

Feature Study

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Ecosystem Engineering by Beavers: Impacts on Biodiversity and Hydrology

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Abstract This study systematically explores the combined impact of beaver activities on hydrological processes and biodiversity. The integration of hydrological model analysis and ecological monitoring cases reveals that beaver dam construction can effectively regulate water flow velocity and water level, enhance the exchange between surface water and groundwater, and improve water quality and sedimentation dynamics. Meanwhile, its transformation activities have created diverse habitats such as wetlands and ponds, promoting the diversity of aquatic organisms, terrestrial plants and birds, and providing microhabitats for some rare species. Regional cases further demonstrate that beaver projects not only enhance ecological services such as water storage, flood control and carbon sinks, but also to some extent trigger conflicts between agricultural production and infrastructure. Beavers are of great value in maintaining ecological functions, restoring degraded wetlands, and enhancing the adaptability of ecosystems to climate change. Scientific management and rational guidance for the coexistence of beavers and human systems can help provide natural solutions for wetland protection and ecological restoration. The research on beaver ecological engineering not only deepens scientists' understanding of species-environment interaction, but also provides theoretical support and practical cases for wetland protection and ecological restoration.

Keywords Beaver; Ecological engineering; Biodiversity; Hydrological process; Ecosystem services

1 Introduction

The beaver (*Castor* spp.) is renowned for its behavior of building DAMS to transform the environment and is hailed as the "ecological engineer" of nature (Brazier et al., 2021; Fairfax and Westbrook, 2024). They have significantly changed the local topography and hydrological conditions by cutting down trees and building wooden DAMS to form ponds and wetlands in rivers and streams (Brazier et al., 2021; Grudzinski et al., 2022). This powerful ecological engineering ability is extremely rare among animals, and only a very few species can match it. Historically, due to excessive hunting in the fur trade, beaver populations in Eurasia and North America were once on the verge of extinction. However, in recent decades, their numbers have significantly recovered under legal protection and human reintroduction (Wrobel, 2020; Halley et al., 2021). Today, beavers are redistributed in most of their original habitats and have become an important engineering species in the ecosystem (Halley et al., 2021).

Beavers' activities not only meet their own habitat needs but also have a profound impact on the surrounding environment. As a "key species", the existence of beavers can influence the habitats of many other species through physical creation, and thus holds a unique position in maintaining the structure and function of ecosystems (Fairfax and Westbrook, 2024). The wetlands and slow-flow environments formed by beavers building DAMS have profound impacts on multiple aspects of the ecosystem, including hydrology, water quality, habitat heterogeneity and biodiversity (Grudzinski et al., 2022). Beaver DAMS intercept water flow, increase surface retained water volume, raise water level, expand flood area, and transform the originally narrow and rapid river section into still water ponds and peat wetlands (Brazier et al., 2021). This change in hydrological conditions not only helps to reduce the downstream flood peak flow and smooth out the flood (that is, the so-called "natural flood storage" effect) (Puttock et al., 2021; Thompson et al., 2021), it also enhanced the drought resistance capacity of the basin and increased the water supply during drought periods (Thompson et al., 2021).

Meanwhile, the still water wetland environment promotes sediment deposition and nutrient retention, often improving downstream water quality, such as reducing nitrate and suspended sediment concentrations (Dewey et al., 2022; Grudzinski et al., 2022); On the other hand, it may also lead to the accumulation of organic carbon in wetlands and promote the emission of greenhouse gases such as methane (Fairfax and Westbrook, 2024). Furthermore, the new habitats created by beavers have greatly enhanced the diversity of regional habitats: microhabitats such as still ponds, floodplains, and dead water depressions provide special Spaces for the reproduction and habitat of numerous animal and plant species (Bashinskiy, 2020; Orazi et al., 2022). Therefore, beaver dam construction not only changes the physical environment, but also has a cascading effect on the ecosystem through food web and habitat changes, and is regarded as one of the key factors shaping the watershed landscape (Brazier et al., 2021).

This study will systematically review the impact and ecological value of beaver ecological engineering behavior from two dimensions: biodiversity and hydrological processes. It will summarize the characteristics of beavers as ecological engineers and how their dam-building behavior alters hydrological conditions and habitat structure. It will also analyze the mechanism and empirical research on the impact of beaver dam-building on water flow processes and biodiversity. Discuss the ecosystem services provided by beaver activities and the possible human conflicts they may trigger, and explore management strategies for the coexistence of humans and beavers. This study will also combine regional case studies to demonstrate the diversity of beaver impacts, look forward to future research directions and challenges, and expect to deepen the understanding of this typical ecological engineering species, the beaver, and provide scientific references for wetland ecological restoration and natural resource management.

2 The Ecological Engineering Characteristics of Beavers

2.1 Dam construction and water body renovation

The dam-building behavior of beavers is at the core of their ecological engineering role. Beavers use branches and soil to build DAMS in narrow sections of streams, forming multiple stepped dam and pond systems. These wooden DAMS significantly reduce the longitudinal connectivity of the river, causing the upstream water to converge in front of the DAMS and form still water ponds. On average, each beaver dam can raise the water level in front of the dam, expand the water surface area, and slow down the flow velocity, thereby transforming the river from the previous linear rapids to the form of meandering slow flow and connected ponds (Figure 1) (Brazier et al., 2021; Puttock et al., 2021; Tape et al., 2022). Meanwhile, the dam body often has seepage and overflow. Some of the water flow seeps into the ground or flows around, thereby maintaining a certain water flow connectivity (Wohl and Inamdar, 2025).

Unlike artificial DAMS, beaver DAMS are usually small in scale, porous in structure and dynamic in succession - beavers constantly repair old DAMS or build new ones, and some old DAMS may burst and collapse after being abandoned (Wohl and Inamdar, 2025). This "build - abandon - rebuild" cycle introduces intermittent disturbances and diverse habitat structures to rivers. Overall, beaver dam-building has greatly transformed local water conditions: not only has it raised the surface water level and shaped still water areas, but it has also increased soil moisture content and groundwater recharge through water diversion and seepage (Grudzinski et al., 2022; Oleszczuk et al., 2024). For example, in the multi-site experimental study in the UK, after beavers built DAMS, the peak flow during heavy rain decreased by an average of more than 30%, and the lag time of water flow was prolonged, effectively "shaving the peak and filling the valley" (Puttock et al., 2021).

2.2 Habitat heterogeneity creation and ecosystem reshaping

The pond-wetland complex formed by beavers building DAMS has significantly enhanced the heterogeneity of habitats within the basin. Still water ponds provide new habitats for many aquatic organisms that prefer slow-flowing or still water, such as some aquatic plants, plankton, amphibians and aquatic invertebrates, which can thrive in the ponds (Dalbeck et al., 2020). Meanwhile, the dam body retains water flow and submerges the riverbank, creating wetland and marsh landforms on both sides and giving rise to marsh plant communities. These wetland buffer zones have created feeding and resting places for waterfowl, amphibians and semi-aquatic mammals, significantly enriching the regional habitat types (Orazi et al., 2022).



Figure1 Examples of dam construction and channel avulsion resulting from beaver dam construction from the River Otter catchment, England (Adopted from Brazier et al., 2021)

Image caption: (a) shows an example where a divergent flow path has re-entered the main channel resulting in head-cut erosion. Panel (b) shows the type of multi-thread channel form that occurs downstream of dams in wide, low gradient floodplains. Panel (c) shows a beaver dam on a 4th order stretch of river (Adopted from Brazier et al., 2021)

Beavers' feeding and gnawing on trees along riverbanks can also significantly alter the structure of forests. After being gnawed, trees leave behind a large number of fallen logs and stumps. These wooden remnants provide shelter for decaying wood invertebrates such as beetles, and also become ideal habitats for birds such as woodpeckers and small mammals (Brazier et al., 2021). Studies have shown that in the area where beavers are active, the canopy gap increases, the number of fallen trees rises, the understory vegetation prospers accordingly, and plant diversity is enhanced (Orazi et al., 2022). In addition, beaver projects have strengthened the coupling between land and water: they transport timber by excavating channels and gullies and channel river water into woodlands, making the connection between rivers and floodplains closer (Grudzinski et al., 2022). In the long term, these activities have promoted vegetation succession and the reshaping of ecosystems (Fairfax and Westbrook, 2024).

2.3 The spatiotemporal scale and persistence of beaver engineering

Beavers' environmental transformation has a unique spatial range and temporal dynamics. Spatially, the activities of individual beaver families typically extend several hundred to several thousand meters along streams, and their dam-building effects are mostly confined to the lower reaches of small watersheds (Halley et al., 2021). However, in regions rich in water resources, when multiple families are distributed along the river, their engineering effects will superimpose and then extend to the entire basin (Wrobel, 2020). Take the Northern Slope of Alaska as an example. In recent decades, beavers have moved into the tundra. Satellite images show that tens of thousands of new DAMS have been built locally and the number of ponds has almost doubled, causing significant disturbances

to the hydrology and landscape of the large area of permafrost plateau (Tape et al., 2022). In terms of time, Beaver DAMS and wetlands exhibit dynamic succession characteristics. A dam body can often last for several years to over a decade, but it requires beavers to constantly maintain and reinforce it. Once the population migrates away, the dam body often collapses within a few years, the pond dries up and is restored as a river channel (Wohl and Inamdar, 2025).

However, the long-term occupation of beavers leaves a lasting mark in the sedimentary landforms of the basin - silted peat wetlands and floodplain puddles can still exist for many years or even decades after beavers leave, continuously providing habitats for wetland species (Fairfax and Westbrook, 2024). Therefore, the impact of the beaver project is characterized by delay and inheritance. The spatio-temporal pattern of beaver activities is usually manifested as follows: frequent dam-building and dam-abandonment on a local scale cause habitat cycle replacement, and on a large scale, the spread of beaver populations brings more river sections into the influence range (Tape et al., 2022). Current monitoring in many places in North America and Europe indicates that it takes about 5 to 10 years after beavers return for the wetland network they create to stabilize and enter the expansion stage (Halley et al., 2021). In addition, factors such as climate and terrain also affect the breadth and persistence of beaver engineering: For example, in high mountains or arid areas, beaver dam construction tends to be seasonal or phased, and the dam body may fall into disrepair and be damaged during severe winters or dry seasons (Janiszewski and Hanzal, 2021).

3 The Influence of Beavers on Hydrological Processes

3.1 Water Flow velocity and water level regulation

Beaver dams change the river's hydrodynamic pattern by raising the upstream water level and slowing the flow. On the one hand, the dam body blocks the current and makes the velocity drop sharply (Puttock et al., 2017). The upstream water almost stops and slowly becomes a pond. As a result, flood waves move more slowly, and water stays longer in the channel. Field studies show that in reaches with beaver dams, the average retention time of water can be several times longer, especially in dry periods (Dewey et al., 2022).

On the other hand, building a dam also raises both the surface water level and the groundwater table. The deeper and wider pond in front of the dam lifts the groundwater level of nearby areas, which helps wetland plants and adds to groundwater storage. Studies report that in basins with active beavers, the depth of groundwater near riverbanks is usually lower, while soil moisture is higher. In dry seasons, this plays the role of a "natural reservoir" (Oleszczuk et al., 2024).

More importantly, beavers' dam construction significantly buffered the peak flood flow and played a regulatory role similar to that of a small reservoir (Larsen et al., 2021). In the long-term observation of four pilot river basins in the UK, the responses of the multi-level dam systems rebuilt by Beavers to over 1,000 rainstorm events showed that the total runoff volume of the basin decreased after the dam construction, the time lag from the rain peak to the flow peak increased, and the peak flow generally decreased. Even under extremely heavy rainfall conditions, the Beaver Dam still has a significant effect on reducing flood peaks. It can be seen from this that beavers effectively "shave peaks and fill depressions" by building DAMS and play an active role in natural flood management. Many nature-based solutions propose to utilize beavers or simulated beaver DAMS to achieve river ecological restoration and flood control and disaster reduction (Puttock et al., 2021). It should be noted that the influence of beaver DAMS on water level and flow velocity is contextual: During high-flow seasons or major floods, the dam body may overflow or break, causing some floodwaters to discharge, and thus the peak shaving effect will be reduced (Auster et al., 2021).

3.2 Surface water-groundwater exchange mechanism

Beaver dam construction not only alters surface water flow, but also enhances the exchange between surface water and groundwater by influencing riverbed infiltration and lateral overflow (Smith et al., 2020). After the dam is built, a raised head difference is formed in front of the dam. The water body forms a pressure gradient before and after the dam, pushing the river water to seep into the underground aquifer through the riverbed and riparian soil (Grudzinski et al., 2022). Research has found that the retention of the beaver dam causes a change in the

subsurface flow (soil flow) path of the river: the underground runoff that originally flowed downstream along the river channel is changed to seep laterally, replenishing the underground aquifers on both banks. This process has raised the groundwater level in the riverbank zone. Monitoring in the tundra region of Alaska has shown that beaver DAMS can raise the groundwater level within several hundred meters downstream by 10 to 15 cm, significantly widening the moist zone along the river (Tape et al., 2022). In addition, beaver DAMS often have overflow over the top or openings on the side of the dam, with small streams of water flowing around the dam, forming curved floodplain wetlands. These slow seepage further promote the infiltration of surface water into the ground. Therefore, the areas where beavers build DAMS exhibit a stronger "water conservation" function, increasing the exchange frequency and volume between surface water and groundwater (Oleszczuk et al., 2024).

The benign exchange of groundwater and surface water has multiple benefits for the ecosystem: On the one hand, the increased groundwater reserves can recharge the river flow during the dry season and maintain the continuous flow of streams (Thompson et al., 2021); On the other hand, the water seeping into the ground stays in the aquifer for a longer time, which is conducive to the decomposition and removal of pollutants through microbial action (such as the removal of nitrates through denitrification). A review study by the EPA found that nitrate nitrogen in the Beaver Dam area decreased significantly after permeation through the soil, as water retention and groundwater exchange provided sufficient time for denitrifying bacteria to act (Grudzinski et al., 2022). In addition, groundwater exchange also stabilizes water temperature: warm surface water seeps into the ground during the day and slowly flows back into the river at night, which helps to reduce the fluctuation of water temperature between day and night (Majerova et al., 2015). In a study conducted in Colorado, USA, the strong groundwater gradient caused by beaver DAMS was more than ten times higher than the seasonal hydrological fluctuations. The soil flow driven by this gradient effectively removed approximately 44% of nitrate nitrogen (Dewey et al., 2022).

3.3 Dynamic changes in water quality and sediment

Building beaver dams strongly changes water quality and sediment movement. On the one hand, dams trap sediment and reduce the amount carried downstream. When the flow slows in front of the dam, more than 90% of suspended particles settle in the pond, so the water below the dam becomes clearer (Ecke et al., 2017). Studies in different climate zones confirm this. Downstream of dams, water usually shows lower turbidity and fewer suspended solids compared with upstream areas without dams. This "sediment trap" effect also lowers silt build-up in the lower channel and helps keep the riverbed stable.

On the other hand, beaver wetlands filter nutrients. Plants and sediments in the pond can absorb nitrogen and phosphorus, reducing their loss downstream. A global review of 267 studies shows that nitrate levels below dams drop significantly, while total nitrogen and total phosphorus change little or fall slightly (Grudzinski et al., 2022).

The slower current and larger contact between water and land also favor nutrient removal (Cooper et al., 2025). But wetlands created by beavers are rich in organic matter and often lack oxygen, which may bring some drawbacks. For example, dissolved organic carbon and ammonia nitrogen can rise, and microbes may turn mercury in the mud into toxic methylmercury. The US Environmental Protection Agency reports that methylmercury and dissolved organic carbon often increase slightly downstream of dams, linked to microbial activity in low-oxygen wetland conditions (Grudzinski et al., 2022). In addition, dam pond sludge can release methane through anaerobic fermentation. Some researchers worry that large beaver wetlands may boost greenhouse gas emissions. Yet field data from cold regions show that methane increases are small and do not cancel out the ecological gains in carbon storage and water quality improvement (Fairfax and Westbrook, 2024).

4 The Promoting Effect of Beaver Activities on Biodiversity

4.1 Responses of aquatic and semi-aquatic biological populations

Beaver dam construction causes the river environment to change from turbulent to gentle, providing a new suitable habitat for various aquatic and amphibian organisms, which is usually conducive to improving the diversity and abundance of aquatic organisms. Most amphibians benefit from the still water habitats created by beavers, and the community richness increases, which makes beaver ponds regarded as the key "microhabitat" for maintaining regional amphibian diversity (Dalbeck et al., 2020). The response of fish communities to beavers

building DAMS is rather complex and varies depending on the ecological habits of different fish species. Small still water tolerant fish (such as crucian carp, American killifish, etc.) often thrive in beaver ponds, while large migratory fish that need to swim long distances upstream to spawn (such as Atlantic salmon) may be blocked by dam bodies (Auster et al., 2021; Tape et al., 2022). However, many case studies have shown that beaver ponds provide sheltered habitats for fish to avoid drought and cold, abundant food and spawning grounds, and have positive effects on the overall fish community (Brazier et al., 2021). In a long-term study in Scotland, positive changes occurred in the population structure of brown trout (*Salmo trutta*) in streams after the introduction of beavers (Needham et al., 2021).

4.2 Changes in terrestrial plant communities and bird diversity

The ecological engineering of beavers is not limited to aquatic systems; it also has a wide-ranging impact on the terrestrial ecology of riverbanks, typically manifested as changes in vegetation structure and an increase in bird diversity. Beaver dam construction triggers secondary succession and community replacement of riverbank vegetation. Beavers have created a new pattern of interlaced forest and water and inlaid vegetation through flooding and foraging. The terrestrial plant community shows higher spatial heterogeneity (Orazi et al., 2022). Bird diversity is another typical example driven by the beaver project. Beaver wetlands offer open water surfaces and foraging shallows for waterfowl and wading birds, while standing dead trees attract woodpeckers and cave nest birds to make use of them. In studies in central Europe, beaver activity significantly increased the richness and number of birds along rivers: the number of breeding bird species and individual density recorded in beaver sections were higher than those in the unmodified control sections (Fedyne et al., 2024). The Beaver Project has formed a series of positive ecological chain reactions from plants to invertebrates to birds by enriching habitat types and food resources (Orazi et al., 2022).

4.3 Establishment of microhabitats and rare species shelters

Beaver activities form numerous special microhabitats in river landscapes, providing crucial shelters and habitats for some rare or endangered species. For instance, beaver wetlands often play the role of "refugia" in drought or fire conditions. Beavers increase humidity by storing water and create miniature shelters for species survival in increasingly frequent extreme droughts and fire events (Auster et al., 2021). For instance, in the winter of cold high-latitude regions, the subglacial waters covered by beaver ponds provide an unfrozen deep-water habitat for fish and amphibians, where many species can escape the deadly low temperatures and hypoxic conditions (Tape et al., 2022). In addition, beaver habitats often feature a rich variety of microhabitats, such as slow-flowing mudflats, shallow water depressions, and dead wood accumulation zones, which may be essential habitats for certain rare species. Beavers construct diverse microhabitat networks through their engineering behaviors, which not only shelter common species but also provide irreplaceable habitats for some rare species sensitive to environmental conditions (Orazi et al., 2022).

5 Regional Ecosystem Services and Beaver Coexistence Management

5.1 Enhancement of ecosystem services: water storage, flood control and carbon sink functions

Beaver activities bring a variety of service functions to the ecosystem, including water resource regulation and storage, flood control and disaster reduction, water quality purification and carbon sink enhancement, etc. Firstly, the small reservoirs and wetlands formed by beavers building DAMS play a significant role in the "natural water storage" of river basins. They increase groundwater recharge and soil moisture content, and improve the availability of water resources during the dry season. This is of positive significance for alleviating water shortage during the dry season and enhancing the guarantee of agricultural irrigation. The Beaver Dam has achieved certain flood control functions by reducing flood peaks and delaying runoff. This ecological service has attracted much attention in areas with increasing flood risks. Beavers have been introduced as one of the measures for natural flood management in places such as the UK (Puttock et al., 2021). Beaver Wetland offers water purification services. Slow flow and wetland vegetation make beaver ponds "biological filters" that can remove agricultural non-point source pollutants such as nitrogen and phosphorus (Grudzinski et al., 2022). In addition, beaver activities also have a significant impact on the carbon cycle. The wetlands it creates deposit a large amount of organic peat, sequestering carbon elements and having carbon sink functions (Thompson et al., 2021).

5.2 Conflicts with agriculture and infrastructure

Beaver activities can also conflict with human interests, posing management challenges. The most common conflict is the problem of farmland or infrastructure flooding caused by beavers building DAMS. In addition, beavers' gnawing of trees may damage ornamental or economic trees, which has caused dissatisfaction among people near woodlands and orchards. Moreover, beavers digging holes and building nests may weaken the structure of embankments and increase the risk of embankment breaches. Therefore, in areas where beavers are spreading again, local conflicts are frequently reported. Research shows that there are significant differences in the attitudes of different interest groups towards beavers: the general public and environmentalists mostly hold a positive attitude, believing that the ecological benefits of beavers outweigh the problems. However, some farmers and forestry practitioners tend to emphasize its negative impacts (Ulicsni et al., 2020; Hohm et al., 2024). But the human conflicts caused by beavers can be managed and mitigated. Many cases show that after conflict coordination and the application of technical measures, most landowners can accept coexistence with beavers (Coz and Young, 2020).

5.3 Beaver reintroduction project in natural solutions

In recent years, driven by the concept of "Nature-Based Solutions", beavers have been reintroduced as a low-cost and efficient strategy for ecological restoration and climate adaptation (Fairfax and Westbrook, 2024). Many European countries (such as the United Kingdom, Germany, Belgium, etc.) have implemented or are planning to reintroduce beavers to historical distribution areas in order to restore degraded wetlands, enhance the water storage capacity of river basins, and improve biodiversity (Halley et al., 2021; Bylak et al., 2024). The ecological effects of reintroducing the project are generally encouraging: For example, in the river water test project in Devon, UK, five years after the reintroduction of beavers (Eurasian beavers), 13 new dam wetlands were created in the project area. This not only improved the local water quality and habitat diversity, but also proved to reduce the flood peak in downstream villages and towns (Campbell-Palmer et al., 2021). The experience of most reintroduction projects in Europe shows that the habitats of beavers have expanded rapidly after their return, and local public awareness of the ecological benefits of beavers has also gradually deepened (Oliveira et al., 2023).

6 Regional and Case Studies

6.1 Typical cases of beaver activities in north america

The beavers of the American continent, *Castor canadensis*, have created countless wetlands in the vast water systems and are regarded as one of the key forces shaping the hydrological landscape of North America. However, the fur trade in the 19th century almost wiped it out. Since the 20th century, beaver populations across North America have naturally recovered or been reintroduced, and their ecological engineering effects have once again drawn attention. A typical case is the Rocky Mountain region in the western United States: due to climate warming and land use, many streams have degraded into seasonal rivers. The local area has successively carried out the project of introducing beavers to restore water sources. The results show that the dam construction by beavers effectively increases the water storage during the low-flow period in summer and alleviates seasonal drought (Thompson et al., 2021).

In addition, the multiple cases of wildfires in California have highlighted the value of beaver wetlands - the "beaver fire Belt" has become a highlight of media coverage. In the 2020 California wildfires, a valley area inhabited by beavers remained an oasis-like vegetation after the blaze, while the surrounding slopes were all scorched to ashes. This fire-resistant ability is attributed to the high moisture content and dense hygrophytes maintained by the beaver wetland, which prevented the spread of fire. Through remote sensing comparison, it was found that the degree of vegetation damage in the sections with beavers was much lower than that in the areas without beavers, indicating that the beaver project provided a valuable fire buffer (Auster et al., 2021).

6.2 The ecological and social effects of reintroducing beavers in europe

Since the second half of the 20th century, Europe has gradually carried out the reintroduction and diffusion protection of the Eurasian beaver (*Castor fiber*). Currently, beavers have returned to most of their native distribution areas except for a few countries in Southern Europe. As one of the earliest countries to restore beavers,

Germany introduced beavers in the middle of the 20th century. Their population has grown rapidly in river basins such as the Elbe and Rhine, creating a large number of new wetland landscapes (Halley et al., 2021). For example, in Bavaria, the number of beavers has increased to approximately 20,000 over the past few decades, and both the plant and animal diversity of their habitats have improved (Orazi et al., 2022).

Beavers in the UK had been extinct for hundreds of years. Since the 21st century, they have been experimentally reintroduced in Scotland and England. A five-year trial was conducted in Knapdale, Argyll, Scotland. The results proved that beavers had a significant positive effect on the restoration of local wetlands and biodiversity. In 2016, the government decided to allow beavers to remain in Scotland and provide legal protection. The 10-year trial carried out on the River Otter in Devon, England, serves as an example: The beaver family has multiplied into 15 families and built a series of DAMS, significantly reducing the flood risk in the villages and towns downstream of the basin and increasing the species of birds and invertebrates inhabiting the wetlands (Campbell-Palmer et al., 2021).

6.3 Beaver engineering impacts in extreme environments (arid regions, cold regions, etc.)

Beaver engineering demonstrates unique ecological roles and challenges in various extreme environments. In arid and semi-arid regions, rivers seasonally dry up and droughts occur frequently. The dam-building and water storage functions of beavers are particularly valuable. Some experiments in the arid grasslands of western North America have shown that the introduction of beavers has significantly prolonged the water surface coverage time of streams and raised the groundwater level, providing a continuous water source for plants in the riverbank zone. In states such as Nevada and Utah, streams with beaver activity maintain water flow in summer, better supporting the survival of fish and wildlife, while streams without beavers often dry up to the bottom (Thompson et al., 2021). As a result, beavers are regarded as a kind of "ecological reservoir" and "oasis" builder in arid areas. Of course, the arid environment also restricts the performance of beaver engineering - during years of drought, water shortage may cause beavers to evacuate and the dam to fail. Therefore, in such areas, people have also attempted to use artificial simulation Beaver Dam Analogues technology to assist in maintaining water flow in order to wait for the beaver population to grow and take over (Puttock et al., 2021).

In high-altitude and cold regions (such as tundra and permafrost areas), beaver expansion may have negative impacts. In recent years, in the western part of Alaska within the Arctic Circle, warming has shifted the forest line northward, causing beavers to enter tundra rivers to build DAMS and form a large number of new lakes. Although this increases surface water, it accelerates the thawing of permafrost: water bodies thaw the soil, absorb heat, cause the surrounding permafrost to sink and release a large amount of stored carbon (Figure 2) (Tape et al., 2022). The extremely cold winter also limits the beaver's active period and the supply of dam-building materials. However, once the climate warms, the distribution of beavers is bound to further advance towards the polar regions and plateaus (Dewey et al., 2022).

7 Future Research Directions and Challenges

7.1 Long-term monitoring requirements in multi-scale and multi-ecosystem environments

Studies have already shown many ecological effects of beaver engineering, but large knowledge gaps still exist. These gaps require monitoring across long periods and at multiple scales. Most current work looks at short-term changes, usually 5 to 10 years, while long-term effects over decades or centuries remain unclear (Halley et al., 2021). Cross-ecosystem comparisons are also limited. Beaver activities may differ in forests, plains, dry grasslands, and tundra, yet most data come from temperate forests and wetlands (Grudzinski et al., 2022). Scale is another key factor. Local impacts are often obvious, but at the basin scale, only a higher density of dams makes the changes stand out (Puttock et al., 2021). Models and remote sensing can help measure large-scale impacts, but they need calibration with field data. In the future, high-resolution satellite images may be used to trace the long-term spread of dams and wetlands (Tape et al., 2022). Monitoring should also cover different fields, including hydrology, ecology, and social and economic aspects, to create a more complete picture (Hohm et al., 2024).

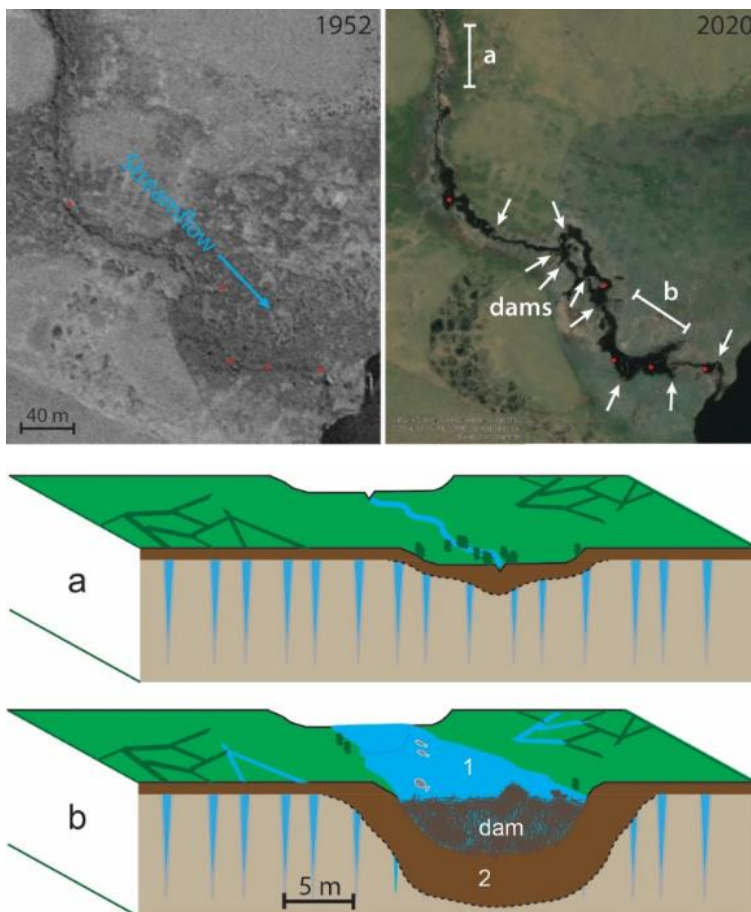


Figure 2 Beaver pond construction in permafrost and idealized cross-section (Adopted from Tape et al., 2022)

Image caption: Stream flowing through ice-rich permafrost into a lake in a 1955 aerial photograph (note ice wedge polygons), and in a 2020 GeoEye satellite image showing multiple beaver dams and ponds (enlarged black areas denoted by red dots). Lower panels a & b portray (1) observed impoundment by beaver dams and (2) theoretical changes resulting from increased heat absorption, enhanced groundwater flow, permafrost thaw, and subsidence (Adopted from Tape et al., 2022)

7.2 Changes in hydrological ecological effects under the background of climate change

Global warming and more extreme weather may alter the way beaver projects function. Rising temperatures could expand their range and increase their impact. In the Arctic tundra, for example, their spread is linked to more vegetation and shorter freezing periods caused by warming (Tape et al., 2022). But changing water conditions may also affect dam stability. Heavy rain and floods may destroy dams, reducing their flood control function. Long droughts may dry out wetlands, pushing beavers to migrate. Climate change may also reshape wetland services. During long dry periods, wetlands can play a larger role in storing water and cooling the environment. Yet warm winters may bring more methane emissions, reducing their role as carbon sinks. These trade-offs must be carefully weighed (Fairfax and Westbrook, 2024).

7.3 Social acceptance and policy support mechanism construction

The future of beaver protection depends on society and policy as much as on science. Public and stakeholder awareness of their value is key to long-term success (Hohm et al., 2024). Experience shows that projects succeed more often in regions with stronger public support (Oliveira et al., 2023). Laws and policies also matter. While some European countries list beavers as protected, actual management often lacks clear guidance. Because their activities cross administrative borders, policies must promote cross-regional cooperation. Europe can learn from its endangered species protection efforts by setting up international monitoring, data sharing, and joint studies on population dynamics, gene flow, and disease spread. Together, these actions can form a pan-European strategy (Halley et al., 2021). Bringing beaver protection into broader resource and climate policies will also help secure more funding and stronger institutional backing.

8 Concluding Remarks

The beaver (*Castor* spp.) is often called an "ecological engineer" because of its dam building and water management habits. These actions change river systems in a deep way and leave long-term effects on biodiversity and ecosystem services. The ponds and wetlands created by beavers can slow and store flood water, refill dry streams, clean water, and make habitats more diverse. This, in turn, helps many animals and plants to thrive. As climate change speeds up and wetland loss becomes more serious, the study of beavers and their role in ecosystems is becoming more urgent.

A large number of research and practical cases have shown that beavers have significant value in maintaining ecological functions, restoring degraded wetlands, and enhancing climate adaptability. In the reintroduction projects in Europe and North America, beavers have demonstrated their potential as a "nature-based solution": they rely on natural processes to restore rivers and wetlands and offer multiple benefits that artificial engineering cannot replace. This fact indicates that reintroducing beavers or scientifically guiding the activities of existing populations is expected to become an important part of future natural solutions.

In the future, with better knowledge of their ecological role and better management tools, people and beavers may reach a balance. The main step is careful management and proper guidance. Setting up monitoring systems and conflict response plans can help the public understand the value of beavers and learn ways to live with them. At the same time, policies should place beaver protection within larger water and biodiversity frameworks. If coexistence is set as the goal and management continues in a scientific way, this old species can support sustainable development and bring more resilience and life to the Earth we share.

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Conflict of Interest Disclosure

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