. Beaver mitigation programmes can be expensive but this is highly dependent on land uses and landowner perceptions, so any such costs should be measured against the costs of no mitigation or setting land aside for nature conservation.

Beavers do not like to move far from water, concentrating the vast majority of their activities close to the water's edge. Therefore, conflicts tend to be along this water–land fringe (Table 7). Habitat suitability declines with distance from freshwater for beavers, and most beaver foraging is constantly recorded within a 10 - 30m range (Macdonald et al., 1995; Jones et al., 2009; Swinnen et al., 2017).

Table 7. Potential sources of conflict with beavers

Type of activity	Potential conflict	Potential solutions	
Foraging	Loss of crops	Temporary/deterrent fencing	Create more wetlands and naturalized riparian zones
	Loss of ornamental vegetation	Permanent/deterrent fencing	
		Planting unpalatable species	
		Tree guards	
		Anti-game/sand paint	
Burrowing	Bank erosion	Riparian buffer zone	
	Undermining of infrastructure	Greenbank protection/reinforcement	
		Livestock exclusion/grazing regimes	
		Mesh facing	
		Metal piling	

		Hardcore infrastructure—stone facing	
Damming	Loss of crops	Removal	
	Loss of trees	Notching	
	Damage to infrastructure	Flow devices	
	Downstream effects of dam failures	Beaver dam analogues	
		Culvert protection	
		Building on higher ground/out of flood zone	
		Use oversized culverts/larger bridge arches	

Trees can be protected from beaver foraging impacts either individually or as stands of trees, mainly through fencing or application of protective, anti-game paints. The selection of which trees to protect can be due to a range of reasons—for example those that risk falling and causing damage; crop trees; important specimens of conservation value; or trees that are part of an important collection. Larger stands of trees close to a water's edge or areas requiring prevention of beaver access can sometimes more readily be fenced off rather than spending time and effort on individual protection, if applicable. A significant issue with fencing along watercourses is that during high water, fences may become clogged with debris or washed out. Various designs exist, depending on the topography of a site, and a range of materials could be used, provided beavers cannot squeeze through. Large-scale fencing projects can be expensive and may not complement other land-use, so generally any fencing is targeted and/or involves other mitigation techniques (Nolte et al., 2005).

It can be considered more cost-effective and more ecologically favourable to promote the naturalisation of riparian areas as more effective buffers to reduce beaver conflicts with other land use practices. The more naturalized this riparian edge is, the fewer the beaver impacts, for several reasons. Naturalized riparian strips have a mixed range of plant species from which beavers can selectively forage and therefore have varying foraging pressure, allowing regrowth and encouraging biodiversity; the root systems stabilize banks more effectively than crops, grass, or low numbers of single mature trees, thereby making banks more resilient to burrowing; and reclaiming human land-uses such as agriculture back from the riparian edge decreases the direct and conflicting impact of beaver foraging, digging, or risk of flooding. Continuous and heavy grazing and high stocking densities will promote erosion, soil compaction, and degradation of riparian vegetation. Exclusion fencing provides the most immediate action to enable riparian vegetation recovery (Smith and Prichard, 1992). If this is not possible, alternative management strategies can be practiced, recognizing the varying needs of both landowners and the riparian system in question (Chaney et al., 1990; Collins, 1993). Implementing shorter grazing periods, providing effective plant rest periods during the growing season, spreading the grazing load, regularly moving livestock, and avoiding grazing during vulnerable periods (e.g. waterlogged banks) can significantly improve riparian vegetation and minimize stream damage such as bank erosion and soil compaction (Olson and Hubert, 1994; Fitch et al., 2003). Also relocating feed stations, mineral licks, shelter provisions, shade trees, and chemical/fertilizer treatments away from riparian zones (Collins, 1993) are helpful. The preservation and restoration of these 'buffer zones' are therefore typically the most long-term and durable solution to reduce beaver conflicts (Campbell-Palmer et al., 2016).

It should be noted that beavers will use an area regardless of presence of trees; therefore, it would often be more beneficial for tree roots to be stabilized on the banks rather than leave them with little vegetation. Thus, selecting tree species that react to beaver foraging by becoming shrubby in structure not only provides ongoing food resources but also can protect commercial or ornamental species planted behind. Selecting these species next to roads, for example, for planting schemes and allowing beavers to forage reduces the chances of trees being felled onto roads. Leaving a beaver-felled tree in place is key, if possible, as its removal only serves to accelerate further felling.

One of the most commonly reported types of beaver damage is flooding caused by dam building and the blocking of culverts (Baker and Hill, 2003). Any mitigation method involving dam removal, alteration of the watercourse, and/or installation of any devices in it should be subject to local legalities and checked in advance of any application. Any dam removal as a management strategy will display immediate results and can quickly become a cycle of ongoing effort and expense, as beavers have both the determination and physical abilities to re-dam surprisingly quickly—in some cases reportedly reinstating a dam, with the associated extent of flooding, in as little as 24 hours (Taylor et al., 2017). Repeated dam removal will also see an escalation of tree felling in the general area, as beavers tend not to reuse material from any dismantled dams. There are two main methods to control beaver flooding which involve building constructions; these can generally be split into exclusion or fence systems to prevent damming, and deception or pipe systems (Taylor and Singleton, 2014).

Table 8. Varying levels of management options

Low	*Level of human intervention* →			*High*
Information to general public and landowners to increase beaver acceptance	Protective measures, e.g. tree protection, fencing	Dam removal, flow devices	Live trapping and translocation	Local eradication of beavers
Low	*Perceived seriousness of damage* →			*High*

Summary of Risks and Opportunities within Cairngorms National Park

Potential risks

- Increased erosion of bare banks through burrowing and lack of structural support of riparian vegetation, along with the undermining of mature tree species which may fall into river pulling root bulb and bank.
- Impacts on riparian areas of Caledonian pine forest, older Scot's pine specimens
- Various protection designations throughout the CNP, including SSI's, SPA's, SAC's and a Ramsar site. These are mainly associated with wetlands and associated species such as waders.
- Pearl mussels – as the precise locations are not known to authors, recruiting populations are present. It has been suggested by some authors that beavers can present a risk through dam creation and sediment trapping. This is deemed unsubstantiated by others. Should beaver occupy the same stretches, the likelihood of physical damming should be assessed before any actions taken. Dam mitigation can be undertaken straightforwardly if and as needed.
- Access to public paths due to fallen trees – this would not doubt be an occurrence at some stage but current park path monitoring and maintenance schedules exist to deal with these effectively
- Damming increasing water levels in areas of wading bird breeding?
- Felling of accessible mature aspen stands

Figure 46. Some riverine sections of the main CNP rivers consist of stretches, often associated with livestock grazing, in which the riparian zone is highly degraded. Beavers are less likely to be attracted to such areas but will readily use for dispersal. Beaver burrowing in such areas is likely to generate some level of bank collapse and increased erosion as substrate is not suitable for maintaining burrow structures.

Potential Opportunities

- Increase wetland habitat coverage within CNP.
- Creation of more deadwood – a recognised lacking element with more recent forest management specifically creating a variety (standing, submerged, laying etc). All of which would be achieved through beaver activities.
- Educational opportunities – established active territories will exhibit field signs and habitat changes that provide fantastic interpretation and public engagement opportunities. Depending on locations and infrastructure beavers and their activities could be part of guided walks and an ecotourism activity. Beavers can contribute to wildlife tourism and readily lend themselves to tourism opportunities, being territorial, often with identifiable homes which they regularly utilize at routine times, enabling observations (exiting early evening and returning early morning). This makes it feasible to organize regular walks, place information displays, and facilitate viewing through hides or platforms. For example, such infrastructure was invested by the Scottish Beaver Trial during the first official reintroduction of beavers to Britain (https://www.scottishbeavers.org.uk), after which local community-focused wildlife business took on visitor education and wildlife watching opportunities
- Encourage more holistic livestock grazing regimes.
- Have a significant expansive impact on current beaver distribution in Scotland.

Desk and Field Assessment of potential conflict with agricultural land and fishing beats within Cairngorms National Park

As shown by Figure 47 below, the Cairngorms National Park is a predominantly upland landscape in contrast to the lowland agricultural landscapes that dominate much of Tayside. Indeed as shown in Figure 48, using the Scottish Governments definition and datasets (Prime Agricultural Land - data.gov.uk) the Cairngorms National Park contains no land that is considered 'Prime Agricultural Land'.

However, based upon 2019 CEH landcover maps, the Cairngorms National Park does still contain around 68ha of arable land and 11,084 ha of improved grassland. Critically, as illustrated in Figure 48 this agriculturally valuable land is concentrated in low lying floodplain areas alongside watercourses and could overlap with beaver habitat. This is particularly the case in the Spey catchment (Figure 50) where most agricultural land is concentrated. On some smaller side channels where beaver dam capacity exists, beavers could potentially cause conflict in these areas via damming and localised inundation of agricultural land. Whilst BDC model results illustrate that most of the main course of the Spey is too large and powerful to be dammed, beavers may still cause a conflict via bankside burrowing activities. To give a better understanding of the potential overlap between potential beaver activity and agricultural land, an additional mapping exercise has been undertaken to define where suitable habitat (any habitat ranked from barely suitable to highly suitable), overlaps with areas of arable or improved grassland. Summary results for this analysis are presented for each habitat class in table 9. In total 37 ha of Arable land and 672 ha of improved grassland are identified as being within areas suitable for beaver. As shown by the summary maps in Figure 51 for the whole CNP and 52 for the Spey, by the very nature of beaver activity this overlap will only be in the riparian zone and could largely be mitigated by not farming right up to the river bank and allowing for healthy buffer zones. A management strategy that would bring a whole host of other, biodiversity, channel stabilisation, flood management and carbon storage benefits. From the mapping work it is also clear that most of these conflicts would likely arise in the Spey, with overlap between beaver habitat and agricultural land use being significantly lower in the Dee and Don.

Table 9. Area of Arable and Improved Grassland land use that other laps with each class of beaver habitat suitability within CNP.

	BHI	Area (ha)
Arable	Barely Suitable	34.9
	Moderately Suitable	0.7
	Suitable	1.2
	Highly Suitable	0.9
Improved Grassland	Barely Suitable	160.0
	Moderately Suitable	172.6
	Suitable	251.6
	Highly Suitable	87.9

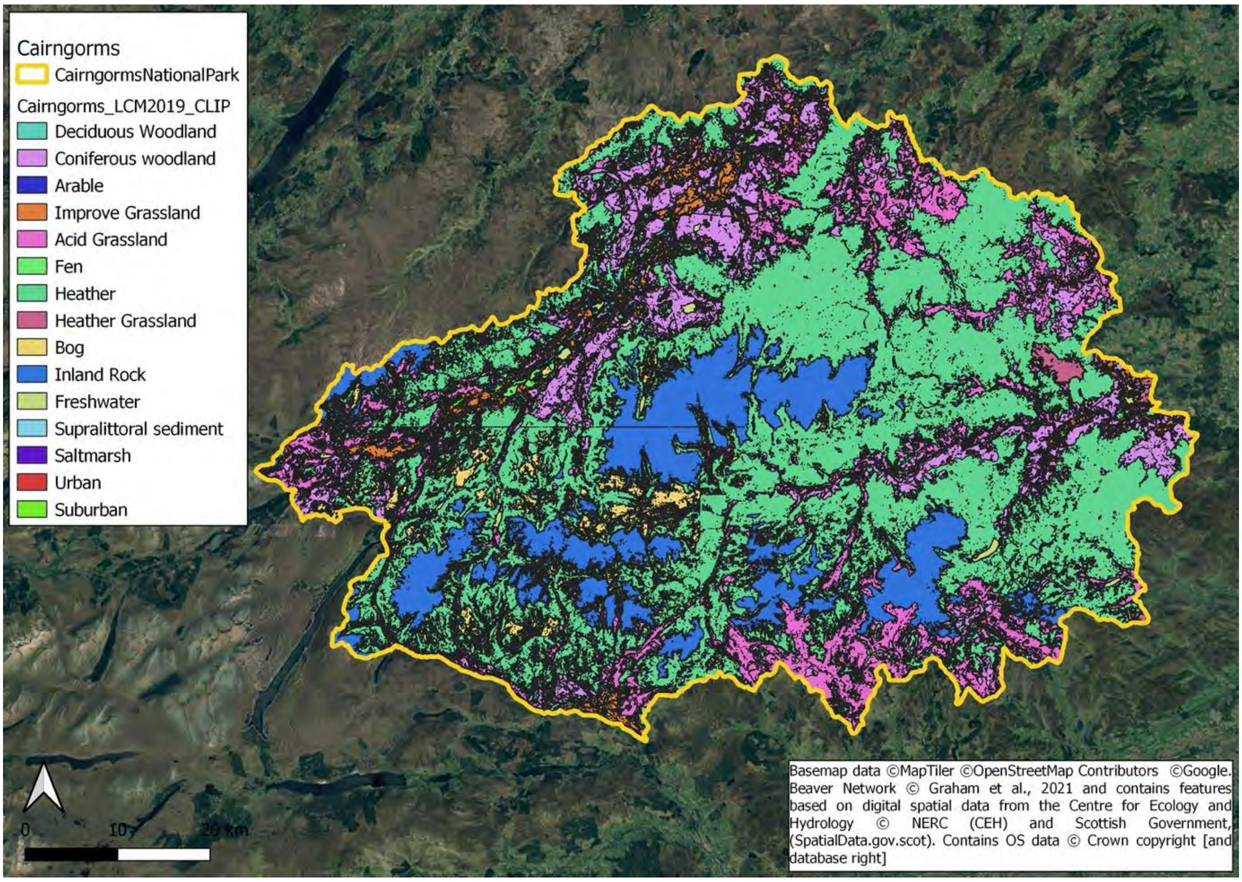

Figure 47. Main habitat types within the Cairngorms National Park based upon CEH landcover map 2019 data..

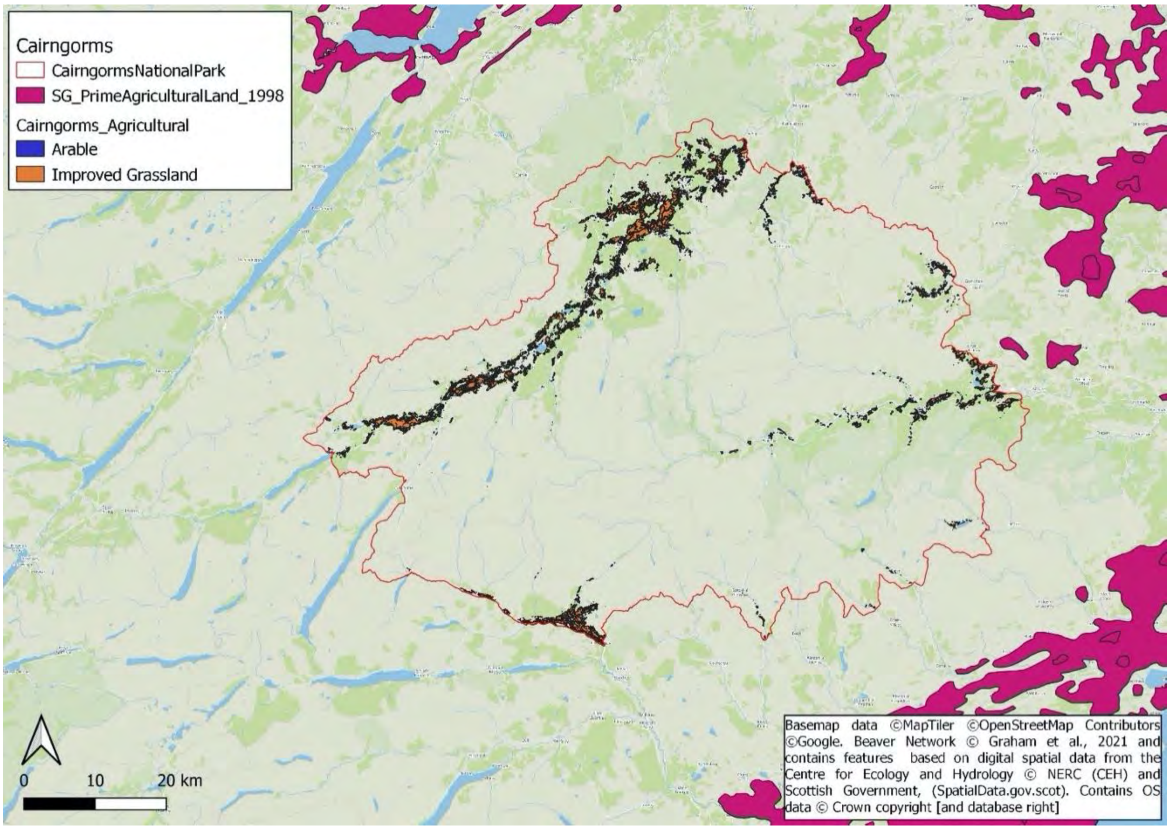

Figure 48. Main rivers with main habitat types within the Cairngorms National Park.

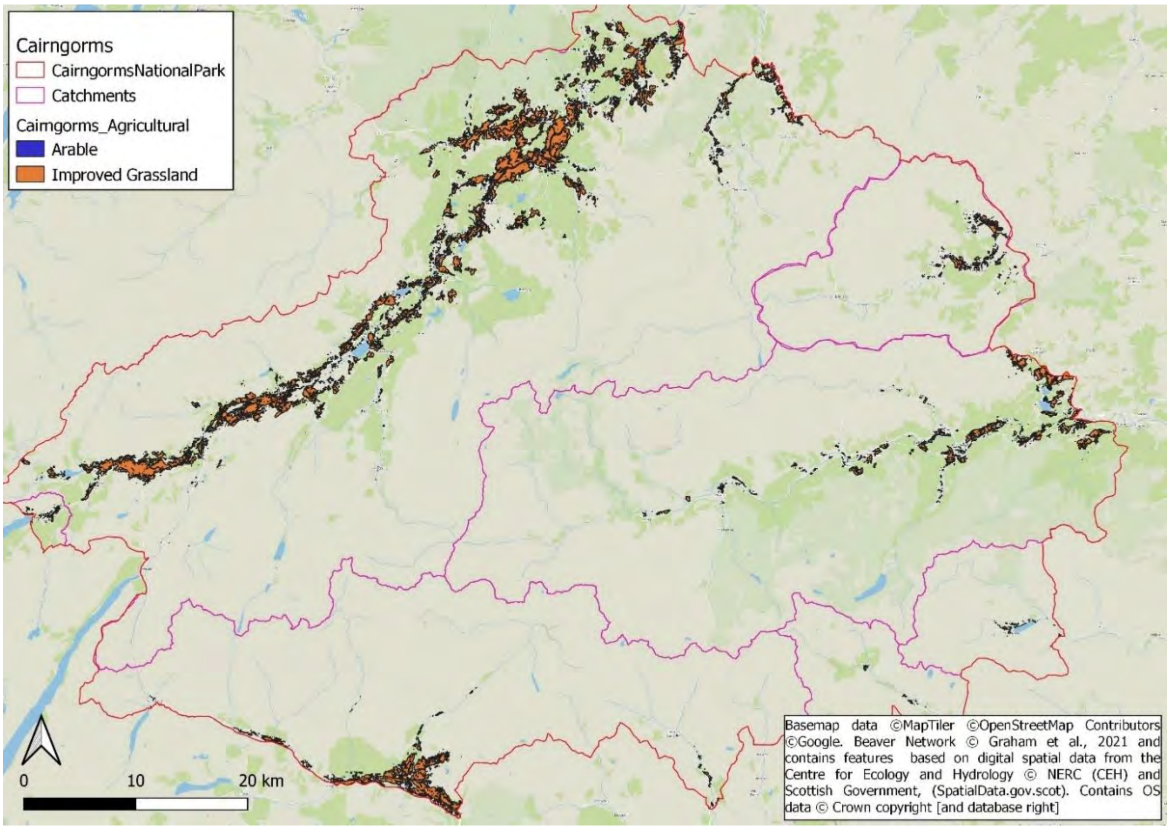

Figure 49. Areas relating to agriculture, namely arable and improved grassland, within the Cairngorms National Park, in particular associated with the main river systems.

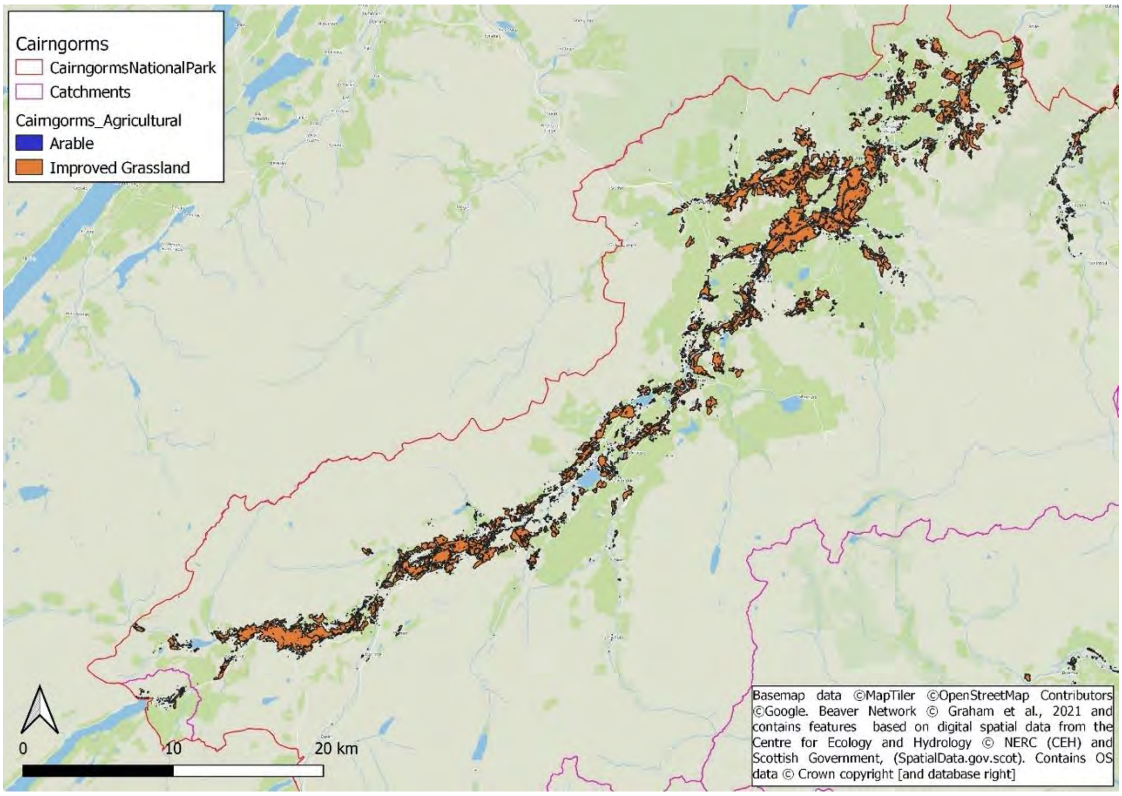

Figure 50. Areas relating to agriculture, namely arable and improved grassland, within the Spey catchment.

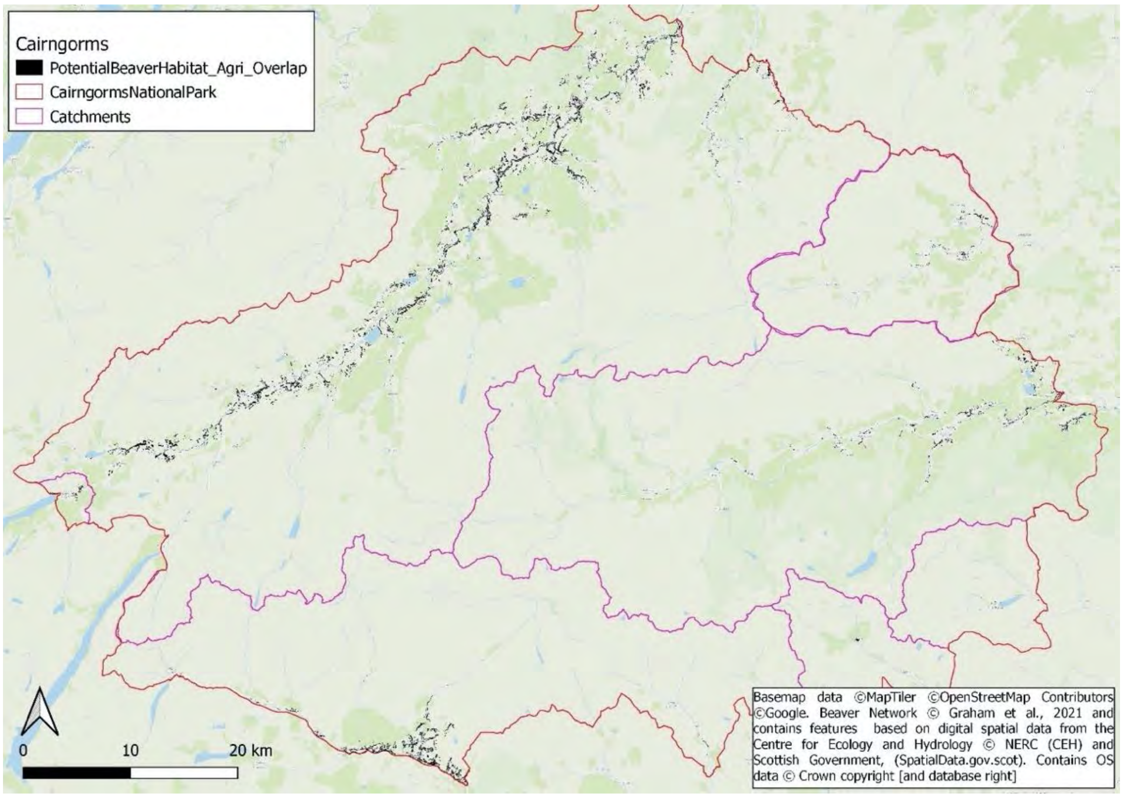

Figure 51. Areas relating to agriculture, namely arable and improved grassland, within the Cairngorms National Park, in particular associated with the main river systems. Potential areas of overlap of suitable beaver habitat and agriculture is marked in yellow.

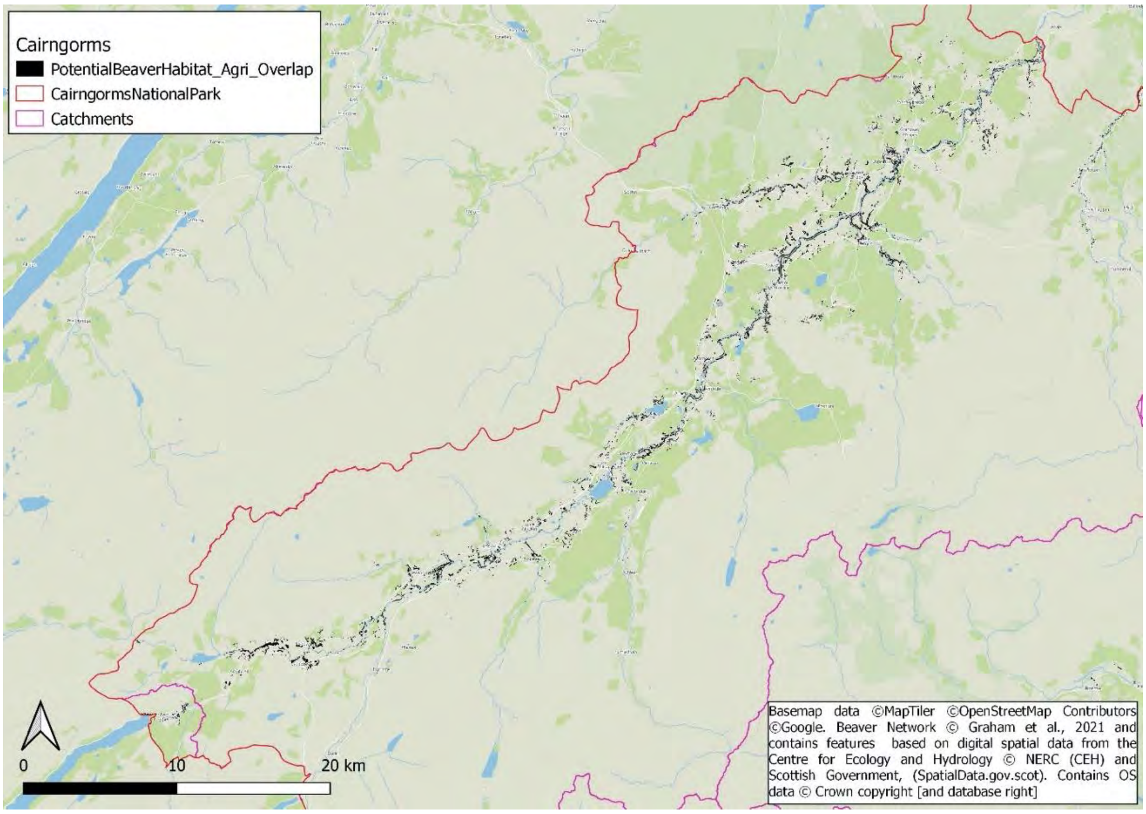

Figure 52. Potential areas of overlap of suitable beaver habitat and agriculture are marked in black.

The key benefits of beaver activity for salmonids that are commonly cited include increased habitat heterogeneity (Hägglund & Sjöberg, 1999; Smith & Mather, 2013) and quality (Pollock et al., 2003). In particular, ponds created upstream of beaver dams provide juvenile overwintering and rearing habitat (Cunjak, 1996; Needham et al., 2021), and can be a critical refuge for larger fish (Hägglund & Sjöberg, 1999; Needham et al., 2021). The beneficial response from a fisheries perspective is usually quantified in terms of increased fish abundance (Hägglund & Sjöberg, 1999; Jakober et al., 1998; Needham et al., 2021), condition and growth (Sigourney et al., 2006; but see Rabe, 1970, and Johnson et al., 1992; Needham et al., 2021), and overall productivity (Mitchell & Cunjak, 2007; Nickelson et al., 1992; Pollock et al., 2004). Conversely, the principal negative consequence of beaver activity often cited is the potential for dams to impede or delay salmonid migration, particularly for upstream moving adults during their migration to the spawning grounds (Lokteff et al., 2013; Rupp, 1955; Taylor et al., 2010). Furthermore, dams may reduce the availability of suitable spawning habitat in impounded areas, where there may be insufficient flow velocity to purge the gravels, which salmonids use for spawning and egg incubation, of the fine sediments deposited (Knudsen, 1962; Taylor et al., 2010). Malison & Halley (2020), however, found that beaver dams did not block the movement of juvenile salmonids or their ability to use upstream habitats and suggest that it is unlikely that dams negatively impact the juvenile stage of salmon or trout populations. A recent study in Scotland suggests that in autumns with high rainfall, brown trout will successfully navigate beaver dams, often using natural bypass channels created around the dams. Therefore, overall impacts within the CNP are not expected to be significant, with local site specific mitigation available as required. The most likely reported issue is expected to be beaver burrowing, and the undermining and/ or felling of mature trees along the main river stem that impacts on fishing beat sections.

Recommendations for 'preparation for arrival'

Throughout the CNP there are numerous small stream habitats which beavers would utilise and adapt to suit their needs, along with many smaller wet wooded lochans and mire communities that would afford high quality living space.

From the both the field sign survey and habitat suitability modelling it is evident that multiple sites within the CNP would provide suitable beaver habitat. These key criteria being; long-term foraging resources including regenerative capacity; stable water provisions avoiding significant water level fluctuations and/or capacity for beavers to modify to suit their needs; bankings with suitable substrate to enable manipulation; avoiding steep gradient and flashy water system; and those without immediate potential conflict with other land uses. Several sites including the Loch Kinord and Insh Marshes would meet these criteria. Importantly they theoretically would retain beavers for some time without immediate dispersal.

The River Spey on the whole would offer highly suitable habitat for beaver release and supporting multiple families in current state, recognising that on a river system any released animals will move quickly from a release point and successfully select the best areas of habitat through their own choice.. Beavers are highly adaptable and capable of both seeking mates and suitable habitat especially on linear systems in which they can move unrestricted. Carrying capacity on the River Spey in its current state is estimated to be high. Therefore, the chances of released beavers moving immediately into areas in which immediate direct conflicts would arise are unlikely. Going forward, as populations establish and increase then sections of the River Spey would benefit from habitat improvement strategies such as changes to livestock grazing regimes (e.g. stocking densities, access to riparian vegetation) and native broadleaf planting.

Many other areas i.e. the majority of the River Dee and Don, have patches of suitable habitat but on the whole lacking complex riparian vegetation. Therefore, such areas would require extensive habitat improvements and riparian regeneration. Not only would this significantly increase the suitability for beavers but also bring a whole host of other benefits in line with CNP policy e.g. increasing wetland.

Conclusion

The main purpose of this report was to establish the likelihood of Eurasian beavers naturally colonising the Cairngorms National Park from existing Scottish populations. To determine this OS maps where consulted to establish all the potential dispersal routes into the CNP that beavers could utilise. A field based survey was undertaken to ground truth the feasibility of these options. This work has also relied on the most recent Tayside beaver survey, as these have been identified as the most likely source of dispersing individuals – given both proximity but also recognising this is most likely the only real range expanding beaver population in Scotland. Of course, there is always the possibility of an individual roam much further and taking more risky routes (i.e. over steep and open ground), and beating the odds to make such a catchment jump. However, this also recognises that the vast majority of individuals are highly unlikely to do this, and the odd successful individual does not warrant whole catchment jumps for this species and has highly low chance of leading to the establishment of a viable populations. Therefore, we conclude that it is most highly unlikely that there are any viable colonisation routes into the CNP due to both topography and significant artificial barriers, namely the Pitlochry Fish Ladder.

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Appendices

Appendix 1: Review of Impacts of beaver return (Adapted from Brazier et al., 2021)

1. Introduction

Over millions of years, beavers (Castoridae) have developed the ability to modify ecosystems profoundly to meet their ecological needs. In doing so, they also provide valuable habitats for many other species that thrive in wetlands. They engineer ecosystems by building dams, which retain ponds, full of sediment, nutrients, plants and wildlife. These dams slow the flow of water, reducing peak flows downstream (Puttock et al., 2017), storing and gently releasing water in times of drought (Hood and Bayley, 2008). Beavers excavate canals, laterally across floodplains, to access and transport food and building resources, enhancing floodplain connectivity and geomorphic dynamism (Pollock et al., 2014, Gorczyca et al., 2018). They coppice trees, providing deadwood habitat and allowing sunlight to reach understory vegetation which in turn responds in abundance and diversity (Law et al., 2017), providing rich habitat for insects, birds, bats and amphibians (Willby et al., 2018, Stringer & Gaywood, 2016, Dalbeck et al., 2020). Beavers were once present throughout Europe, Asia and North America in large numbers, managing water resources, working with natural processes, supporting the healthy functioning of freshwaters – the very definition of a keystone species.

Consider the potential implications of removing such an animal from our ecosystems. Large areas of stored surface water are lost, rivers flow faster, becoming flashy in times of flood and with lower baseflows in times of drought. Woody debris, carbon in water - an essential building block of life in ponds, streams, rivers, estuaries and marine environments is reduced, undermining the food-chains that it supported. Wetlands dry up, wildlife move on, or are possibly lost from ecosystems entirely. During the Anthropocene, our catchments have largely become a product of human activity that realises all of these implications, with associated additional pressures including; hydrological extremes, diffuse pollution and soil erosion (Hewett et al., 2020). The natural disturbance and dynamic equilibrium maintained by beaver activity drives geomorphic and ecological complexity, in their absence riparian ecosystems have taken on a simpler form both in terms of their structure and their function (Brown et al., 2018).

In the Northern hemisphere, beavers were hunted to near extinction and extirpated entirely in countries such as Great Britain (GB) ca. 400 years ago (Conroy & Kitchener 1996). Thus, our living memory of what beaver-lands were like, is limited, in landscapes where natural recolonisations or reintroductions are now taking place. Our understanding of how <u>other</u> species co-existed with beavers, many of them dependent upon wetlands such as beaver ponds, is similarly limited. There is thus a requirement to understand the impact of beavers in contemporary ecosystems, particularly in landscapes that, since their extirpation, have been over-exploited, degraded and altered by intensive farming and urban development.

To bring together understanding of the role that beavers may play in the management of water resources, freshwater and terrestrial ecosystems, this paper reviews the state-of-the-art scientific understanding of the beaver as the quintessential ecosystem engineer. We focus upon research considering both *C. fiber* – the Eurasian beaver and *C. canadensis* – its North American counterpart, as they re-establish in ecosystems within which their numbers were decimated and are reintroduced or return to ecosystems from where they were extirpated, due to their high value fur (for hats), castoreum (as a painkiller and perfume) - Nolet & Rosell, (1998), and their scaly tail, which led the Catholic church to classify beavers as a fish – fit for consumption on Fridays and Saints days (Coles, 2006; Kitchener & Conroy, 1997; Manning et al., 2014).

The remaining two species of beaver are related to pre-historic Castoridae which included as many as 40 species, for example, the giant beaver (*C. castorides* spp.) (Martin, 1969) and the terrestrial *C. paleocastor* spp, famed for its spiralised burrows (Martin & Bennett, 1977). Today, the two extant species of beaver are genetically distinct with differing numbers of chromosomes (Kuehn et al., 2000). Despite their genetic and minor physiological differences, there are many similarities between the species. For example, they are visually similar and difficult to differentiate by sight alone (Kuehn, et al., 2000). Until relatively recently, it was considered that the North American beaver had a tendency to build dams and lodges more frequently and of a greater size than the Eurasian beaver, but it has now been shown by Danilov & Fyodorov (2015) that, under the same environmental conditions, the building behaviour of the two species does not differ.

In recent decades species reintroductions across Europe, followed by natural expansion has led to the return of *C. fiber* to much of its Eurasian range (Halley et al., 2012) with a recent review of national population studies, estimating that the *C. fiber* population in Europe numbers over 1.5 million individuals (Haley et al, 2020). As such, there is an increasing need for understanding of the impacts of beaver in intensively populated and managed modern European landscapes. This review focuses on Europe and *C. fiber* but draws on relevant research into *C. canadensis* in North America. The review summarises how beaver impact: (1) ecosystem structure and geomorphology, (2) hydrology and water resources, (3) water quality, (4) freshwater ecology and (5) humans and society. It concludes by examining future scenarios that may need to be considered as beavers expand in the northern hemisphere with an emphasis upon the ecosystem services that they can provide and the associated management that will be necessary to maximise the benefits and minimise conflicts.

[2.] BEAVER IMPACT UPON THE ENVIRONMENT – CONTEMPORARY UNDERSTANDING

[2.1] Impacts of beaver upon geomorphology

[2.1.1] Overview

We take this opportunity to revisit Gurnell's (1998) review on the hydrogeomorphological effects of beaver, which provides an excellent foundation for our understanding. Beavers, as ecosystem engineers, have a marked influence upon the terrestrial and riverine environments that they occupy (Westbrook, Cooper & Baker, 2011). Beavers are primary agents of zoogeomorphic processes; here we acknowledge their influence upon river form and process (Johnson et al., 2019) and discuss recent literature on the impacts of beaver on hydrogeomorphology.

[2.1.2] Canal and burrow excavation

Beavers are well known for their construction of impressive lodges, sometimes as tall as 3m (Danilov & Fyodorov, 2015), but beavers, especially in river systems, typically excavate bank burrows in which to establish dwellings (Collen & Gibson, 2000; Rosell, et al., 2005). Beavers often excavate multiple burrows in a single territory, which can contribute significant volumes of sediment to a watercourse (Lamsodis & Ulevičius, 2012, de Visscher, et al. 2014) and also create areas of weakness which can lead to localised erosion and, in some instances, the collapse of earthen flood embankments (Harvey et al., 2019).

Beavers commonly dig shallow channels, often referred to as canals, which extend laterally from beaver ponds. These structures enable beavers to access food and building resources more easily (Butler, 1991; Gurnell, 1998). Often developing into dense networks, these canals contribute significantly to the local hydrogeomorphology of floodplains, creating hydraulic roughness, tortuous flowpaths and complex topography in otherwise planar landscapes (Hood & Larson, 2015). Like burrows, these canals may act as a source of fine sediment (Lamsodis & Ulevičius, 2012, Puttock, et al., 2018) or, in the event of significant overbank flows and floodplain inundation, sites of deposition. It is interesting to consider that early humans might have moved over (crossing channels on beaver dams) and through beaver landscapes criss-crossed by canals, observing beaver transporting woody building materials by water with ease, and subsequently learning to do so themselves (Coles, 2006).

[2.1.3] Woody debris contribution

Woody debris is a key driver of geomorphic complexity, has been shown to be a fundamental aspect of 'natural' stream geomorphology and a critical habitat for aquatic life (Gurnell et al., 2002, Harvey et al., 2018, Thompson et al., 2018, Wohl, 2014, 2015, Collen and Gibson 2000). Beaver increase the rate of both large and small woody material contribution to river systems (Gurnell et al., 2002). In small streams, the large woody material (for example felled trees) is less mobile and often remains in place, exerting a strong influence on geomorphic processes, increasing bed heterogeneity through promoting localised scour and deposition (Gurnell et al., 2002). The contribution of smaller woody fragments or cuttings has been shown to significantly increase willow (*Salix* spp) recruitment due to the provision of propagules, which can establish on gravel/sand bars (Levine & Mayer, 2019). This increases the stability of depositional features and promotes rates of aggradation and bed/bank stability.

[2.1.4] Dam Building

Beavers have a preference for habitats with deep, slow flowing water, in order to feel safe from predators (Collen & Gibson, 2000; Hartman & Tornlov., 2006; Swinnen, et al., 2019). Therefore, their dam building activity is typically restricted to lower order streams where stream power is limited (Gurnell 1998; Rosell et al., 2005; Graham et al., 2020; Macfarlane, et al., 2015) and water depths may not be sufficient (normally < 0.7m depth) for beaver movement and security. When dam building does occur, it increases the area of lentic (still freshwater) habitats in systems that are typically dominated by lotic (free flowing freshwater) habitats (Hering et al., 2001). Damming typically reduces downstream connectivity, and conversely increase lateral connectivity, forcing water sideways into neighbouring riparian land, inundating floodplains and creating diverse wetland environments (Hood & Larson, 2015) as well as contributing to soil and ground water recharge (Westbrook et al., 2006). Dams vary significantly in their size and structure depending on physical factors such as hydrology, topography and building materials but also ecological factors (Graham, et al., 2020). Hafen et al., (2020) found that primary dams, that maintained a lodge pond, were significantly larger than secondary dams, which are used to improve mobility and the transport of woody material, concluding that beaver ecology, in addition to channel characteristics, exerts a primary control on dam size.

[2.1.5] Agents of erosion

Erosion often occurs at the base of dams, due to a localised increase in gradient and stream power (Lamsodis & Ulevičius, 2012, Gurnell, 1998). Woo & Waddington (1990) observed that flow across the dam crest may be concentrated in gaps, enhancing erosion of the stream bed and banks downstream of the dam, forming plunge pools and widening the channel respectively. Lamsodis & Ulevicius (2012) observed the geomorphic impacts of 242 dams in lowland agricultural streams in Lithuania; of which, 13 (5.4%) experienced scour around the periphery of the dam.

Beaver dams are also key sites for channel avulsion (John & Klein, 2004, Giriat, et al., 2016), as shown in . John & Klein's (2014) study investigated the geomorphic impacts of beaver dams on the upland valley floor of the 3rd order River Jossa (Spessart/Germany). Due to the creation of valley-wide dams, which extended beyond the confines of the bank, multi-thread channel networks developed across the floodplain. Newly created channels would deviate from the main stream channel, re-entering the river some way downstream. At the point where the newly created channel enters the stream, a difference in elevation results in the development of a knickpoint. This knickpoint then propagates upstream through head-cut erosion, eventually relocating the main stem of the channel.

Figure 31. Examples of dam construction and channel avulsion resulting from beaver dam construction from the River Otter catchment, England. A. shows an example where a divergent flow path has re-entered the main channel resulting in head-cut erosion. B. shows the type of multi-thread channel form that occurs downstream of dams in wide, low gradient floodplains C. Shows a beaver dam on a 4th order stretch of river. Photos © Hugh Graham and Alan Puttock, reproduced with permission.

[2.1.6] Agents of Aggradation

Hydrogeomorphic changes, due to beaver engineering, are likely to have implications for stores and downstream fluxes of sediment and associated nutrients (Butler & Malanson, 1994; Lizarralde et al., 1996). Sediments mobilised and transported from upstream are deposited in beaver ponds, due to a decrease in velocity associated with a reduction in water surface gradient, (Giriat et al., 2016) and consequently stream power (Butler & Malanson, 1994).

Puttock et al., (2017) showed lower concentrations and loads of suspended sediment leaving a beaver site in contrast to those entering the site, whilst (Puttock et al., 2018) showed that within the same site the beaver pond sequence was storing 100 t of sediment combined with an associated 16 t of carbon and 1 t of nitrogen. It is therefore suggested that beaver dams and ponds can create landscapes with depositional sediment regimes exerting a significant influence over channel sediment budgets, akin to the pre-anthropocene dam and woody debris that once played a vital role in the evolution of river networks and floodplains, through the storage of sediment and nutrients and creation of riparian wetland and woodland (Brown et al., 2018).

The large mass of sediment (over 70 kg per m^2 of ponded extent) being stored in a relatively small area (1.8 ha) reported by Puttock et al., (2018) represents similar levels of aggradation to those reported in studies, primarily from North America. Beaver dam sequences on low order streams have previously been shown to account for up to 87 % of sediment storage at reach scales, whilst the removal of a sequence of beaver dams in Sandon Creek, British Colombia, lead to the mobilisation of 648 m^3 of stored sediment (Butler & Malanson, 1994, 1995; Page et al., 2005). Butler & Malanson et al., (1995; 1994), also reported sediment accumulation rates of 2–28 cm yr^{-1} and 4–39 cm yr^{-1} for different beaver pond sequences in Glacier National Park, Montana. Values of sediment accumulation from North American beaver systems indicate the estimated average accumulation value of 5.4 cm yr^{-1} presented by Puttock et al., (2018) in Great Britain may be at the lower end of what is possible in bigger dam-pond complexes or systems with a more plentiful sediment supply. In one of the few other studies in European landscapes, de Visscher et al., (2014) studied sediment accumulation in two beaver pond sequences in the Chevral River, Belgium. de Visscher et al., (2014) estimated the total sediment mass deposited in the dam sequences at 495.9 t. From the two pond sequences, average pond area was 200.4 m^2, average sediment depth 25.1 cm and average sediment mass of 14.6 t, equating to a normalised mass of 72.65 kg of sediment deposited per m^2 of pond. These values are very similar to the mean sediment depth of 27 cm and mean normalised mass of 71.40 kg m^2 reported from the intensively managed grassland catchment in the UK (Puttock et al., 2018).

The sediment data published also demonstrate that beaver ponds can exhibit high sediment accumulation rates in comparison with other wetland systems. As an example, in a review of sediment accumulation rates in freshwater wetlands (Carol A. Johnston, 1991) a mean annual accumulation rate of 0.69 cm yr^{-1} was reported across 37 different wetland types, ranging from riparian forest to wet meadows. As with the biodiversity benefits of beaver ponds (see Willby et al., 2018 and section 3 below) the high sediment accumulation rate of beaver ponds in relation to other freshwater wetlands, may reflect the highly dynamic nature of beaver systems, their constant evolution and sustained maintenance (i.e. continuous dam-building).

The long term fate of sediment will depend on the availability and composition of deposited sediment, the flow regime and the preservation of dam structures (Butler & Malanson, 2005; de Visscher et al., 2014). Over many years, sediment may continue to accumulate until each pond fills completely and sediments are colonised by plants forming beaver meadows (Polvi & Wohl, 2012). However, beavers can also contribute to downstream sediment budgets; through the excavation of canal networks and bank burrows (de Visscher et al., 2014; Lamsodis & Ulevičius, 2012), in addition to the release of sediment following dam outburst floods (Curran & Cannatelli, 2014; Levine & Meyer, 2014). Beaver dam failure can result in releases of sediment (Polvi & Wohl, 2012) meaning that sediment storage in ponds can be transient (de Visscher et al., 2014). However, different sediment retention dynamics have been reported following dam collapse. For example, Giriat, Gorczyca and Sobucki, (2016) found that there were very minimal losses of sediment from beaver ponds studied in Poland, following a dam collapse. Similarly, the majority of sediments were retained in ponds and subsequently stabilised following dam reconstruction (Curran & Cannatelli, 2014; Levine and Meyer, 2014) most likely reducing the downstream release of sediment from any single dam failure within the complex (Butler and Malanson., 2005, Puttock et al., 2018). Whilst recent studies in North America involving extensive survey work have expanded knowledge of beaver dam persistence significantly (Hafen et al., 2020), including persistence during large rainstorm events (Westbrook et al., 2020), resilience, failure and associated sediment dynamics is likely to be highly spatially and temporally variable. As identified in section 2.2. for both hydrological, geomorphic and associated sediment/water quality impacts a greater mechanistic understanding of dam failure is therefore still required.

Finally, high levels of nutrient-rich sediment have also been shown to result in further biogeomorphic alterations i.e. colonisation by homogeneous patches of herbaceous or shrubby species, adding roughness to topography, reduced water velocities and encouraging further deposition of sediments. Additionally, partial felling and submergence of woody debris disrupts flows and when felled in-channel, creates reinforcement for existing dam structures (Curran & Cannatelli, 2014).

[2.1.7] Impacts of dams on river profile

Beaver dams have two main effects on river profile; (i) long-profile is altered such that a stepped profile develops with sections of reduced gradient, that promote aggradation, upstream of dams separated by hydraulic jumps, created by flow over the dams, which initiates erosion. (ii) Channel planform typically increases in complexity with many studies reporting; greater sinuosity, channel width and the development of a multi-thread planform (Ives, 1942; Pollock et al., 2014; John and Klein, 2014; Wegener, Covino & Wohl, 2017). These increases in cross-profile complexity are driven by an increase in the heterogeneity of flow direction, which drives lateral flow, increasing bank erosion, channel widening and subsequent localised deposition (Gorczyca et al., 2018).

[2.1.8] Agents of river restoration

In an undisturbed or near-pristine riverine system, the engineering behaviour of beaver may simply maintain an evolving geomorphic structure, sustaining a state of dynamic equilibrium in river function. In degraded landscapes, (which are much more common), where river planforms are incised, single thread, straightened, even dredged and lacking in geomorphic diversity, beaver have a dramatic impact on channel planform at multiple scales. In North America, beaver dams and their human-constructed counterparts, known as beaver dam analogues, have been shown to restore degraded river systems

(Pollock et al., 2007), primarily through the aggradation of channel beds, leading to greater channel-floodplain connectivity (Pollock et al., 2014, Macfarlane et al., 2015).

Dams, however, are not rigid structures – they influence and are influenced by flow regimes (Johnston & Naiman, 1987) as is evidenced in Figure 32 (after Pollock et al., 2014). In narrow, incised channels, typical of degraded landscapes, beaver dams will capture some sediment but predominantly provide a foci for erosion. In these confined channels, unit stream power is high and therefore dams will frequently blow-out and erode laterally. The resultant effect is a widening of the channel, which leads to a concomitant decline in stream power, thus allowing for greater aggradation rates and less frequent blow-outs altering the sediment regime from net erosional to net depositional (Butler, 1995; Butler & Malanson, 2005). Over time, incised, straightened streams can be restored to complex multi-threaded channel systems that represent a return to the pre-anthropocene streams and rivers that were once common across north-west Europe (Brown et al., 2018). In Poland, beaver initiated geomorphic processes were shown to alter artificially homogenized river reaches and thus it has been suggested that they may have a substantial role to play in the renaturalization of river systems (Gorczyca et al., 2018).

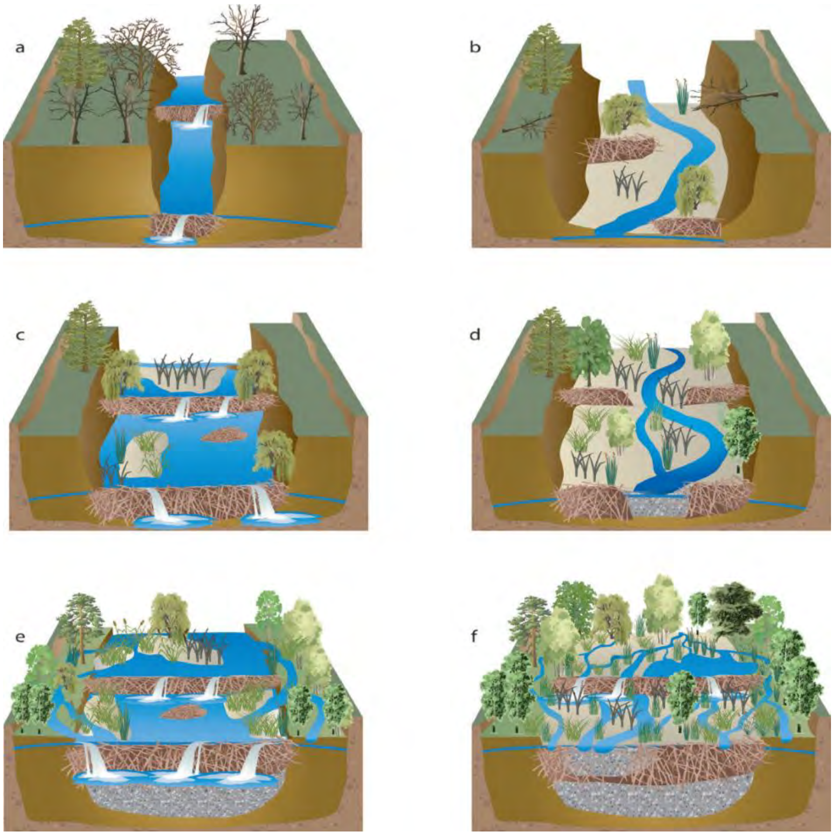

Figure 32. The influence of beaver activity on the geomorphology of incised streams: a) low-flow damming of confined channels with high-flow blowouts causes overtopping, bank widening and excavation of the channel bed; b) sediment becomes more mobile and the channel reconfigures with vegetation establishment; c) channel widening reduces high-flow peak stream power and this provides suitable conditions for wider, more stable dams; d) sediment accumulates in ponds and raises the height of the channel with dams overtopped and small blow-outs occurring where dams are abandoned; e) process repeats until dams are rebuilt, channel widens and the water table rises sufficiently to reconnect river channel to the floodplain; and f) high heterogeneity occurs with vegetation and sediment communities establishing themselves, multi-threaded channels and ponds increase reserves of surface water and dams and dead wood reduce flows and provide wetland habitats. Source: adapted from Pollock et al, 2014.

[2.1.9] Summary of geomorphic impacts

Beaver damming activity is mostly limited to ≤ 5th order streams as low stream power is favourable for dam-building and persistence, with a reduction in the frequency of blowouts;

Beavers drive a transition in sediment dynamics from dominantly erosional to net depositional, whilst increasing the spatial variability of both erosional and depositional features;

Geomorphic change due to beaver, is often characterised by changes in channel planform, longitudinal profiles, water surface and channel bed slope, increased sinuosity and enhanced floodplain connectivity and surface roughness

[2.2] Impacts of beaver upon hydrology

[2.2.1] Overview

There is an increased need to recognize the influence of biology upon river form and process (Johnson et al., 2019) and beavers as recognised ecosystem engineers are a key example of the ability of an animal to influence hydrological functioning. Whilst other beaver engineered structures discussed in Section 2.1., such as burrows and canals, have a measurable impact (Grudzinski et al., 2019), the biggest (and most studied) hydrological impact of beavers results from their dam building ability and the consequent impoundment of large volumes of water in ponds (Butler & Malanson, 1995; Hood & Bayley, 2008). Dam and pond features can alter hydrological regimes, both locally and downstream (Burchsted & Daniels, 2014; Polvi & Wohl, 2012). Beaver activity can reduce downstream hydrological connectivity, and conversely increase lateral connectivity, forcing water sideways into neighbouring riparian land, inundating floodplains and creating diverse wetland environments, (Macfarlane et al., 2015) whilst also contributing to soil and ground water recharge (Westbrook et al., 2006).

Multiple studies have identified beaver dam sequences and wetlands as a cause of flow attenuation – so called 'slowing the flow' (Green & Westbrook, 2009; Gurnell, 1998; Pollock et al., 2007). This impact has been attributed to the increase in water storage in beaver pond sequences, relative to undammed reaches, (Westbrook et al., 2020) and increased hydrological roughness from the creation of dams and complex wetlands (Puttock et al., 2017), resulting in water being trapped or slowed as it moves through, over and around beaver dams. For example, Green and Westbrook, (2009) found the removal of a sequence of beaver dams resulted in an 81% increase in flow velocity. The slow movement of water in beaver impacted sites is attributed to two main mechanisms (1) increased water storage and (2) stream discontinuity and reduced longitudinal hydrological connectivity (Puttock et al., 2017). The increase in storage provided by beaver ponds and wetlands (Grygoruk & Nowak, 2014; Gurnell, 1998; Woo & Waddington, 1990) lengthens water retention times and reduces the velocity of the water. This in turn can increase the duration of the rising limb of the flood hydrograph which can reduce the peak discharge of floods (Burns & McDonnell, 1998; Green & Westbrook, 2009; Nyssen et al., 2011). Additionally, water stored in beaver ponds is released slowly as the porous dams gently leak both during and following rainfall, elevating stream base flows even during prolonged dry periods (Majerova et al., 2015; Puttock et al., 2017; Woo & Waddington, 1990), increasing environmental resilience to risks including drought and fire (Fairfax et al., 2020).

Water levels in ponds vary significantly as a result of meteorological conditions both over long (i.e seasonal) and short (i.e. inter-event) timeframes (Westbrook et al., 2020, Puttock et al., 2017). Consequently, seasonal variations in water storage have been observed (see Majerova et al., 2015 for an example). It might be expected that the attenuating impact of flow due to storage will be less during wet periods. However, it has been proven that beaver activity still attenuates flow during large events. For an example, see Nyssen, Pontzeele & Billi, (2011) who conducted one of the few in-channel hydrological studies of Eurasian beaver; finding that flow attenuation was in fact greatest during largest events. In 2013, Westbrook et al., (2020) monitored the largest recorded flood in the Canadian Rocky Mountains west of Calgary, Alberta, challenging the commonly held assumption that dams fail during large floods (the majority fully or partially persisted) and showing that water storage offered by beaver dams (even failed ones) delayed downstream flood peaks. Therefore, It has been argued that the observed discontinuity or reduced downstream hydrological connectivity resulting from beaver dam building activity - also shown by Butler and Malanson, (2005), is a key reason for the flow attenuation impact persisting even for larger events during wetter periods (Puttock et al., 2017).

Of course, beaver dam construction is highly variable and depends on the existing habitat, building material availability and channel characteristics (Collen & Gibson, 2000; Woo & Waddington, 1990). Woo and Waddington (1990) identified multiple ways in which dam structure will influence flow pathways and that stream flow can overtop or funnel through gaps in the dams, leak from the bottom of the dams or seep through the entire structure. Whilst the impact of dam structure upon connectivity and therefore, flow velocity will differ, (Hering et al., 2001; Woo & Waddington, 1990), all dams will increase channel/hydraulic roughness and therefore, deliver some flow attenuation effect, which can be most significant when a suite of dams in close proximity are constructed (for example see Puttock et al., 2017 case study). Thus, in addition to dam structural variations, it is important to note that the number of dams and their density will strongly influence any observed differences in hydrological function. Existing work has also discussed the importance of the number of dams in a reach, with beaver dams having the greatest impact on hydrology when they occur in a series (Beedle, 1991; Gurnell, 1998). Similarly, sequences of (non-beaver) debris dams in 3rd order, Northern Indiana (USA) streams were found to increase the retention time of water by a factor of 1.5-1.7 (Ehrman & Lamberti, 1992). Ponds located in series provide both greater storage and greater roughness, resulting in a greater reduction in flow velocities as shown by Green and Westbrook, (2009). In another study, pond sequences have been shown to reduce the peak flows of 2-year return floods by 14% whereas individual dams reduced flood peaks of similar events by only 5.3% (Beedle, 1991).

There are very few hydrological modelling studies into the impacts of beaver dam sequences upon flow regimes. In European landscapes, this perhaps reflects the fact that until recently there has been both a dearth of beaver dams themselves and also a lack of empirical understanding of the impact on hydrological functioning. In a notable exception, Neumayer et al., (2020) undertook hydraulic modelling of beaver dam sequences and evaluated their impacts during flood events. Utilising surveys of beaver dam cascades in Bavaria and 2D hydraulic modelling, Neumayer et al., (2020) predicted that during small flood events, beaver dams can deliver significant impacts upon peak flows (up to 13 % reductions) and lag/translation times (up to 2.75h). But, Neumayer et al., (2020) also predicted that during larger floods (return period ≥ 2 years) the impact upon peak flows of a single dam sequence may be smaller (ca 2 %) and perhaps negligible at the catchment outlet. However, Neumayer et al., (2020) modelled the impacts of beaver dams on channels larger than those that other research has shown might support greatest densities of dams (i.e. Graham et al., 2020 show that dams rarely persist on >5th order streams) and thus it is suggested that further modelling work is required into the downstream hydrological impacts of small streams with high dam densities. In addition, further research is required to understand what the cumulative catchment outlet effects might be if beavers return to being widespread and catchments contain multiple dam sequences (i.e. hundreds of dams) in all headwater streams.

[2.2.2] Summary of Hydrological Impacts

Beavers can reduce longitudinal (downstream) connectivity, whilst simultaneously increasing lateral connectivity, pushing water sideways.

Beavers can increase surface water storage within ponds and canals, whilst also elevating the water table and contributing to groundwater recharge.

Beaver dam sequences and wetlands can attenuate flow during both high and low flow periods.

[2.3] Impacts of beaver upon water quality

The altered flow regimes and water storage capacity discussed in Section 2.2. can also modify sediment regimes and nutrient and chemical cycling in freshwater systems. As a consequence of reduced downstream connectivity and a change from lotic to lentic systems, beaver activity is believed to alter both local and downstream sediment dynamics, and water quality via both abiotic and biotic processes (Cirmo & Driscoll, 1996; Johnston et al., 1995). It has been argued that two key mechanisms affect the difference in sediment dynamics of water quality observed in beaver systems: (1) slowing of flow resulting in the physical deposition of sediment (reviewed in Section 2.1) and associated nutrients/chemicals, (2) an increase in both ponded water and a local rise in water tables, results in an overall increase in wetness altering the biogeochemical cycling of nutrients (Puttock et al., 2017).

[2.3.1] Impacts on nutrient cycling

When beaver dams inhibit the transport of fine sediments, large volumes of organic and inorganic compounds become stored within beaver ponds (Rosell et al., 2005), including; nitrogen, phosphorus and particulate (bound) carbon (Lizarralde et al., 1996; Naiman et al., 1994). This change increases the volume of anoxic sediments and provides organic material to aid microbial respiration. Nutrients are temporarily immobilised in pond sediments and taken up by aquatic plants, periphyton and phytoplankton. Increases in plant available nitrogen, phosphorus, carbon and increased light availability (due to canopy reduction) favour the growth of instream and riparian vegetation, thus further immobilizing nutrients within plant biomass that re-establishes local nutrient cycles (Rosell et al., 2005). In addition to the impacts of large volumes of sediment, the reduction in free-flowing water and increased decomposition has been shown to increase anaerobic conditions in both pond surface water and saturated soils (Ecke et al., 2017, Rozhkoca-Timina et al., 2018).

Lazar et al., (2015) show that beaver ponds have a denitrification impact whilst results from Puttock et al. (2017) showed Total Oxidized Nitrogen (TON) and Phosphate (PO_4-P) to be significantly lower in waters leaving a beaver impacted site compared with water quality entering. These reductions manifest both in terms of concentrations and loads of nutrients, suggesting that beaver activity at the site created conditions for the removal of diffuse pollutants from farmland upstream. Correll et al., (2000) found that prior to dam construction, TON concentrations were significantly correlated with river discharge but after dam construction, no significant relationship was observed, although there was a correlation between discharge and nitrate (NO_3-N). Similarly, Maret et al., (1987) identified reductions in Total Kjeldahl Nitrogen (TKN) downstream of beaver dams during high flows. It has also been shown that beaver ponds are particularly effective at NO_3-N retention (K.J. Devito et al., 1989). It is suggested therefore, that in agriculturally-dominated catchments where diffuse pollution rates are high, beaver ponds may be effective tools to manage N-related diffuse pollution problems from intensive agriculture upstream (Lazar et al., 2015).

Puttock et al., 2017 show that beaver ponds can also act as sinks for phosphorus associated with sediments, whilst Maret et al (1987) identified that suspended sediment was the primary source of phosphorus found leaving a beaver pond; therefore, during conditions when more sediment is retained behind the dam than is released, total phosphorus retention will increase. In a study of a beaver impacted and non-beaver impacted catchment, (Dillon et al., 1991), found total phosphorus export was higher in the non-impacted catchment suggesting that phosphorus was being stored somewhere within the catchment – most probably in the beaver ponds. Lizarralde et al., (1996) also reported that while phosphorus concentrations were significantly higher in riffle sediments, due to extensive wetland creation, total storage was highest in Patagonian beaver ponds. Previous studies have focused primarily on the relationship between discharge and phosphorus concentrations and yields leaving ponds, with inconclusive results. Devito et al. (1989) reported a strong positive correlation between phosphorus loads and stream discharge. However, Maret, Parker and Fannin, (1987) report a negative correlation between phosphorus concentrations and discharge and Correll et al., 2000 report no correlation between nutrient flushing and stream discharge following dam construction. Climatic and seasonal changes (Devito & Dillon, 1993; Klotz, 2007) and organic matter availability (Klotz, 2007; Klotz, 2013) have been shown to affect in-pond phosphorus-dynamics. With regard to downstream impact, the key consensus, that is supported by the correlation between suspended sediment and phosphate concentrations observed in Puttock et al., (2017) is that beaver ponds are effective at retaining phosphorus associated with high sediment loads (Devito et al., 1989; Maret et al., 1987).

Ecke et al., 2017 suggest age dependency as a factor in nitrogen and phosphorus dynamics, with older, more solid dams increasing retention compared to younger more leaky dams. In a review of beaver impacts upon nitrogen and phosphorus content in ponds and downstream, Rozhkoca-Timina et al., (2018) cite contradictory information and study results as showing there is a strong contextual dependence and it is clear that further research into the controlling mechanisms of nutrient retention is required.

In contrast to the trends observed for nitrogen and phosphorus, multiple studies i.e. Puttock et al., (2017) and Cazzolla et al., (2018) found concentrations and loads of Dissolved Organic Carbon (DOC) increase due to beaver activity. This increase is attributed to enhanced sediment and nutrient storage in-addition to the overall increase in wetland extent creating an environment rich in organic matter, as previously shown by Vecherskiy et al., (2011). Similarly, Law et al., (2016), using colour as a proxy for DOC, observed increased concentrations below a series of beaver dams. Dams trap sediment-bound particulate carbon meaning that ponds can act as net stores of carbon (D. Correll et al., 2000; Lizarralde et al., 1996; Naiman et al., 1986). However, as a consequence of this overall increase in carbon availability, significant exports of DOC have been observed either downstream (D. Correll et al., 2000; Naiman et al., 1994) or in comparison with non-beaver impacted catchments (Błędzki et al., 2011). Several authors have speculated that the cause of this DOC release relates to: (i) incomplete decomposition processes making DOC more available for loss (Cirmo & Driscoll, 1996); (ii) enhanced production during primary productivity; (iii) a product of enhanced microbial respiration (D. Correll et al., (2000) (iv) retention of particulate organic carbon and litter entering the site and subsequent decomposition (Law et al., 2016). Based upon research in western Siberia Cazzolla et al., (2018) argue that beaver activity simultaneously increases nutrient cycling and DOC availability at the same time as increasing carbon sequestration as carbon is accumulated in sediment and removed from the short-term carbon cycle.

pH has been shown to be a first order control on DOC production and transport in other wetlands (Clark et al., 2007; Grand-Clement et al., 2014). However, Cirmo and Driscoll, (1996) found that a beaver impacted catchment contained higher levels of DOC both before and after $CaCO_3$ treatment (to reduce acidity) when compared with a non-impacted catchment, suggesting that pH plays a limited role in the production of DOC in beaver ponds. Puttock et al., (2017) showed pH to be marginally more alkaline in water leaving the site, which is in agreement with other studies showing more acidic waters in beaver ponds than immediately downstream (Cirmo & Driscoll, 1993, 1996; Margolis et al., 2001). However, whether these changes in pH were of a large enough magnitude to alter within site biogeochemical cycling is as yet unclear.

Increased water availability in beaver systems, in addition to a change in chemistry associated with a transformation from lotic to lentic waters, has also been ascribed by multiple studies to control increased leaching of heavy metals from soils and increased concentrations in waters downstream. Releases from pond or increases in downstream concentrations of calcium, iron and magnesium (for example) were observed by (Naiman et al., 1994) and (C. A. Johnston et al., 1995), whilst (Levanoni et al., 2015; Margolis et al., 2001) also observed downstream increases in manganese and observed increasing methylmercury concentrations both downstream of beaver sites and in macroinvertebrates within beaver sites. In a meta-analysis review Ecke et al., (2017) found young ponds to be a source for methylmercury in water, whilst old ponds were not, again highlighting that beaver systems are complex and dynamic with a high degree of context dependence required to understand their impacts upon water quality.

[2.3.3] Summary of water quality Impacts

Beaver wetlands and dam sequences can change parts of freshwater ecosystems from lotic to lentic systems impacting upon sediment regimes and biogeochemical cycling.

By slowing the flow of water, suspended sediment and associated nutrients are deposited, with ponds shown to be large sediment and nutrient stores.

Increased water availability, raised water tables and increased interaction with aquatic and riparian vegetation have all been shown to impact positively upon biogeochemical cycling and nutrient fluxes.

[3.] BEAVER IMPACTS UPON LIFE – CONTEMPORARY UNDERSTANDING

[3.1] Impacts of beaver upon aquatic ecology

Enhancement of natural processes, floodplain inundation, lateral connectivity and structural heterogeneity in beaver-impacted environments creates a diverse mosaic of habitats. Such habitats are underpinned by greater provision of food, refuge and colonisable niches, which form the cornerstone of species rich and more biodiverse freshwater wetland ecosystems (Gurnell, 1998; Rosell et al. 2005; Gaywood, 2015; Campbell-Palmer et al. 2016; Stringer & Gaywood, 2016; Brazier et al. 2020). Readers are directed to three reviews on this topic: Stringer & Gaywood (2016), which provides a comprehensive overview of the impacts of beaver on multiple species, Dalbeck, et al. (2020) which considers the impacts of beavers on amphibians in temperate European environments and Kemp et al. (2012) which provides a valuable meta-analysis of the impacts of beaver on fish. This section builds on these reviews to summarise the findings of research into the impacts of beaver activity on aquatic plants, invertebrates and fish. We focus on these groups as they are widely considered to be strong indicator species of freshwater health and function (Herman & Nejadhashemi, 2015; Turley, et al., 2016; Law, et al., 2019a).

[3.1.1] Aquatic vegetation (Macrophytes)

Beavers affect aquatic vegetation through direct and indirect mechanisms over a range of spatial and temporal scales (Rosell et al. 2005). Natural disturbances, including; herbivory, food caching, tree-felling (Harrington et al. 2015; Campbell-Palmer et al. 2016) and/or dam-induced extension of wetland area (Gurnell, 1998; Puttock et al. 2017) can aid macrophyte recruitment (Levine & Mayer, 2019), regenerate riparian areas (Jones et al. 2009) and enhance plant biodiversity from the local to the landscape scale (Law et al. 2014a; 2014b; Willby et al. 2018; Law et al. 2019b). Canopy-opening and floodplain inundation creates wetland areas with reduced shading (Johnston & Naiman, 1990; Donkor & Fryxell, 2000), providing opportunities for shade-intolerant, opportunistic and wetland plant species (Marshall et al., 2013; Law et al. 2016; 2017; 2019b). Early successional shifts in newly created wetted zones promote emergent vegetation (Ray et al. 2001), whilst transitional edges form around pond margins, characterised by rich, diverse and structurally complex plant communities (McMaster & McMaster, 2001).

Over time, beaver wetland creation, maturation and abandonment, can result in the siltation of ponds, creating novel habitats in marshy beaver meadows characterised by spatial variability in moisture-regimes which drives higher plant species richness (Ray et al. 2001; Wright et al. 2002; 2003; Polvi & Wohl, 2012). As beaver meadows mature, terrestrial succession often occurs, leading to herbaceous encroachment, typically comprising grasses, shrubs and sedges, with studies showing evidence of an eventual return to open, forested, stream environments (Naiman et al. 1988; Pollock et al. 1995; McMaster & McMaster, 2001; Ray et al. 2001; Little et al. 2012; Johnston, 2017).

[3.1.2] Invertebrates and amphibians

Beaver increase the heterogeneity of stream depth, flow velocity and benthic habitats such as: silty substrates, woody material (Clifford et al. 1993; France, 1997; Rolauffs et al. 2001) and both submerged and emergent vegetation, which separately support unique invertebrate species and assemblages (Benke et al. 1999; Wissinger & Gallagher, 1999; Bush & Wissinger, 2016; Law et al. 2019b). Beaver ponds support more lentic species (Collen & Gibson, 2001; Margolis et al. 2001; Rosell et al. 2005) and typically demonstrate increased invertebrate abundance (Czerniakski & Slugocki, 2018; Osipov et al. 2018; Strezelc et al. 2018; Willby et al. 2018), biomass (Osipov et al. 2018) and/or density (McDowell & Naiman, 1986). Beaver ponds may harbour unique assemblages, dominated by collector-gatherers, shredders and/or predators (McDowell & Naiman, 1986; Law et al. 2016; Strzelec et al. 2018; Robinson et al. 2020). However, diversity may be reduced due to the typically homogeneous benthic habitat within ponds resulting from increased fine sediment deposition (Descloux et al. 2014; Pulley et al. 2019). At broader scales, varying successional stages in beaver wetlands, as well as longitudinal variability in habitat type along beaver dam-pond sequences (e.g. Margolis et al. 2001), increases the taxonomic, trophic and/or β-diversity of aquatic invertebrate communities compared to environments lacking beaver modification. This is primarily due to the heterogeneity of habitat benefiting a range of both lotic and lentic species (Law et al. 2016; Pollock et al. 2017; Willby et al. 2018; Bush et al. 2019). Furthermore, the storage of sediment and nutrients within beaver ponds improves water quality (Puttock et al. 2017) downstream and therefore enhances habitat for pollution-sensitive species (Rosell et al. 2005; Strzelec et al. 2018).

The gradual release of water from beaver ponds maintains flows during dry periods (Section 2.1.), thereby increasing invertebrate resilience to drought by providing refuge pools and greater post-drought recolonisation potential (Wissinger & Gallagher, 1999; Wild, 2011). High-head dams promote high velocity and turbulent water over, through or around dams in side-channels, creating habitat suitable for lotic species, which can otherwise be rare in low-gradient stream reaches (Clifford et al. 1993; Law et al. 2016). In addition, cold hyporheic upwelling and lower stream temperatures downstream of high-head dams, and at depth in beaver ponds, has been shown to benefit the reproductive success of invertebrate species such as mayflies (Fuller & Peckarsky, 2011).

Beaver-engineered woody structures, such as dams and lodges, offer key invertebrate habitats resulting in greater abundance (France, 1997), biomass, density (McDowell & Naiman, 1986; Rolauffs et al. 2001), productivity, richness (France, 1997; Rolauffs et al. 2001) and diversity (Benke et al. 1984) compared to beaver ponds and free-flowing streams. Direct benefits for invertebrates arise from physical complexity, such as the interstices of dams, lodges, bank burrows and canals, which offer spaces suitable for novel microhabitats (Hood & Larson, 2014; Willby et al. 2018), refuge from predators (Benke & Wallace, 2003), egg laying (oviposition) sites (Gaywood, 2015) and emergent metamorphosis (Wallace et al. 1993). These woody structures also provide attachment sites for filter-feeding organisms and foraging resources for species that feed on woody material (xylophagous) and those that feed on the epixylic biofilms which grow on woody surfaces (Hering et al. 2001; Godfrey, 2003; Strzelec et al. 2018). For example, deadwood-eating (saproxylic) beetles are known to occupy beaver-impacted habitats (Zahner et al. 2006; Horak et al. 2010; Stringer & Gaywood, 2016). In addition, the retention of organic particulate matter in beaver ponds enhances foraging opportunities for aquatic invertebrates, particularly gatherers and shredders (Wohl, 2013; Johnston, 2014; Law et al. 2016). Organic drift can also bring wider benefits within catchments, increasing the abundance and/or richness of invertebrates in areas both downstream (Redin & Sjoberg, 2013) and upstream (Rolauffs et al. 2001) of beaver-modified sites.

Dalbeck et al., (2020) conclude that beavers and their habitat creating activities can be pivotal determinants of amphibian species richness, particularly in the headwater streams. The creation of lentic zones in beaver modified wetlands is cited as an essential breeding habitat for amphibian species, but can also be important for entire life history requirements (Cunningham et al. 2007), with beaver ponds offering sites where reliable spawning and early metamorphosis can take place, in instances comprising exclusive ovipositional sites within wider wetlands (Dalbeck et al. 2014). Beaver modifications, which increase lentic-rich habitat heterogeneity and/or raise light levels and solar radiation, warming patches of water, in turn support healthier amphibian assemblages. Such improvements manifest via greater species-richness (Cunningham et al. 2007), diversity (Cunningham et al. 2007; Dalbeck et al. 2007; Bashinskiy, 2014; Vehkoaja & Nummi, 2015), colonisation rates and abundance (Stevens et al. 2007; Dalbeck et al. 2014; Anderson et al. 2015; Vehkaoja & Nummi, 2015), older-pond density (Stevens et al. 2006), size and productivity compared to unmodified habitats, with connectivity between ponds and through beaver canals reducing distances between breeding and foraging sites (Anderson et al. 2015). Woody complexes which form lodges and dams may also provide valuable habitat which amphibians can use for larval food provision and development (Tockner et al. 2006), potential overwintering hibernation sites (Stevens et al. 2006) or cover from predators (Tockner et al. 2006), with cover options offering predatorial and larval protection by areas of shallow emergent-vegetated pond margins (Dalbeck et al. 2007; Vehkaoja & Nummi, 2015). Conversely, lotic obligate species may be negatively affected by beaver activity (Stringer & Gaywood, 2016), although studies have demonstrated the persistence and high abundance of stream-dependent species on the unimpounded reaches of beaver modified streams (e.g. Cunningham et al. 2007).

[3.1.3] Fish

Beavers and fish have cohabited for millennia (Malison & Halley, 2020) and have previously been shown to coexist positively (Kemp et al., 2012). As such, it is no surprise that beaver-induced habitat changes, particularly increased heterogeneity, can benefit fish populations (Figure 3). Documented benefits include increased: growth rates, (Rosell & Parker, 1996; Pollock et al. 2003; Malison et al. 2015), survival (Bouwes et al. 2016) biomass (Bashinsky & Osipov, 2016), density (Bouwes et al. 2016; Wathen et al. 2019), productivity (Pollock et al. 2003; 2004; Osipov et al. 2018), species richness (Snodgrass & Meffe 1998) and diversity (Smith & Mather, 2013). Additional benefits to fish include the creation of juvenile rearing habitat (Leidholt-Bruner et al. 1992; Pollock et al. 2004; Johnson & Weiss, 2006), overwintering habitat (Chisholm et al. 1987; Cunjak, 1996; Malison et al. 2015), migratory respite (Virbickas et al. 2015), enhanced spawning habitat (Bylak et al. 2014), greater invertebrate food availability (Rolauffs et al. 2001) and refugia from; low-flows (Hägglund and Sjöberg, 1999), high discharge (Bouwes et al. 2016), temperature extremes (Wathen et al. 2019) and predation (Bylak et al. 2014). It is for these reasons, that recent approaches in the US have used beaver reintroduction to enhance habitat in support of salmonid reintroduction and/or conservation (Bouwes et al. 2016).

Due to the wide range of changes that beavers bring about, the benefits listed above will likely manifest for a variety of freshwater fish species though a wider understanding of these impacts is required as most research has focused upon interactions between beaver and salmonid species. Salmonids, particularly anadromous species (migrating from the sea to spawn in rivers) hold significant financial, cultural and recreational value from a fisheries perspective (Butler, et al., 2009). Unfortunately, for a variety of reasons, which have nothing to do with beavers, populations of salmonid populations in Europe are in decline and the two most abundant native salmonids, the Atlantic salmon (S. solar) and the Brown/Sea trout (*S. trutta*) are under threat (Forseth, et al., 2017). Research in the US has largely shown that beaver reintroduction aids the recovery of salmonid populations (e.g. Bouwes, et al., 2016; Wathen, et al., 2019); however, despite the long-term coexistence of these species, the expansion and reintroduction of beavers across European landscapes, now substantially altered due to anthropogenic activity, has raised concerns regarding the potential impact that beaver activity may have on salmonid species (Malison & Halley, 2020).

Two recent studies have investigated the impacts of beaver on salmonid habitat and populations in upland streams (Bylak & Kukula, 2018; Malison & Halley, 2020). Both of these studies report increased habitat patchiness and heterogeneity in river systems that are typically dominated by fast flowing habitat. Neither study found evidence to suggest that beaver dams prevented fish movement either upstream or downstream. However, Malison & Halley (2020) did find that the presence of beaver dams affected the frequency of movement between stream reaches, suggesting that either beaver dams may act to restrict daily home ranges of salmonids, or the increased local habitat complexity around beaver dams reduces the need for salmonids to travel greater distances. A conflicting finding of these studies is that of the use of ponds by salmonids. In agreement with numerous studies that found beaver ponds to provide valuable rearing habitat (Malison, et al., 2014; Weber, et al., 2017) and habitat niches for different stages of salmonid life cycles (Bouwes, et al, 2016; Wathan, et al., 2019), Bylak & Kukula (2018) observed that brown trout used different beaver-created habitats throughout their life stages. However, Malison & Halley (2020) reported that they did not observe beaver ponds being used as salmon rearing habitat. Both studies report either no significant effect of beaver on fish populations (Malison & Halley, 2020) or a positive impact on the community composition and patch dynamics (Bylak & Kukula, 2018).

Virbickas, et al. (2015) studied the impacts of beaver on two lowland Lithuanian streams. Unlike, the studies from upland streams, Virbickas, et al. (2015) found evidence to suggest that beaver dam sequences do restrict upstream movement of salmonids with reaches below and between ponds being used but no salmonids or redds (spawning sites) being observed upstream of beaver dam complexes. Whilst the presence of beavers did enhance community evenness upstream of dams, this effect was attributed to the exclusion of salmonids, which typically dominated fish communities downstream of dams.

The scale of such studies should be considered carefully in the context of mobile and dynamic species of fish. Bylak & Kukula (2018) present data from the longest period of monitoring in Europe. They show that the response of fish to beaver activity enhances metacommunity resilience but consequently localised fish communities may alter for short periods of time. However, in these upland systems, high flows capable of 'blowing out' dams are more frequent (Macfarlane, et al., 2017) thus allowing unimpeded fish movement during these periods. In lowland systems, such as those investigated by Virbickas, et al., (2015) the increased hydrological stability may result in a longer lasting separation of fish communities up and downstream of beaver dams. In low gradient systems, where spawning habitat is located solely in the upper reaches of a catchment, the presence of dams could potentially limit access to these reaches, affecting spawning success or resulting in the formation of new spawning habitat, such as the clean gravel bars which commonly form at the tail end of beaver ponds and immediately downstream of dams (Bouwes, et al., 2016).

Further research on the impacts of fish across varied European landscapes is required. These studies should seek to understand the effect of beaver on fish communities at the catchment scale. It is well established that fish can navigate beaver dams (Virbickas, et al., 2015; Bouwes, et al., 2016; Bylak & Kukula, 2018; Malison & Halley, 2020). However, a greater understanding is required to quantify the importance of any reduced longitudinal movement of fish alongside the known benefits including an increase in food availability and greater habitat diversity.

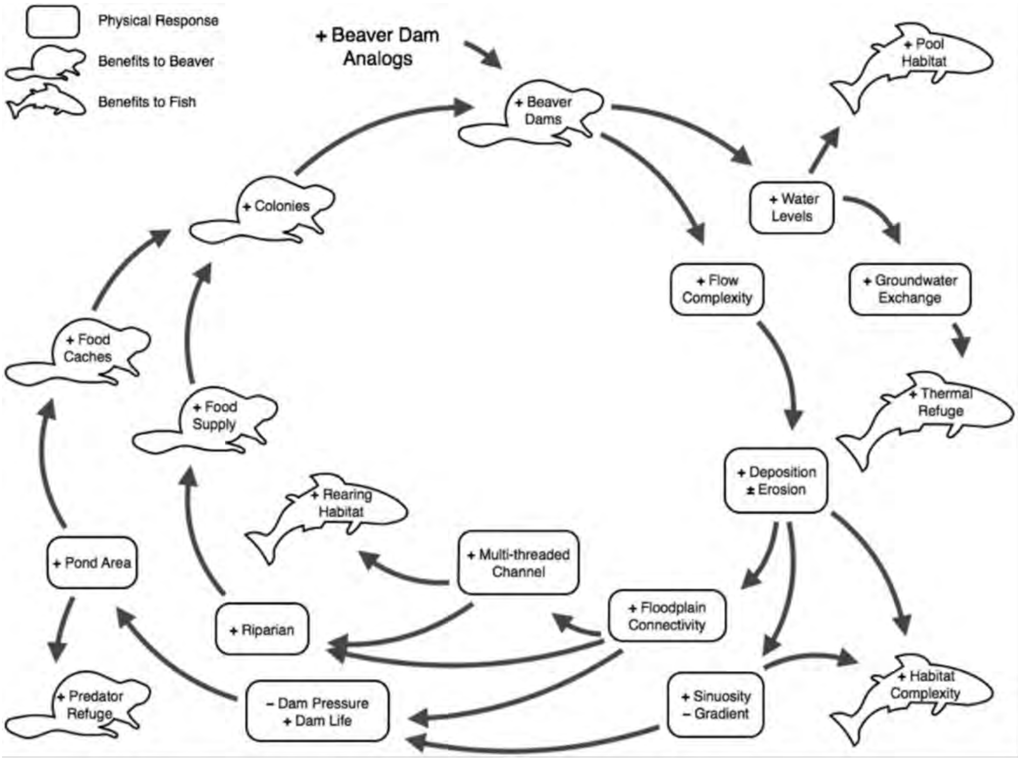

Figure 33 Flow Diagram of expected change following beaver return. From Bouwes et al., 2016.

[3.1.4] Aquatic Ecology Summary

Beaver activity extending wetland areas aids aquatic plant recruitment, abundance and species diversity

Nutrient rich beaver meadows result in mature beaver managed landscapes, contributing diverse plant life and increasing patchiness in otherwise homogeneous (especially intensively farmed) landscapes

Heterogeneity of beaver habitat leads to greater diversity of invertebrates, benefitting both lotic and lentic species.

Slow release of water from beaver ponds elevates baseflow downstream supporting greater aquatic life, improving resilience especially in times of drought.

A multitude of benefits accrue for fish due to beaver activity such as increased habitat heterogeneity and food availability.

It is established that salmonid species can navigate beaver dams, though there is evidence that the presence of dams does alter the way they move within river networks. The impact of dams on salmonid movement is highly dependent on location and upstream movement may be reduced in low gradient, low energy systems.

[3.2] Human – beaver interactions

The potential benefits and impacts of beaver reintroduction (outlined above for the environment) can also manifest for humans. Notably, flow attenuation resulting from beaver damming will be likely to reduce potential for flooding of properties downstream. There is a further socioeconomic benefit not as yet explored in this article; as beavers bring more wildlife to ecosystems, beaver lands can become a focus of wildlife tourism, where humans interact with wild animals or with animals in enclosures (Higginbottom, 2004; Moorhouse et al., 2017). Wildlife tourism is a growing global trend which can engage people with nature, with their experiences often contributing towards local communities, providing benefits for mental health and well-being, and incentivising nature conservation behaviours (Curtin, 2009; Curtin and Kragh, 2014; Higginbottom, 2004; Lackey et al., 2019; Newsome et al., 2019; Skibins et al., 2013).

Much wildlife tourism is centred upon 'charismatic species' (Curtin, 2010; Skibins et al., 2013), but some is motivated by the intention to support wider biodiversity rather than charismatic species alone (Hausmann et al., 2017). Beavers are often considered charismatic and, as a keystone species, are associated with biodiverse landscapes, which they create and maintain. Thus, they exhibit both those traits that motivate wildlife tourism. Beaver tourism activities that currently exist in Europe include 'beaver safaris', guided tours of beaver-modified landscapes and information centres (Campbell et al., 2007; Halley and Rosell, 2002; Rosell and Pedersen, 1999). Beaver tourism and associated support for local communities is therefore often cited as one of the reasons for reintroduction where beavers are not yet present (Campbell et al., 2007; Gaywood, 2018; Gurnell et al., 2009; Jones et al., 2012; Moran and Lewis, 2014).

There are, however, a number of challenges experienced where beaver and humans interact. In Europe, these are observed mostly where beaver impacts interact with human interests within the riparian zone (Campbell-Palmer et al., 2016; Halley & Rosell, 2002; Heidecke & Klenner-Fringes, 1992), particularly in upper and marginal reaches of watercourses where beaver will undertake the largest-scale habitat alteration (Halley & Rosell, 2002, Graham et al, 2020). For example, where water is stored behind beaver dams, it may inundate land owned by humans which could lead to a financial cost, especially when associated with agriculture or forestry (Campbell-Palmer et al., 2016; Gaywood et al., 2015; Morzillo & Needham, 2015; Parker et al., 1999). Other notable impacts can include beaver burrow collapse and bank erosion in agricultural land (Campbell-Palmer et al., 2016; Gurnell, 1998), beaver grazing on arable crops (Campbell-Palmer et al., 2016; McKinstry & Anderson, 1999), or the felling of particular trees of human importance (Campbell-Palmer et al., 2016, 2015). Perhaps not surprisingly, beaver are perceived more negatively by people where these conflicts occur (Payne & Peterson, 1986; Enck et al., 1992; McKinstry et al., 1999; Jonker et al., 2010).

Practical management interventions exist that can be employed in order to address these factors, including: dam removal, bank stability management, flow device installation (to lower water levels), tree protection, restoration of riparian zone as management, supported further by compensation or positive incentive payments (Campbell-Palmer et al., 2016, 2015; Morzillo and Needham, 2015; Pollock et al., 2017). To reduce the potential for further conflicts, however, particularly those that occur between people over species management (Marshall et al., 2007; Redpath et al., 2015), it is recognised that engaging with affected individuals and sharing in the decision-making processes for management of beaver is vital (Coz & Young, 2020; Decker et al., 2016, 2015; Redpath et al., 2013).

A recent study of local peoples' attitudes towards beaver in Romania and Hungary demonstrated that beaver were often viewed negatively when related to provisioning ecosystem services but positively regarding regulatory or cultural services. As such the study called for recognition of this complexity in perceptions to minimise conflicts, through 'reciprocal learning' between conservationists and locals in adaptive management (Ulicsni et al., 2020). For beaver, there are a number of management frameworks which seek to engage with affected parties across Europe in a variety of ways, for example:

in Bavaria (Germany), regional authorities employ two beaver managers to oversee a network of volunteer beaver consultants throughout the region (Schwarb & Schmidbauer, 2003; Pillai & Heptinstall, 2013); in the Netherlands, the government monitors the beaver population and provides management advice to landowners (Pillai & Heptinstall, 2013); in France, the state authorities provide an advisory service at a catchment scale (Campbell-Palmer et al., 2016, 2015; River Otter Beaver Trial, 2019). However, although engagement is a key component of management strategies, there are to date, few European studies describing attitudes towards beaver (Ulicsni et al., 2020).

The case is different in Great Britain where beaver are currently being reintroduced at a politically devolved level (with the reintroduction status at varying stages throughout the nations) as there have been a number of studies of attitudes towards the species. This may be because an understanding of social factors is a requirement of reintroduction according to the guidelines set by the International Union for the Conservation of Nature (IUCN and SSC, 2013); these guidelines were published in 2013 after many of the reintroduction projects in mainland Europe (Halley and Rosell, 2002), and of course these guidelines do not apply to established or naturally dispersing populations of beaver that were not therefore ‘reintroduced’. Additionally, there is a recent increase in recognition in the literature that the human dimension of environmental projects is a key component of their success or failure (Bennett et al., 2017b, 2017a; Chan et al., 2007; IUCN and SSC, 2013; Redpath et al., 2015). For example, conflicts between humans and wildlife, or between humans about wildlife, may result in threats to species populations or the future success of any attempted species reintroduction (Dickman, 2017; Manfredo & Dayer, 2004; O’Rourke, 2014).

The British studies of attitudes may have limitations (most notably the ability to which they can be deemed representative of a wider population), but they have consistently demonstrated a majority in favour of beaver projects, ranging between 63% and 95.19% of respondents (Auster et al., 2019). However, the intricacies of the social debate run deeper than a simple “for or against” question. A nationwide survey found an association between support for reintroduction and a positive view of potential impacts, and vice versa (Auster et al., 2019). The respondents from the occupational sectors of ‘Farming and Agriculture’ or ‘Fisheries and Aquaculture were less likely to have a favourable view of beaver impacts and were thus often (though not unanimously) opposed to beaver reintroduction, which is in line both with other studies conducted in Great Britain (Gaywood, 2018; Crowley et al., 2017; Lang, 2004; Scott Porter Research and Marketing Ltd, 1998; Auster et al., 2020a) and the aforementioned conflict challenges which have been observed across mainland Europe.

Socially, when whomever gains or losses from beaver reintroduction is examined it is concluded that (in certain scenarios) those people who experience the benefits may differ from those who experience the costs (Brazier et al., 2020; Gaywood, 2018). Although it is often cited that the potential benefits of beavers will outweigh the costs (Brazier et al., 2020; Campbell et al., 2007; Gaywood, 2018; Gaywood et al., 2015; Gurnell et al., 2009; Jones et al., 2012; Tayside Beaver Study Group, 2015), the costs that do occur may be attributed to a small number of people who themselves derive little or no direct financial benefit. This distinction between potential beneficiaries and the negatively impacted parties is perhaps most easily demonstrated in the case of beaver damming, where a downstream community may benefit significantly from flood alleviation whilst the landowner upstream may experience flooding on their property. Thus, strategic management decisions will need to consider how to bridge this disconnect and address potential conflict issues whilst allowing for the potential opportunities for biodiversity, flow attenuation, water quality and ecotourism to be maximised.

It is highlighted herein, that to enable maximisation of the opportunities from beaver reintroduction that are reviewed above, these conflicts will need to be appropriately recognised; the best management strategies are those where issues are mutually addressed between wildlife management authorities and stakeholders (Redpath et al., 2013; Rust, 2017; Treves et al., 2009; Auster et al 2020b). There are real opportunities resulting from beavers, as discussed above, but there are real conflict challenges to be addressed as well, and they should be considered as one within a holistic approach with a closed loop between the beneficiaries and the negatively affected. Further, in the case of reintroduced beavers, such management considerations will need early attention if the potential for later conflicts is to be reduced, particularly as challenges may not yet exist but could occur post-introduction (Coz & Young, 2020; Auster et al., 2019; Conover & Decker, 1991).

Finally, holistic management strategies will need to incorporate effective communication to aid the reduction of potential conflict issues. In a case from Poland, beavers had been reported as of concern by fishery managers, who cited damage to pond levees. Some of the participants had received compensation for reported damage, but a number of fishery managers had undertaken both authorised and unauthorised beaver culls as the beavers were viewed as problematic. In this scenario, it was reported that "poor communication" by conservation bodies was a particular part of the problem, with a lack of information on management measures and unresponsiveness from government agencies being factors which were suggested to have exacerbated conflict (Kloskowski, 2011). However, the literature recognises that, when stakeholders are appropriately engaged and communication is effective, trust can be fostered between stakeholders and the wildlife management authorities (Decker et al., 2016, 2015; Redpath et al., 2013; Rust, 2017; Treves et al., 2009). This in turn can enable an environment within which, as Redpath et al. remarked in 2013, wildlife management issues and decisions can be 'shared as one' (Redpath et al., 2013).

[3.2.1] Summary of Human-Beaver Interactions

There are real opportunities for humans provided by beavers, as well as real potential conflicts between humans and the activity of beavers. The opportunities may be realised by different people to those who incur the costs in certain contexts.

Effective management strategies should consider the beneficiaries and cost-bearers in a holistic manner, bridging the distinctions within a closed loop management system.

Management strategies require clear communication in order to gain trust between stakeholders and the wildlife management authority, thus providing an environment that is conducive towards addressing issues as a collective and reducing the potential for conflict between parties.

[4.] CONCLUSION: FUTURE SCENARIOS AND CONSIDERATIONS

The beaver is clearly the very definition of a keystone species. The myriad ways in which it alters ecosystems to suit its own needs, which in turn supports other species around it, demonstrate its value in re-naturalising the heavily degraded environments that we inhabit and have created. The impacts of beaver reintroduction reviewed herein; to deliver changes to ecosystem structure and geomorphology, hydrology and water resources, water quality, freshwater ecology and humans and society are profound. Beaver impacts are not always positive, at least from a human perspective, thus it remains critical that the knowledge gaps identified above are addressed as beaver populations grow, to ensure that improved understanding coupled with clear communication of beaver management can prevail.

Where beavers do deliver positive change, on balance benefits are shown to outweigh the costs associated with beaver reintroduction or management. It is unlikely that any other species, including humans, will deliver these changes, thus it would seem rational to conclude that beaver population expansion should be supported, wherever habitat is suitable and the species naturally occurred historically. Indeed, it is suggested that reintroducing beavers, is a genuine example of 'working with natural processes' or implementing 'nature-based solutions', which are both low cost and multi-faceted. As such, beaver reintroduction can underpin approaches to reverse the decline of species extinctions whilst also delivering ecosystem services, which may increase resilience to climate change and mitigate associated risks such as flooding and drought.

Of course, such an environmentally progressive approach needs to be implemented hand-in-hand with an appropriate management regime, ideally funded by Government, in order to capitalise on the environmental goods and services that beavers provide, and established as part of a national (or even international) strategy for the reintroduction of the beaver. Such management approaches have been normalised in places such as the German state of Bavaria, where beavers now deliver the wide range of ecosystem services reviewed above, with a pragmatic and flexible approach towards beaver management to support people who experience negative impacts whilst supporting a favourable conservation status of the species (Schwab & Schmidbauer, 2002; Pillai & Heptinstall, 2013). Other countries, including GB where beaver populations are in their infancy, but expanding, would do well to adopt similar management strategies (for an example, see the River Otter Beaver Trial, 2019) in order to ensure that successful reintroduction of beavers maximises the environmental opportunities and minimises the social conflicts that may manifest.

Case Study: Hydrology and Water Quality –Devon Beaver project

Puttock et al., 2017 undertook research at an enclosed and therefore controlled beaver reintroduction site in Devon, South West England (DWT, 2013). The site is situated on a first order stream. In March 2011, a pair of Eurasian beavers was released into a 3 ha enclosure, dominated by mature willow and birch woodland, in addition to gorse scrub. Upstream, the site was fed by a 20 ha catchment area dominated by intensively-managed grassland. As illustrated in Figure 4, beaver activity at the site created a complex wetland, dominated by 13 ponds, dams and canal networks (Puttock et al., 2015). Flow was monitored upstream and downstream of the beaver ponds.

Monitoring of the site between 2013 and 2016 showed that the 13 ponds covered >1800 m^2 and stored >1 million litres of water. Across 59 rainfall-runoff storm events the outflow below the beaver impacted site showed a more attenuated response relative to water entering the site. Events exhibited on average 34 % lower total event discharges, 30 % lower peak discharges and 29 % longer lag times below the beaver dam sequence in contrast to flow entering the site. Critically, Puttock et al., (2017) analysed a sub-set of the largest flood events of greatest interest from a flood risk management perspective. Results showed the flow attenuation impact to persist. Additionally, whilst the inflow to the site was ephemeral, drying up during drought periods, the outflow from the site never dried up during the monitoring period, highlighting the ability of increased water storage in beaver wetland environments to maintain base flow in river systems.

Analysis was undertaken into sediment storage within the site and water quality entering and leaving the site. A site survey (see Puttock et al., 2018), showed that ponds held over 100 tonnes of sediment, 15 tonnes of carbon and 1 tonne of nitrogen. Pond size was shown to be the greatest control over storage, with larger ponds holding more sediment per unit area. Source estimates indicated that >70 % of the sediment trapped in the ponds was from the upstream agriculturally-dominated catchment. A summary of water quality results taken during rainfall-runoff events (see Puttock et al., 2017) showed that on average, compared to water entering the site, water downstream of the beaver dam sequence contained 3 times less sediment, 0.7 times less nitrogen, 5 times less phosphate, but twice the dissolved organic carbon content. Associated flow attenuation was shown to result in further reductions in total loads.

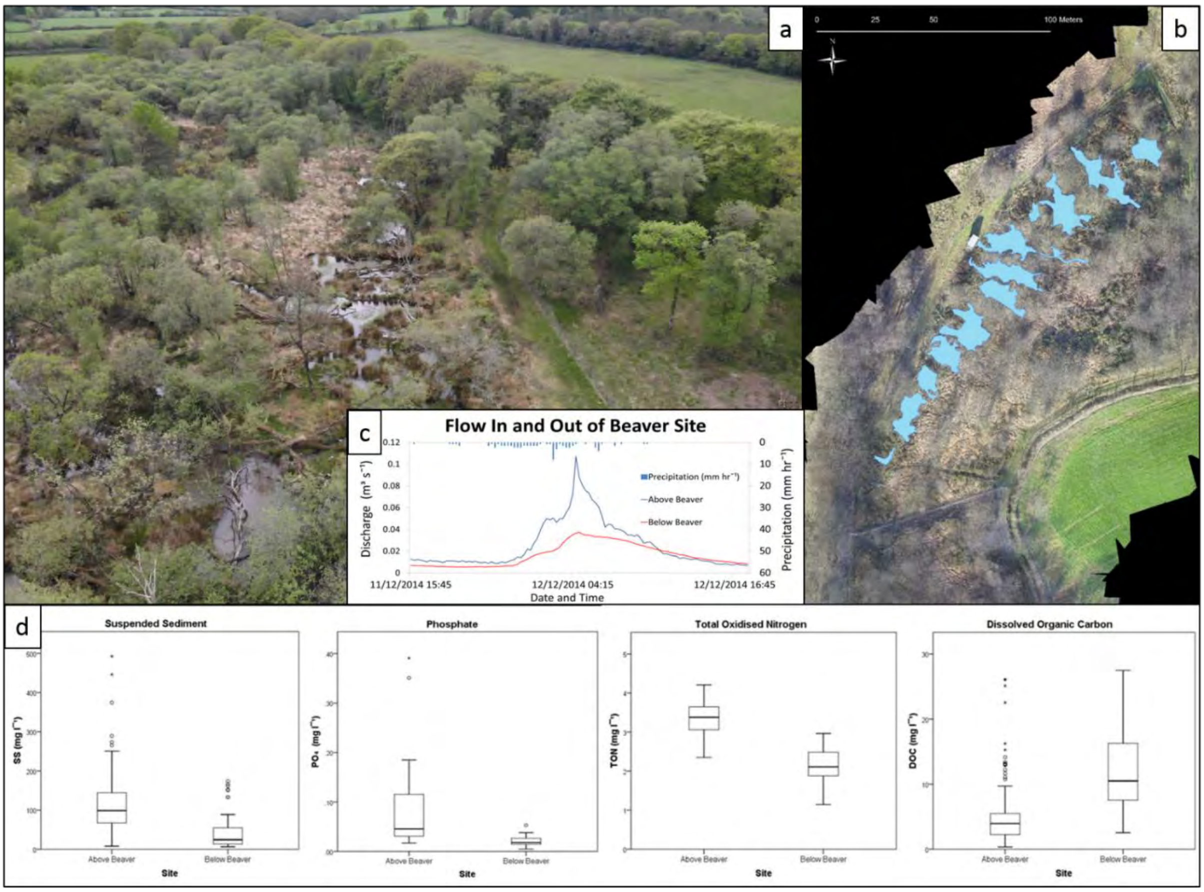

Figure 34.A summary figure for the Devon Beaver Project: a) aerial photo showing the beaver wetland nestled amongst an agriculturally dominated landscape; b) survey results for locations of 13 dams and ponds; c) an example hydrograph showing the contrast in flow regime between water entering the site (blue) and water leaving the site (red); d) summary water quality results from the site for each figure 'Above Beaver' to the left is the concentration entering the site and 'Below Beaver' to the right is concentration leaving the site. From left to right: suspended sediment, Phosphate, Total Oxidised Nitrogen and Dissolved Organic Carbon.

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