Hydraulic Modelling of Eurasian Beaver Structural Modifications:

Implications for Evaluating their Contributions to Natural Flood Management in Scotland

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Abstract

The concurrent climate and biodiversity crises in Scotland necessitate the exploration of ecosystem-based adaptation to simultaneously address increased flood risk and the loss of native species. This research investigated the contributions of Eurasian beaver reintroductions to natural flood management in Scotland. It did this by reviewing the relevant literature on the primary structural modifications built by beavers and translating them into modellable features. A 1D hydraulic model of a small Scottish river system was then built and the presence of these structures simulated to analyse their effects on flooded areas during a 1 in 10-year event. Several key findings emerged that suggest these structures can have a marginal net attenuative effect on a hyper-local scale, but with significant uncertainty dependent on dam size and channel morphology. There were divergent upstream and downstream effects that were not reflected in total flood extent calculations. The modelling process brought about a critical examination of the utility models in assessing the contributions of beaver reintroductions to the field of natural flood management, concluding that models are inherently limited in their ability to capture the complexity of natural systems. Insights from the theories of complex adaptive systems and deep ecology further complicate what it means to evaluate the contributions of non-human species to flood risk management, and whether their ecosystem services should be the sole justification for their reintroduction.

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Summary

Climate change is forecasted to increase the rate of fluvial flooding and exacerbate the rate of biodiversity loss across Scotland. Interdisciplinary interventions such as ecosystem-based adaptation are needed to address these concurrent crises. Natural flood management is a type of ecosystem-based adaptation being explored across Scotland, due to its ability to increase natural flood resilience while expanding habitats for native species. Beavers have been reintroduced to Scotland and existing literature suggests their impacts on river systems may qualify as a form of natural flood management. However, more research is needed to quantify their effects on flood risk and explore their impacts on individual channel systems. This research project aimed to contribute to the evidence base by modelling how structures built by beavers affect flood extent and examining the use of modelling technologies to evaluate their contributions to natural flood management. It engaged with a two-part methodology to accomplish this. First, a systematic literature review was conducted to establish how Eurasian beavers modify their landscapes in hydrologically or hydraulically significant ways. Boundaries were placed to limit the results of the literature review to the primary structures built by beavers, in order to feasibly build the model within the research timeline. The primary structures deemed relevant to include in the model were dams, burrow-lodges, canals, slides, and food storage areas. The results of the literature review were paired with the capabilities of the HEC-RAS 1D hydraulic modelling software to translate findings into modellable features. Second, a 1D hydraulic model of a small portion of the rivers Ettrick and Yarrow in South-eastern Scotland was built upon which to simulate a beaver reintroduction through the input of their modelled structures. The output of interest was flooded areas in meters squared. Flow data for a 1 in 10-year flood event was calculated to examine the effects of beaver structures under high-likelihood flood events, for which the study region is at risk and government flood maps were available to validate the baseline model. The model was calibrated through the inclusion of bridges, flood walls, blocked obstructions, and editing of land cover classifications to reflect the hydraulic conditions of the area. Two ‘reintroduction’ areas were qualitatively identified as potentially suitable for beaver reintroduction. Beaver structures were inputted into both areas, using average dimensions reported in the literature, to evaluate their effects. A sensitivity analysis investigated the uncertainty in the literature regarding possible beaver dam dimensions, to ascertain the minimum and maximum impacts of beaver dams on flooded areas. The results of the simulations showed that ‘average’ beaver structures marginally attenuated flooding in both areas. However, results were hyper-local in effect and had differential impacts upstream and downstream of the dams, which were not well-reflected in measurements of total flood extent. The sensitivity analysis suggested that the flood attenuation effects of dams were uncertain and dependent on dam sizes, which were controlled by channel morphology. Minimum dam sizes showed the most flood attenuation while maximum dam sizes showed a net increase in flooding, at both reintroduction areas. The results must be taken contextually due to issues in model validation. In addition, due to limitations in both the data available from the literature and the model, many assumptions had to be made that contributed significant uncertainty to the results of the model. The results of the study also suggested that the complexity of beaver systems was not well captured by this model due to the necessary input of boundary conditions that resulted in analytical sacrifices. Philosophical and ethical considerations arose from this research regarding the reduction of species' value to their ecosystem services and the implications of this in addressing the climate and biodiversity crises in Scotland.

Abbreviations

NFM	Natural Flood Management
SEPA	Scottish Environmental Protection Agency
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
BMS	Beaver Modified Structures
EYRS	Ettrick-Yarrow River System
CAS	Complex Adaptive Systems

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1. Introduction

1.1 Purpose & Scope

Scotland lacks preparedness for climate change and is particularly vulnerable to the risks of coastal and fluvial flooding (Adams *et al.,* 2022; GovScot, 2019). Fluvial flooding is forecasted to become worse across the UK in the coming decades as a result of increasing precipitation from climate change (Adams *et al.*, 2022; Kay *et al.*, 2021). Several inland water catchments in Scotland have been identified as hotspots for hydrological hazards in terms of both increasing frequency and magnitude (Collet *et al.*, 2018). Concurrently, climate change is also expected to exacerbate the rate of biodiversity loss in Scotland due to the effects of extreme weather on habitat suitability and food sources for native species (Ellis & Eaton, 2018; GovUK, 2021). Recent research calls for urgent action to be taken to address the dual crises of climate change and biodiversity loss (Pörtner *et al.*, 2023). There is a need to explore and evaluate the efficacy of ecosystem-based adaptation in Scotland to simultaneously address these numerous, ongoing crises and better bridge the fields of disaster risk reduction, climate change adaptation, and biodiversity conservation.

Natural flood management (NFM) is a nature-based solution addressing flood risk through ecosystem restoration (Lane, 2017). It includes practices such as river re-meandering, regional reforestation and afforestation, and the creation or restoration of ponds, marshes, mangroves, and wetlands (Cohen-Shahcham *et al.*, 2016; Lane, 2017; Wingfield *et al.*, 2019). NFM is increasingly being implemented across riparian areas of Scotland due to its multitude of benefits, one of which is the creation of habitats that support regional biodiversity (Waylen *et al.*, 2018; Wingfield *et al.,* 2019). The Eurasian beaver, reintroduced to Scotland in 2009, is a keystone species that is often described as an 'ecological engineer' due to its ability to transform landscapes by modifying its surroundings through the construction of dams, lodges, and ponds, which impact the geomorphology and hydrology of the rivers and channels they settle in (Law *et al.*, 2017; Gaywood, 2018; Gurnell, 1998). Through this, they diversify habitats for other species including fish, amphibians, insects, and birds (Brazier *et al.,* 2021; Janiszewski *et al.,* 2014; Stringer & Gaywood, 2016). The input of these structures, and their subsequent ecosystem services, could potentially qualify the reintroduction of the beaver to appropriate locations in Scotland as a type of NFM (Puttock *et al.*, 2020), however, more research is needed to better understand how and to what extent beavers affect flood risk. It has been established that many nature-based flood management strategies support species recovery and biodiversity (Inácio *et al.,* 2020; Meli *et al.*, 2014), but this study aimed to flip the relationship to investigate to what extent species reintroductions could support flood management.

Few studies have investigated the effects of beaver reintroductions on flood risk in the UK, and those that have are largely focused on the English context (Bokhove *et al.,* 2018; Graham *et al.,* 2022; Puttock *et al.*, 2020). Existing literature on Scottish beaver reintroductions stresses the importance of site-specific evaluations for reintroduction efforts (Gaywood, 2018; Graham *et al.*, 2022; IUCN/CPSG, 2022) suggesting the need for further research in Scotland. The recently published Scottish Beaver Strategy for 2022 - 2045 (IUCN/CPSG, 2022) outlines how, following the success of the Scottish Beaver Trial, further site-specific research is needed to support future reintroductions and mitigate any adverse effects the species may have (ibid.). This paper contributes to the evidence base of how beaver reintroductions to Southern Scotland may impact local flood risk to better understand the framing of their contributions to the fields of NFM and disaster risk management overall. Secondarily, it contributes to the understanding of model utility in assessing beaver impacts, to critically examine their role as tools in evaluating species' reintroductions.

1.2 Research Aim & Questions

This research project aimed to investigate the relationship between flood risk and modelled beaver presence in a Scottish river system. It aspired to bridge together several different disciplines that often operate in silos, including ecology, hydrology, disaster risk management, and climate change adaptation. To fulfil this aim within the scope of the research timeline, two research questions were proposed:

> *RQ1:* What does the existing literature state about how Eurasian beavers structurally modify river hydrology and/or hydraulics and how can these effects be conceptualised in the hydraulic modelling software HEC-RAS?
>
> *RQ2:* How does the input of modelled structures reflecting beaver presence affect total flooded areas during a simulated 1 in 10-year flood at Ettrick Water? To what extent can models assist in understanding the contributions of beavers to natural flood management?

This research was inductive in nature as it sought to describe and establish patterns of association (Blaikie, 2009). The project used a mix of qualitative and quantitative methods to collect the necessary data. Findings from the literature review of *RQ1* were used to inform the methodology of *RQ2,* which modelled a stretch of river in Southern Scotland and simulated beaver reintroductions through the input of hydraulic structures.

2. Background & Context

2.1 Beaver Reintroductions to Scotland

The Eurasian beaver was reintroduced to two sites in Scotland in 2009 after an estimated 500-year absence and they have been designated as protected species since 2016 (Gaywood, 2018). One planned reintroduction took place in the district of Knapdale on the west coast and another unplanned in Tayside, in mid-eastern Scotland (ibid.). The Knapdale reintroductions were a part of the Scottish Beaver Trial of 2009 to 2014, a governmental research project into the effects of reintroducing beavers to Scotland (ibid.). The Tayside beaver populations were established through unauthorised reintroductions or accidental escapes, the cause is not certain, but have been allowed to remain in the area following several years of observation (Campbell-Palmer *et al.*, 2021; Gaywood, 2018).

Following the success of the Beaver Trial and the subsequent designation of beavers as a protected species in Scotland, in 2022 the International Union for the Conservation of

Nature (IUCN) and Conservation Planning Specialist Group (CPSG) published Scotland's Beaver Strategy for 2022 to 2045 (IUCN/CPSG, 2022). The strategy's third objective highlights the need to "identify areas where beaver presence results in changes to physical processes that can confer benefits/risks to ecosystem services" (ibid., p. 31). This objective is broken into two key actions, to "further develop beaver dam models to understand the changes in physical processes…[and] use beaver dam models to predict the benefits/risks to the physical processes" (ibid., p. 31). This objective aligns with a gap in the literature regarding beaver impacts on hydrology and flood risk. In their review of beaver-environmental feedback loops, Larsen *et al.* (2021) highlight "a clear and profound knowledge gap in how beavers may impact hydrology" (p. 6). This is also noted by Gorczyca *et al.* (2018), who state that despite this "the number of papers on beaver-related flood risk on a channel system scale remains small" (p. 1049). For this reason, this study took a case study approach to modelling beaver impacts on flood risk on the channel-level scale.

2.2 Context of Case Study Region

Ettrick Water, or Ettrick River, is a 36.6 km long tributary of the River Tweed in the Scottish Borders region of South-Eastern Scotland (SEPA, 2015). It flows northeast and is fed into by the river Yarrow and several other small tributaries before flowing through the town of Selkirk. Populated areas along Ettrick Water are listed as potentially vulnerable by the Scottish Environmental Protection Agency (SEPA), due to their exposure to high likelihood fluvial floods, which are defined as 1 in 10-year events (SEPA, 2022). The river is designated as being in moderate ecological condition, with documented concerns about the health of fish populations in the river (SEPA, 2015). Several NFM and traditional flood management techniques have been explored in this area including the reforestation of riverbanks, re-meandering of channel sections, and the construction of floodwalls in Selkirk (Tweed Forum, 2023). The modelled portion of this region included two areas that met the basic ecological needs of Eurasian beavers, based on findings from the literature review. Further context of the study region is expanded on in Section 4.1.1 of the modelling methodology.

2.3 Conceptual Clarifications

This study was not guided by one single theoretical framework but drew upon the theories of complex adaptive systems (as described by Preiser *et al.*, 2018) and deep ecology (Devall & Sessions, 1985) in the analysis and discussion. Although no research is entirely free of either values or theory, this study did not strictly adhere to the philosophical assumptions and central ideas of any one theory and used several different theoretical approaches to enrich the discussion of the empirical findings.

3. Literature Review

3.1 Methodology

A systematic literature review was conducted to answer *RQ1*. This review followed the methodology outlined by the Preferred Reporting Items for Systematic Reviews and Meta-

Analyses (PRISMA) (Page *et al*., 2021). The review exclusively looked at the effects of the Eurasian beaver (*Castor fiber)* on river hydrology and hydraulics; a distinct species from the American beaver (*Castor canadensis)* which is larger in size and has different dam-building behaviours (Gurnell, 1998; Rurek, 2021). Additionally, much of the existing literature on beaver-hydrological relationships focuses on *C. Canadensis*, suggesting a need for scientific research focused on its European relative (Gorczyca *et al.*, 2018; Gurnell, 1998). The purpose of the literature review was to collate a database of the structures commonly built or modified by beavers that influence the hydrology or hydraulics of their aquatic environments.

Web of Science and Scopus were searched to identify relevant studies. The keyword search included truncated terms in the string: ((Eurasian AND beaver* OR castor AND fiber) AND (hydrolog* OR hydraulic*)). Aligning with the PRISMA methodology, returned studies were assessed for relevance to the *RQ1* based on the eligibility criteria outlined in Table 1.

Table 1

Eligibility Criteria for Reviewed Studies

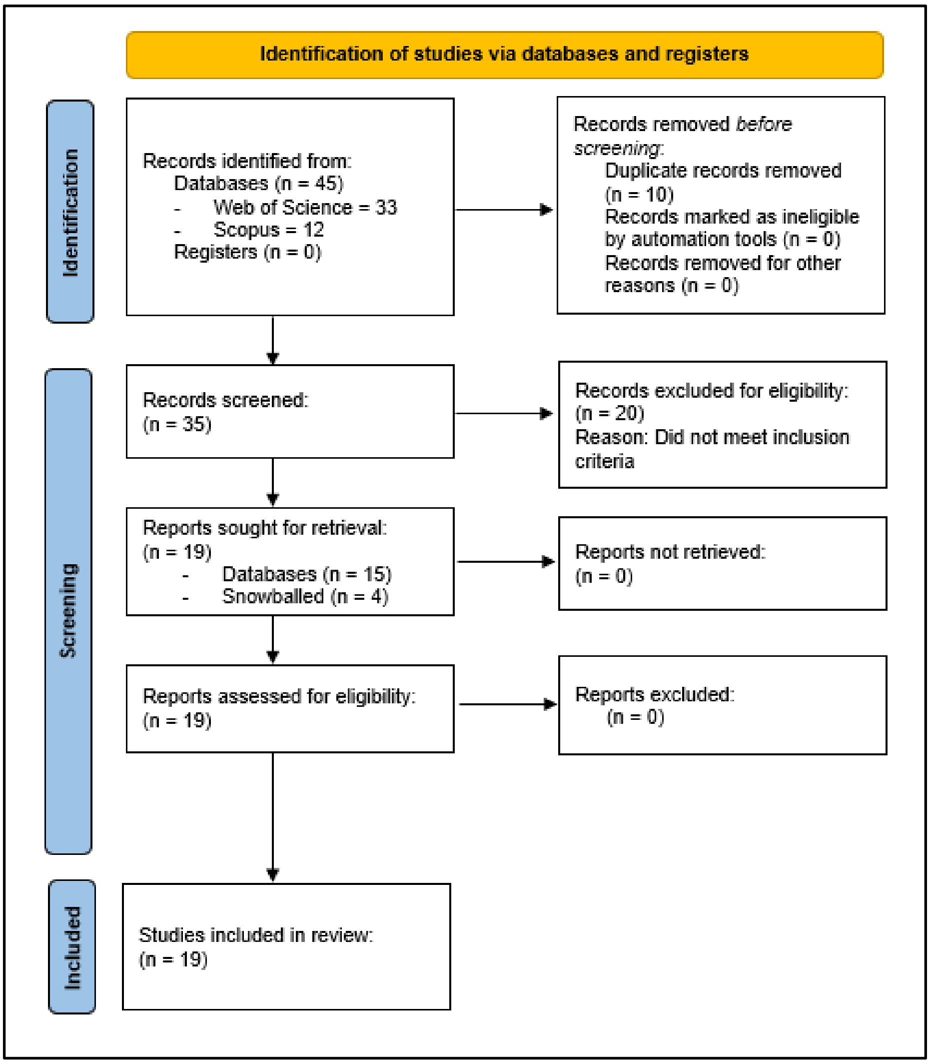
Inclusion	Exclusion
Studying effects of Eurasian beaver (*Castor fiber)*	No inclusion of data regarding *Castor fiber*
Discusses impacts to river hydrology and/or hydraulics	No mention of impact on river hydrology or hydraulics
Assesses beaver effects in their historical or current range	Does not assess effects in species historical range
Contains quantitative or semi-quantitative results (to provide numerical inputs to the model)	Only non-numerical outcomes
Peer reviewed studies	Grey literature

The literature review focused on physical structures constructed by beavers to place boundaries around modellable effects. These are referenced as beaver-modified structures (BMS) throughout this paper. To narrow the scope of the research, beaver changes to groundwater storage, evapotranspiration, sedimentation, or hyporheic exchange were not analysed, despite their hydrological significance.

A PRISMA stylised flow diagram was produced for transparency and replicability of the reviewing procedure, seen in Figure 1. Details of the PRISMA methodology followed throughout this process can be found in Appendix A.

Figure 1

PRISMA Flow Diagram Outlining the Literature Review Process



Note. Diagram adapted from Page *et al.* (2021).

The second aspect of this question was: *how can these (beaver) effects be conceptualised in the hydraulic modelling software HEC-RAS?* To answer this, the structures were analysed in terms of how they could be represented in a 1D model to simulate beaver presence and gauge their impact on flooded areas within the study region. Results were analysed based on the capabilities of the HEC-RAS 1D model, ascertained from the User's Manual (USACE, 2023b). The results of the review served as the inputs to the model to answer *RQ2*.

3.2 Results of the Literature Review

The literature review yielded 19 studies deemed relevant to answer *RQ1*. The studies varied in design, including field studies (5), before-and-after control impact designs (2), literature reviews (6), historical reviews (1) retrospective analysis studies (4), and hydraulic modelling studies (1). Several of the studies investigated beaver impacts worldwide, including information about *C. Canadensis*, in which case only data pertaining to *C. Fiber* was extracted. Details of the 19 reviewed studies are summarised in Appendix B.

3.2.1 Characteristics and Dimensions of Beaver-modified Structures

Eurasian beavers live in family groups made up of two adult parents and their young, referred to as a colony (Gurnell, 1998). One colony typically consists of 3-5 beavers (ibid., p. 168). They modify the hydrology and hydraulics of river systems primarily through the construction of dams, ponds, lodges and/or burrow structures, canals excavated in the floodplain, slides along the riverbanks, and the storage of felled trees for food over winter (Brazier *et al.*, 2021; Gurnell, 1998; Nica *et al.*, 2022). Beavers build dams to increase the underwater area adjacent to their burrows/lodges for the foraging of food (wood, aquatic vegetation, grasses), as they are strong swimmers and prefer to travel underwater for safety and to increase their foraging efficiency (Gurnell, 1998; Puttock *et al.*, 2017; Neumayer *et al.*, 2020). They do not always build dams where they settle, but where "water depths may not be sufficient (normally <0.7 m depth) for beaver movement and security" (Brazier *et al.*, 2021, pp. 3-4). A conceptual illustration of a beaver dam can be seen in Figure 2. They typically forage in a 10 m buffer around the channel they settle in but may go as far as 100 m from the channel in search of sustenance, including areas of human settlement (Gorczyca *et al.*, 2018; Gurnell, 1998). Dam building is frequently cited as the most significant hydrological impact that beavers have on river systems (Grudzinski *et al.*, 2022; Neumayer *et al.*, 2020; Puttock *et al.*, 2017). Several dams may be constructed by a single beaver colony (Gurnell, 1998), and a sequence of closely spaced dams is referred to as a dam cascade (Larsen *et al.* 2021; Neumayer *et al.*, 2020).

Figure 2

Beaver Dams and Their Influences on Hydrology

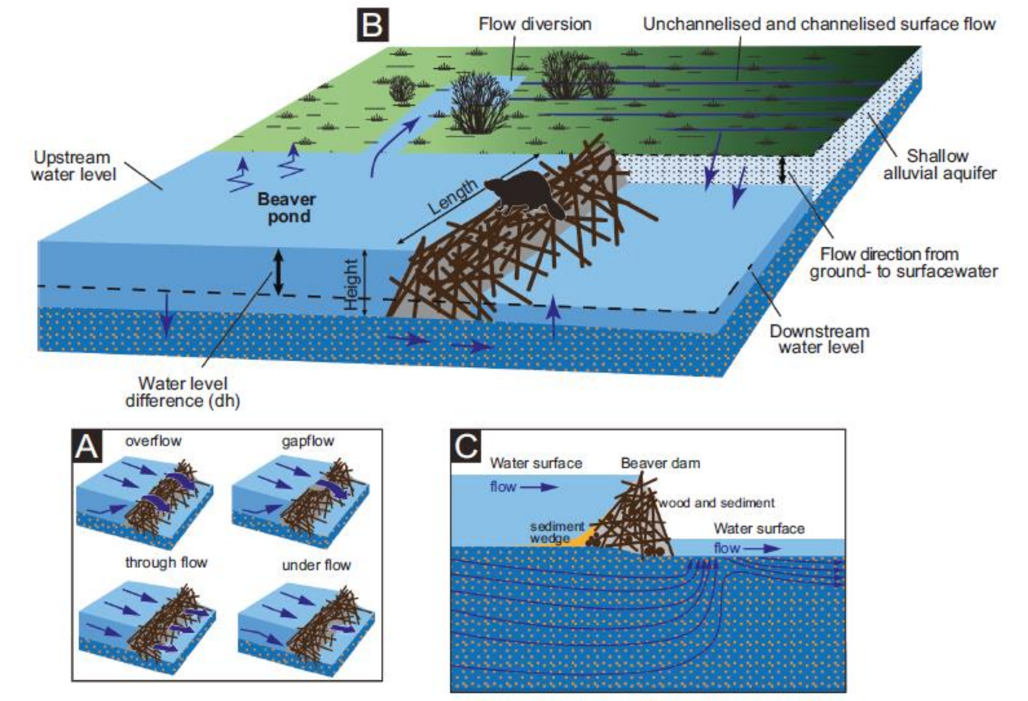


Fig. 4. Conceptual models of the influence of beaver dams on surface and subsurface hydrology. Inset A) specifies different types of beaver dams and through flow, modified from Woo and Waddington, 1990. B) Conceptualization of hydrological feedbacks as a result of beaver dam construction on surface and groundwater flow paths and storages. Inset C) illustrates potential hyporheic exchange pathways, modified from White, 1990.

Note. Figure extracted from Larsen *et al.* (2021, p. 9). Attribution statement: © 2021 Larsen *et al*. Published by Elsevier B.V.

There were varying descriptions of beaver dam systems across the literature, with different structural features observed depending on the field study. Additionally, the terms used to describe dam measurements varied, with seemingly interchangeable use of dam length and dam width between certain studies. This created ambiguity regarding dam measurements. All the literature agreed that beaver modifications are highly dependent on the local geomorphology of the channel. This was an important consideration in modelling beavers in the Ettrick River as several assumptions had to be made about how beavers would modify this particular system.

Dams were the most frequently cited structure constructed by beavers and had the most associated data regarding their dimensions, which is summarised in Table 2 below.

Table 2

Dam Dimensions Reported in the Literature and Composite Average Dimensions

Source	Dam height (m)	Dam width (m)	Dam length (m)
Graham *et al.* (2022)	Not cited	Not cited	75
Grygoruk & Nowak (2014)	0.3	Not cited	Not cited
Gurnell (1998)	0.4 - 1.7	Not cited	2.5 - 24
Average	1.05	N/A	13.25
Kocięcka & Liberacki (2018)	0.2 - 0.45	3.5	3.5 - 5.5
Average	0.33	3.5	4.5
Puttock *et al.* (2017)	Not cited	Not cited	30
Puttock *et al.* (2020)	Not cited	Not cited	60
Rurek (2021)	0.3 - 1.2	0.5 - 1.6	0.8 - 26.5
Average	0.75	1.05	13.65
Neumayer *et al.* (2020)	0.1 - 1.7	1.5 - 36	15 - 70
Average	0.9	18.75	42.5
Nyssen *et al.* (2011)	0.1 - 0.9	Not cited	3 - 210
Average	0.5	N/A	106.5
Composite average	0.59	7.77	43.18

Note. Wherever authors cited ranges they were converted to averages (row immediately below); average of averages taken to create a single composite average for dam dimensions. Gurnell (1998) figures include data from Curry-Lindahl (1967).

Beaver dam height measurement methods were inconsistent, with some studies measuring from the channel bed to the top of the dam crest (e.g., Neumayer *et al.*, 2020) and other studies measuring from the baseline water level (e.g., Rurek, 2021). To counter this, only dam height data measured from the baseline water level was included in the composite average calculation, as this methodology was more abundant. Hartman & Törnlöv (2006) only noted freeboard data, which was exlcuded from the results.

Following dams, beaver ponds were the most frequently cited artefact of beaver settlements. Data was initially collected regarding beaver pond dimensions, but it was later determined that they were not a relevant primary input to the model given they are a function of dam creation. This will be expanded upon in Section 3.2.2.

Dam density figures varied across the literature. Larsen *et al.* (2021) noted that documented numbers range from “between less than 1 (e.g., 0.1) to > 70 dams per km of river reach” (p. 5), although they do not distinguish between *C. Fiber* or *C. Canadensis* in this range. Gurnell (1998) suggested that several dams may be built by a single colony. Rurek (2021) observed dam spacing of 5 m apart but noted that this was an unusually high density. Neumayer *et al.* (2020) found in their field survey that the median number of beaver dams in a cascade was 3. Similarly, Puttock *et al.* (2020) observed that the reintroduction of one beaver pair to one of their study sites in 2018 resulted in the construction of 3 dams, but at sites of earlier reintroductions beavers built 6 - 7 dams. Nica *et al.* (2022) suggested an average of 10 dams per kilometer. Puttock *et al.* (2017) found that since the reintroduction of one beaver pair in 2011, 13 dam or pond structures emerged. Nyssen *et al.* (2011) observed cascades with a range between 1 - 6 dams. There was substantial variation in expected dam density based on how long the beavers had lived in an area, the size of the area they were reintroduced to, the topographic features of the environment, and food availability.

Beaver lodges varied in description depending on the type of lodge constructed in the river system. Curry-Lindahl (1967) described built lodges in rivers as cabins, consisting of several rooms which “vary in length from 5 to 10, sometimes 15 m with a width of 2 to 3 m and a height of 1 to 2 m” (p. 12). Nica *et al.* (2022) reported lodge shelters on the waterfront as being “3.5 m high with a main room (second level) 60/70 cm large” (p. 645). They stated that such structures have “a diameter of 6 m at the base and a height of 1.70 m … [and] can reach up to 50 cm above the ground around it” (ibid., p. 645). Brazier *et al.* (2021) detailed lodges to be " ... as tall as 3 m" (p. 3) but suggested beavers that settle in river systems prefer to construct burrows. Gurnell (1998) described these burrow-lodges, in which beavers construct shelters by digging into the riverbank, as containing nest chambers approximately 0.3 - 0.7 m above the entrance to the burrow (p. 175). These chambers are usually 0.4 - 0.5 m high and require minimum bank heights of 1.5 - 2 m (ibid.). Larsen *et al.* (2021) described burrow-lodges as typically having lengths “less than 10 m, but they may extend up to several 100 m and are around 15–30 cm in diameter with occasional widened sequences” (p. 17). Gorczyca *et al.* (2018) suggested that beaver burrows may be "several metres long and > 2 m in height" (p. 1056). Rurek (2021) stated that “burrows can be 10s of metres long” (p. 17).

Beaver canals, or channels, are described by Grudzinski *et al*. (2020) to be constructed by beavers to extend their foraging area by digging ditches in the floodplain that extend out from ponds, connect ponds, or lie at the bottom of ponds. Canal dimensions in the literature depended on several factors, including the geomorphology surrounding the channel and whether there were dams present in the system. De Visscher *et al.* (2014) found in their field study that canals were, on average, 11.6 m long, 0.289 m deep, and 0.491 m wide (p. 1608). Larsen *et al.* (2021) noted canal lengths could be over 100 m, between 0.35 and 0.7 m deep, and 0.6 - 0.9 m wide (p. 17).

Gorczyca *et al.* (2018) observed that beaver slides ranged between heights of 0.5 - 2.5 m, incising banks by 0.2 - 0.7 m (p. 1054). No other studies noted slide dimensions. The quantitative findings of this section were converted into averages for all BMS described, which can be found in Table 6 of Section 4.1.5.

3.2.2 Application of the Findings: Representing BMS in a 1D Model

Beyond numerical figures, qualitative information about the likelihood of beavers to construct different types of structures based on the terrain of the study region was essential to inform assumptions about how dams would likely interact with the modelled area. These justifications will be made here, and then details about their specific application to the model will be explained in Section 4.1.5 of the modelling methodology.

Dams were deemed to be the most influential and significant BMS input to the study region based on the literature review. Dam cascade size was not the focus of this research project as it has been well-documented that increasing dam/pond cascades have an increasing attenuative effect on flood waters (Brazier *et al.*, 2021; Larsen *et al.*, 2021; Puttock *et al.*, 2017). The literature varied widely in documenting dam density, but there was general agreement that dams increase in number over time (Gurnell, 1998; Larsen *et al.*, 2021), therefore a conservative estimate of 3 dams per cascade was chosen for a “new” reintroduction model in agreement with the median observed by Neumayer *et al.* (2020) and Nyssen *et al*. (2011) and aligning with general descriptions of dam density made by Gurnell (1998).

Ponds were frequently cited as significant artefacts of beaver systems in the literature, however, the following key quotes illuminated why they were not applicable inputs to this model. Grygoruk & Nowak (2014) defined beaver ponds as “small reservoirs that appear as a result of damming streams, canals or ditches" (p. 2277). This suggested that ponds are not primary structures built by beavers, but secondary consequences of dam creation. This conclusion was supported by Rurek’s (2021) statement that “... the reach of the pond is connected with the relief of the valley and with the beaver dam” (p. 6). Brazier *et al.* (2021) also noted that “dams also do not necessarily have a pond associated with them and in-channel dams would likely not have a significant ponding effect except for during high-flow events” (p. 4). Ponds were therefore not modelled in this study because, theoretically, they are created by the presence of dams. Additionally, without sufficient pond flow data, their input to the model would have significantly increased model uncertainty.

Given the high riverbanks along both the Ettrick and Yarrow channels, the literature suggested that beavers would be more likely to dig burrows along the banks than construct woody lodges. Gorczyca *et al.* (2018) found that high banks (4 - 6 m) favoured the construction of burrow-lodge structures. Nica *et al.* (2022) elaborated on this by explaining that holes in the bank are often utilised by beavers as natural burrows, but in their absence, beavers will dig burrows where banks are sufficiently tall. They suggest that "at least 50% of [beaver] shelters are dug burrows" (p. 644). Brazier *et al.* (2021) corroborated this, stating that, "... beavers, especially in river systems, typically excavate bank burrows in which to establish dwellings" (p. 3). Similarly, Gurnell (1998) noted that beavers preferentially construct burrows over lodges whenever bank heights extend a minimum of "... 1.5 - 2 m above the roof of the burrow entrance" (p. 175). They also stated that "on average each beaver colony builds over one lodge, secondary lodges are used for different purposes" (ibid., p. 176). Similarly, Brazier *et al.* (2021) suggested that "beavers often excavate multiple burrows in a single territory" (p. 3). With a lack of more substantial burrow density data than this, it was elected to model two burrow-lodges per beaver reintroduction site as, like dam density, a conservative estimate was deemed most appropriate for a "new" reintroduction.

Canals, also called channels, were included in the model but certain data was excluded from average dimensions calculations. In their literature review, Grudzinski *et al.* (2020) cited several European studies that noted canal dimensions, however, they also noted that no dams were present in these systems. As this model was centred around dam construction, these dimensions were removed from the calculations. No canal density data was cited, but Grudzinski *et al.* (2020) described that beavers will dig and extend canals over time to access new foraging areas. Following the same reasoning described for dams and burrows, two canals were elected to be modelled. In addition to their built structures, beavers also "increase the rate of both large and small woody material contribution to river systems" (Brazier *et al*., 2021, p. 3). Gurnell (1998) noted that "food may be accumulated in cashes for later consumption. They may be stored inside or outside the lodge and be anchored to the dam or riverbed" (p. 176). No studies reported the specific dimensions of such food storage areas, but many cited their presence as significant and so they were included as two areas per reintroduction site in the model. Details of how BMS were modelled are found in Section 4.1.5.

The qualitative findings from the literature review were reconceptualised as features in a 1D model by pairing descriptions of BMS with tools available in the HEC-RAS software (USACE, 2021b). These pairings are presented in Table 3 below with justifications from the literature.

Table 3

Depiction of BMS in a HEC-RAS 1D model

Beaver-modified structure (BMS)	Depiction in a 1D model	Justification

Dams	Modified inline weirs with culverts to account for dam permeability.	"… Hydrologically, **a well-constructed beaver dam acts like a low weir**, causing water storage which impacts on both high and low flows in the river system" (Gurnell, 1998, p. 179). "The **permeability of the dams is realized by inserting round culverts** (up to 70 pcs/dam) parallel to the flow direction. The locations of the culverts are homogeneously spread across the surface of the dams" (Neumayer *et al.*, 2020, pp. 5-6).
	Modified manning's *n* value (of the weir).	"All **dams will increase channel/hydraulic roughness** and therefore, deliver some flow attenuation effect" (Brazier *et al.*, 2021, p. 9). "The **hydraulic roughness of the mesh elements representing a dam** was set … in the range of the generally used roughness of copse and branches in hydraulic modeling" (Neumayer *et al.*, 2020, pp. 5-6).
Burrow-lodges	Lateral structures on the riverbank with pipe culverts under mean water level.	"... **Burrows may function in a manner similar to a piping system.** Precipitation water from the floodplain surface between levees flows into damaged ventilation shafts and widens them transporting riverbank material to the river channel…**Burrows often become filled with water**, which weakens the stability of the riverbank, and water saturation leads to bank subsidence or landslides" (Gorczyca *et al.*, 2018, p. 1056). "The entrance inside the burrowing is **always situated under the water's level**" (Nica *et al.*, 2022, p. 614). "The **entrance to the burrow is always located under the water**" (Rurek, 2021, p. 14).
Pond creation	An artefact/result of dam construction.	Justified in-text.
Canals/channels	Modified terrain points laterally in the floodplain near dams.	"Beavers excavate canals, **laterally across floodplains**, to access and transport food and building resources, enhancing floodplain connectivity" (Brazier *et al.*, 2021, p. 2). "... Excavating side **channels adjacent to the dam** (Grudzinski *et al.*, 2022, p. 4). "Canals can also **alter wetland morphology** and dimensions" (Grudzinski *et al.*, 2020, p. 202).
	Manning's *n* adjustments in floodplain.	"These canals contribute significantly to the **local hydrogeomorphology of floodplains**, creating **hydraulic roughness**, tortuous flow paths, and complex topography in otherwise planar landscapes" (Brazier *et al*., 2021, p. 3).
Slides	Reduction in bank gradient.	"... As beavers slide down beaver slides, **material is eroded** and accumulated at the toe of the slide" (Gorczyca *et al.*, 2018, p. 1054).

Felled tree storage	Manning's *n* value calibration polygons within channel and floodplain.	"**Tree trunks often block the channel entirely** and trigger local accumulation of fine sediment and wood debris, reducing flow velocity and causing local channel widening" (Gorczyca *et al.*, 2018, p. 1054). "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**" (Brazier *et al.*, 2021, p. 3). "... Feature of beaver impacts is the very large increase in large woody debris within aquatic habitats, especially within dams themselves but also elsewhere **in the channel and floodplain system**" (Larsen *et al.*, 2021, p. 27).

Note. Manning's *n* value is a measure of hydraulic roughness, explained in Section 4.1.3.

4. Hydraulic Modelling

4.1 Modelling Methodology

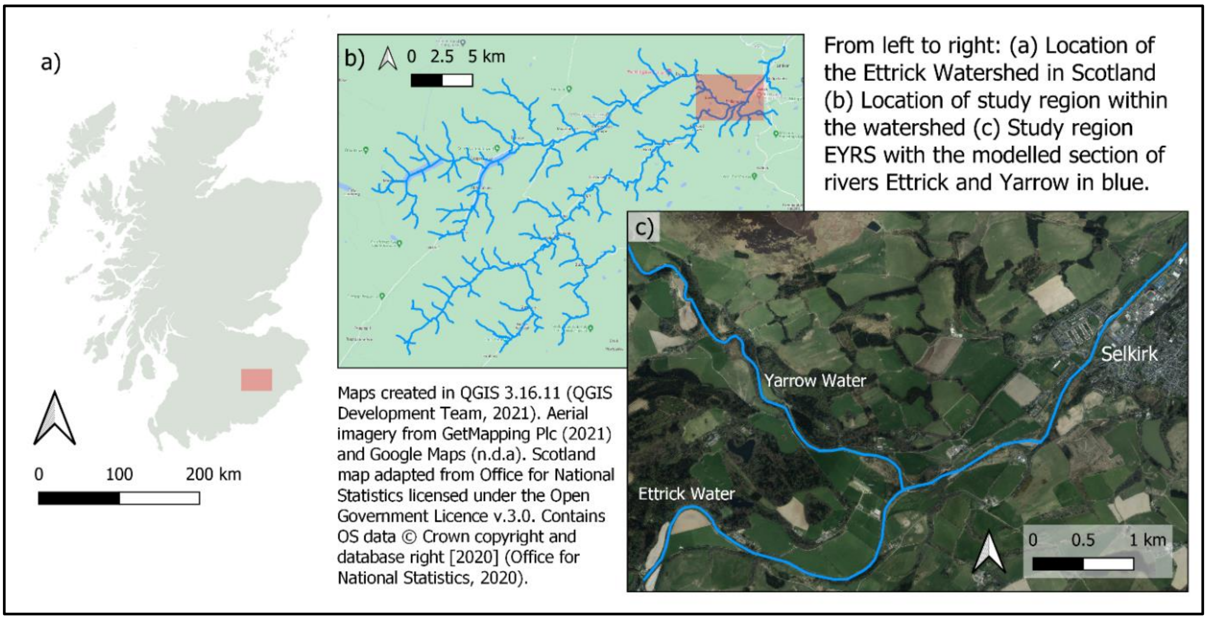
The second research question (*RQ2*) was addressed using a model-based approach. This was achieved by building a hydraulic model based on the rivers Ettrick and Yarrow, using the United States Army Corps of Engineers Hydrologic Engineering System's River Analysis System (HEC-RAS) software (USACE, 2021b), and inputting BMS derived from the literature review. The output of interest to this study was the area (m^2) of flood inundation. This software was selected because it is publicly available and widely used in semi-recent flood risk studies (El Bilali *et al.*, 2021; Huţanu *et al.*, 2020; Iosub *et al.*, 2015; Vojtek *et al.*, 2019, Zainalfikry *et al.*, 2019).

4.1.1 Study Region Selection & Model Design

An area of approximately 18 km^2 was modelled in the north of the Ettrick Water catchment where the river meets the Yarrow tributary and flows through Selkirk (see Figure 3 below). The Ettrick River and Yarrow River were both included in the model, as both have gauging stations from which flow data could be estimated. Smaller tributaries that are present in the area were not modelled due to a lack of associated flow data. The modelled area is hereafter referred to as the Ettrick-Yarrow River Systems (EYRS).

Figure 3

Study Region and Modelled Area (EYRS)



From left to right: (a) Location of the Ettrick Watershed in Scotland (b) Location of study region within the watershed (c) Study region EYRS with the modelled section of rivers Ettrick and Yarrow in blue.

Maps created in QGIS 3.16.11 (QGIS Development Team, 2021). Aerial imagery from GetMapping Plc (2021) and Google Maps (n.d.a). Scotland map adapted from Office for National Statistics licensed under the Open Government Licence v.3.0. Contains OS data © Crown copyright and database right [2020] (Office for National Statistics, 2020).

The EYRS was modelled as it contains areas that meet the basic ecological requirements for beaver populations to colonise (Gurnell, 1998), and includes human settlements exposed to high-likelihood floods (SEPA, 2022). Gurnell (1998) cited that beavers commonly establish themselves in the oxbows of narrower channels between 8 - 40 m wide that are buffered by riparian forests. Nyssen *et al.* (2011) remarked that these forest buffers should be at least 10 m. Brazier *et al.* (2021) suggested that beavers are likely to build dams where water depths are below 0.7 m (p. 3). The EYRS contains several oxbows buffered by <10 m of riparian forest and the average channel dimensions and mean water levels meet these requirements. This study did not undertake a quantitative ecological niche analysis or population viability analysis to locate the most appropriate beaver reintroduction sites in Scotland (a research project in itself) but selected this location qualitatively by comparing maps of lower-order streams, forested areas, and high likelihood flood risk areas for which high-resolution terrain data was available.

The model design was a 1D river model with steady flow. A 1D model was selected over a 2D model due to the demonstrated use of 1D HEC-RAS models to measure inundated areas (Huţanu *et al.*, 2020; Iosub *et al.*, 2015; Vojtek *et al.*, 2019) and anticipated high number of structural modifications to be inputted into the system, which, according to the HEC-RAS User’s Manual, can be better suited for 1D modelling (USACE, 2023a). 2D models capture more complexity in floodplains, however without field survey data the benefits of 2D modelling would not have been fully realised in this study. The output of interest, flooded areas (m^2), was selected as it is a relevant gauge of changes to flood risk and an available output of the HEC-RAS software through the RAS-Mapper feature (USACE, 2023c). Neumayer *et al.* (2020) also justify the relevance of quantifying this output for beavers: “hydraulic properties like flow depth, inundation areas, velocity, or flood duration can be affected significantly by beaver dams” (p. 2).

Steady flow simulations were selected (over unsteady flow) due to limited access to detailed flow hydrographs for the rivers Ettrick and Yarrow. The model was run using flow data corresponding to a 1 in 10-year flood (10% recurrence), the methodology of calculation for which is outlined further below. SEPA classifies the area surrounding Ettrick Water as being at high risk of fluvial flooding, which they describe as a 10% chance of flooding each year or 1 flood every 10 years (SEPA, 2022). Therefore, investigations into measures addressing 1 in 10-year flood events were deemed relevant to the flood risk context of this study area. Modelling events of this frequency regarding beaver reintroductions is further justified by Neumayer *et al.* (2020) in their statement:

> Flood protection measures are usually designed to prevent damages during larger flood events, starting from return periods of 100 years. As decentralized measures and, in particular, beaver dams are assumed to have a minor impact during larger events, we considered different flood peaks. These include events with return periods of 20, 5, and 2 years (p. 6).

1 in 10-year flood data was the highest frequency available for public download from SEPA (2022), necessary for model validation, and fell in the 2 - 20 year range outlined by Neumayer *et al.* (2020) above, and thus was selected as the flood scenario for this study.

This methodology was informed by other studies that utilised HEC-RAS 1D models for flood risk analysis (Huţanu *et al.*, 2020; Iosub *et al.*, 2015; Vojtek *et al.*, 2019), the results of the literature review, and guidance from the HEC-RAS User's Manual (USACE, 2023b). This study did not attempt to assess how beaver reintroductions to this area of Scotland would affect overall flood risk, as this would require much more extensive modelling and social research. The purpose of this model was to explore how structures built by beavers can be translated into modellable features and how these features impact flooded areas during a 1 in 10-year event.

4.1.2 Data Collection & Flow Calculations

A LiDAR Digital Terrain Map (DTM) for the area was downloaded at 50 cm resolution (Scottish Government, 2020). Aerial imagery at 25 cm resolution was downloaded from Digimaps (GetMapping Plc, 2021). 1 in 10-year flood inundation maps were downloaded from SEPA (2022) for model validation. A land cover map of the UK was downloaded from SpatialData.gov.scot (Space Intelligence & NatureScot, 2021). Manning's roughness coefficient (*n),* which describes the energy loss of flow in a channel, was inputted for this map using data from Te Chow's (1959) influential book *Open-Channel Hydraulics*. The geospatial data required pre-processing, which is described in Appendix C.

HEC-RAS requires users to enter flow data at the upstream end of each river reach being modelled for a Steady Flow Analysis. Originally, a 1 in 10-year flooding event was selected due to the public availability of SEPA's (2022) flood risk maps that outline the expected inundated area for such an event, for baseline model validation. However, during the modelling process, it was realised that the SEPA flow data used to build these models was not publicly accessible. This meant the flow rate for a 1 in 10-year flood for each river reach needed to be calculated. The Log-Pearson Type III (LP3) distribution was used to estimate flows, a commonly used statistical tool to determine flow recurrence rates in flood risk analysis (Griffis & Stedinger, 2007; Farooq *et al.*, 2018). This statistical analysis was completed on Microsoft Excel using the pre-filled equations supplied by the Western Oregon State University (WOSU) Log Pearson Type III (LP3) Calculator (WOSU, n.d.) to simplify the process. Ettrick Water's historical peak flow data was obtained from gauging stations

Lindean (NRFA, 2023b) and Brockhoperig (NRFA, 2023a), which were located downstream and upstream of the model boundaries, respectively. Yarrow Water peak flow data was obtained from Philiphaugh gauging station (NRFA, 2023c), which was located within model boundaries. The skew coefficient (C_m) was calculated using Pearson's Second Calculation for the Coefficient of Skewness (Jambu, 1991; Pearson, 1894):

$$\text{Skewness} = \frac{3 \cdot (\underline{x} - M_d)}{S}$$

Where $\underline{x}$ is the mean, M_d is the median, and S is the standard deviation of the annual maximum flow data. The associated frequency factors (K values) were provided in the calculator, using values derived by Haan (1977), to complete the LP3 equation. A summary of the data used and the resulting flow for each gauging station is listed in Table 4. A detailed flood frequency analysis was not a core component of this study, and these values were estimations.

Table 4

Flow Data and Estimated 1 in 10-year Flow for Gauging Stations.

	Gauging station		
Flow Data	Ettrick Lindean	Ettrick Brockhoperig	Yarrow Philiphaugh
Record length (years)	60	56	59
Average maximum flow (m^3/s)	230.82	63.13	98.76
Median maximum flow (m^3/s)	224.62	59.753	88.378
Standard Deviation	60.73	21.32	55.03
Calculated skewness (C_m) (logarithmic scale)	-0.117144603	0.066794298	-0.049471655
Estimated 1 in 10-year flow (m^3/s)	315.27	89.83	163.27

Note. All flow data downloaded from the National River Flow Archive (NRFA, 2023a; 2023b; 2023c).

4.1.3 Base Model Building

The DTM was uploaded to HEC-RAS with an OSGB36/EPSG 27700 projection, following the Scottish Public Sector LiDAR (Phase 4) data projection (Scottish Government, 2020) to create a terrain layer of the channel. A new geometry layer was added in the RAS Mapper feature of HEC-RAS to outline the river catchment following the high ground detailed by the DTM and aided by aerial imagery, as outlined in the HEC-RAS tutorials (USACE, 2021a). Channel centrelines, bank lines, and flow paths were digitised. The rivers were joined via a junction point. Floodplain delineation through the digitising of flow paths was informed by SEPA (2022) maps. With a lack of field data, river cross-sections were drawn at approximately 0.2 - 0.5 km distance apart, as advised in the HEC-RAS User's Manual (2023b).

Manning's roughness coefficients were taken from Te Chow (1959) and assigned to different floodplain sections as classified in the land cover map (Space Intelligence & NatureScot, 2021). The *n* value for the main channel was assigned a set value of 0.045 using Te Chow's (1959) assignment of this value for winding streams with "some weeds and stones" (p. 112). Developed areas were assigned a higher *n* value, depending on the intensity of development, as they represent buildings that would obstruct flow. These values are summarised in Table 5 below. The land cover map overlaid with the channel centrelines is shown in Figure 4.

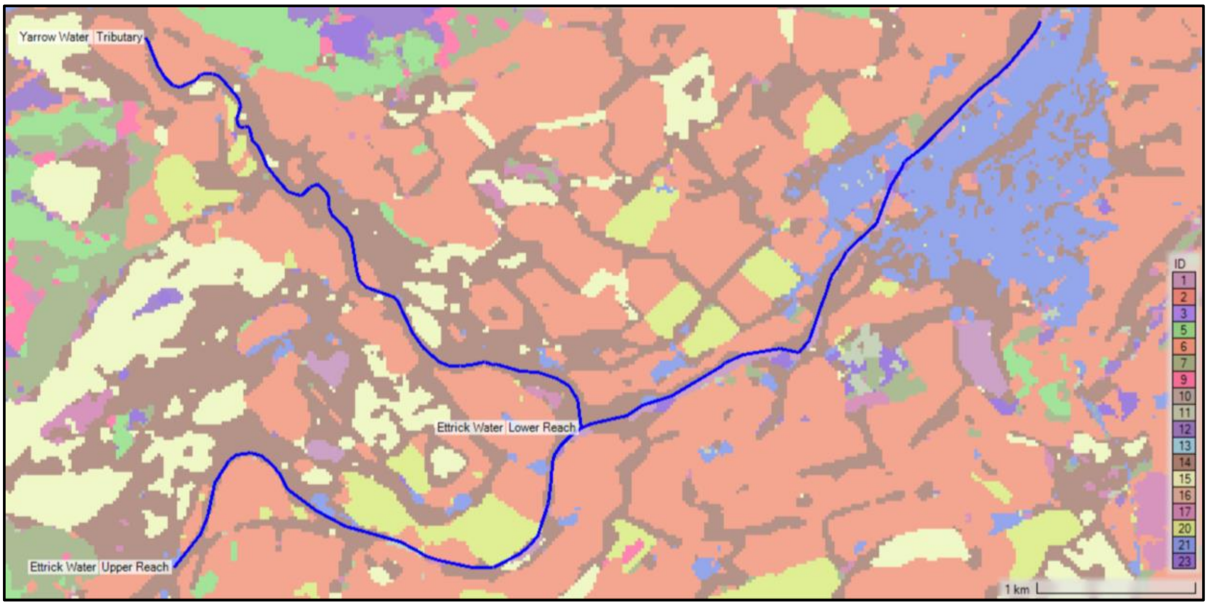
Table 5

Manning's n Values for the EYRS

ID	Land cover classification (Space Intelligence & NatureScot, 2021)	Manning's *n* value assigned (Te Chow, 1959)
2	Developed - High Intensity	5
3	Developed - Medium Intensity	2.5
5	Developed - Open Space	1
6	Cultivated Crops	0.04
7	Pasture-Hay	0.04
9	Deciduous Forest	0.1
11	Mixed Forest	0.1
12	Scrub-Shrub	0.07
13	Palustrine Forested Wetland	0.1
14	Palustrine Scrub-Shrub Wetland	0.1
15	Palustrine Emergent Wetland	0.1
16	Estuarine Forested Wetland	0.1
17	Estuarine Scrub-Shrub Wetland	0.07
20	Barren Land	0.04
21	Open Water	0.03
23	Estuarine Aquatic Bed	0.05

Figure 4

Land Cover Map of the EYRS



Note. Screenshot taken from HEC-RAS (USACE, 2021b). Land cover map adapted from Space Intelligence & NatureScot (2021). See Table 5 above for ID values.

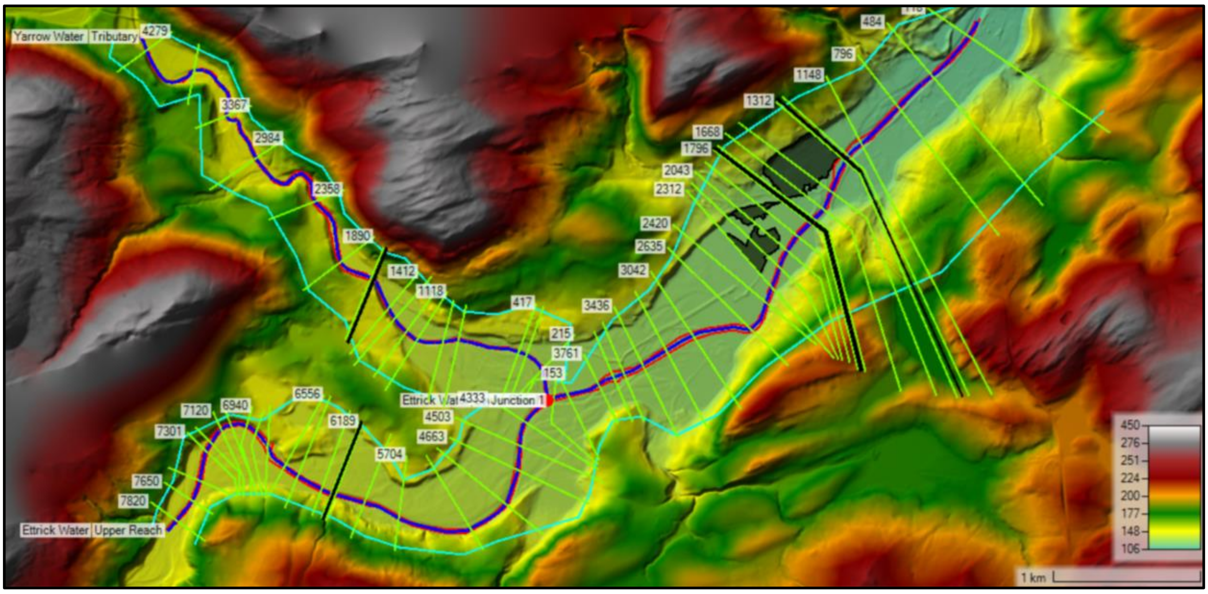
The Steady Flow Data Editor was used to define the flow conditions of the model. Boundary conditions of the model were defined according to the upstream inflow (10-year flow data) for each river and the junction. Normal depth was entered as 0.003 for the downstream boundary condition, which was measured as the approximate slope of the lower reach of the river system. The baseline water surface elevation was inputted as the average water levels at Ettrick Water: 0.636 m (SEPA, 2023a) and at Yarrow Water: 0.441 m (SEPA, 2023b).

4.1.4 Model Calibration & Validation

Over 50 simulations were tested to calibrate the baseline model against the SEPA (2022) maps. The calibration process required many additional steps, including flow calibration, that were essential to attempt to validate the model despite data limitations and are described in Appendix D. It was impossible to fully calibrate the model without knowing the exact flow data used by SEPA. With this considered, the model validation was considered sufficient to continue with modelling beaver settlements on the channels. A screenshot of the final calibrated baseline river model geometry showing the rivers, bank lines, cross-sections, and flow paths overlayed on the terrain map can be seen in Figure 5. The thicker black lines represent where the modelled bridges are located (not to scale). Some areas of obstructed flow were poorly represented in the DTM, therefore further processing was applied (outlined in Appendix D).

Figure 5

Baseline Channel Geometry of the EYRS



Note. DTM adapted from Scottish Government (2020). Screenshot taken from HEC-RAS (USACE, 2021b).

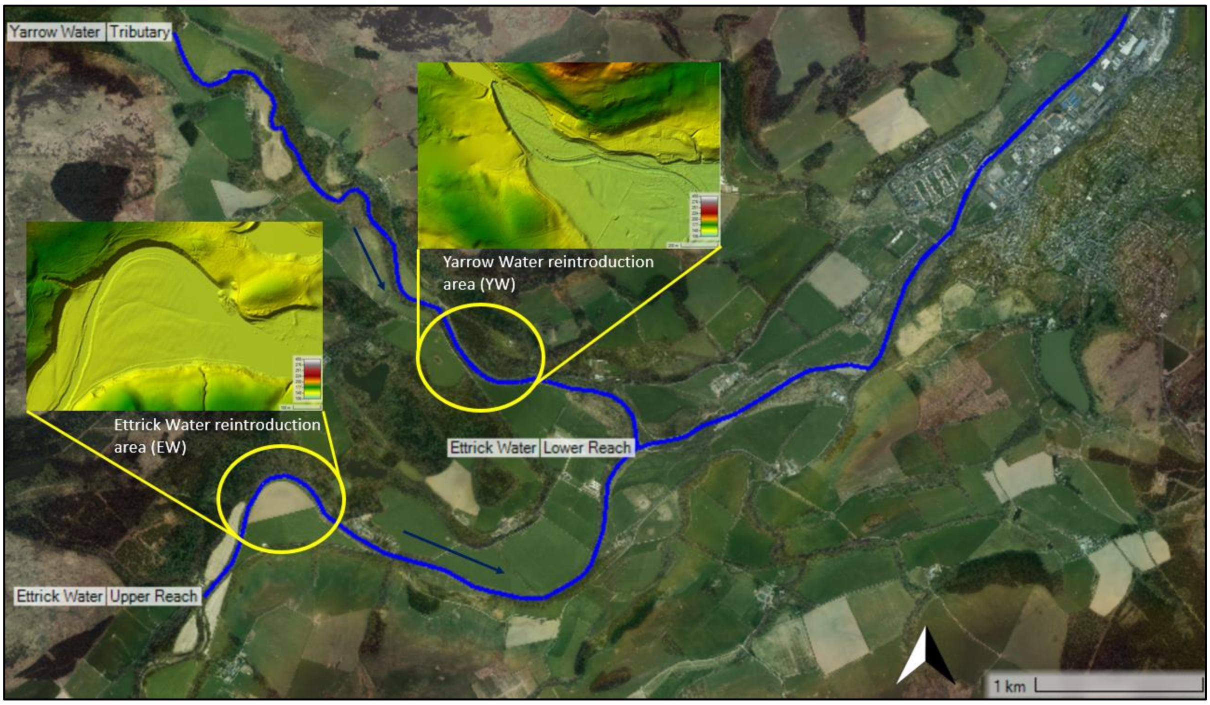
4.1.5 Simulating Beaver Presence

Based on the literature review, the BMS deemed appropriate to include in this model given the channel conditions were dams, burrow-lodges, canals, slides, and food storage (see Section 3.2.2). These structures cover 3 of the 5 characteristics described by Larsen *et al.* (2021) to make up “wet beaver meadow complexes" (p. 19); the missing two characteristics being silt build-up and vegetation feedback loops, which are not accounted for in this model. They cover all what Larsen *et al.* (2021) describe as beavers’ “primary impacts” (p. 32). These modifications were paired with tools available in the HEC-RAS software to simulate their presence in a 1D model (see Table 3, Section 3.2.2).

Two areas meeting the basic requirements of beaver habitat suitability were identified in the model region, one in an upstream oxbow of Ettrick Water and one in a meander downstream on Yarrow Water. The Ettrick Water reintroduction area (EW) is characterised by a steep left overbank but a low-gradient floodplain bordering the right overbank. The Yarrow Water reintroduction area (YW) is characterised by relatively steep banks on both sides of the channel compared to the EW site. These areas are circled in Figure 6. The reintroduction of beavers, simulated by their built structures, was modelled at both locations in three runs; one for each ‘reintroduction’ in isolation and one in which both occurred together.

Figure 6

Aerial Map of the EYRS with ‘Reintroduction’ Areas Circled in Yellow



Note. Aerial imagery from GetMapping Plc (2021). Screenshot taken from HEC-RAS (USACE, 2021b).

Based on the literature review analysis it was interpolated that the reintroduction of one beaver colony to each of these areas would result in the construction of 3 dams (Neumayer *et al.*, 2020; Nyssen *et al.*, 2011), 2 burrow-lodge structures (Gurnell, 1998), slides along dam cross-sections (Gorczyca *et al.*, 2018), 2 canals (Brazier *et al.*, 2021; Grudzinski *et al.*, 2020), and 2 food storage areas (Gorczyca *et al.*, 2018; Larsen *et al.*, 2021). All dimensions used were averages from the literature review, except for food storage areas which did not have associated values. A summary table of average dimensions for these BMS parameters is shown in Table 6. Data scarcity necessitated assumptions to be made throughout the BMS modelling process, which are explicitly stated for every modification below. Following the input of these BMS, a steady flow analysis was run using the same flow data as the calibrated baseline scenario (see Appendix D for calibrated flow data) and flood maps were generated. Area calculations and map creation methods can be found in Appendix E.

Table 6

Average BMS Inputs Extracted from the Literature (see Section 3.2.1)

BMS	Height (m)	Width (m)	Length (m)	Depth (m)
Dams	0.59	7.77	43.18	N/A
Burrows	0.9 (diameter)	N/A	6.5	N/A
Canals	N/A	0.62	55.80	0.41
Slides	1.5	N/A	N/A	0.45

Note. N/A indicates that the dimension category is not applicable.

Dam simulation

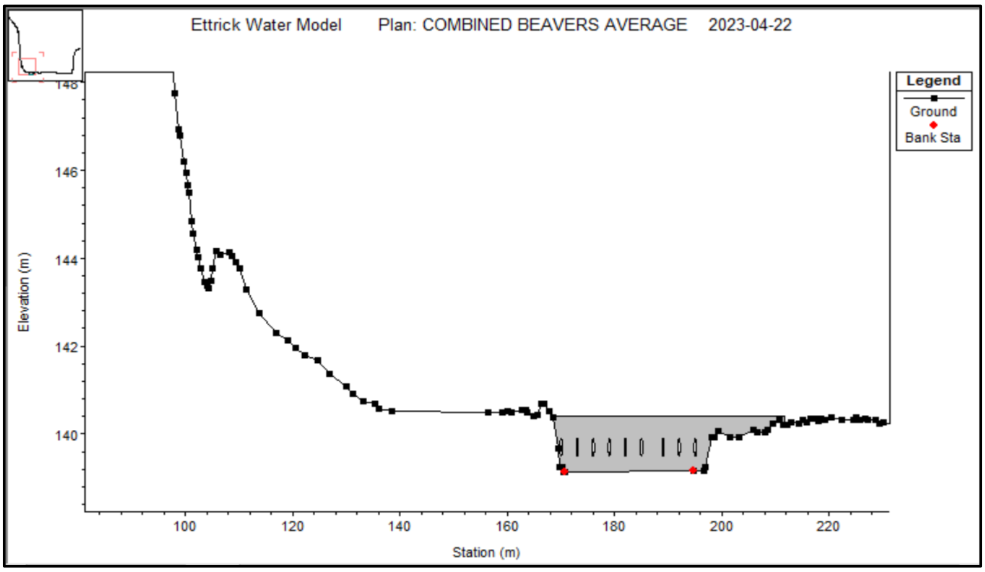
Beaver dams were simulated through the insertion of modified broad-crested inline weirs. In the weir editor, average values for dam height, width and length were inserted (see Table 6). The weir coefficient was left at the default 1.4 after consulting the HEC-RAS User's Manual (USACE, 2023b) and determining this value to be adequate to describe the hydrological nature of a beaver dam (between natural ground and an elevated levee).

The average values in the height column were obtained from studies that measured the dam height as height above the average water level. Therefore, these values were summed with an average water level of 0.636 m for the Ettrick River (SEPA, 2023a) and 0.441 m for the Yarrow (SEPA, 2023b), respectively, to obtain a total dam height from the channel bed. The inputted heights for each dam are summarised in Table F1 of Appendix F.

An important artefact of beaver dams that distinguishes them from weirs is their permeability. As stated by Puttock *et al*. (2017), "... stream flow can overtop or funnel through gaps in the dams, leak from the bottom of the dams or seep through the entire structure" (p. 440). Permeability was accounted for by the inclusion of circular culverts across the weir, like the methods used by Neumayer *et al.* (2020) in their modelling of beaver dams, where they state: "Permeability of the dams is realized by inserting round culverts (up to 70 pcs/dam) parallel to the flow direction. The locations of the culverts are homogeneously spread across the surface of the dams" (p. 6). The culverts in this model were constructed with an estimated diameter of 0.4 m and spaced 3 m apart along the weirs, resulting in 12 - 15 culverts per dam (HEC-RAS caps the number of culverts that can be entered). These values were estimated given the lack of quantitative data on dam permeability. The entrance loss coefficient was assigned to 0.2, after consulting the User's Manual (USACE, 2023b). Culvert top and bottom manning's *n* values were inputted at 0.1, associated with trees/woody debris in a channel (Te Chow, 1959), to reflect their construction material. An example screenshot of how dams and culverts were hydraulically constructed in the software can be seen in Figure 7.

Figure 7

Screenshot of Inline Weir Editor with Culverts Inserted



Note. Screenshot taken from HEC-RAS (USACE, 2021b).

Dams were spaced approximately 100 m apart along the channels. There was a lack of adequate dam spacing data, however, this assumption was based on the reported dam density from Nica *et al*. (2022) of 10 dams per 1km, suggesting that 1 dam may be expected every 100 m, on average.

Burrow-lodges simulation

Beaver burrow-lodges were modelled as lateral weirs along the high riverbanks (North for EW, Southwest for YW) with a circular culvert "burrow" inserted. The culvert headwater connection was set to the bank line and the tailwater connection was set to "out of the system", to simulate flow being removed from the river into the burrows, as "burrows often become filled with water" (Gorczyca *et al.*, 2018, p. 1056). The culvert roughness was set to 0.1, like that of those to represent dam permeability, to reflect woody debris (Te Chow, 1959) as burrow-lodge entrances are typically covered with twigs and brush for security (Gurnell, 1998; Nica *et al.*, 2022). It was not possible to model the burrows extending upwards and opening into a nesting chamber, as described by Gurnell (1998), only to extend the culverts into the riverbanks at a length of 6.5 m with a diameter of 0.9 m (see Table 6). The entrance loss coefficient was set to 0.2 for the same reasoning described above for the dam culverts. The "burrows" were positioned upstream of the dams where ponded areas would accumulate water, aligning with the described positioning of burrows relative to dams (Gurnell, 1998). The culvert was inserted below the mean water level as burrow entrances are "always located under the water" (Rurek, 2021, p. 14).

Canal simulation

There was limited data regarding the dimensions of canals constructed by *C. Fiber,* and no data specifying how many canals might be expected to be constructed, as they are dug based on need. From qualitative descriptions, it was assumed that canals are likely to be constructed in the floodplain where water levels are low, extending out from ponded areas (Grudzinski *et al.*, 2020; Gurnell, 1998). Therefore, an estimated 2 canals were inputted into the floodplain by manually altering the terrain data points in these areas to the dimensions listed in Table 6.

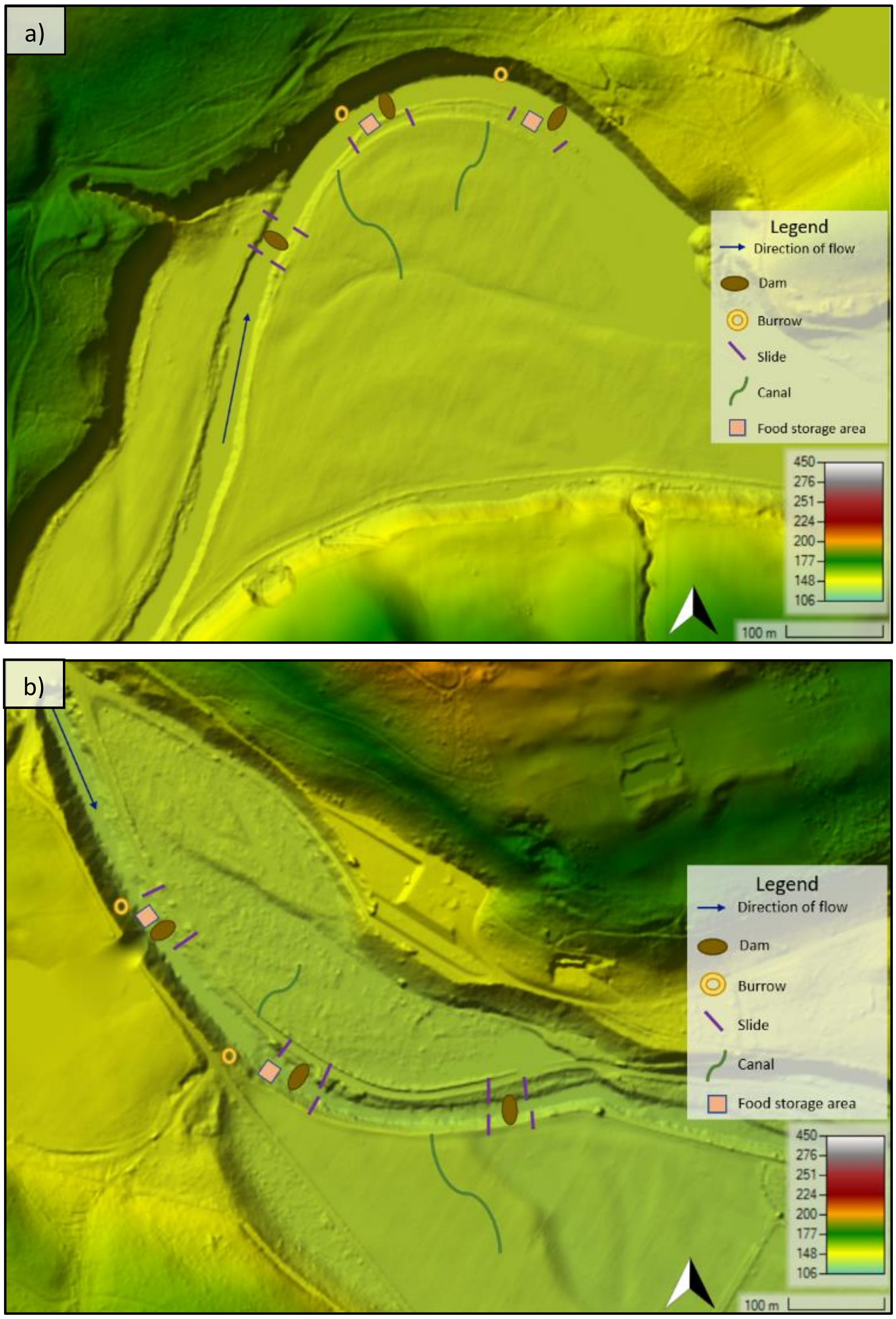
Beaver slides & food storage area simulation

Slides were modelled by reducing the bank line gradient by 0.4 m over a 1.5 m height. These figures were averages taken directly from ranges described by Gorczyca *et al*. (2018) due to a lack of other slide dimension data. They suggest beavers construct numerous slides down riverbanks therefore slides were simulated along dam cross-sections wherever bank heights were not prohibitively steep. Food storage areas were modelled as Manning's *n* calibration polygons next to the dam and on the riverbed. Again, there was a lack of data regarding the dimensions of food storage areas therefore they were drawn to be 5 m^2, based on the assumption that several piles of logs, with diameters ~0.5 - 0.6 m (Gorczyca *et al.*, 2018, p. 1053) would be collected to supply the colony throughout winter. These manning's *n* calibration regions were assigned a value of 0.1 to reflect woody debris (Te Chow, 1959).

Figure 8 below shows a map of the modelled EYRS with symbology reflecting the locations of BMS inputs.

Figure 8

Visual Depiction of BMS Inputs to EW (a) and YW (b) Reintroduction Areas



Note. Symbols are not to scale.

4.1.6. Sensitivity Analysis

A sensitivity analysis was conducted on the final model. Song *et al.* (2015) defines sensitivity analysis for hydrological modelling as an "investigation of the response function that links the variation in the model outputs to changes in the input variables or/and parameters, which allows the determination of the relative contributions of different uncertainty sources to the variation in outputs” (p. 741).

The subject of the sensitivity analysis was beaver dam dimensions, for several reasons. First, dams are frequently cited in the literature as the most influential hydrological structure built by beavers. Puttock *et al.* (2017) stated that “of all the structures built by beavers, their dams have the largest visible, ecological, and hydraulic impact” (p. 2). This is supported by Grudzinski *et al.* (2022) who reported “of these [beaver] habitat alterations, dam construction is often attributed to significant impacts to the stream channel and riparian floodplain” (p. 3). Second, compared to other BMS, dams had the most data associated with their dimensions in the literature review and the largest ranges regarding their possible values, indicating their significance in influencing the uncertainty of the results. Finally, it is frequently cited in the literature that beaver dam size is highly dependent on the dimensions and geomorphology of the channels they settle in. Gurnell (1998) noted that dam size changes according to the topography. They explain that “dams may simply occupy the active river channel, they may extend across low gradient banks or they may extend across floodplains and/or side channels to create wide ponds” (ibid., p. 175). Similarly, of 51 dams analysed, Neumayer *et al.* (2020) found that “47% of the dams lie completely within the river... . Approximately 20% of the dams are higher than the riverbanks, whereas 33% reach into the meadows” (p. 10). This dam dimension sensitivity analysis allowed the dams in this system to take on these different forms, therefore accounting for some of the uncertainty about dam manifestation in this system.

Input parameters of beaver dams were changed to their minimum and maximum values reported in the literature (see Table 7 below). Application of dam heights followed the same methodology as for average dimensions (summed with average water level and channel bed elevation). Inputted heights can be found in Table F2 of Appendix F. Culverts were adjusted accordingly to dam heights and widths, to ensure at minimum and maximum dimensions there was still permeability. For minimum dam dimensions, culvert numbers and the elevation at which they were inserted were lowered, and the diameter was reduced to 0.1 (as the minimum width of dams was only 0.8 m, meaning a 0.4 m diameter would indicate 50% permeability). For maximum dam dimensions, culvert diameter was kept the same (0.4 m) but additional rows/culverts added to account for increased dam height/width. Again, dam permeability was not well-documented in the literature and therefore these estimations are a significant source of uncertainty in this model. All other BMS dimensions remained the same for this analysis.

Table 7

Minimum and Maximum Dam Dimensions Reported in the Literature

Variable change	Height (m)	Width (m)	Length (m)
Minimum dimensions	0.1	0.5	0.8
Maximum dimensions	1.7	36	70

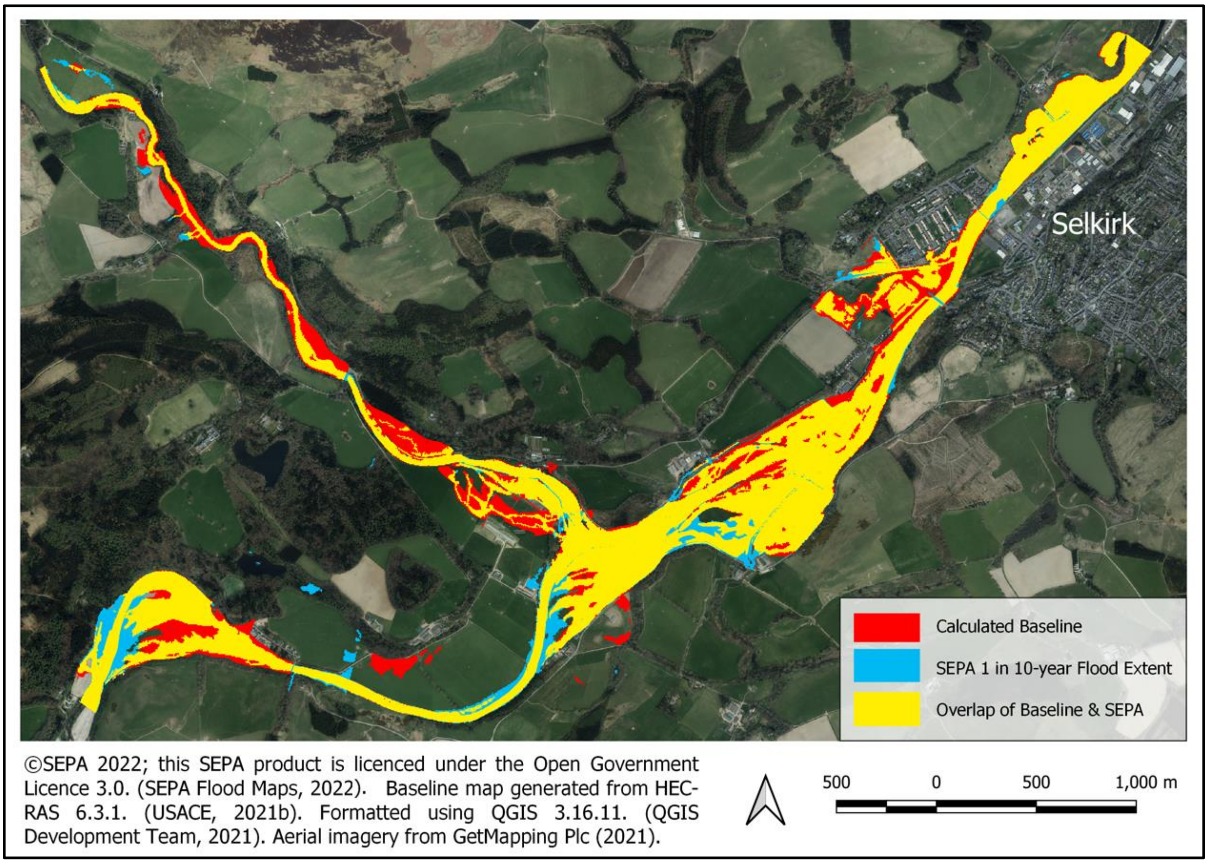
Note. Sources of these figures listed in Table 2 of Section 3.2.1.

4.2 Model Results

The developed baseline map of the EYRS during a 1 in 10-year flood event showed an area of 1,859,026 m^2 (1.86 km^2) becoming inundated. The SEPA (2022) 1 in 10-year flood maps indicated a flooded area of 1,607,018 m^2 (1.61 km^2). Therefore, the baseline model calculated 252,008 m^2 (0.25 km^2) of flooding not shown in the SEPA maps, reflecting a 15.68% difference. It should be noted that the SEPA flood maps were clipped to include only the modelled area (i.e., additional tributaries not modelled were removed) in order to accurately compare inundated areas. Considering the data constraints, the model was deemed as validated as feasibly possible within the research timeline. A map of this baseline flood scenario, before the input of any BMS, is shown in Figure 9 below, overlaid with the SEPA (2022) 10-year flood map to highlight where the maps differ.

Figure 9

Calculated Baseline Map of the EYRS During a 1 in 10-year flood event, Overlaid with the SEPA 10-year Flood Map for the Region



©SEPA 2022; this SEPA product is licenced under the Open Government Licence 3.0. (SEPA Flood Maps, 2022). Baseline map generated from HEC-RAS 6.3.1. (USACE, 2021b). Formatted using QGIS 3.16.11. (QGIS Development Team, 2021). Aerial imagery from GetMapping Plc (2021).

Note. Additional SEPA attribution statements can be found in Appendix G.

Following the addition of BMS using average values, flooded areas slightly decreased in both reintroduction areas. Both areas run together yielded a net decrease in flooded areas by 4,114m^2 or 0.22%. These results are summarised in Table 8 below. These area calculations encompass the entire EYRS modelled, and so large portions of the model that were unaffected by the BMS are included. For this reason, the area difference in m^2 is also presented, as percentage change over a large area can be misleading.

Table 8

Results of Average BMS Inputs

Simulation	Area flooded (m^2)	Area difference from baseline (m^2)	Percent difference from baseline
EW_{avg}	1,858,614	-412	-0.02%
YW_{avg}	1,855,306	-3,720	-0.2%
Combined EW_{avg} & YW_{avg}	1,854,912	-4,114	-0.22%

In the EW reintroduction area, the input of average dam dimensions resulted in the simulation of dams that extended into the floodplain beyond bank lines by 12 - 20 meters. In the YW reintroduction area, average dam dimensions were not fully realised as the dam height did not surpass the bank height, resulting in entirely in-channel dams that stopped at the banks on either side.

Results maps for the input of BMS at each reintroduction area are shown below in Figures 10-11. The maps are zoomed into the areas where changes occurred to floodwaters, which were exclusively around where BMS were inputted. The combined EW & YW map is not shown as it is identical to the individual simulations. The maps depict areas in red (baseline) where flooding decreased, blue areas (simulation) where flooding increased, and yellow areas (the overlap between the baseline and the simulation) where there was no change.

Figure 10

Flood Extent at EW Following BMS Inputs at Average Dimensions (EW_{avg})

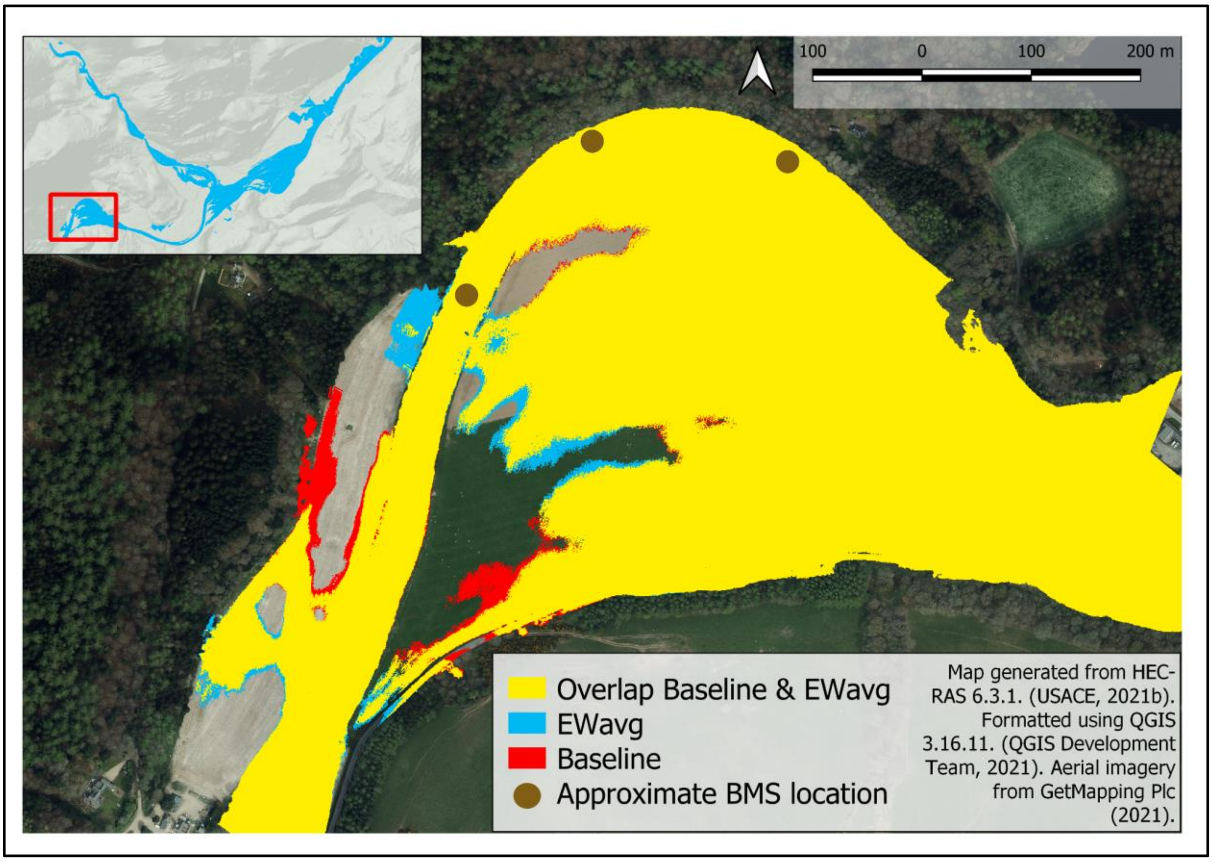
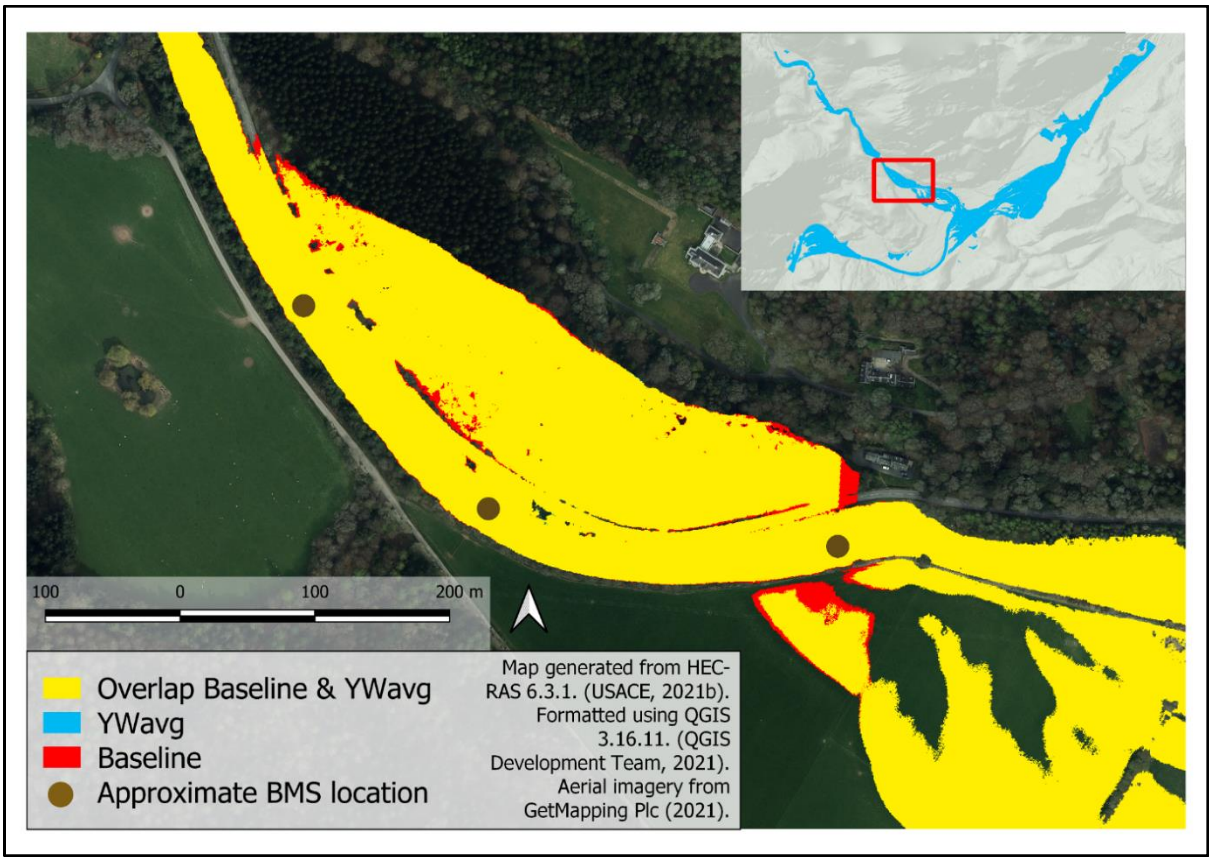


Figure 11

Flood Extent at YW Following BMS Inputs at Average Dimensions (YW$_{avg}$)



The results of the sensitivity analysis added nuance to the findings by demonstrating the sensitivity that dam dimensions had on inundated areas. Compared to the baseline, model scenario flood extent uncertainty at EW ranged from -1,623 m^2 to +331 m^2. At YW, it ranged from -16,060 m^2 to +1,770 m^2. These findings are summarised in Table 9 below:

Table 9

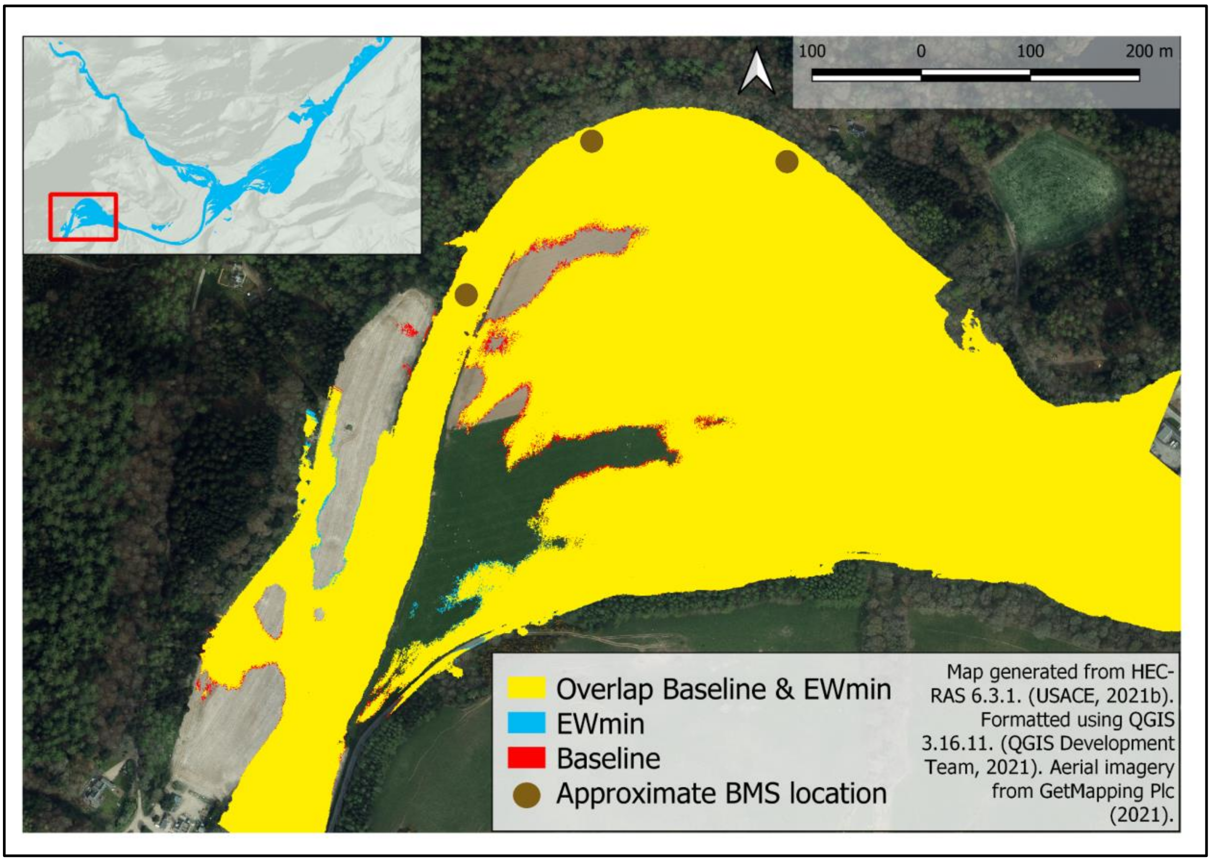
Results of Sensitivity Analysis

Simulation	Area flooded (m^2)	Area difference from baseline (m^2)	Percent difference from baseline
EW_{min}	1,857,403	-1,623	-0.09%
EW_{max}	1,859,357	331	0.02%
YW_{min}	1,842,966	-16,060	-0.86%
YW_{max}	1,860,796	1,770	0.10%

Dams in the EW_{max} simulation manifested by extending into the floodplain by 45 - 50 meters. Dams in YW_{max} did not exceed the bank heights and therefore remained confined to the channel but differed from YW_{avg} dam dimensions in their increased height. Dams in both EW_{min} and YW_{min} occupied a small portion of the channel as they were only 0.8 m in length and 0.5 m wide. Four result maps were generated that reflect inundated areas for dams at their minimum and maximum dimensions in the EW and YW reintroduction areas. These maps are helpful to conceptualise the flooding dynamics upstream and downstream of the dams, which are not reflected in total inundated area calculations. These are shown in Figures 12-15 below. The direction of water flow in all maps is from left to right.

Figure 12

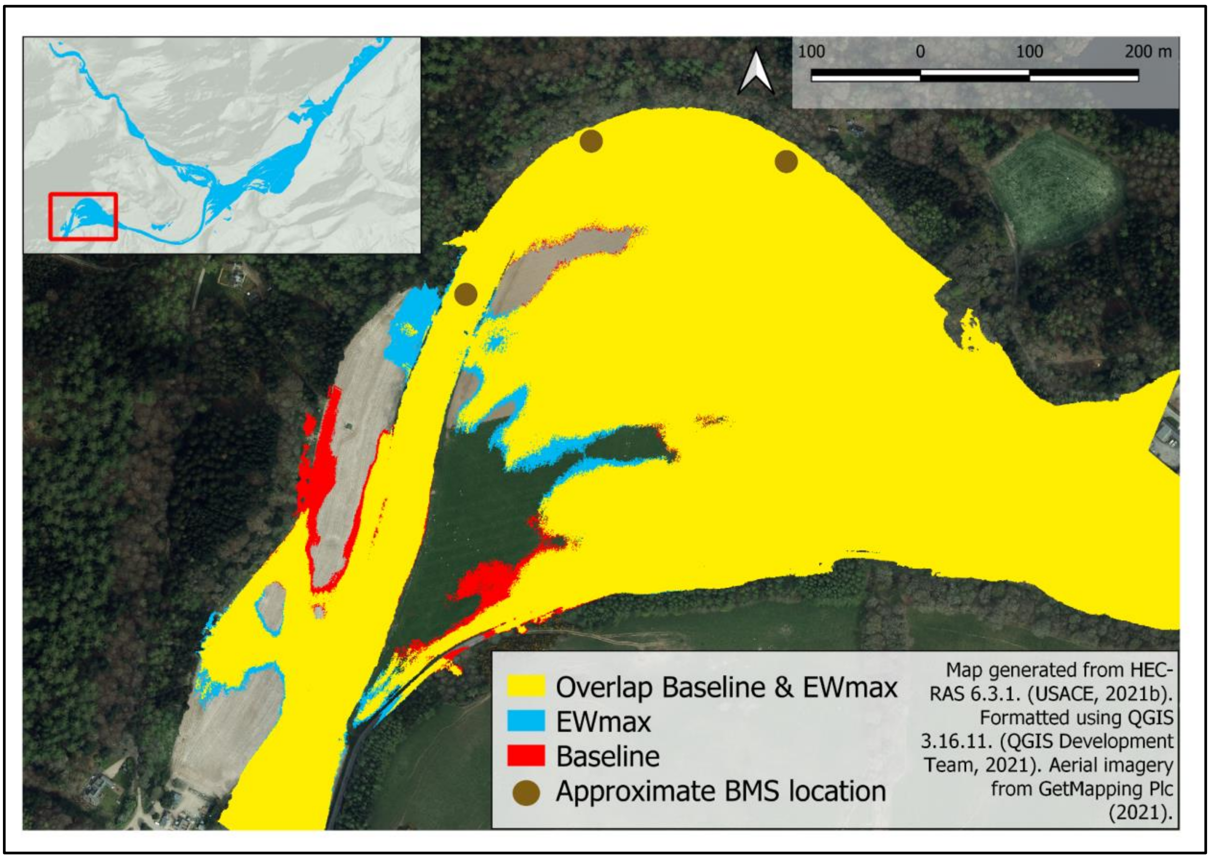
Flood Extent at EW Following BMS Inputs at Minimum Dimensions (EW_{min})



Map generated from HEC-RAS 6.3.1. (USACE, 2021b). Formatted using QGIS 3.16.11. (QGIS Development Team, 2021). Aerial imagery from GetMapping Plc (2021).

Figure 13

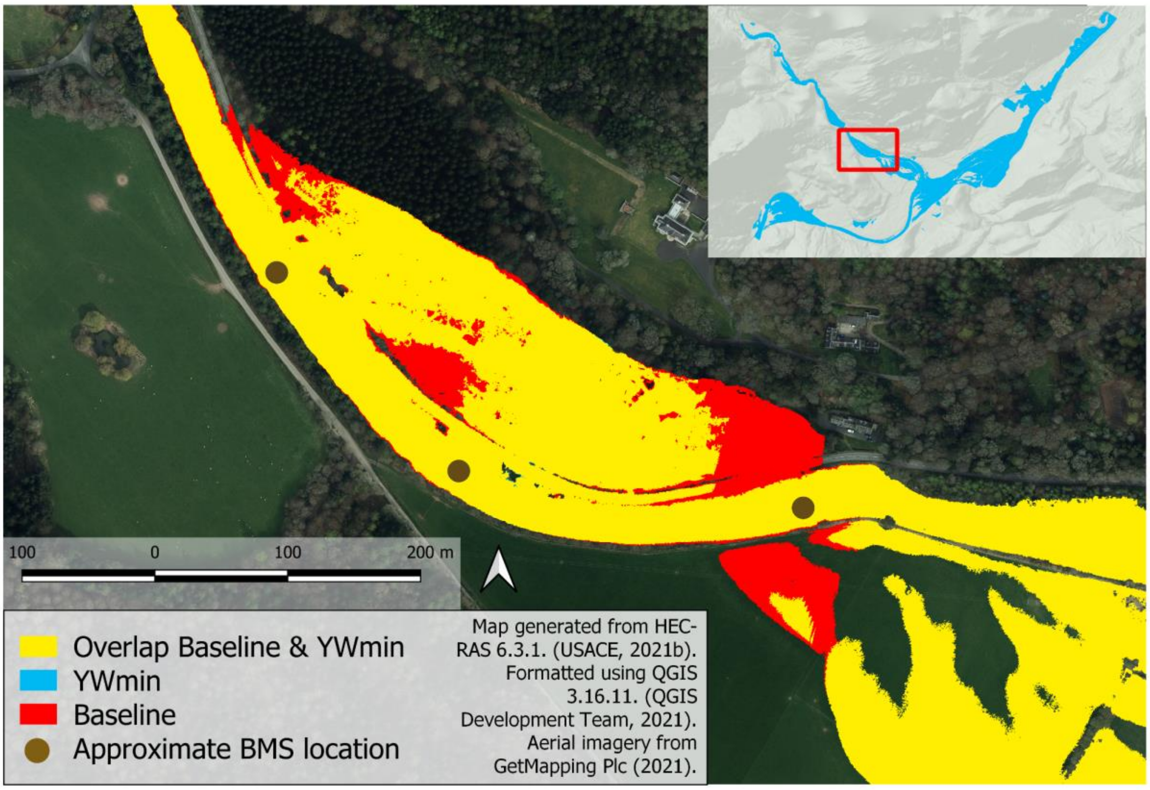
Flood Extent at EW Following BMS Inputs at Maximum Dimensions (EW$_{max}$)



Map generated from HEC-RAS 6.3.1. (USACE, 2021b). Formatted using QGIS 3.16.11. (QGIS Development Team, 2021). Aerial imagery from GetMapping Plc (2021).

Figure 14

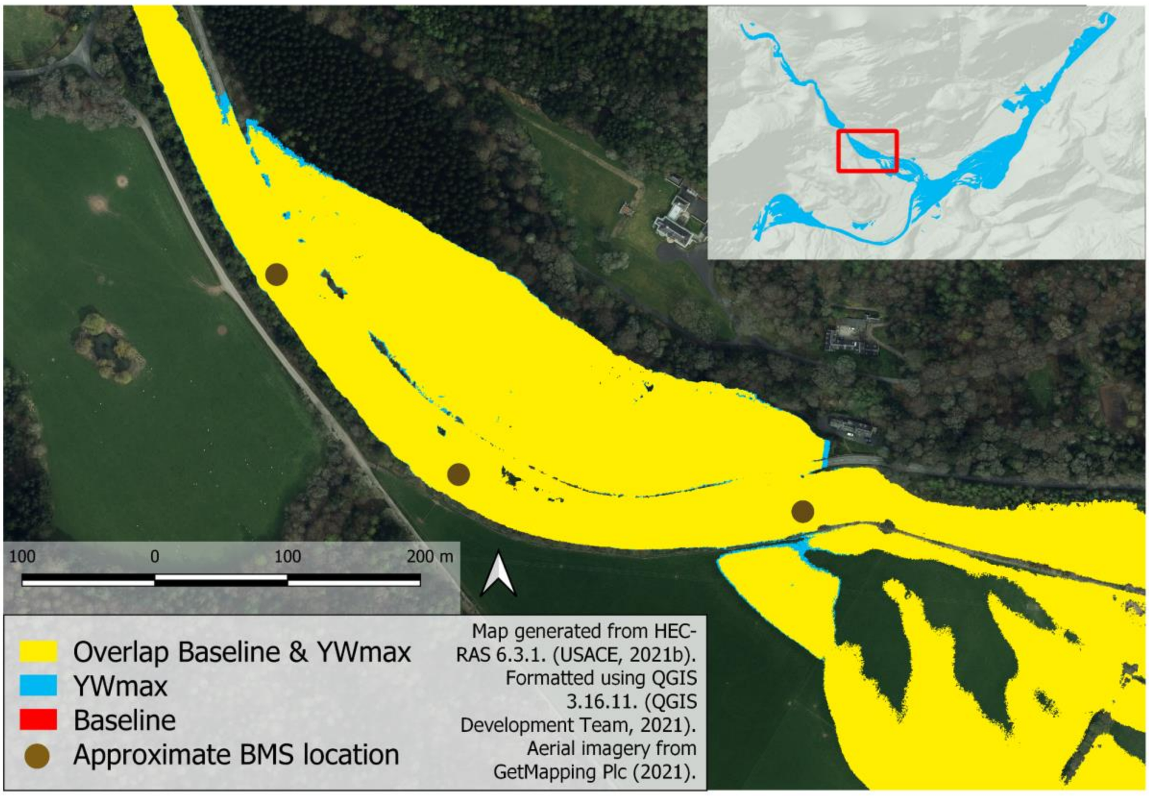
Flood Extent at YW Following BMS Inputs at Minimum Dimensions (YW_{min})



Map generated from HEC-RAS 6.3.1. (USACE, 2021b). Formatted using QGIS 3.16.11. (QGIS Development Team, 2021). Aerial imagery from GetMapping Plc (2021).

Figure 15

Flood Extent at YW Following BMS Inputs at Maximum Dimensions (YW_{max})



Map generated from HEC-RAS 6.3.1. (USACE, 2021b). Formatted using QGIS 3.16.11. (QGIS Development Team, 2021). Aerial imagery from GetMapping Plc (2021).

5. Discussion

5.1 Model Uncertainties & Impact on Result Interpretation

The validation of the model was a significant source of uncertainty in this study. No detailed statistical analysis was performed to compare the baseline 10-year flood scenario against reality. Therefore, the results must be taken contextually as all percent and area comparisons are relative to the simulated baseline, which presented a 15.68% overestimation of flooded areas in comparison to SEPA maps (SEPA, 2022). Further research contributing to the refinement of hydraulic modelling in the area is needed to corroborate any results. No field surveys were taken to determine precise river cross-sections or bridge data, and future studies of this river system should undertake detailed surveys to fill in crucial data gaps. A lack of access to SEPA flow data for 10-year floods, resulting in the use of estimated flow frequency data, served as a major limitation in validating the model. In addition, this model did not account for soil water infiltration, hyporheic exchange, or evapotranspiration, amongst other highly influential hydrological processes, which may have contributed to over or underestimations of flow.

However, these validation limitations were accepted within the scope of this research given the point of this study was not to create a hydrologically accurate model of the EYRS. The purpose of this study was to translate findings from the literature review about the effects of beavers on hydrological/hydraulic systems into modellable features to compare the flood extents before and after a simulated reintroduction. These findings still bear significance despite limitations in validating the baseline simulation as they are relative in nature. The results reflect a difference between two simulated states thereby making the findings relevant within the model system, so long as the confines and boundaries of the system are made clear. Indeed, data uncertainty and insufficient model validation are oft-cited limitations of much hydraulic modelling research (El Bilali *et al.*, 2021; Neumayer *et al.*, 2020), but as studies of this nature grow in number, results may be corroborated to better contribute to a larger and more refined picture of how beavers affect flood risk.

Assumptions were frequently used while modelling the beaver dams and other BMS, with a significant amount of interpolation necessary to apply findings from the literature review to the modelled channels and HEC-RAS software. Modelling BMS as modified human-engineered structures limited their accurate representation, but a lack of available hydraulic software designed to simulate ecological structures made it inevitable. The way in which input parameters were modified was dependent on what the existing literature stated about how beavers affect river dynamics and were therefore limited by the extent and quality of the available literature. There was substantial variation in dam measurement methods across the literature, particularly regarding dam permeability and the relationship between dam size and channel morphology. Using average values for the different BMS simulated was a limitation of this research, as it is frequently noted in the literature that beaver modifications are specific to their environment.

The initial intention was to conduct a regression-based model to compare structural dimensions against channel characteristics (width, length, gradient, flow) and use this to infer the dam dimensions that would be most appropriate for a channel of this size. However, there were not enough studies that reported these dimension combinations to calculate such a relationship. Future research is needed in this domain to develop predictive models of the modifications that arise from beaver reintroductions on different channel types. The permeability of the dams was estimated, using guidance from qualitative descriptions in the literature review, however, this remains a significant source of uncertainty in determining the relationship between dam building and flood attenuation. Additionally, upon simulating beaver presence, it was realised that the forested buffers of the reintroduction area at EW were located on high banks, likely unreachable by beavers. Gurnell's (1998) review of the literature about beaver habitat selectivity highlights the "availability of preferred vegetation [as]... an important criterion in habitat selection" (p. 171). In reality, appropriate vegetation would likely need to be planted in the suggested reintroduction areas for population viability. Finally, the technical modelling capabilities of the author were a limitation of this study, as the HEC-RAS software and theory behind hydraulic modelling were self-taught throughout this research process.

To summarise this section, as Box (1976) famously noted, "all models are wrong, but some are useful" (p. 1), and indeed this model is inevitably flawed in its accuracy and limited in its real-world applicability. The way that this model simulated beaver presence is not an accurate reflection of how a beaver reintroduction would look at this location in reality. However, there is a need to develop complex ways to measure the benefits of diverse adaptation projects to bridge the gap between theory and practice (Martinez & Christiansen, 2018). To this end, the methods as well as the results of this research may serve to corroborate and better refine the development of future beaver system models, increasing their utility in understanding beaver-flood risk relationships over time.

5.2 Discussion of Results

With the limitations of this study made clear, the model generated several interesting results that bore significance in addressing the research questions. These can be broken down into 3 key findings: (1) Average BMS simulating beaver presence marginally reduced total flooded areas during a 1 in 10-year flood event, but on a highly local scale and dependent on dam dimensions; (2) the input of BMS caused the redistribution of flood waters, with different upstream and downstream dimensions not reflected in measuring total flooded areas, and in two cases increased flood extent; (3) channel geomorphology controlled how dam structures manifested in the model, which determined their interaction with floodwaters at the reintroduction areas. The results of this study suggested that average BMS have the ability to marginally reduce flooded areas but are highly context dependent. It was beyond the scope of this study to make any recommendations for or against a beaver reintroduction as a form of NFM in this region, as no ecological niche, population viability, or social feasibility analyses were undertaken.

Finding 1*: Average BMS marginally reduced flooded areas during a 1 in 10-year event, but on a highly local scale and dependent on dam dimensions.*

BMS exhibited a hyper-local effect on flooding, with the flooded areas only changing around their immediate vicinity. A large portion of the river was modelled to capture changes that could have occurred further downstream in the town of Selkirk, however the effects of BMS on flooding were concentrated within ~1 km of their location, at both reintroduction areas. Flooded areas in Selkirk were not impacted by any of the simulations run, however it was worthwhile to include them in the model to observe the lack of downstream effect. The input of average BMS marginally decreased flood extent at both reintroduction areas. However, the sensitivity analysis demonstrated significant uncertainty in the results. Overall, four out of six simulations run (excluding the combined area model) showed a decrease in flooded areas following the input of BMS. The maximum observed decrease in flooding occurred with dam dimensions at their minimum, for both areas, reflecting a potential of up to 0.86% flood reduction at YW and 0.09% at EW. However, measuring the percent difference in total flooded areas can be misleading, given that a large area was modelled relative to the area of change. A 0.86% decrease in flooding corresponds with the removal of 16,060 m^2 of flooded areas which may be substantial for surrounding local properties. Dams at their maximum dimensions increased flooding at both sites, by 0.02% (331 m^2) at EW and 0.1% (1,770 m^2) at YW. This will be explored under Finding 2.

The attenuative effect of average dam sizes was in general agreement with the literature. Puttock *et al.* (2017) found that beaver activity attenuates flow in small channels primarily due to their built structures impeding water velocity via increased storage upstream of dams and decreased longitudinal stream connectivity. Nyssen *et al.* (2011) found that beaver dams may significantly lower peak discharges in small streams, which they attributed to the water storage capabilities of dams that level out flow hydrographs. Puttock *et al.* (2020) evidenced similar patterns of attenuated peak flows resulting from dam cascades, which they linked to enhanced water storage, lateral water diversion and higher hydraulic roughness from dam presence. Graham *et al.* (2022) also looked at beaver presence impact on peak flow outcomes and found similar results, even for larger flood events. However, the flood-attenuating results contradicted findings from Neumayer *et al.*'s (2020) modelling study, which found that although beaver dams may attenuate peak flows for small flood events (<1 in 2-year) they may increase flooded areas "by up to 359%" (p. 19). The latter finding supported the observed increase in net flooding in the EW_{max} and YW_{max} simulations, although to a much higher extent. Neumayer *et al.* (2020) found negligible results for beaver dam effects on peak flows of flood events larger than a 2-year return period. All these studies also measured variable outcomes, over different temporal and spatial scales, which can result in a misalignment of results. This indicated the importance of measuring several different outcomes in future beaver-flood risk research, as measuring only inundated areas can be a misleading characterization of beaver effects on other outcomes such as flow velocity, flood depths and durations.

Finding 2: *Flood waters are redistributed from the input of BMS, with differential effects upstream and downstream of dam cascades.*

At both reintroduction areas, the results of inputting BMS showed differential effects on floodwaters upstream and downstream of the dams which were not reflected in total flooded area calculations. As seen in Figure 10, in EW_{avg} the flooding downstream of the cascade mostly decreased, but the flooding increased immediately upstream of the first dam. The total area calculations reflected that there was a net decrease in flooding following this intervention but did not reflect divergent upstream and downstream flooding. This finding was consistent with the documented effects of beaver dams on increasing upstream flooding of dams, as the primary reason why beavers construct dams under low-flow conditions is to flood upstream areas and create ponds for enhanced foraging (Gurnell, 1998; Larsen *et al.*, 2021). Indeed, the flood attenuation effect observed in four of the simulations is likely due to the increased upstream water storage behind the dams. Brazier *et al.* (2021) noted that “damming typically reduces downstream connectivity, and conversely increases lateral connectivity, forcing water sideways into neighbouring riparian land, inundating floodplains, and creating diverse wetland environments” (p. 4). Larsen *et al.* (2021) elaborated that “through flow diversion of stream water and the accompanying rise in groundwater levels, floodplain inundation can also be far more extensive than would otherwise occur without beaver dams, especially during flood events” (p. 3). John & Klein (2004) sum this concept up in their statement, “if a beaver dam reaches the top of the channel banks, overbank flow occurs near the dam, inundating areas of the floodplain” (p. 228). The effect of water being diverted sideways by the dams was observed in 3 out of 6 simulations, in agreement with this effect. This also explained why the flood extent increased in both EW_{max} and YW_{max} compared to average dam dimensions, as the larger dam size resulted in increased water impoundment and therefore more extensive upstream flooding (blue areas on maps). Although YW_{max} showed no attenuation at all, EW_{max} showed some downstream flood reduction not reflected in the total area calculation. Upstream flooding was an anticipated result from the literature review and supported the lack of inclusion of beaver ponds in the model, although this may have resulted in an underestimation of downstream flood attenuation in the 3 scenarios where upstream flooding was not observed. Upstream flood attenuation could not be explained by the literature and could be a result of modelling errors.

In the YW_{avg} simulation (Figure 11), there was no observed upstream flooding of the beaver dam cascade. This could be explained by Gurnell’s (1998) suggestion that “in zones of dam construction, there will be patches which are unaffected by the backwaters from the dams” (Gurnell, 1998, p. 183). Graham *et al.* (2022) also noted that in their study, smaller dams were “not large enough to form a floodplain pond, but still impound water within the channel and push water onto the floodplain at high flows” (Graham *et al.*, 2022, p. 3). It is possible that this flow scenario was not sufficiently high to push water onto the floodplain in this channel, which could explain the lack of upstream ponding. Larsen *et al.* (2021) also explained that confined ponds, where the water level upstream of the dam remains within channel confines, can be found when “the channel is very large relative to dam size” (p. 3). This could explain the significant decrease in flooding that resulted from the YW_{min} simulation without observable upstream flooding.

Initially, efforts were made to measure the relative areas of upstream and downstream flooding to aid in this comparison, however, this was complicated by flooding that occurred between dams within the cascades, and so visual analysis of the flooded areas from the maps was the primary means of assessing these dynamics. This limitation is documented by Larsen *et al.* (2021) in their statement:

> ... a major limitation to understanding flood attenuation impacts is the cumulative storage and flow diversion processes that can occur both within and between beaver dams. This is likely why modelling studies of beaver flood impacts that do not explicitly include flow diversion find minimal impact on flood water storage (p. 8).

Finding 3: *The geomorphology of channels and floodplains controlled dam size, resulting in the manifestation of floodplain, in-channel, and partially in-channel dams which affected flood water redistribution.*

This finding was evidenced by modelling BMS inputs in two geomorphologically distinct areas and by the sensitivity analysis, where dam sizes were controlled by channel morphology. Puttock *et al.* (2017) noted that "beaver dam building activity is not a uniform activity and depends on the existing habitat, building material availability and channel characteristics" (p. 440). All dam dimensions were changed to their minimum and maximum values, however, the length and height of the dams in the YW reintroduction area were controlled by the height of channel banks, resulting in floodplain dams (EW_{avg} & EW_{max}), in-channel dams (YW_{avg} & YW_{max}) and partially in-channel dams (EW_{min} & YW_{min}). The results showed that partially in-channel dams had the largest net attenuative effect. These dam manifestations provided good coverage of the potential types of dams beavers could construct according to Gurnell (1998), and secondarily may have addressed the types of dams that emerge over time. Gurnell (1998) described this: "Dams can evolve through time. For example, small within-channel dams can be progressively extended into long channel-floodplain dams as the beaver colony increase the height and build up the dam laterally" (p. 175).

The effect that these different dam types had on flooding is connected to Finding 2, as they impacted upstream and downstream flooding in distinct ways depending on their dimensions. However, this section focuses on how the geomorphological differences between the two reintroduction sites affected inundated areas, wherein YW_{avg} presented a larger decrease in inundated areas than EW_{avg} but also reflected the most uncertainty with dams at their minimum and maximum dimensions. Graham *et al.* (2022) offers a potential explanation for the different effects observed between the two reintroduction areas. They suggested that in channels with high banks, the threshold of water storage for dams is reached more quickly, due to the reduced floodplain area over which water may be diverted and stored, and so dams in lower profile valleys may be more effective at attenuating flow. Although the results suggested that the dams at higher-banked YW yielded a larger net decrease in flooding, analysing the upstream/downstream dynamics suggested that these figures may be misleading as the EW reintroduction site showed substantial flooding upstream of the dam cascade which positively skewed the net flood result. This is supported by Larsen *et al.* (2021) who state that "in a semi- or unconfined valley river floodplain system, beaver dam complexes are likely to create more spatially complex flow networks" (p. 3).

This stresses that the site of dam placement, even within one small river system, was highly influential on flood outcomes. The same dam dimensions cannot be applied to different channel morphologies and have the same effect. This finding was relevant as substantial effort was undertaken to adapt the inputted BMS to the river system based on qualitative descriptions in the literature (see Section 3.2.2). However, even with these adaptations, this research revealed the significant uncertainty in how dams would manifest. This finding agreed with the literature overall. Graham *et al.* (2022) stated that "local topography and channel/floodplain geomorphology are…likely to exert a strong control on attenuation processes" (p. 11). Larsen *et al.* (2021) echoed this by suggesting that "stream-valley morphology is also a critical determinant of the potential hydrological impact of beaver dams" (p. 3). This finding may explain the gap in the literature that was observed in modelling beaver reintroductions to new areas as, with an absence of field surveys, their dam-building behaviour is difficult to predict and arguably impossible to accurately model.

5.3 Evaluating the Utility of Models in Assessing Beaver Contributions to NFM & Beyond

The results of this research shed light on how beaver structures can be conceptualised in hydraulic models and their possible impacts on flood inundation during 10-year flood events. However, engaging with this methodology also led to a critical examination of the value of models in assessing the contributions of beavers to NFM. Here, the application of complex adaptive systems (CAS) theory, as described by Preiser *et al.* (2018), is helpful in conceptualising the utility of models to understand complex phenomena. The theory of deep ecology, first coined by Naess (1973) and elaborated on by Devall & Sessions (1985) offers an alternative value system through which species reintroductions could be valued, beyond their contributions to NFM. These theories will be used to guide this discussion section to critically evaluate how quantifying beaver ecosystem services serves human societies during this time of climatic and ecological crisis.

5.3.1 The Limits of Quantifying the Ecosystem Services of Complex Adaptive Systems

As has been discussed, models are inevitably flawed (Box, 1976), however in flood risk analysis they are depended on to quantify the effects of interventions on risk (Wingfield *et al.*, 2019). Conceptualising the hydrological and hydraulic impact of beaver reintroductions as a modellable phenomenon has several benefits. First, it may assist in understanding the basic feedback loops that operate between beavers and their local environment. Ecosystem services more easily conceptualised when framed in terms that are analogous to human systems of design and engineering (Volk, 2013). This theme emerged from the literature review, in which authors frequently compared BMS to grey infrastructures, such as dams to weirs (Gurnell, 1998) or burrows to piping systems (Gorczyca *et al.*, 2018). This may enhance appreciation of the flood attenuating potential beavers have. In Auster *et al.*'s (2022) survey of perspectives on beavers in downstream communities in the UK, they highlighted that several anti-beaver perceptions coincided with uncertainty or doubt regarding beaver ecosystem services, which detailed models can help counteract. In addition, according to Larsen *et al.* (2021) there are still significant knowledge gaps regarding the effects of beaver interactions with their environments, and models are valuable tools to better understand the potential risks and rewards of their reintroductions. Several studies from the literature review made use of technical or conceptual models to effectively explain relationships between beavers and their physical environments (Gorczyca *et al.*, 2018; Larsen *et al.*, 2021; Neumayer *et al.*, 2020) that also personally aided the author throughout this study.

However, the results of this research made clear just how complex beaver systems are. Beaver-modified systems fulfil the "six organizing principles" of complex adaptive systems (CAS) described by Preiser *et al.* (2018), which are as follows: (1) they are "constituted relationally" (2) they "have adaptive capacities" (3) their "behaviour comes about as a result of dynamic processes” (4) they “are radically open” (5) they “are determined contextually” and (6) their “novel qualities emerge through complex causality” (p. 4). The complexity of beaver effects was reduced for the sake of this research. To conduct this study within a reasonable time frame, numerous beaver-environmental interactions fell outside of the model boundaries. Isolating the outcome of flood extent in connection with isolated variables resulted in several analytical sacrifices, with the full potential of the variables (BMS) not realised when they were not allowed to interact with other hydrological feedback loops within this model. Larsen *et al.* (2021) importantly note that:

> … The very nature of beaver dams also complicates our ability to model how storage changes should impact downstream discharge. This is because the influence of beaver dams on the hydrological processes ... are largely dependent on highly localised factors such as substrate type, construction materials, design integrity, and age, properties which may not be easy to transfer between different beaver impacted systems or even between individual dams (p. 9).

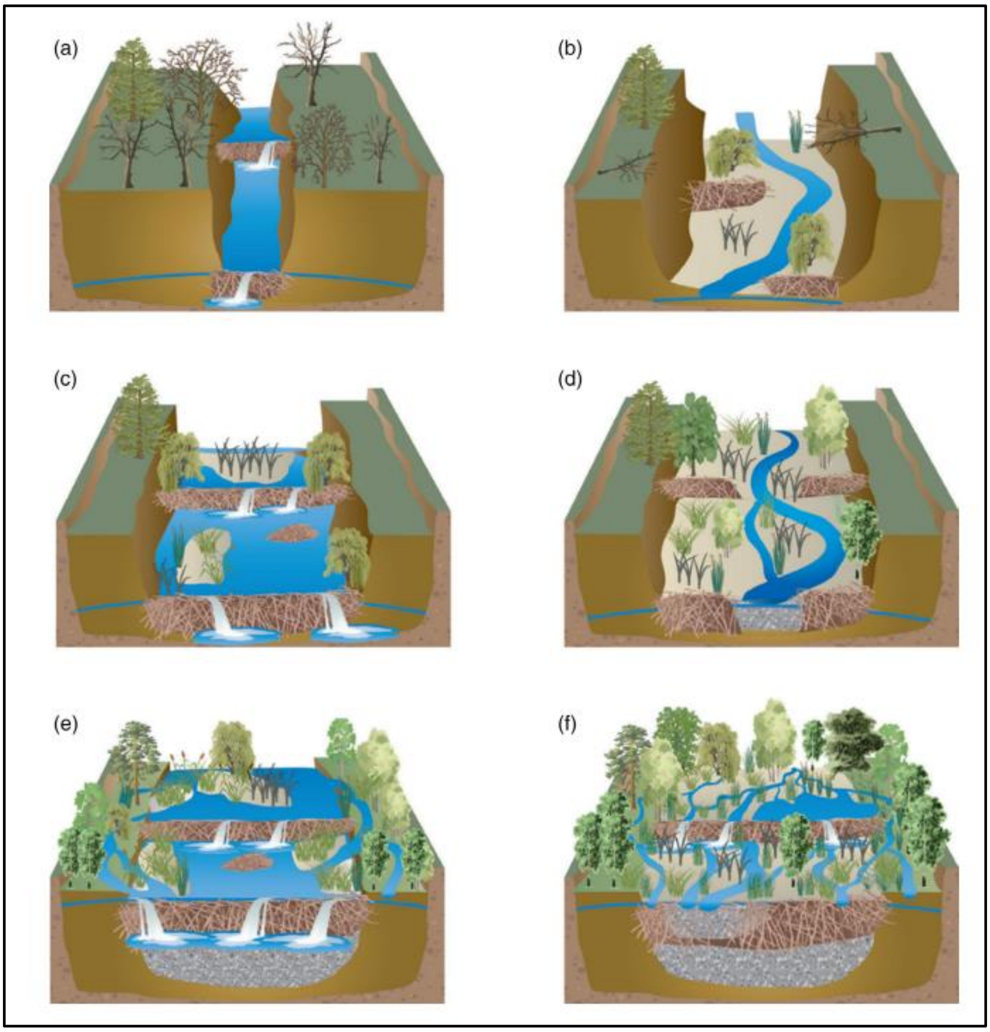
This speaks to the difficulty of modelling an “average” dam, also evidenced by Finding 3, as beavers will always adapt their structures, and especially dams, to meet their ecological needs (ibid; Gurnell, 1998). This calls into consideration the ability to which CAS can be engineered within a traditional approach of risk analysis. Using hydraulic modelling software designed for human-engineered interventions has limitations in its application to natural systems. It is also essential that models not be considered in isolation, and that efforts are made to corroborate them for ease of comparison. This was a limitation encountered in the literature review, wherein comparing dimensions of BMS was restricted by the use of different measurement methodologies and terminologies between studies. Volk (2013) highlights the inconsistency of methodologies as an issue in modelling ecosystem services generally and calls for the application of “methodological blueprints” (p. 4) to combat this.

Models can aid in understanding, but NFM interventions cannot be held to the same modelling standard as human-engineered systems, as they will inevitably fail to be as predictable. Wingfield *et al.* (2019) criticise the overdependence on models to prove benefits before action can be taken in the case of NFM: “Rather than embracing the notion of creating a more resilient system, the computational complexities of increasing our knowledge base almost entirely through modelling [leads] to a narrowing of the scope of NFM away from a systems approach …” (p. 748). They warn against NFM practitioners getting caught up in “a need to demonstrate a measurable benefit to flood risk reduction through monitoring, hydrological modelling or a cost-benefit analysis” (p. 744-5). To fully appreciate beaver-modified systems as CAS, and adequately value their contributions to NFM alongside other benefits, models are necessary but must not be considered in isolation. A broader holistic understanding of how beaver reintroductions affect physical and social landscapes, beyond only quantitative outcomes, is needed to better inform reintroduction policies (Larsen et al., 2021).

This model was a static snapshot, whereas CAS have adaptive capacities that respond to feedback through which novel qualities can emerge (Preiser *et al.*, 2018). Studies that discussed the effects of beavers on river systems over time described how biodiverse, mineral-rich wetland systems develop from channel re-meandering and sediment accumulation on the floodplain (Brazier *et al.*, 2021; Larsen *et al.*, 2021). Figure 16 provides a helpful conceptual illustration of this temporal process. Upstream flooding caused by floodplain inundation from dam creation increases habitat areas supporting riparian and aquatic biodiversity and may increase surface and groundwater storage capacities mitigating drought risk (Larsen *et al.*, 2021, p. 32). Static models cannot be expected to capture such dynamic change with intersectional benefits, and measuring flood extents can be misleading when upstream flooding may serve as a source of resilience to other threats. Iacob *et al.* (2014) highlights this issue of "time lags" (p. 784) before benefits are realised as being a challenge in evaluating NFM more broadly.

Figure 16

Beaver Impacts on Channel Systems Over Time, from Initial Reintroduction (a) to the Development of Complex, Diverse Wetland Systems (f)



Note. Extracted from Brazier *et al.* (2021, p. 8). Attribution statement: © 2020 Brazier *et al.* WIREs Water published by Wiley Periodicals LLC.

The boundaries of this model resulted in analytical sacrifices that limited a broader application of the model results. The creation of boundary conditions inevitably clashes with Preiser *et al.*'s (2018) fourth principle that CAS are "radically open" (p. 4). In this way, models are inherently antithetical to capturing the complexity of CAS, despite their utility in understanding them. It does not negate their relevance in contributing to an enhanced understanding of beaver systems, however it is important that limitations and assumptions are explicitly stated to avoid misinterpreting results (Iacob *et al.*, 2014; Volk, 2013). This is particularly important when it comes to modelling beaver reintroductions, where results can be misleading in terms of labelling species to have net positive or net negative impacts (Larsen *et al.*, 2021), and such broad categorisations may determine whether a species is allowed to exist or not. Indeed, Larsen *et al.* (2021) highlighted that the science behind quantifying some of these temporal effects of beavers is still "highly uncertain and context dependent. Thus, extrapolating the financial value of these services may be premature for widespread management and policy use, which is symptomatic of a broader problem in ecosystem service quantification" (p. 38). They stressed that their impacts must be put in a holistic context, in which effects are considered in a relational sense and therefore their properties as CAS, and benefits to NFM, more readily understood (ibid.). This criticism was echoed by Gunton *et al.* (2017) in their discussion of how ecosystem services, despite acting as a good incentive towards nature conservation, are inherently reductionist in their approach toward appreciating ecosystem complexity. The conceptualisation of ecological processes as ecosystem services, whether in economic or, in this case, 'risk reduction' terms, fails to capture the nuances and adaptive capacities of CAS (ibid.), and therefore does not serve as a fair evaluation of their NFM potential. The third objective of Scotland's Beaver Strategy outlined in the introduction of this paper risks falling under this limitation by focusing on the need to use models to better identify the ecosystem services offered by this species (IUCN/CPSG, 2022).

5.3.2 Deep Ecology & the Case for Expanding Anthropocentric Value Systems

The process of answering the research questions of this thesis raised philosophical and ethical issues that merit further discussion. The limits that models have in capturing CAS coincide with the limitations that inherently lie with valuing the role of beavers, or other non-human species, solely based on how they may serve human needs. Values are core to risk analysis and evaluation, as they determine what should be protected from harm (Slovic, 1998). Broadly defined, anthropocentrism is a human-oriented value system that sees the environment, biodiversity, and 'wilderness' as resources for human extraction or use and centres human needs as above and separate from natural landscapes (Kopnina, 2012). Arguably, anthropocentrism has been a significant driver in causing the concurrent climate and biodiversity crises (ibid.). Traditional views of ecosystem services tend to be anthropocentric and utilitarian in nature (ibid.; Gunton *et al.*, 2017), which do little to address the root causes of these crises. As the understanding of how climate change jeopardises the current state of society grows, a collective introspection regarding the mindset that led to this state becomes imperative. Deep ecology is the school of thought that pushes against a "shallow approach to environmental problems" (Devall & Sessions, 1985, p. 65). It overlaps with the theory of ecocentrism and holds the core philosophy that non-human species and ecosystems have the intrinsic value to exist beyond the services they offer humans (ibid.; Kopnina, 2012). Modelling how beavers affect flood risk to better understand their contributions to NFM is no doubt important but will remain insufficient in addressing the larger climate and biodiversity crises without efforts to expand the valuation of native species beyond their ecosystem services. It is no question that preserving human life and reducing suffering is the top priority moving forward into a world that will increasingly experience frequent and severe flooding. But this section aims to complicate the extent to which modelling ecosystem services, and the dominant anthropocentric value system that underpins this process, addresses or significantly questions the underlying causes of a climate-changed world.

The results of this study showed that the input of BMS reduced flood extent during high-likelihood fluvial floods in four out of six modelled scenarios. However, the flood reduction was relatively small, and in two cases flooding increased. Although much of the reviewed literature agreed that beavers can reduce flood risk through the creation of resilient wetlands, much uncertainty remains to what extent and results are highly context-dependent (Larsen *et al.,* 2021; Neumayer *et al.,* 2020). Uncertainty also surrounds the adverse impacts beavers may have on local woodlands and agricultural lands, leaving potential for human-wildlife conflict (Coz & Young, 2020; Larsen *et al.*, 2021). ‘Beaver Dam Analogues’ are an emerging research interest, in which beaver structures are simulated via human engineering without actual beavers to avoid such conflicts and uncertainty (Auster *et al.*, 2022). This well encapsulates the issue of valuing ecosystem services anthropocentrically, without value being placed on the existence of the actual species. Functionally, many species could go extinct and be replaced by human engineering ingenuity (Kopnina, 2012), which begs the question: If species do not directly serve us, does that justify their extinction?

Undoubtedly, beaver reintroductions present more uncertainty than human-engineered flood structures like concrete levees. However, they also convey more intangible value, agency, and opportunity for emergent benefits such as enriched biodiversity and, as recent research suggests, enhanced mental health of surrounding inhabitants (Gandya & Wattsa, 2021; Larsen *et al.,* 2021). Such values are less tangible, and therefore more difficult to conceptualise in traditional risk analysis. Their adverse effects can be managed and planned for and should not serve as an absolute barrier to reintroductions. As Puttock *et al.* (2020) state: “it must be recognized and reconciled that managers will not have the level of control over beaver engineering they do over human engineering … beavers will bring unique but manageable issues; stakeholder and public engagement will therefore be required to mitigate the risk of conflict” (p. 14). Alongside the needed holistic approach toward appreciating beavers as CAS and their potential ecosystem services to NFM, expanding value systems in flood risk analysis more generally may allow for a greater appreciation of the intangible value beavers provide, including their intrinsic value in the Scottish landscape. As Brazier *et al.* (2021) noted “during the Anthropocene, our catchments have largely become a product of human activity…with associated additional pressures including; hydrological extremes, diffuse pollution, and soil erosion” (ibid., p. 2). NFM offers great potential to address such pressures, but addressing their anthropocentric origin requires a critical examination of an approach to land management that has historically undervalued native species. Paradoxically, an anthropocentric approach to risk has led to greater risks for human society through the widespread destruction of natural resources (Kopina, 2012). Moving forward, combatting the concurrent biodiversity and climate crises will require a paradigm shift away from an anthropocentric value system to one that considers the value of ecosystems beyond their utility to humans - for our sake just as much as the beavers.

6. Conclusion

Scotland faces more frequent and severe flooding due to climate change which is forecasted to worsen the ongoing biodiversity crisis. As beaver reintroductions continue across the country their potential risks and rewards to NFM must be carefully evaluated. This research explored how Eurasian beavers affected the high-likelihood flood risk in a small Scottish river system by modelling their built structures and analysing their impact on flood extent. The results of this study suggested that modelled beaver-modified structures can marginally reduce flooded areas on a hyper-local level but are highly context-dependent. A dam dimension sensitivity analysis showed that results were uncertain and flood extent increased with dams at their maximum dimensions. Partially in-channel dams, created by dams at their minimum dimensions, showed the most flood-attenuative effect, but changes remained small. Limitations in the modelling process and data accessibility resulted in significant model uncertainty while modelling beaver structures. Still, the methods of modelling their reintroduction may serve as groundwork for future research endeavours. Methodological blueprints that measure beaver impacts against channel data may better corroborate research in this field and increase abilities to predict dam formations based on channel sizes. This process also illuminated several philosophical and ethical considerations regarding the utility of models in quantifying the ecosystem services of species reintroductions. Models are, and will continue to be, necessary in better understanding complex systems, but remain limited and fundamentally flawed in capturing emergent and dynamic elements of beaver reintroductions. In addressing the climate and biodiversity crises, holistic approaches to modelling alongside a reappraisal of the value systems that underpin them will be necessary to address the underlying paradigms that have led, in part, to the genesis of these crises.

References

Adams, K. J., Metzger, M. J., Helliwell, R. C., & Pohle, I. (2022). Understanding knowledge needs for Scotland to become a resilient Hydro Nation: Water stakeholder perspectives. *Environmental Science & Policy*, *136*, 157-166. https://doi.org/10.1016/j.envsci.2022.06.006

Auster, R. E., Barr, S. W., & Brazier, R. E. (2022). Beavers and flood alleviation: Human perspectives from downstream communities. *Journal of Flood Risk Management*, *15*(2), e12789. https://doi.org/10.1111/jfr3.12789

Blaikie, N. (2009). *Designing social research: The logic of anticipation*. Polity.

Bokhove, O., Kelmanson, M., & Kent, T. (2018). Using flood-excess volume to show that upscaling beaver dams for protection against extreme floods proves unrealistic. *Earth ArXiv*. https://doi.org/10.31223/osf.io/w9evx

Box, G. E. (1976). Science and statistics. *Journal of the American Statistical Association*, *71*(356), 791-799.

Brazier, R. E., Puttock, A., Graham, H. A., Auster, R. E., Davies, K. H., & Brown, C. M. (2021). Beaver: Nature's ecosystem engineers. *Wiley Interdisciplinary Reviews: Water*, *8*(1), e1494. https://doi.org/10.1002/wat2.1494

Campbell-Palmer, R., Rosell, F., Naylor, A., Cole, G., Mota, S., Brown, D., Fraser, M., Pizzi, R., Elliott, M., Wilson, K., Gaywood, M., & Girling, S. (2021). Eurasian beaver (Castor fiber) health surveillance in Britain: Assessing a disjunctive reintroduced population. *Veterinary Record*, *188*(8). https://doi.org/10.1002/vetr.84

Collet, L., Harrigan, S., Prudhomme, C., Formetta, G., & Beevers, L. (2018). Future hot-spots for hydro-hazards in Great Britain: a probabilistic assessment. *Hydrology and Earth System Sciences*, *22*(10), 5387-5401. https://doi.org/10.5194/hess-22-5387-2018

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (2016). Nature-based solutions to address global societal challenges. *IUCN: Gland, Switzerland*, *97*, 2016-2036. http://dx.doi.org/10.2305/IUCN.CH.2016.13.en

Coz, D. M., & Young, J. C. (2020). Conflicts over wildlife conservation: learning from the reintroduction of beavers in Scotland. *People and Nature*, *2*(2), 406-419. https://doi.org/10.1002/pan3.10076

Curry-Lindahl, K. (1967). The beaver, Castor fiber Linnaeus, 1758 in Sweden extermination and reappearance. *Acta Theriologica*, *12*(1), 1-15.

De Visscher, M., Nyssen, J., Pontzeele, J., Billi, P., & Frankl, A. (2014). Spatio-temporal sedimentation patterns in beaver ponds along the Chevral river, Ardennes, Belgium. *Hydrological Processes*, *28*(4), 1602-1615. https://doi.org/10.1002/hyp.9702

Devall, B., & Sessions, G. (1985). *Deep Ecology: Living as if nature mattered.* Gibbs Smith.

El Bilali, A., Taleb, A., & Boutahri, I. (2021). Application of HEC-RAS and HEC-LifeSim models for flood risk assessment. *Journal of Applied Water Engineering and Research*, *9*(4), 336-351. https://doi.org/10.1080/23249676.2021.1908183

Ellis, C. J., & Eaton, S. (2018). The biogeography of climate change risk for Scotland's woodland biodiversity: epiphytes. *Scottish Geographical Journal*, *134*(3-4), 257-267. https://doi.org/10.1080/14702541.2018.1526315

Farooq, M., Shafique, M., & Khattak, M. S. (2018). Flood frequency analysis of river swat using Log Pearson type 3, Generalized Extreme Value, Normal, and Gumbel Max distribution methods. *Arabian Journal of Geosciences*, *11*, 1-10. https://doi.org/10.1007/s12517-018-3553-z

Gandya, S., & Wattsa, R. (2021). Potential psychological benefits of nature enrichment through the reintroduction of the Eurasian beaver (Castor fiber) to Britain: A narrative literature review. *European Journal of Ecopsychology*, *7*, 41-74.

Gaywood, M. J. (2018). Reintroducing the Eurasian beaver Castor fiber to Scotland. *Mammal Review*, *48*(1), 48-61. https://doi.org/10.1111/mam.12113

GetMapping Plc. (2021). High Resolution (25cm) Vertical Aerial Imagery [images]. 1: 500. Retrieved from https://digimap.edina.ac.uk/

Google Maps (n.d.a). [Ettrick Water]. Retrieved April 20 2023 from https://mt1.google.com/vt/lyrs=r&x=%7Bx%7D&y=%7By%7D&z=%7Bz%7D

Google Maps (n.d.b). [Selkirk]. Retrieved March 15 from https://goo.gl/maps/8RbxYCx8i97VYE6P9

Gorczyca, E., Krzemień, K., Sobucki, M., & Jarzyna, K. (2018). Can beaver impact promote river renaturalization? The example of the Raba River, southern Poland. *Science of the Total Environment*, *615*, 1048-1060. https://doi.org/10.1016/j.scitotenv.2017.09.245

GovScot. (2019, February). *Delivering sustainable flood risk management: guidance (2019).* Scottish Government - Riaghaltas Na h-Alba. https://www.gov.scot/publications/flood-risk-management-scotland-act-2009-delivering-sustainable-flood-risk-management/pages/5

GovUK. (2021, May). *Species reintroductions and other conservation translocations.* GovUK. https://www.gov.uk/guidance/species-reintroductions-and-other-conservation-translocations

Graham, H. A., Puttock, A. K., Elliott, M., Anderson, K., & Brazier, R. E. (2022). Exploring the dynamics of flow attenuation at a beaver dam sequence. *Hydrological Processes, 36*(11), e14735. https://doi.org/10.1002/hyp.14735

Griffis, V. W., & Stedinger, J. R. (2007). Log-Pearson type 3 distribution and its application in flood frequency analysis. I: Distribution characteristics. *Journal of Hydrologic Engineering*, *12*(5), 482-491. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:5(482)

Grudzinski, B. P., Cummins, H., & Vang, T. K. (2020). Beaver canals and their environmental effects. *Progress in Physical Geography: Earth and Environment*, *44*(2), 189-211. https://doi.org/10.1177/0309133319873116

Grudzinski, B. P., Fritz, K., Golden, H. E., Newcomer-Johnson, T. A., Rech, J. A., Levy, J., Fain, J., McCarty, J. L., Johnson, B., Keng Vang, T., & Maurer, K. (2022). A global review of beaver dam impacts: Stream conservation implications across biomes. *Global Ecology and Conservation*, e02163. https://doi.org/10.1016/j.gecco.2022.e02163

Grygoruk, M., & Nowak, M. (2014). Spatial and temporal variability of channel retention in a lowland temperate forest stream settled by European beaver (Castor fiber). *Forests*, *5*(9), 2276-2288. https://doi.org/10.3390/f5092276

Gunton, R. M., van Asperen, E. N., Basden, A., Bookless, D., Araya, Y., Hanson, D. R., Goddard, M. A., Otieno, G., & Jones, G. O. (2017). Beyond ecosystem services: valuing the invaluable. *Trends in Ecology & Evolution*, *32*(4), 249-257. https://doi.org/10.1016/j.tree.2017.01.002

Gurnell, A. M. (1998). The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography*, *22*(2), 167-189. https://doi.org/10.1177/030913339802200202

Haan, TC. (1977). *Statistical methods in hydrology*. The Iowa University Press, Iowa.

Hartman, G., & Törnlöv, S. (2006). Influence of watercourse depth and width on dam-building behaviour by Eurasian beaver (Castor fiber). *Journal of Zoology*, *268*(2), 127-131. https://doi.org/10.1111/j.1469-7998.2005.00025.x

Huţanu, E., Mihu-Pintilie, A., Urzica, A., Paveluc, L. E., Stoleriu, C. C., & Grozavu, A. (2020). Using 1D HEC-RAS modeling and LiDAR data to improve flood hazard maps accuracy: A case study from Jijia Floodplain (NE Romania). *Water*, *12*(6), 1624. https://doi.org/10.3390/w12061624

Iacob, O., Rowan, J. S., Brown, I., & Ellis, C. (2014). Evaluating wider benefits of natural flood management strategies: an ecosystem-based adaptation perspective. *Hydrology Research*, *45*(6), 774-787. https://doi.org/10.2166/nh.2014.184

Inácio, M., Karnauskaitė, D., Mikša, K., Gomes, E., Kalinauskas, M., & Pereira, P. (2020). Nature-based solutions to mitigate coastal floods and associated Socioecological impacts. In *Nature-Based Solutions for Flood Mitigation: Environmental and Socio-Economic Aspects* (pp. 35-58). Cham: Springer International Publishing. https://doi.org/10.1007/698_2020_675

Iosub, M., Minea, I., Hapciuc, O., & Romanescu, G. H. (2015). The use of HEC-RAS modelling in flood risk analysis. *Aerul si Apa. Componente ale Mediului*, 315.

IUCN/CPSG (2022). *Scotland's Beaver Strategy 2022-2045*. IUCN SSC Conservation Planning Specialist Group, MN, USA. Available at: https://www.nature.scot/doc/scotlands-beaverstrategy-2022-2045

Jambu, M. (1991). Chapter 3 - 1-D Statistical Data Analysis. In M. Jambu (Ed.), *Exploratory and multivariate data analysis* (pp. 27-62,). Elsevier. https://doi.org/10.1016/B978-0-08-092367-3.50007-1

Kay, A. L., Rudd, A. C., Fry, M., Nash, G., & Allen, S. (2021). Climate change impacts on peak river flows: Combining national-scale hydrological modelling and probabilistic projections. *Climate Risk Management, 31*, 100263. https://doi.org/10.1016/j.crm.2020.100263

Kocięcka, J., & Liberacki, D. (2018). Planning of small retention in forests based on natural factors that increase water resources (M., Stryjecka, Trans). ROCZNIK OCHRONA ŚRODOWISKA, 20, 1302-1317.

Kopnina, H. (2012). The Lorax complex: Deep ecology, ecocentrism and exclusion. *Journal of Integrative Environmental Sciences*, *9*(4), 235-254. https://doi.org/10.1080/1943815X.2012.742914

Lane, S. N. (2017). Natural flood management. *Wiley Interdisciplinary Reviews: Water*, *4*(3), e1211. https://doi.org/10.1002/wat2.1211

Larsen, A., Larsen, J. R., & Lane, S. N. (2021). Dam builders and their works: Beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. *Earth-Science Reviews*, 218, 103623. https://doi.org/10.1016/j.earscirev.2021.103623

Janiszewski, P. A. W. E. U., Hanzal, V., & Misiukiewicz, W. (2014). The Eurasian beaver (Castor fiber) as a keystone species–a literature review. *Baltic forestry*, *20*(2), 277-286.

Law, A., Gaywood, M. J., Jones, K. C., Ramsay, P., & Willby, N. J. (2017). Using ecosystem engineers as tools in habitat restoration and rewilding: beaver and wetlands. *Science of the Total Environment*, *605*, 1021-1030. https://doi.org/10.1016/j.scitotenv.2017.06.173

Martinez, G., & Christiansen, L. (2018). *Adaptation metrics: perspectives on measuring, aggregating and comparing adaptation results.* UNEP DTU Partnership, Copenhagen.

Meli, P., Rey Benayas, J. M., Balvanera, P., & Martínez Ramos, M. (2014). Restoration enhances wetland biodiversity and ecosystem service supply, but results are context-dependent: a meta-analysis. *PloS one*, *9*(4), e93507. https://doi.org/10.1371/journal.pone.0093507

Naess, A. (1973). The shallow and the deep, long-range ecology movement. A summary. *Inquiry*, *16*(1-4), 95-100. https://doi.org/10.1080/00201747308601682

Neumayer, M., Teschemacher, S., Schloemer, S., Zahner, V., & Rieger, W. (2020). Hydraulic modeling of beaver dams and evaluation of their impacts on flood events. *Water*, *12*(1), 300. https://doi.org/10.3390/w12010300

Nica, A. Petrea, M. S., Simionov, I. A., Antache, A., & Cristea, V. (2022). Ecological Impact of European Beaver, Castor Fiber. *Scientific Papers: Series D, Animal Science-The International Session of Scientific Communications of the Faculty of Animal Science*, *65*(1).

NRFA. (2023a). *21017 - Ettrick Water at Brockhoperig.* National River Flow Archive. Retrieved March 11, 2023, from https://nrfa.ceh.ac.uk/data/station/info/21017

NRFA. (2023b). *21007—Ettrick Water at Lindean*. National River Flow Archive. Retrieved March 11, 2023, from https://nrfa.ceh.ac.uk/data/station/info/21007

NRFA. (2023c). *21011 - Yarrow Water at Philiphaugh*. National River Flow Archive. Retrieved March 11, 2023, from https://nrfa.ceh.ac.uk/data/station/info/21011

Nyssen, J., Pontzeele, J., & Billi, P. (2011). Effect of beaver dams on the hydrology of small mountain streams: example from the Chevral in the Ourthe Orientale basin, Ardennes, Belgium. *Journal of Hydrology*, *402*(1-2), 92-102. https://doi.org/10.1016/j.jhydrol.2011.03.008

Office for National Statistics. (2020). NUTS Levels 1 and 2 (January 2018) Map in United Kingdom [map]. Retrieved from https://geoportal.statistics.gov.uk/documents/ons::nuts-levels-1-and-2-january-2018-map-in-united-kingdom/about

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery*, 88, 105906. https://doi.org/10.1016/j.ijsu.2021.105906

Pearson, K. (1894). Contributions to the mathematical theory of evolution. *Philosophical Transactions of the Royal Society of London. A*, *185*, 71-110.

Pörtner, H. O., Scholes, R. J., Arneth, A., Barnes, D. K. A., Burrows, M. T., Diamond, S. E., Duarte, C. M., Kiessling, W., Leadley, P., Managi, S., McElwee, P., Midgley, G., Ngo, H. T., Obura, D., Pascual, U., Sankaran, M., Shin, Y. J., & Val, A. L. (2023). Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science*, *380*(6642), eabl4881. https://doi.org/10.1126/science.abl4881

Preiser, R., Biggs, R., De Vos, A., & Folke, C. (2018). Social-ecological systems as complex adaptive systems. *Ecology and Society*, *23*(4). https://www.jstor.org/stable/26796889

Puttock, A., Graham, H. A., Cunliffe, A. M., Elliott, M., & Brazier, R. E. (2017). Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. *Science of the total environment*, 576, 430-443. https://doi.org/10.1016/j.scitotenv.2016.10.122

Puttock, A., Graham, H. A., Ashe, J., Luscombe, D. J., & Brazier, R. E. (2020). Beaver dams attenuate flow: A multi-site study. *Hydrological processes, 35*(2), e14017. https://doi.org/10.1002/hyp.14017

QGIS Development Team. (2021). QGIS Geographic Information System (Version 3.16.11) [Computer software]. https://qgis.org/en/site/

Rurek, M. (2021). Characteristics of Beaver Ponds and Landforms Induced by Beaver Activity, S Part of the Tuchola Pinewoods, Poland. *Water*, *13*(24), 3641. https://doi.org/10.3390/w13243641

Scottish Borders Council. (2017, October 24). Selkirk Flood Scheme picks up Saltire Award. https://www.scotborders.gov.uk/news/article/2116/selkirk_flood_scheme_picks_up_saltire_award

Scottish Government (2020). Lidar Composite Digital Terrain Model Scotland (Phase4) 50cm resolution [map]. 1: 2000. Retrieved from https://spatialdata.gov.scot/geonetwork/srv/api/records/63a6482f-1bcf-4b75-92f4-cb4e9e413d4d

Selkirk Flood Scheme. (2017, February 27). *Selkirk Flood Protection Scheme.* http://selkirkfloodscheme.com/

SEPA. (2015). *Water Environment Hub*. Water Environment Hub; SEPA. https://www.sepa.org.uk/data-visualisation/water-environment-hub

SEPA. (2022). *Flood Maps*. Scottish Environment Protection Agency. https://map.sepa.org.uk/floodmap/map.htm

SEPA. (2023a). *SEPA Water Level Data—Ettrick Water @ Lindean*. Scottish Environment Protection Agency. https://www2.sepa.org.uk/waterlevels/default.aspx?sd=t&lc=14990

SEPA. (2023b). *SEPA Water Level Data—Yarrow Water @ Philiphaugh*. Scottish Environment Protection Agency. https://www2.sepa.org.uk/waterlevels/?sd=t&lc=14985

Slovic, P. (1998). The risk game. *Reliability engineering & system safety*, *59*(1), 73-77. https://doi.org/10.1016/S0951-8320(97)00121-X

Song, X., Zhang, J., Zhan, C., Xuan, Y., Ye, M., & Xu, C. (2015). Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications. *Journal of hydrology*, *523*, 739-757. https://doi.org/10.1016/j.jhydrol.2015.02.013

Space Intelligence & NatureScot (2021). Scotland Habitat and Land cover map - 2020 [map]. Retrieved from https://spatialdata.gov.scot/geonetwork/srv/api/records/88cea3bd-8679-48d8-8ffb-7d2f1182c175

Stringer, A. P., & Gaywood, M. J. (2016). The impacts of beavers Castor spp. on biodiversity and the ecological basis for their reintroduction to Scotland, UK. *Mammal review*, *46*(4), 270-283. https://doi.org/10.1111/mam.12068

Te Chow, V. (1959). *Open-Channel Hydraulics*; McGraw-Hill Civil Engineering Series; McGraw-Hill Book Company: New York, NY, USA.

Tweed Forum. (2023). Ettrick and Yarrow Riparian Project. *Tweed Forum*. https://tweedforum.org/our-work/projects/ettrick-and-yarrow-riparian-project/

USACE. (2021a). *2D Unsteady Flow (2021)*. HEC-RAS Training; USACE Hydrologic Engineering Center. https://www.hec.usace.army.mil/confluence/rasdocs/rastraining/latest/hec-ras-classes/2d-unsteady-flow-2021

USACE. (2021b). Hydrologic Engineering Center's River Analysis System (HEC-RAS) (Version 6.3.1) [Computer software]. https://www.hec.usace.army.mil/software/hec-ras/

USACE. (2023a). *1D vs. 2D Hydraulic Modeling*. HEC-RAS 2D User’s Manual; USACE Hydrologic Engineering Center. https://www.hec.usace.army.mil/confluence/rasdocs/r2dum/latest/steady-vs-unsteady-flow-and-1d-vs-2d-modeling/1d-vs-2d-hydraulic-modeling

USACE. (2023b). *HEC-RAS User’s Manual*. HEC-RAS User’s Manual; USACE Hydrologic Engineering Center. https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest

USACE. (2023c). *Inundation Mapping with HEC-RAS Mapper*. HEC-RAS User’s Manual; USACE Hydrologic Engineering Center. https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/viewing-results/inundation-mapping-with-hec-ras-mapper

Vojtek, M., Petroselli, A., Vojteková, J., & Asgharinia, S. (2019). Flood inundation mapping in small and ungauged basins: sensitivity analysis using the EBA4SUB and HEC-RAS modeling approach. *Hydrology Research*, *50*(4), 1002-1019. https://doi.org/10.2166/nh.2019.163

Volk, M. (2013). Modelling ecosystem services–Challenges and promising future directions. *Sustainability of Water Quality and Ecology*, *1*, 3-9. https://doi.org/10.1016/j.swaqe.2014.05.003

Waylen, K. A., Holstead, K. L., Colley, K., & Hopkins, J. (2018). Challenges to enabling and implementing Natural Flood Management in Scotland. *Journal of Flood Risk Management*, *11*, S1078-S1089. https://doi.org/10.1111/jfr3.12301

Wingfield, T., Macdonald, N., Peters, K., Spees, J., & Potter, K. (2019). Natural flood management: Beyond the evidence debate. *Area*, *51*(4), 743-751. https://doi.org/10.1111/area.12535

WOSU (n.d.). *Log Pearson Type III Calculator*. Retrieved March 15, 2023, from https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fpeople.wou.edu%2F~taylors%2Fes476_hydro%2FLog_Pearson_Type_III_Calculator.xls&wdOrigin=BROWSELINK

Zainalfikry, M. K., Ab Ghani, A., Zakaria, N. A., & Chan, N. W. (2019). HEC-RAS One-Dimensional hydrodynamic modelling for recent major flood events in pahang river. In *Proceedings of AICCE'19: Transforming the Nation for a Sustainable Tomorrow*, 1099-1115. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-32816-0_83

Appendix A

Elaboration of PRISMA Methodology

The PRISMA methodology was selected for its thoroughness. It is often used for intervention studies, which many studies on this topic were likely to be, but can also be used for other study designs meaning it can account for both normative and descriptive studies (Page *et al.*, 2021). All returned studies went through a process of abstract screening by the author to assess their relevance based on the inclusion criteria. Four ‘snowballed’ articles were included following their identification from the bibliographies of reviewed studies. It was decided that the inclusion criteria for this review would not be limited to only effects from reintroduced beavers or only effects in the UK after preliminary searches yielded few results for these queries. Instead, the criteria followed that as long as the study focused on the effects of Eurasian beavers on hydrology and/or hydraulics, in their current or historical range, it was likely that results would serve as relevant inputs to the model. Hydrology and hydraulics were key words as the inquiry aimed to capture structures built by beavers that affect these processes, in order to create appropriate inputs to a hydraulic model. Data was collected from reports by extracting relevant numerical, and occasionally non-numerical, information to inform BMS modelling. Depending on the study this meant extracting information from both the methods and results sections of the selected studies. These methods were carried out by one reviewer (the author). No specific methods or tools were utilised to assess the risk of bias in the studies, or of the reviewer, which is a limitation of the literature review that deviates from the PRISMA methodology (Page *et al.*, 2021).

Appendix B

List of Studies Retrieved from Literature Review

Appendix B

List of Studies Retrieved from Literature Review

Author (Year)	Geographic Scope	Study design & relevancy	Source; date retrieved
Brazier *et al.* (2021)	Worldwide	Systematic literature review of beaver ecosystem modifications with a summary of hydrological effects.	Web of Science (WoS); 25/01
Curry-Lindahl (1967)	Sweden	Historical review of the beaver in Sweden. Included lodge dimensions.	Snowballed; 18/02
De Visscher *et al.* (2014)	Belgium	Field study with measurements of dams and ponds.	WoS; 25/01
Gorczyca *et al.* (2018)	Poland	Field study survey that documented beaver features including slides and lodge/burrow dimensions.	WoS; 25/01
Graham *et al.* (2022)	England, UK	Before-and-after control impact experimental design that quantified dam effects on flow.	WoS; 25/01
Grudzinski *et al.* (2020)	Worldwide	Literature review on the environmental impact of beaver canals with dimensions.	Snowballed; 18/02
Grudzinski *et al.* (2022)	Worldwide	Literature review on dam impacts to their hydrological environments.	WoS; 25/01
Grygoruk & Nowak (2014)	Poland	Retrospective study that compared high and low beaver activity time periods on hydrology.	WoS; 25/01
Gurnell (1998)	Worldwide	Literature review that detailed dam-building activity and hydrogeomorphological effects with quantitative and qualitative findings.	WoS; 25/01
Hartman & Törnlöv (2006)	Sweden	Field study on dam building stream selectivity. Documented freeboard dimensions of dams.	Snowballed; 18/02
John & Klein (2004)	Germany	Retrospective analysis that explored the effects of beaver return to pond storage.	Snowballed; 18/02
Kocięcka & Liberacki (2018)	Poland	Field study that measured dam effects on water retention.	WoS; 25/01
Larsen *et al.* (2021)	Worldwide	Literature review of beaver-environment feedbacks, significantly focused on hydrology and feedback loops.	WoS; 25/01

Neumayer *et al.* (2020)	Germany	Survey of beaver territories and hydraulic modelling of beaver dams. Noted specific model inputs used.	WoS; 25/01
Nica *et al.* (2022)	Worldwide	Systematic literature review that detailed lodge/shelter dimenions.	WoS; 26/01
Nyssen *et al.* (2011)	Belgium	Retrospective study that analysed river flows before and after a beaver reintroduction.	WoS; 26/01
Puttock *et al.* (2017)	England, UK	Long-term field study that monitored the reintroduction of beavers to river flows.	WoS; 26/01
Puttock *et al.* (2020)	England & Wales, UK	Before-and-after control impact design that conducted hydrological monitoring before and after beaver releases.	WoS, 26/01
Rurek (2021)	Poland	Field study that measured existing (active and abandoned) beaver dams and their sedimentation patterns.	WoS, 26/01

Appendix C

Pre-processing of Terrain Data

There were several steps of data pre-processing that were necessary to prepare the terrain data for upload to HEC-RAS. This was done using the publicly accessible geospatial mapping software QGIS (QGIS Development Team, 2021). The downloaded 50cm resolution DTMs were uploaded to QGIS in ASC format and mosaiced together to create one TIFF raster file which was clipped according to the study area to reduce computational times. Geoprocessing tools were utilised to fill sinks and fill gaps where there were holes in the raster data.

Appendix D

Model Calibration Process

Before intervening with model parameters to simulate beaver presence through dam construction, it was important to validate the model against reality. This is important in modelling research, as it verifies that the model bears similarity to the hydrological nature of the catchment in reality (El Bilali *et al.*, 2021; Huţanu *et al.*, 2020; Iosub *et al.*, 2015; Vojtek *et al.*, 2019, Zainalfikry *et al.*, 2019). Calibration of the model was undertaken to include structures and aspects of the system that influence flow. To better assist in model calibration, the SEPA (2022) flood maps were uploaded to HEC-RAS as a reference layer for comparison. Four bridges were added, three along Ettrick River and one at Yarrow Water. This required the drawing of additional cross-sections along the floodplain. HEC-RAS allows users to input bridges as a part of the geometry data, with various inputs regarding bridge size and water entrance pathways needed. As no field studies were undertaken as a part of this research, data regarding bridge elevation and width were taken from the terrain data and aerial imagery. Google Maps Street view (Google Maps, n.d.b) was also helpful in determining approximate starting and ending points of the bridges and gauging their overall structure in relation to the channel. The default weir coefficient of 1.4 was used for all bridges, and bridge thickness was assumed to be 1 m for larger bridges and 0.7 m for one small bridge upstream - estimations based on deductions from the DTM.

Google Maps (n.d.b) street view (with imagery from April 2022) was used to verify the land cover map classifications of Manning’s *n* values, as these values can have a significant effect on flow (Te Chow, 1959). The land cover map listed two categories as unclassified, which were arbitrarily associated with a low *n* value of 0.06. When reviewing the land cover map for the area, these regions were marginal and infrequent across the floodplain and so this inaccuracy associated with the land cover data was deemed insignificant in effects on flood mapping. In several cases, it was found that the land cover map had errors and therefore the associated *n* values were incorrect. For example, several built-up parts of the town were classified as “Open Water” when the aerial imagery showed there were houses and other buildings at these locations. The way flood waters would interact with houses versus open water is substantially different and so it was important to change these input parameters to better match the reality of the landscape. It was not possible to edit the classification of the land cover map so “Open Water” was instead associated with a higher manning’s *n* (2.5) value after it was ensured that it was not correctly assigned to any open water bodies in the modelled region. Similarly, there were several areas in Selkirk on the north-western floodplain of the Ettrick River that were built up with large buildings not reflected in the terrain data. Therefore, the model assumed a continuous low elevation and flooding was overestimated. To calibrate these details, blocked obstructions were added to the geometry of the floodplain, which were drawn as polygons and assigned a higher elevation value where tall buildings were observed in aerial imagery.

The town of Selkirk has flood walls built alongside the floodplain in part of the modelled river, to protect against low likelihood floods with severe consequences, such as a 1 in 500-year flood events (Scottish Borders Council, 2017). Although the location and thickness of the floodwalls could be seen from SEPA maps and aerial imagery, the height of several of the walls was unknown. Using pictures of the walls (Selkirk Flood Scheme, 2017), a height of approximately 1.5 m was assumed. The height of the walls was reflected in the terrain data on the eastern side of the Ettrick River, and therefore exact heights could be inputted, and so this assumption was only made for walls on the western side. This data inaccuracy may be due to the walls being constructed after the LiDAR imagery was captured. The lack of precise flood wall measurements contributed uncertainty to the model but their input better calibrated results to the SEPA flood maps. The walls were modelled as levees along the cross-section. An additional floodwall runs along Riverside Road on the eastern side of the lower reach of Ettrick River and the western side of the middle reach, which were modelled in the same way.

It was also necessary to calibrate the estimated flow rates that were calculated for the gauging stations (as seen in Table 4). The gauging station for Yarrow River at Philiphaugh was located less than 1 km up from its junction with the Ettrick River, whereas the upstream boundary point of the Yarrow was over 4.2 km upstream of the junction. This suggested that the flow rate calculated for the Yarrow (163.27 m^3/s) was likely an overestimation, given that it would only reach this rate after having flowed downhill for several kilometers and increased in velocity. The same issue was encountered for the flow data calculated for the Ettrick Water gauging stations at Lindean (315.27 m^3/s) and Brockhoperig (89.83 m^3/s), the former of which is located just downstream of the model boundaries before it meets the River Tweed and the latter of which is located >25 km upstream. Given that the Lindean gauging station was closest to the model downstream boundary, it was concluded that the two other upstream flow rates where the model begins at Ettrick and Yarrow should logically sum to equal 315.27 m^3/s at the junction. Initially, 163.27 m^3/s was subtracted from 315.27 m^3/s to yield an approximate upstream flow boundary condition at the modelled mouth of the Ettrick to be 152 m^3/s. However, upon calibration test runs with this flow data flooding appeared to be overstated along the Yarrow and understated at the upstream boundary of the Ettrick, compared to the SEPA (2022) maps. Given that the upstream boundary of the Yarrow would likely have lower flow than the downstream gauging station, an estimated 20 m^3/s of flow was subtracted from the Yarrow (= 143.27m^3/s) and added to the Ettrick (= 172m^3/s). Again, this contributed uncertainty to the model but better calibrated the model against the SEPA flood maps. Flooding was still overstated on the Yarrow and understated at Ettrick, but to a lesser extent. As a final calibration step, cross-sections were also inserted where the beaver dams would be placed, prior to any BMS being inputted to the model, as cross-section placement was presumed to have an effect on flooding in the baseline model.

Appendix E

Area Calculations and Map Creation Methodology

To calculate the areas and create maps of the resulting simulations all HEC-RAS results layers were exported as raster files to QGIS. The SEPA (2022) flood maps were converted from a vector to a raster file. A geoprocessing tool (*r.report)* available in the software was used to calculate raster areas. Area calculations in QGIS were performed as planimetric area calculations (as opposed to ellipsoidal) so that the areas were all georeferenced against the same project projection (EPSG 27700). Percent difference was calculated by subtracting the intervention result area from the baseline area and then dividing this figure by the baseline area. All results maps were formatted in QGIS (QGIS Development Team, 2021).

Appendix F

Average, Minimum, and Maximum Dam Height Tables

Dam elevation from the channel bed was calculated by summing the average, minimum, or maximum dam heights from the literature review (see Tables 6-7) with the average water level for each river (EW = 0.636 m (SEPA, 2023a); YW = 0.441 m (SEPA, 2023b)) and the channel bed elevation. These tables show the channel bed elevations that were ascertained from the terrain data for each river, at each dam location, and the final dam elevation data that was inputted to the model.

Table F1

Average dam dimensions; EW = Ettrick Water, YW = Yarrow Water

Area (dam #)	Channel bed elevation (m)	Average dam elevation (m)
EW (1)	139.18	140.40
EW (2)	138.81	140.03
EW (3)	138.53	139.75
YW (4)	131.66	132.69
YW (5)	131.30	132.33
YW (6)	129.24	130.27

Note. Dam numbers are in ascending order from left to right of the BMS map (Figure 8).

Table F2

Minimum and maximum dam dimensions; EW = Ettrick Water, YW = Yarrow Water

Area (dam #)	Channel bed elevation (m)	Min height (m)	Max height (m)
EW (1)	139.18	139.92	141.52
EW (2)	138.81	139.55	141.15
EW (3)	138.53	139.27	140.87
YW (4)	131.66	132.20	133.80
YW (5)	131.30	131.84	133.44
YW (6)	129.24	129.78	131.38

Appendix G

Additional Attribution Statements for SEPA River Flood Maps

Aberdeen Harbour Master

©Aberdeen Harbour Board (2014).

Aberdeenshire Council Lidar

Aberdeenshire Council, Aberdeen City Council, James Hutton Institute, Scottish Environment Protection Agency (2016)

Airbus

IR Aerial Photography- ©GeoPerspectives. • Digital Terrain/Surface Model- ©GeoPerspectives. • Lidar Digital Terrain Models and Digital Surface Models- ©Infoterra Ltd.

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Getmapping

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Nextmap © Intermap

National River Flow Archive

Data from the UK National River Flow Archive

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