DIGGING IN:

The complexity of gravel removal for flood mitigation

A case study analysis

CLIMATE IMPACTS GROUP

EARTHLAB
UNIVERSITY of WASHINGTON

Acknowledgments

This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement PC-01J22301 through the Washington Department of Fish and Wildlife. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency or the Washington Department of Fish and Wildlife, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Aerial photo of the lower Skagit River delta. Photo: UW Climate Impacts Group, aerial support provided by LightHawk.

Suggested Citation

Hasert, R., and Mauger, G. 2023. Digging In: The complexity of gravel removal for flood mitigation; a case study analysis. A report prepared by the University of Washington Climate Impacts Group for Whatcom County. Seattle, WA.

Cover photo: Unsplash, creative commons.

Table of Contents

INTRODUCTION

Many rivers in the Pacific Northwest are characterized by high concentrations of sediment. Puget Sound rivers are important sources of sediment in upstream areas, and can come from a variety of places within a watershed, including glaciers high in the watershed, as well as from middle and lower basin sources (e.g. bank erosion, landslides). As sediment makes its way to the lower reaches, the river gradient flattens, leading to slower flows and more opportunities for sediment to be deposited. In these areas, deposited sediment can range from silt (very fine particles) to coarse gravel. Sediment may be stored for short or long periods of time. Sediment transport often occurs during flood events, and patterns of aggradation (sediment deposition on the riverbed) and degradation (incision or downcutting of the riverbed) can vary significantly along the course of a river. In some cases a reach can switch from aggradation to degradation, or vice versa, over a period of years to decades.

Rivers such as the Puyallup in Washington State, as well as the Fraser and Chilliwack-Vedder rivers in British Columbia, are all examples of dynamic rivers that transport high amounts of sediment material downstream. Where aggradation occurs, sediment can have the effect of reducing channel flow capacity, leading to a higher chance of overbank flow and associated flooding.

Aerial photo of the Fraser River during low winter flow, with gravel bars exposed. Photo: Dru, Flickr

Gravel removal: The removal of sediment from exposed gravel bars.

Washington Department of Fish and Wildlife guidelines define gravel removal through the following criteria:

- **Extraction should be 1-2 feet above water surface elevation at time of extraction**
- **Grade to smooth slope toward edge of water at 2% gradient**
- **Leave top (upstream 1/3 of bar) undisturbed**
- **Limit riparian vegetation disturbance**

Gravel removal can be done via direct dredging in the river, or through gravel bar removal — a term that describes the excavation of gravel bars that extend above the water surface during average flow conditions (Figure 1). Although the goals are the same as for dredging, gravel removal is generally considered less invasive. All case studies presented here examine gravel removal.

Gravel removal to alleviate flooding often seems like an intuitive approach. Removing riverbed and bank material would in theory make space for additional water volume during flood events. But the picture is not that simple: The effect on flood levels is not always predictable because the effect depends on the size of a given flood, and because flood events can rapidly bring in new sediment. Add to that the negative consequences for habitat, as well as the associated regulations, and gravel removal becomes a difficult flood mitigation tool to justify over alternative approaches.

This document aims to shed light on the modern context of gravel removal as a flood mitigation tool, highlighting the complexities related to sediment dynamics, project costs and permitting, and potential habitat impacts.

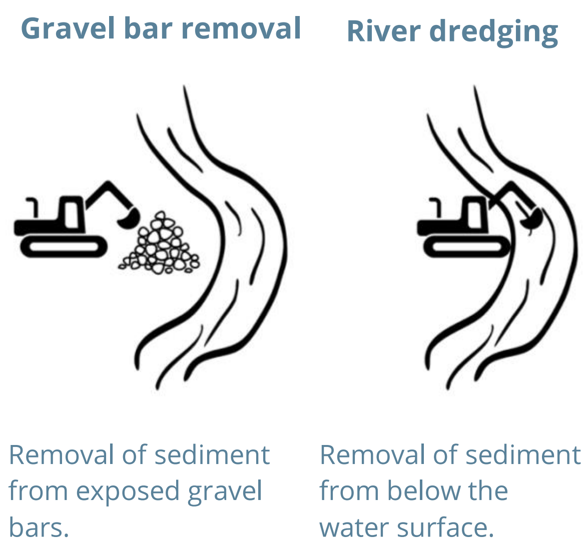


Figure 1. Differences between gravel bar removal vs river dredging.

KEY FINDINGS

- The effectiveness of gravel removal at reducing flood heights is generally limited to the immediate vicinity of the removal site. For example, researchers found that gravel removal on Pierce County rivers would reduce flood elevations by 1 foot or less, with little effect upstream or downstream of the removal site.

- The duration of benefits is short-lived because rivers replenish removed gravel over time. For example, researchers found that gravel bars along the Fraser River in BC replenish removed gravel within just one or two years.

- Habitat impacts can be significant if gravel removal is done repeatedly and at scale. Though researchers have found minor impacts to fish habitat at one-off gravel removal sites, the impact of scaled, regularly occurring gravel removal could be significant. This would include negative impacts to threatened and endangered fish populations as well as other species that rely on habitat that gravel bars provide.

- Permitting gravel removal is a complex and lengthy process. The listing of several salmon species on the Endangered Species List in the 1990s led to significant efforts to protect and enhance river habitat. In Washington State, gravel removal activities must undergo numerous review procedures, involving federal, state, tribal, and local regulatory authorities to protect salmon and other endangered fish species.

- Costs — both in terms of time and money — of gravel removal can be significant. Total project costs can mount when considering the permitting, implementation, habitat mitigation, and monitoring costs. Staff time is another consideration: The Pierce County pilot study, for example, took 10 years to complete.

- To achieve meaningful reductions in flood risk, gravel removal would need to occur in many different places along a river and be repeated regularly to ensure continued flood mitigation benefit.

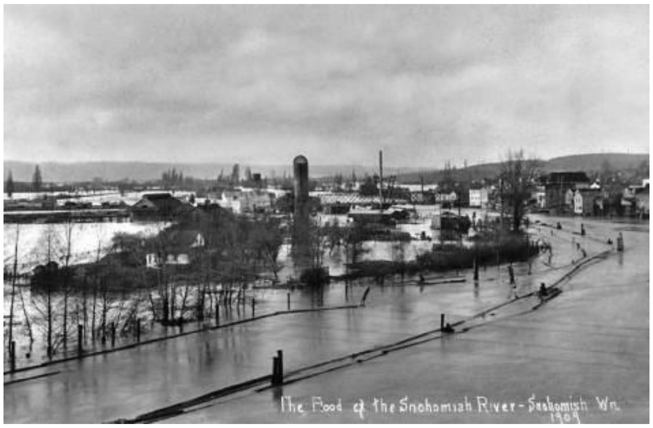
BACKGROUND INFORMATION

Historical Context

From the late 1800s until the 1980s, direct, in-river dredging as well as gravel bar removal were common practices across Pacific Northwest rivers (Pierce County 2023). A common flood mitigation approach during this period was to clear logjams and narrow and straighten river channels to facilitate navigation and convey flood waters rapidly downstream (Pierce County 2023). Though not well-understood at the time, recent research suggests that this approach may lead to higher-than-normal rates of aggradation downstream (CIWEM 2014). As a result of natural rates of aggradation and exacerbating effects from floodplain modifications, sediment deposition continued to occur in the slow-water reaches of lower floodplains, which in turn led to a growing interest in regularly (often annually) removing gravel from these confined, slow-water reaches.

Levees were built along many of the major river systems in the Pacific Northwest, such as the Nooksack, Skagit, and Puyallup, and provided some of the first large-scale infrastructure projects to hold back flood waters from adjacent communities and farmland. These structures were also built with the intention to confine rivers, minimizing channel migration to maximize usable land for agriculture and development. Widespread construction of levees continued throughout the Pacific Northwest, and they are now almost ubiquitous in the populated sections of many river basins.

Gravel removal in the Pacific Northwest has historically been done for a variety of purposes. In-channel mining (dredging) was a common practice throughout many Northwest rivers (Figure 2).



Flooding on the Snohomish River, Wash., 1909.
Photo: Paul DorPat

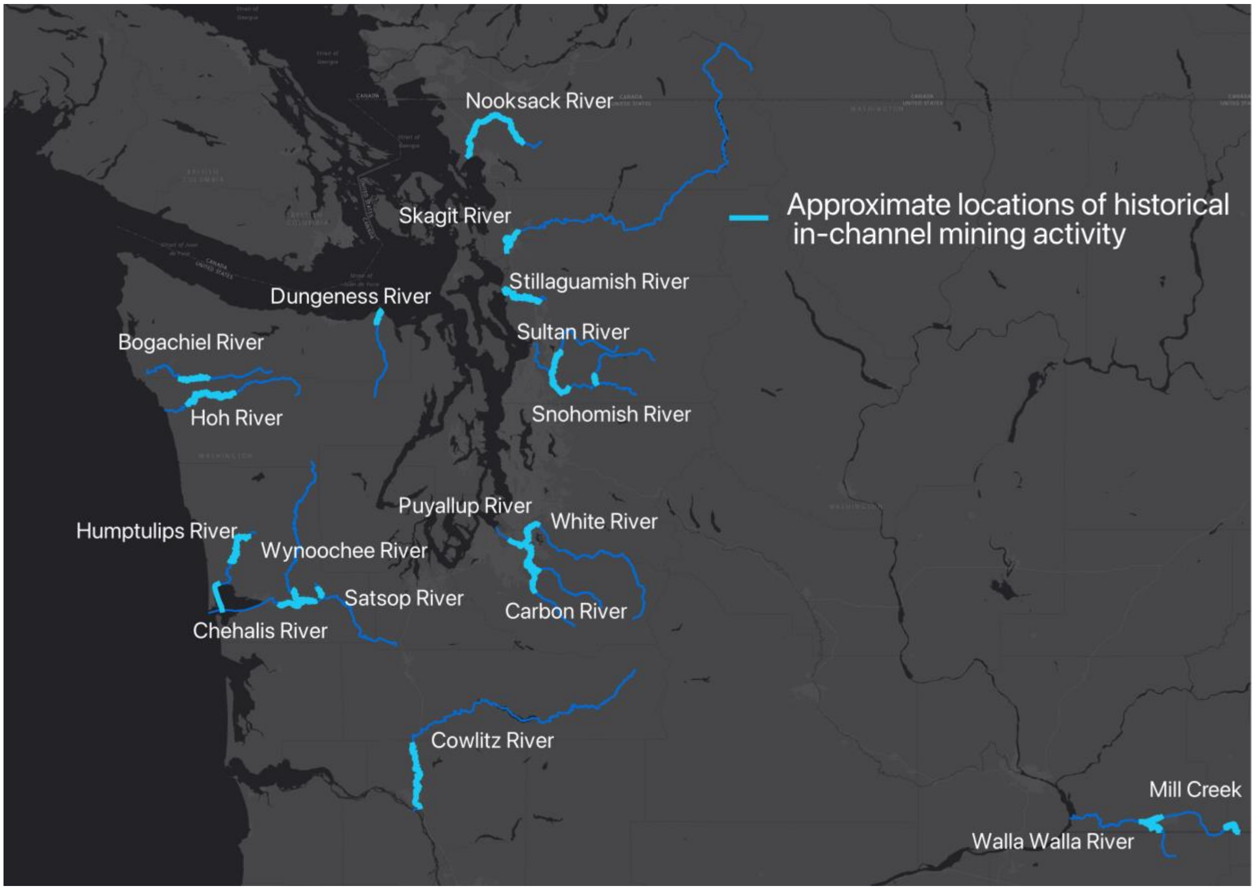


Figure 2. In-channel river mining sites in Washington State since 1970. Adapted from (Collins 1995).

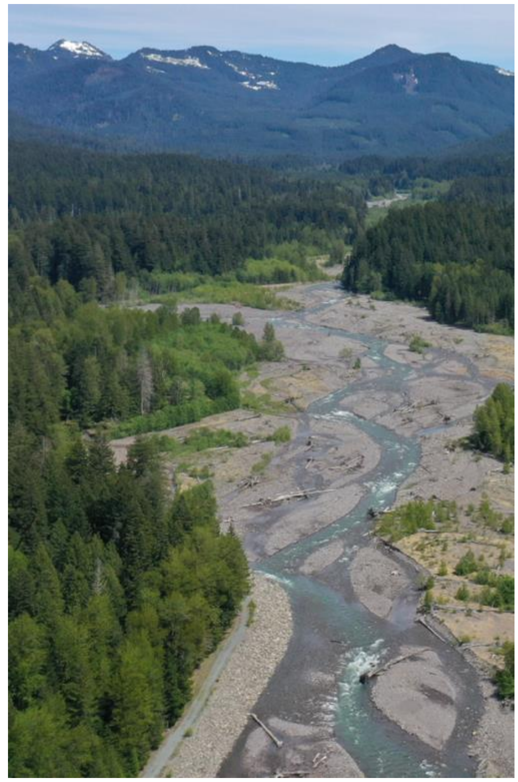
In some rivers, such as the Puyallup River, gravel removal was used as a flood risk reduction action, with the primary goal of increasing channel capacity and flow speed. In other instances, such as on the Nooksack River, gravel removal and dredging were undertaken primarily as a source for commercial aggregate material and/or navigation. For those rivers where gravel removal was intended to reduce flood risk, the need can be partially attributed to increased sediment rates as a result of levees and river confinement effects on sediment supply, though many other factors affect sediment transport and deposition rates. The gravel material that made up much of the sediment being removed could also be sold, making up some of the costs of operations. This made it a cost-effective flooding risk reduction strategy (Angove 2022, Van Nayatten 2022). Today, the market for gravel has changed, and excess material from gravel bar removal can be an additional cost burden to the project strategy (Angove 2022, Van Nayatten 2022).

Riverine Impacts

Gravel removal can have several direct and indirect effects in how rivers function. While in-river dredging along the riverbed was one of the more invasive types of sediment and removal techniques, the more common practice has been to excavate gravel bars — where gravel is removed from gravel bars outside of the wetted channel (Figure 1). Degraded aquatic habitat, a narrower, deeper channel profile, higher sediment transport, and increased flows downstream — which may affect other flood protection infrastructure — are examples of unintended consequences of gravel removal.

A gravel mine on the Wynoochee River, Wash. in 1965 that was created by gravel bar removal and shoreline mining. These types of mining techniques are no longer practiced in Washington. Evidence of turbid water discharge from the sediment pond to the river can be seen at the center of the photo. Photo: Lloyd Phinny, Washington Department of Fisheries.

Rivers often search for an equilibrium in which the amount of sediment coming into a reach is balanced by the amount going out. Rivers adjust by accumulating more sediment when flows cannot transport as much sediment as is entering a reach and become a source of sediment when flows can transport more sediment than is being transported into the reach. Gravel removal can disrupt this process and cause unforeseen sediment impacts or effects on other flood protection infrastructure downstream from the gravel removal site. For example, gravel removal can leave a wide, flat gravel bar surface that changes the confinement of the flow, altering the flow hydraulics around the bar at moderate and larger flows (Kondolf et al. 2002).



Upper Nisqually River, Wash.
Photo: Pierce County.

Policy and Permitting Landscape

Up until the 1990s, states and localities were able to conduct their own riverine maintenance. However, in 1993, amendments to the Clean Water Act, Section 404, designated the U.S. Army Corps of Engineers as the regulator of all mechanized maintenance and material extraction in floodplains. This change in regulatory authority also included a new permitting system and review processes for any riverine dredging or gravel removal. During the 1990s, many salmonid species present in Washington were added to threatened or endangered species lists under the Endangered Species Act. Given this listing, and paired with the new USACE gravel removal oversight, the USACE was required to consult with many different agencies, tribes, and interest groups to ensure gravel removal would not impact salmon populations. The negative impacts on salmon habitat quality and quantity, paired with other permitting requirements — such as both State Environmental Policy Act (SEPA) and National Environmental Policy Act (NEPA) Environmental

Impact Statement review — increased the headwinds of gravel removal as a flood mitigation tool in Washington.

Climate Change Impacts

Climate change is expected to change the way sediment moves through river systems, increasing both the supply of sediment to rivers and the rate that it is transported downstream. Receding snowpack and glaciers will expose greater amounts of soil to erosion, increasing sediment run-off into rivers. Warmer winter temperatures will change both the amount of precipitation falling as rain instead of snow, and the timing of spring run-off. Heavy rain events are projected to become more intense, which could lead to more erosion and landslides. Wildfire risk is expected to increase; this would also increase the supply of sediment to rivers. Both the loss of snowpack and heavier rains will contribute to larger and more frequent floods in the future. Higher peak flows are faster and more erosive, potentially accelerating bank erosion and carrying more sediment downstream (Mauger et al. 2015, Lee et al. 2016, Riedel and Sarrantonio 2021).

Higher sediment fluxes could lead to higher rates of channel aggradation (a rise in the stream bed) in susceptible reaches. Changes in riverbed elevation could be temporary, resulting from 'pulses' of sediment that slowly migrate down river, or could be chronic, reflecting a long-term trend in aggradation (Pfeiffer et al. 2019). Flood protection strategies will need to consider these changing sediment regimes and accompanying flooding dynamics as a result of climate change.

Panorama of the lower Skagit River, showing large gravel bars. Photo: Sam Beebe, Flickr.

CASE STUDIES

Gravel removal in Pacific Northwest rivers

The following information provides insights on current and previous gravel removal plans in several Northwest rivers (Figure 3). The information presented here was found through an extensive search of gravel removal plans and activities in several Northwest rivers. Published journal articles, reports, and interviews with several floodplain managers and hydrologists provided the basis for these insights. Gravel removal was once a widely practiced flood management technique, but a variety of factors have changed the viability of the practice in recent decades. As evidence of the decrease in gravel removal activities, only a handful of Washington State counties have investigated gravel removal feasibility, and no plans have been implemented. Similarly in British Columbia, instances of gravel removal for flood control are rare, with one such case examined here. The rivers discussed in this case study provide only a few of the many relevant examples that are likely to exist.

Lower reach of the Skagit River, Wash. Photo: UW Climate Impacts Group, aerial support provided by LightHawk.

Case Study Locations:

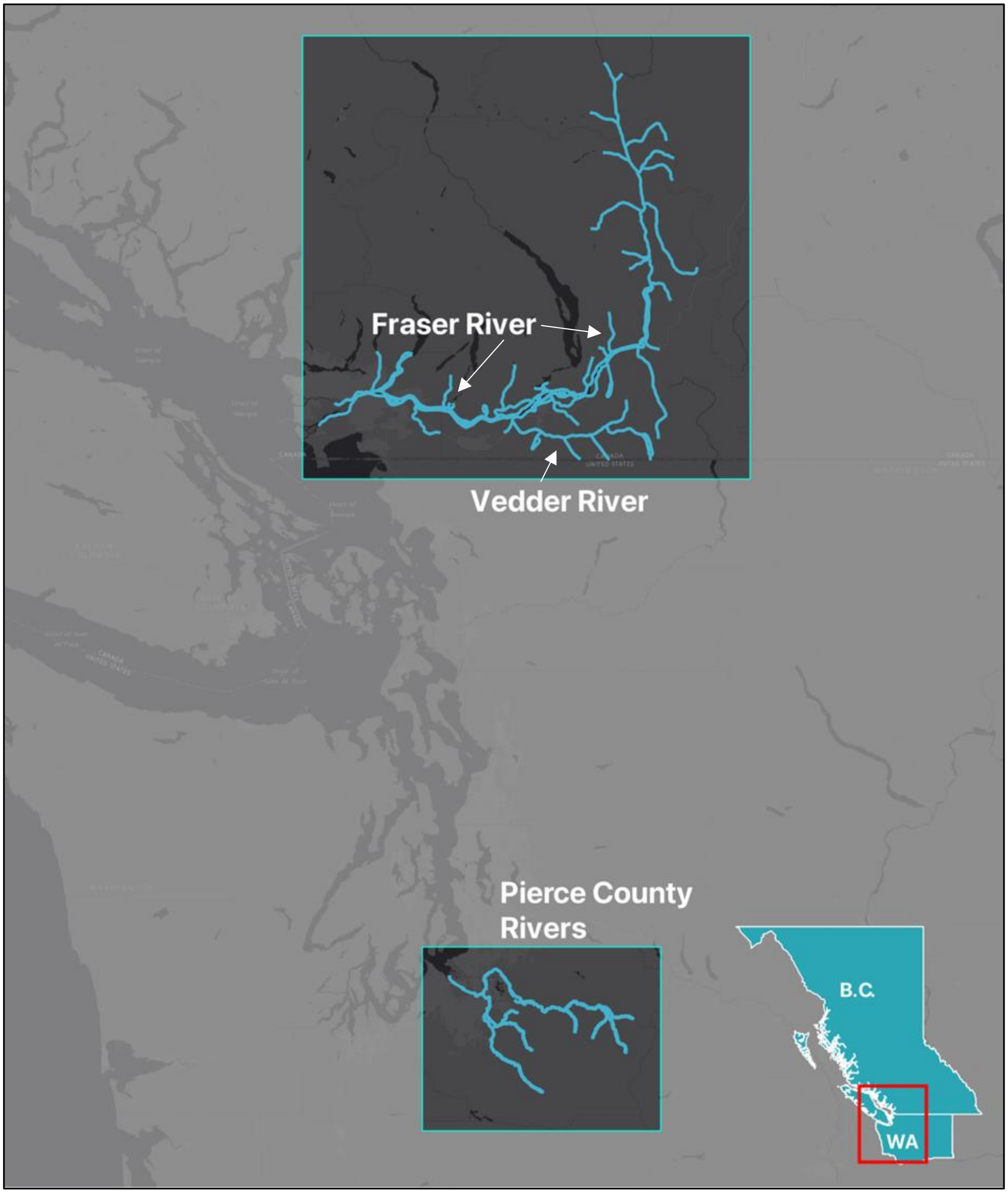


Figure 3. Locations of the case study rivers examined in this report.

Puyallup River

Background

From the early 1900s through the 1980s, Pierce County pursued dredging as a flood reduction strategy (Pierce County 2023). Early on, Pierce County floodplain managers observed that gravel removal efforts were only marginally successful in controlling erosion and flooding and incurred high costs due to the need for repeat dredging to maintain benefits (Pierce County Public Works 2019). Habitat degradation was also a concern (Pierce County 2023). In the late 1990s, gravel removal in Pierce County was largely halted over time due to rising costs, habitat concerns, and increased permitting stringency, as a result of newly listed salmon species on the Endangered Species Lists (Pierce County Public Works 2019).

Renewed Interest in Gravel Removal

Following severe flooding in 2006 and 2009, elected government officials directed Pierce County to investigate the feasibility of gravel bar excavation as a strategy to reduce flood risk. Pierce county defined gravel bar excavation as: “above the summer low-flow water surface and extending upwards toward the bank at a 2 percent slope, or gravel removal from below the low-flow water surface” (Pierce County Public Works 2019). An initial focus of the first pilot project was to investigate whether sediment removal could be undertaken “in areas where it would be difficult to implement long-term flood hazard reduction strategies, where other cost-effective short-term management strategies do not exist, and where flood damage to public resources is likely to occur in the foreseeable future.” (Pierce County Public Works 2019). Pierce County’s study included three distinct phases that were adapted based on modeling results, as well as community and government agency feedback (Figure 4).

The first pilot project phase (Phases I and II, Figure 4) investigated the effectiveness of gravel removal to protect flood-prone infrastructure, such as levees. The aim of this first phase was to identify specific areas along the Puyallup river that might provide the most effective flood reduction while also minimizing impacts on habitat.

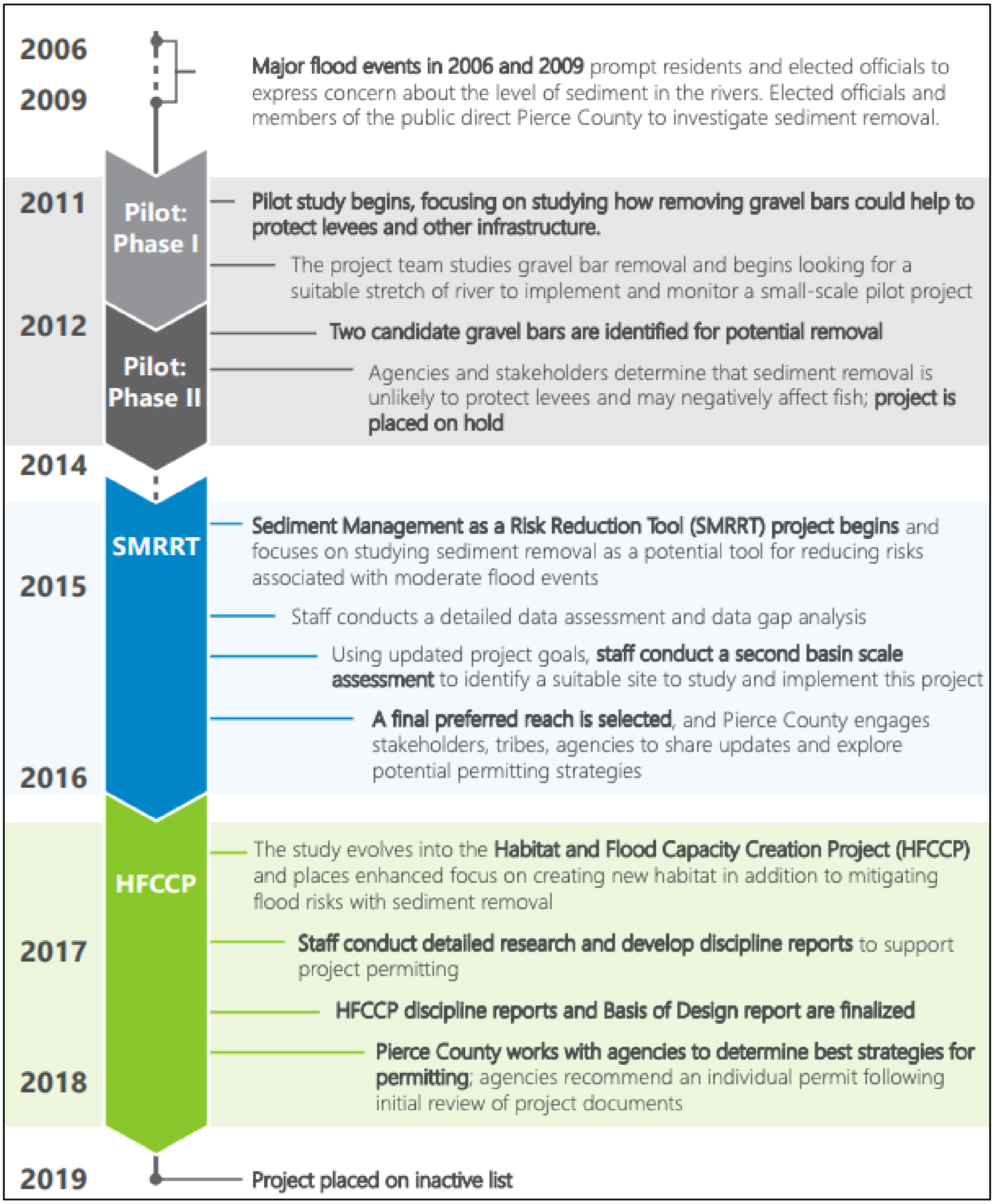


Figure 4. Timeline of pilot gravel removal activities for Pierce County. Figure credit: Pierce County HFCCP Summary Report, 2019.

The second phase of the pilot project — the Sediment Management as a Risk Reduction Tool (SMRRT) project — built upon the first pilot and identified 12 initial reaches through a set of hydraulic, geomorphic, and biological criteria. The 12 reaches were pared down to two candidates for a gravel removal pilot (Figure 5). Pierce County conducted a data gaps analysis to assess information needs and anticipated costs. Additional efforts were made to determine the difficulty of permitting, including the potential complexity of an Environmental Impact Statement. The SMRRT phase revealed potential gravel removal project sites that also contained degraded or low-quality habitat conditions, such as straightened, high gravel banks. The SMRRT team selected two reaches (reaches P1 and P2, Figure 5) due to their partial confinement by levees, or other critical infrastructure that would make other forms of flood mitigation prohibitively costly. However, flooding remained an issue despite improvements in channel capacity through previous setback levee projects. At the conclusion of the SMRRT, the estimated costs to gather missing data — namely geomorphic, sediment trends, hydraulic, and habitat data — were considered too high to continue the pilot project further.

	P1 "Cannery Reach"	P2 "Sportsman Reach"
Geomorphic	+	
Hydraulics and Sediment	+	
Fisheries	+	
Land Use And Social	+	
Hazardous Materials		+
Wetlands and Wildlife	+	
Geology, Soils and Groundwater	+	

Figure 5. Criteria for evaluating the two reaches initially selected for a gravel removal pilot project on the Puyallup River (Pierce County Report, 2019).

Sediment removal benefits were estimated to last 5 to 10 years before the gravel bars would aggrade back to previous elevations based on observed sediment transport and aggradation trends at each of the reaches (Table 1). However, as noted by Pierce County reports and staff, these estimates could be drastically reduced during a high flood event, meaning that flood benefits may not last beyond the next major flood event. Similar longevity of flood reduction estimates were found for the South Fork of the Snoqualmie River in a different gravel removal study on that river (King County 2011). Additional feedback from various stakeholder groups, state and federal agencies, and tribal governments also raised concerns over the complexity of permitting, the uncertain duration of flood mitigation benefits, and significant negative consequences for habitat and salmon.

Table 1. Estimated amount of time gravel removal would provide flood mitigation benefit.

Estimated longevity of flood benefits from gravel removal	
Pierce County	5-10 years
Other river estimates:	
South Fork Snoqualmie	8-10 years
Fraser River	1-2 years*

*Researchers estimated this replenishment rate based on observations at gravel removal sites on the Fraser River that were more for the purposes of material extraction than flood mitigation. (Rempel & Church, 2009).

Despite the findings from the SMRRT, Pierce County continued its efforts to identify an appropriate pilot gravel removal project in response to continued support for the approach. The county developed a third iteration of the pilot project where gravel removal would be one part of a habitat creation project. The project was renamed the Habitat and Flood Capacity Creation Project (HFCCP) to reflect the emphasis of habitat creation in addition to gravel removal. This pairing of habitat improvement and gravel removal was done for a variety of strategic reasons. As the summary report notes, "rather than simply mitigating impacts on habitat caused by sediment removal, the team determined that the project would more likely receive permits if habitat creation was incorporated directly into the design of the project" (Pierce County Public Works 2019). However, after initial review by would-be permitting agencies, it was determined that the HFCCP would not qualify for a streamlined permitting process and instead be subject to a full permit review for gravel removal (Table 2). The required USACE Individual Permit requires an alternatives analysis, a cumulative effects analysis, identification of a representative site, and additional on-site and/or off-site mitigation (Pierce County Public Works 2019). Components of the Individual Permit are listed in Table 2.

Table 2. Overview of the permitting process and approximate time required to obtain permits for a gravel removal project in Washington State. Permits are contingent on activities such as an alternatives analysis, a cumulative effects analysis, identification of a representative site, and additional on-site and/or off-site mitigation. Adapted from King County, 2013.

Permit	Agency	Time
Clean Water Act Section 404 - Individual Permit	U.S. Army Corps of Engineers	6-24 months
Rivers and Harbors Act - Section 10 Permit		
National Environmental Protection Act determination		
National Historic Preservation Act - Section 106		
Clean Water Act Section 401 - Individual Permit	WA Department of Ecology	3-12 months
Clean Water Act Section 402 - Individual Permit		1-2 months
Coastal Zone Management certification		2-4 months
State Environmental Protection Act determination; Environmental Impact Statement		9-18 months
Hydraulic Project Approval	WA Department of Fish and Wildlife	1-2 months
Endangered Species Act - Section 7 consultation	U.S. Fish and Wildlife Service; National Marine Fisheries Service	3-12 months
Aquatic Lands Use authorization	WA Department of Natural Resources	6-12 months
Hydraulic Project Approval	WA Department of Fish and Wildlife	1-2 months
County and local permits (grading, critical area ordinance, shoreline management act, etc.)	Applicable county and city	N/A

Costs from the multiple phases of the pilot were also significant (Table 3). The three pilot phases cost approximately $2 million in total (Pierce County Public Works 2019, Angove 2022). The project team estimated another $2.5 million for the actual implementation of the final phase 3 HFCCP pilot. Additional costs from required mitigation were also anticipated, but not estimated. Pierce County conducted a cost-benefit analysis for the HFCCP pilot project and determined that the estimated benefits were not high enough to justify the costs. The HFCCP was placed on Pierce County's inactive project list in 2019 due primarily to the anticipated high cost of implementation, insufficient benefits, habitat impacts, and permitting complexities.

Table 3. Approximate cost of the pilot studies and the anticipated cost of pilot implementation. Implementation cost estimates did not include additional mitigation costs.

Pilot studies costs:	**$2 million**
Pilot implementation estimate (HFCCP):	**$2.5 million**
Habitat Mitigation:	**Not estimated**

Understanding Flooding and Sediment Dynamics:

Other research projects have also studied flood mitigation strategies for the Puyallup, White, and Carbon Rivers. In 2010, the US Geological Society (USGS) conducted flood protection scenario modeling. Czuba et al. (2010) estimated the relative effectiveness of gravel removal and setback levees for reducing flood risk in the lower reaches of each of the three major tributaries of the Puyallup (White, Carbon, and Puyallup rivers). These simulated modifications were compared to baseline conditions to estimate the changes in factors such as channel flow conveyance, water surface elevation, and upstream and downstream sediment deposition.

The researchers found that across two river sites, gravel removal was likely to decrease peak water surface elevations by about 1 foot directly adjacent to the removal sites. In contrast, **setback levees were modeled to reduce water-surface elevations by approximately four times more** than gravel removal for the same two sites (Czuba et al. 2010). Results for the third site suggested that gravel removal would result in no appreciable change in surface-water height.

Most rivers with human modifications that restrict the channel have subcritical flow: where flows are slowed due to constrictions, and the water backs up behind the constricting point (Czuba et al. 2010). Since the water-surface elevation upstream is controlled by water-surface elevations downstream, any modifications that decrease the downstream elevation also lower those upstream, depending on the amount of increased conveyance that results from the modification. This is true for setback levees, which were estimated to significantly reduce water-surface elevations between 0.5 - 1 mile upstream of the implementation reach. The much smaller amount of material removed from gravel bars was not enough to have an appreciable upstream benefit.

Unlike dredging, gravel removal only excavates the highest elevation material that is deposited during high-flow events, and not the sediment that is underwater at normal flows or in moderate flood events. The Czuba et al. (2010) modeling suggests that setback levees would increase the options available for gravel removal locations by creating a wider active channel where gravel could be deposited away from sensitive aquatic habitat of the river (Czuba et al. 2010). This may be one possible option for a paired management strategy, permitting and cost considerations aside.

Aerial view of the lower Puyallup floodplain. Photo: Floodplains for the Future.

Important takeaways from Pierce County:

- **Longevity of flood reduction:** Despite extensive modeling, the County could not fully determine just how long gravel removal would last before the river replenished it. While average annual deposition rates suggested a project lifespan of 5-10 years, the modeling suggests that a single large flood event could fill in multiple years' worth of material where removal had occurred.
- **Expenses at all stages of the process:** The pilot study for a select number of potential removal areas was a lengthy and expensive process. Pierce County staff spent over 10 years and $2 million in pilot study explorations alone. It is estimated that implementation costs for a single site would be at least that amount again. Habitat mitigation projects would bring costs even higher, though costs were not estimated.
- **Permitting is difficult:** Federal, state, and local permitting and review processes (Table 2) will be required for gravel removal projects. The HFCCP pilot phase showed that even with habitat creation and restoration as a main project focal point, any gravel removal activity would still not exempt the project from permitting associated with gravel removal.
- **Opportunity costs must be considered:** The gravel removal pilot process took a considerable amount of time and resources. The multi-stakeholder engagement processes, the difficulty in permitting, and variation in flood mitigation effectiveness and longevity, make gravel removal a more time-consuming and resource-intensive mitigation strategy than it may appear on the surface. Opportunity costs associated with pursuing gravel bar excavation projects over other, more proven flood mitigation projects should be considered.
- **The pilot study process may be a valuable exercise:** Though the pilot study was ultimately never implemented, the process for investigating the viability and impacts of gravel removal in Pierce County rivers proved to be a valuable process. Findings about the relative ineffectiveness of gravel removal as a flood mitigation tool, the complex nature of permitting, and the high costs of both the study and implementation, all proved to be a valuable reality-check on gravel removal as a viable strategy when compared to other strategies. Gravel removal was a topic of interest to many groups within Pierce County, so project leads sought to keep these entities engaged at all parts of the process.

Fraser River

Background:

The Fraser River drains approximately one-quarter of the geographic area of the province of British Columbia (Rosenau and Angelo 2007). This large river system is characterized by high-volume flooding events and significant amounts of sediment transport. Surrounding development and agriculture in the lower Fraser floodplain are significantly impacted by flooding. Gravel removal in the Fraser River began in the early 1950s, namely as a source for aggregate material for use in construction (Weatherly & Church, 1999). The easy access to gravel bars and large quantities of material made it a profitable source during a period of high demand in British Columbia (Rosenau and Angelo 2007). In the mid-1970s local governments, conservation groups, First Nations, and provincial agencies became increasingly concerned over gravel removal's impacts on fish habitat and began restricting the number of gravel removal sites (Rosenau and Angelo 2007). Concerns continued to mount, and in the 1990s a temporary moratorium on gravel removal was put in place by the Department of Fisheries and Oceans (DFO). The DFO is a federal-level government organization in Canada that oversees compliance to the Fisheries Act. After the moratorium was put in place, DFO conducted studies of potential impacts on aquatic life and habitat. The Fisheries Act is a federal law which governs fisheries and fish habitat throughout Canada and plays a role in the gravel removal permitting process today (CAN Fisheries, 2022). Despite the temporary moratorium, records suggest gravel removal occurred annually from at least 1964 to 2010 (Rosenau and Angelo 2007). From 1964-1998, gravel removal averaged approximately 130,000 m^3 (Weatherly & Church, 2011). For 2000-2010, average annual removal increased to an average of 167,000 m^3 (Weatherly & Church, 2011; Figure 6).

While many of these gravel removal projects were conducted in the name of flood mitigation, these removal sites were often located in areas that would not provide the flood reduction benefits, nor in locations directly adjacent to critical infrastructure or communities. Instead, many of the gravel removal sites on the Fraser were located on bars that were easily accessible by excavation equipment (Rosenau and Angelo 2007). Rosenau & Angelo (2007) speculate that this pattern of activity indicates that the true purpose of gravel removal on the Fraser River was more likely for commercial extraction rather than flood mitigation.

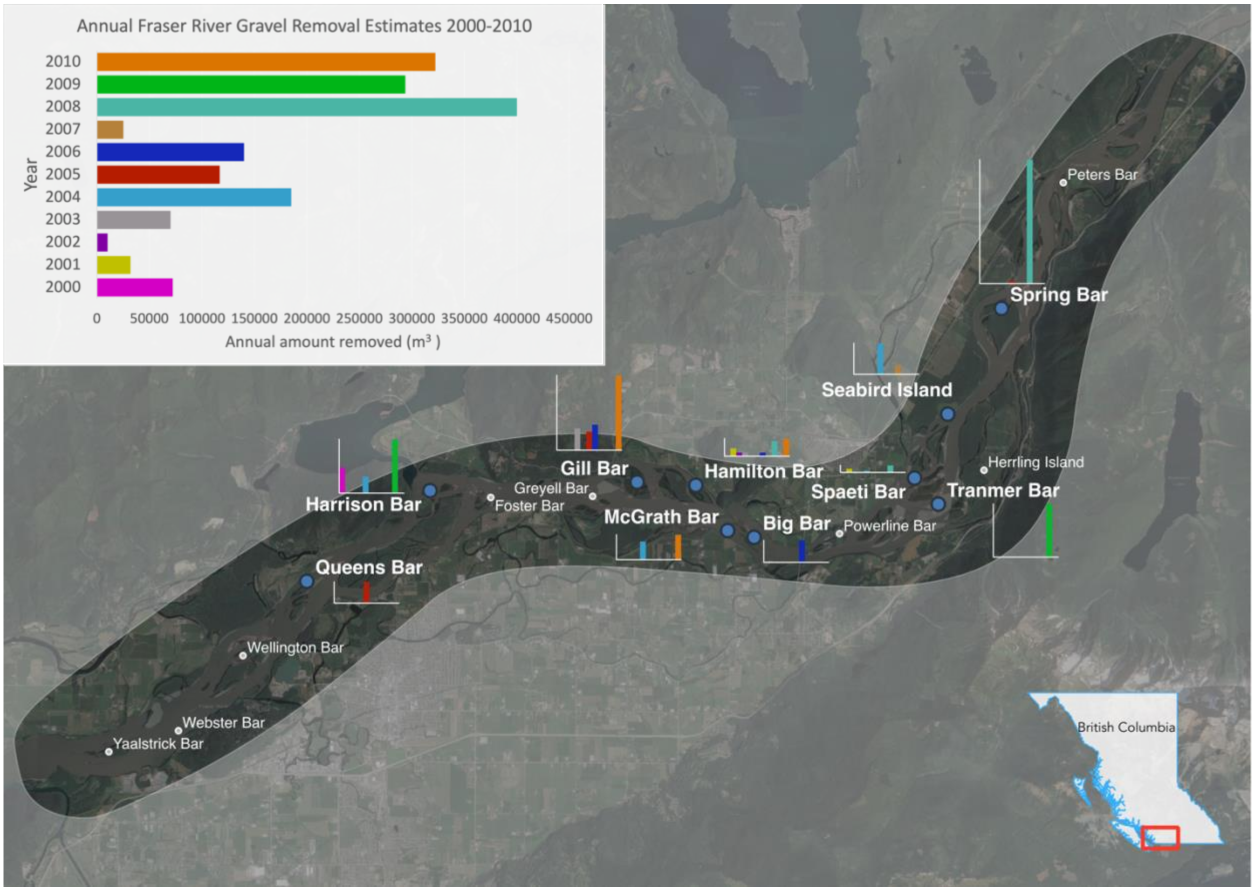


Figure 6. Map of known gravel removal sites on the lower Fraser River. Bar graphs show the annual removal amounts at each site. Total annual removal estimates from all sites are shown in the bar graph in the top left corner. Estimates adapted from Weatherly & Church, 2011.

Gravel Removal Impacts

Researchers have conducted numerous studies on the Fraser River to estimate the impacts of gravel removal on the river's physical characteristics and biological environment. The lower Fraser floodplain is very active, and its channels have historically migrated actively across the floodplain. Downstream transport and deposition of sediment is a major contributor to channel movement over time. Church et al. (1999) found that the amount of sediment moving through the lower reaches of the Fraser River is also variable from one decade to the next (Church et al., 1999). Rempel and Church (2009) find that sediment removed from gravel bars on the Fraser is often replenished within one or two years by spring flooding events. Nonetheless, changes to the physical channel can impact critical fish habitat if done repeatedly or at a large scale (Church et al. 1999, Rempel and Church 2009).

Gravel removal can impact numerous habitat functions as a result of the disturbances to the river's morphology. Gravel removal may result in direct impacts to riverine biology, such as removal of gravel on, or near salmon redds (spawning grounds). Decreased water quality and altered flow regimes are examples of other indirect effects on biological functions. While gravel removal plans have often sought to mitigate these impacts through strategic timing and seasonality (i.e. avoiding salmon spawning), Rosenau (2007) and others remain vocal about the potential for immediate and long-term effects on habitat. Increased turbidity is one such negative effect of gravel mining (Rempel and Church 2009, Canada Privy Council Office 2011). Turbidity— the amount of suspended sediment in the water — can smother benthic invertebrates, which are a major food source for all salmon species in their early stages of life development (Rempel and Church 2009, Canada Privy Council Office 2011). Increased turbidity also reduces light penetration, limiting the growth of plants and algae that are an important food source for invertebrates (Rempel & Church, 2009). Invertebrates such as mayflies, stoneflies, and caddisflies, are an important part of juvenile salmon diets, and their presence (or absence) in salmon habitat is often used as an indicator of habitat response to disturbances (Rempel and Church 2003, 2009). Gravel removal also reduces valuable high bar habitat during flood events, which provides calm water refugia for juvenile salmon to prevent them from being washed downstream (Rempel & Church, 2009). Gravel bars can also create other off-channel habitat, which can provide protection to juvenile fish during low flows as well (Rempel and Church 2009). While Rempel and Church (2009) find that the riverine habitat of the Fraser is unlikely to be impacted by a single gravel removal project at a single site, long-term impacts on habitat from repeated removals — especially gravel removal at a large enough scale to mitigate flooding — remains a significant risk factor.

Shifting Away from Gravel Removal

Gravel removal has not been conducted in the Fraser River since 2011 (Canada Privy Council Office 2011, Weatherly 2022). Stakeholders involved in Fraser River floodplain management show little interest in the practice being used in the future.

The Fraser Basin Council, a multi-stakeholder group for flood mitigation planning in the lower Fraser, makes no mention of gravel removal for flood mitigation in its current planning documents. Instead, the Council's strategic plan for 2021-2026 indicates interest in other mitigation strategies such as levee improvements and setbacks (FBC, 2021). There are likely a multitude of reasons for halting gravel removal for flood reduction over the past decade. Reasons for the diminished interest include the increased costs of gravel removal, greater evidence of habitat impacts, the rapid rate at which gravel bars are replenished, and a change in how flood mitigation is governed in the Province.

Increased gravel bar removal costs in recent decades have disincentivized floodplain managers from pursuing gravel removal projects (Canada Privy Council Office 2011, Weatherly 2022). Other off-river sites with access to the same type of material have become a more productive, cheaper, or reliable source for gravel material. Whereas excess gravel material was once able to offset the gravel removal costs itself, now the material removed from gravel removal projects comes at an additional cost. This is also true for the Vedder River, as described in our case study below. According to river management personnel, gravel removal costs allowed for budget-neutral removal projects up until 2016 (Van Nayatten 2022, Weatherly 2022). However, a change from 2016 onward in the gravel materials market has turned it into an additional cost to the Vedder's annual gravel removal efforts (Van Nayatten 2022). Rising costs, among other factors, halted gravel removal in the Vedder from 2016-2021 (Van Nayatten 2022, Weatherly 2022).

Greater evidence of habitat impacts is another contributing factor. Habitat impacts can happen directly or indirectly from extraction activities. Research suggests that gravel bar extraction can make the gravel bed more mobile at lower flows, increasing the potential to scour salmon redds (Kondolf 2002). Bar excavation has also been shown to eliminate or decrease side channels, which are important habitats for juvenile salmonids (Weigand 1991, Kondolf et al. 2002). Indirect impacts have also been observed: In 2006 on the Fraser, an unsanctioned road was constructed to reach a gravel bar, cutting off a prime spawning channel, killing approximately 2 million incubating pink salmon. Impacts from the removal projects themselves remain a priority concern for fisheries management agencies and conservation organizations that work in the Fraser. Although this particular impact could have been avoided, the episode highlights concerns about the ability to remove gravel in ways that mitigate harm to fish and wildlife (Tyee, 2006).

The size of the Fraser is also a contributing factor in the diminished interest in gravel removal projects. In the face of such large amounts of sediment transport, the scale of gravel removal needed to make an impact on flooding would be approximately 10 times the previous annual average (Church and Weatherly, 2011). Even if that amount of gravel removal could be achieved, Rempel and Church (2009) found the benefits would be short-lived — lasting about 1-2 years until spring run-off flows replenished the excavation area.

In addition to the limited duration of benefits, gravel removal on the Fraser has been found to provide only minor, local flood reduction benefits. Similar to the findings of Czuba (2010) on Pierce County rivers, Church (2012) and other researchers observed that "significant reductions in water level extended upstream only to about half the length of the excavation and was of the order of only 10 cm for a bar-top sediment removal of order 1 million m^3" (Church 2012). Recent removal averaged about 150,000 m^3/year, or about six times less than that (Church, 2012). Moreover, Church (2012) also calls into question the perception that the Fraser riverbed is rising (aggrading) in the long term. If sediment accumulation is more temporary — fluctuating between accumulation and erosion — then it may not be the main driver of increasing flood events over time (Church, 2012). Instead, Church (2012) hypothesizes that the increasing confinement of the river from levees may be a more significant driver than sediment accumulation.

Finally, **a change in governance over flood mitigation** may be another factor in the move away from gravel removal as a flood mitigation strategy. In 2003 the BC provincial government shifted the responsibility of flood mitigation to local municipalities. This change significantly reduced the amount of resources available for flood mitigation, and led to a patchwork of varying approaches along the Fraser. The shift also accompanied funding support from the federal government to implement larger, long-term strategies such as levee repairs and setbacks, as well as property buyouts. But municipalities lacked sufficient capacity to take advantage of these opportunities, leading to lagged implementation of flood mitigation actions (CBC, 2021). Recent floods have highlighted the pitfalls of this shift in flood mitigation responsibilities (CBC, 2021).

Important takeaways from the Fraser River:

- **Gravel removal has become cost-prohibitive:** Gravel removal projects on the Fraser were once economically viable for commercial purposes, allowing gravel removal projects for flood mitigation to be cost-neutral. However, changes in demand, as well as the development of other sources of material, have made gravel removal much less profitable than other sources. Today, gravel material is more of a liability or waste product to companies than a commodity. This creates additional costs for gravel removal projects.
- **Permitting can be difficult:** Permitting and operation at a scale that would meaningfully reduce flooding is likely to be an increasingly complex and lengthy process due to the requirements to protect fish and gather input from a variety of stakeholder groups.
- **Habitat impacts remain a concern:** Though researchers have found the Fraser to be somewhat resilient to a handful of studied gravel removal projects, impacts are likely to be significant if removals were conducted at a scale that would meaningfully mitigate flooding. Previous gravel removal activities have been documented to negatively impact Fraser River salmon.
- **Benefits of gravel removal can vary:** Modeled gravel removal scenarios show only a minor effect on flood levels in the Fraser. The benefits of reduced flooding are also highly local, and studies suggest that removed gravel is replenished by the river within 1-2 years.

Aerial image of the lower Fraser River. Photo: Dru, Flickr.

Vedder River

Background:

The Chilliwack River in southern British Columbia, along with its lower reach known as the Vedder River, have experienced many damaging floods in the last century. The largest floods typically occur in winter as a result of heavy rain events. The Vedder River also experienced flooding similar to the Nooksack River during the 2021 atmospheric river events. The Vedder River actually originates as the Chilliwack River. Historically, the Chilliwack flowed north through present-day Chilliwack and emptied into the Fraser. After a flood in 1875, several large log jams formed which redirected the Chilliwack to a westward course, over-taking the preexisting Vedder Creek drainage (Vedder Article, 2016). Further human modifications to the new water course and surrounding streams, as well as additional high-flow events, eventually cemented the river's new path. In particular, the lower river was straightened and leveed, creating the Vedder Canal, as part of the effort to drain Lake Sumas in the early 20th century. This re-routed section of the Chilliwack River adopted the name of the Vedder Creek, and consequently became known as the Vedder River despite being a continuation of the Chilliwack River (Figure 7).

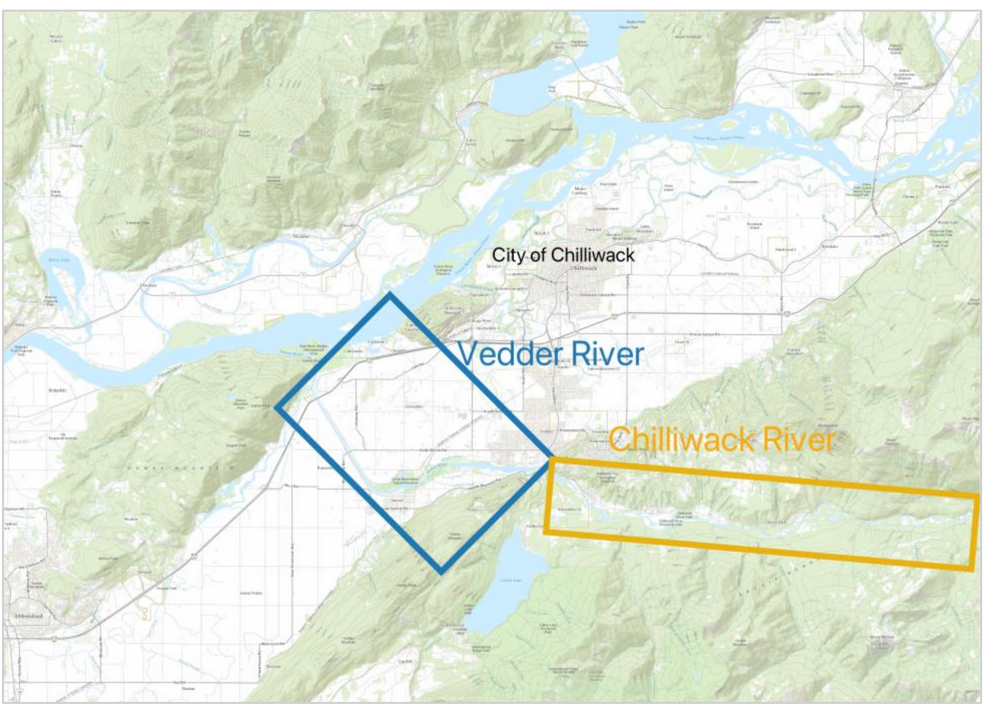


Figure 7. Map showing the locations of the Vedder and Chilliwack rivers.

The Vedder River and canal make up a highly managed river system. Management practices today include gravel removal through gravel bar excavation. The canal and surrounding levees along the total 7.5 mile stretch of the Vedder River are frequently maintained through gravel removal. A major flood event in 1975 brought a large influx of sediment. This event spurred investigations into how to best protect the many farms and communities located in Sumas Prairie, Chilliwack, and Abbotsford from future floods. Managers identified a number of solutions, including setback levees and continued sediment removal beyond the 1975 influx (Vedder Article, 2016). The Vedder canal, which comprises the last three river miles of the Vedder River, is also a crucial component to the Sumas Prairie — formerly Sumas Lake — an area that is prone to flooding and is maintained by the Barrowtown pump station, which pumps excess water into the Vedder canal.

Upper reach of the Vedder River, British Columbia. Photo: Province of British Columbia.

Active management of the Vedder River began with the adoption of the Vedder River Management Plan in 1983, and also created the Vedder River Management Area Committee (VRMAC). The Vedder River Management Area Committee (VRMAC) has planned and managed gravel removals for flood control purposes annually from 1990 to 1997 and biennially from 1998 to the present (Tetra Tech Report, 2015). The VRMAC is comprised of the City of Chilliwack, the City of Abbotsford, BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) Federal Department of Fisheries and Oceans (DFO), as well as stakeholders such as the Fraser Valley Regional District, First Nations, and fishing advocacy groups (VRMAC website, 2023). A technical committee develops and recommends a sediment removal plan to the VRMAC every second year on even years — timing that was established to avoid affecting spawning pink salmon (VRMAC Report, 2022). Sites for sediment removal are then selected in consultation with a registered professional biologist, who also monitors for potential habitat impacts during removal (Vedder Article, 2016). Other considerations include presence of vegetation, proximity to sensitive and valuable habitat, road or other access for machinery, and potential effects of sediment removal on existing channel features and configurations (Vedder Article, 2016).

Unique challenges in a confined system

The relatively short length and highly modified form (straightened, leveed) of the Vedder River limits flood management options. Some setback levees have been implemented along the short stretch of river. Additionally, managers have increased the height of levees to accommodate larger floods, however most levees are now bumping up against levee height restrictions due to seismic and slope stability requirements (Van Nayatten 2022). As a result, managers have concluded that sediment removal is the only viable approach to flood risk mitigation (Van Nayatten 2022). Regulating agencies agree: these constraints have made it easier to permit gravel removal. Awarded permits for gravel removal in the Vedder are contingent on extensive site monitoring requirements of the permittee pre- and post-removal (Table 4). Habitat mitigation consists primarily of placement of large woody debris, deepening entrances to channels, creating riffles at inlets and outlets to excavation sites, and providing modest habitat type excavations in conjunction with the larger pit type excavations (Nova Pacific Environmental 2022). The permit and evaluation process is led by the DFO, Emergency Management British Columbia, Ministry of Public Safety and Solicitor General, the BC Ministry of the Environment, and several other government agencies.

Table 4. Monitoring requirements for gravel removal permits on the Vedder River.

Site Monitoring Requirements for Gravel Removal Projects in British Columbia
Topographic and bathymetric surveys (pre-removal, post-removal, post-freshet)
Surface sediment sampling (pre-removal, post-freshet)
Juvenile fish sampling (two episodes, both at removal and reference sites)
Benthic invertebrate sampling (pre- and post-removal)
Habitat mapping (post-removal, post-freshet)

Despite the recognized need for gravel removal in the Vedder River, permitting remains difficult due to the narrow window of time to perform the required pre-assessment monitoring activities. Specifically, site selection must occur during the low-water period (often September) with the removal work planned for the following winter (often January-March). This leaves little time for permitting and other site-level assessments to be completed before the work can begin. Variable river conditions can often throw gravel removal timelines off schedule, or delay activity until the following year. Since gravel removal is often seen as a near-term, immediate solution to reduce flooding, uncertainty as a result of the narrow permitting window can negate the advantages of this approach.

In 2022 the VRMAC resumed gravel removal in the Vedder River. The removal came after approximately five years of no removal activity, due to a combination of budget constraints and high removal costs, pushback from fisheries and conservation groups over habitat concerns, as well as a perception among VRMAC members that little sediment was accumulating in the reach and so gravel removal was not needed (VRMAC Report, 2021). The 2021 floods deposited approximately 440,000 m^3 of sediment in the Vedder River. For 2022, the VRMAC awarded a $500,000 (CAN) contract for 110,000 m^3 to be removed (City of Chilliwack et al. 2022, Parker 2022; Table 5). However, due to timing constraints, only 35,000 m^3 were removed before high winter flows inundated the gravel bars selected for removal (City of Chilliwack 2023).

Large levees and an existing canal have made the Vedder an artificial system in many ways. The Vedder sediment removal program is one part of a larger, highly intensive flooding reduction program that manages a small portion of the greater Chilliwack watershed. With limited space, and significant investments made in existing levee infrastructure, the VRMAC has a more limited set of options to manage flooding. Gravel removal is one of those remaining options. Moreover, the Vedder River constitutes the lower reach of the larger

Table 5. Approximate annual cost for Vedder River flood management.

Site Assessment Pilot studies costs:	**$250,000**
Gravel Removal:	**$500,000**

Chilliwack River watershed — a system that funnels large amounts of sediment and water from a mountainous basin. Yet flooding reduction strategies are mostly confined to just the Vedder, at least within the purview of the VRMAC. In contrast, a basin-wide program likely has a greater number of places to implement larger-scale flooding reduction strategies, such as sediment traps and setback levees. Moreover, as Czuba et al. (2010) demonstrated in Pierce County rivers, the benefits of sediment removal, if any, can be very localized, and can exacerbate flooding effects downstream. In the case of the Vedder, however, the downstream implications are minimal given the small size of Vedder River floods compared to the Fraser.

Important takeaways from the Vedder River:

- **The Vedder River is unique:** Straightened and leveed during the creation of the Vedder Canal, few viable alternatives exist for reducing flood risk in this section of the river. Given the large fluxes of sediment into the reach, gravel removal was deemed the best approach for mitigating flood risks.
- **Small-scale management:** The gravel removal and flood mitigation conducted on the Vedder River is done at a relatively small scale. The approximately 7.5-mile reach helps to focus management activities to certain areas and reduces the volume of removal that is needed.
- **Extensive monitoring is required:** Permitting agencies require extensive monitoring both pre- and post-removal. This includes topographic surveys, hydraulic modeling, and biological and habitat assessments. This results in a brief window of opportunity for gravel removal, which can be disrupted by unforeseen changes in river conditions (e.g. floods).
- **Gravel removal is one part of a larger flood control project:** The gravel removal conducted in the Vedder River can be viewed as a smaller piece in the larger, intensely managed floodplain that encompasses Sumas Prairie and the greater Chilliwack region. The Sumas Prairie is highly vulnerable due to its low elevation and the economic importance of the agricultural industry. Continual maintenance costs (usually semi-annually in the Vedder) are required to ensure flood protection.

CONCLUSIONS

Growing development within floodplains and increased river confinement (e.g., via levees), in addition to frequent high flows and sedimentation rates, led many early floodplain management officials to focus on sediment removal to help moderate flooding. The prevailing engineering approach to river management over the past century has been to channelize and deepen rivers to quickly convey flood waters downstream. Gravel removal, and even dredging, was once a commonplace flood mitigation tool in Northwest rivers. Today, gravel removal is rarely used as a flood management strategy. Factors such as the limited effectiveness for flood reduction, the variable duration of flood reduction benefits, permitting complexity, the significant negative impacts on habitat and endangered species, and the potential for high project costs. Given the range of alternative flood mitigation strategies now available, these considerations make it difficult to justify the expense and habitat consequences associated with gravel removal. We examined the case studies, in which gravel removal was considered or implemented, in the U.S. Pacific Northwest and southern British Columbia. All three case studies highlighted the following challenges:

- **The effectiveness of gravel removal at reducing flood heights is generally limited** to the immediate vicinity of the removal site. For example, researchers found that gravel removal on Pierce County rivers would reduce flood elevations by 1 foot or less, with little effect upstream or downstream of the removal site.

- **The duration of benefits is short-lived** because rivers replenish removed gravel over time. For example, researchers found that gravel bars along the Fraser River in BC replenish removed gravel within just one or two years.

- **Habitat impacts can be significant** if gravel removal is done repeatedly and at scale. Though researchers have found minor impacts to fish habitat at one-off gravel removal sites, the impact of scaled, regularly occurring gravel removal could be significant. This would include negative impacts to threatened and endangered fish populations as well as other species that rely on habitat that gravel bars provide.

- **Permitting gravel removal is a complex and lengthy process.** The listing of several salmon species on the Endangered Species List in the 1990s led to significant efforts to protect and enhance river habitat. In Washington State, gravel removal activities must undergo numerous review procedures, involving federal, state, tribal, and local regulatory authorities to protect salmon and other endangered fish species.

- **Costs — both in terms of time and money — of gravel removal can be significant.** Total project costs can mount when considering the permitting, implementation, habitat mitigation, and monitoring costs. Staff time is another consideration: The Pierce County pilot study, for example, took 10 years to complete.

- To achieve meaningful reductions in flood risk**, gravel removal would need to occur in many different places along a river and be repeated regularly** to ensure continued flood mitigation benefit.

Other communities have investigated the feasibility of gravel removal and came to largely the same conclusions. In 2011, King County floodplain managers looked into a pilot gravel removal project in the South Fork of the Snoqualmie River. The feasibility study concluded that the relative short duration of benefits (estimated to be 5-10 years), the highly localized nature of flood mitigation benefits, the risk of increased flooding downstream, and the indirect impacts on salmon habitat did not warrant further pursuit of gravel removal for flood mitigation. King County also estimated the pilot to cost between $1 and $3 million and acknowledged that permitting would likely be difficult (King County 2011). Whatcom County also went through similar pilot feasibility exercises for the Nooksack River. Whatcom County found that gravel removal would have similarly minimal, localized benefits. Notably, Whatcom County found that other factors, such as constrictions from downstream levees of the pilot area gravel bars, had a much greater effect on flood heights than gravel accumulation (Whatcom County Flood Control Zone District 2013).

In practice, no single strategy is likely to be enough to fully reduce flood risk to communities. This is particularly true given that floods are projected to be larger and more frequent in the future due to climate change. The challenge for floodplain communities is to identify and implement the optimum mix of flood mitigation strategies that provide the most effective protection for communities while also providing benefits for the riverine ecosystem. Each reach will require a different approach to flood mitigation, and different sites within those reaches will likely need to employ a variety of solutions. In some cases, gravel removal may be an appropriate choice (i.e. in a confined channel adjacent to critical infrastructure, or where reducing flooding overflow is crucial). A paired approach, as suggested by Czuba (2010), where a setback levee strategy is implemented, allowing for high bank gravel deposition during floods, and could be later excavated away from critical habitat areas to maintain capacity, may also be appropriate. Effectiveness is important, given limited resources and the need to balance flood mitigation with other critical priorities that communities face. The case studies summarized here suggest that gravel removal and dredging are rarely the most effective strategy to reduce flooding, neither in terms of costs nor in terms of benefits. Communities and stakeholders need to evaluate multiple flood mitigation options together and select a mix of strategies that best fit their needs and values.

REFERENCES

Angove, A. 2022, November 3. Pierce County sediment removal pilot project discussion.

Canada Privy Council Office. 2011, May 20. Policy and Practice Report: Gravel Removal in the Fraser River. Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River.

City of Chilliwack. 2023. Flood Protection Infrastructure. City of Chilliwack.

City of Chilliwack, City of Abbotsford, and BC Ministry of Forests. 2022, July 6. 2022 Vedder River Floodway Gravel Removal and Gravel Sale.

CIWEM. 2014. Floods and Dredging - a reality check. Chartered Institution of Water and Environmental Management.

Czuba, J., C. Czuba, C. Magirl, and F. Voss. 2010. Channel-Conveyance Capacity, Channel Change, and Sediment Transport in the Lower Puyallup, White, and Carbon Rivers, Western Washington. Scientific Investigations Report, USGS.

King County. 2011. South Fork Snoqualmie River Gravel Removal Study. King County Department of Natural Resources and Parks, Water and Land Resources Division.

Kondolf, M., M. Smeltzer, and L. Kimball. 2002. Freshwater Gravel Mining and Dredging Issues. Washington Department of Fish and Wildlife; Washington Department of Ecology; Washington Department of Transportation.

Lee, S.-Y., A. F. Hamlet, and E. E. Grossman. 2016. Impacts of Climate Change on Regulated Streamflow, Hydrologic Extremes, Hydropower Production, and Sediment Discharge in the Skagit River Basin. Northwest Science 90:23–43.

Mauger, G., J. Casola, H. Morgan, B. Strauch, B. Jones, and T. M. Curry. 2015. State of Knowledge: Climate Change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration.

Nova Pacific Environmental. 2022. Proposed 2022 Vedder River Sediment Removal Project.

Parker, L. 2022, September 6. Sediment removal to start on Vedder River near Chilliwack for flood mitigation. https://dredgewire.com/sediment-removal-to-start-on-vedder-river-near-chilliwack-for-flood-mitigation/.

Pfeiffer, A. M., B. D. Collins, S. W. Anderson, D. R. Montgomery, and E. Istanbulluoglu. 2019. River Bed Elevation Variability Reflects Sediment Supply, Rather Than Peak Flows, in the Uplands of Washington State. Water Resources Research 55:6795–6810.

Pierce County. 2023. Flood Plan FAQs | Pierce County, WA - Official Website. https://www.piercecountywa.gov/7042/Flood-Plan-FAQs.

Pierce County Public Works. 2019. HFCCP Summary Report - Appendix 1.

Rempel, L., and M. Church. 2003. The Harrison Bar Gravel Removal Experiment: Final Report. Department of Geography The University of British Columbia.

Rempel, L. L., and M. Church. 2009. Physical and ecological response to disturbance by gravel mining in a large alluvial river. Canadian Journal of Fisheries and Aquatic Sciences 66:52–71.

Riedel, J. L., and S. M. Sarrantonio. 2021. Debris flow magnitude, frequency, and precipitation threshold in the eastern North Cascades, Washington, USA. Natural Hazards 106:2519–2544.

Rosenau, M., and M. Angelo. 2007. Saving the Heart of the Fraser - Addressing Human Impacts to the Aquatic Ecosystem of the Fraser River, Hope to Mission, British Columbia. Pacific Fisheries Resource Conservation Council.

Van Nayatten, F. 2022, November 23. Vedder River management discussion.

Weatherly, H. 2022, November 4. Fraser River sediment removal and geomorphology discussion.

Weigand, D. 1991. Effect of gravel scalping on salmonid rearing habitats in the Puyallup River. University of Washington.

Whatcom County Flood Control Zone District. 2013. Nooksack River Sediment Pilot Project Analysis. https://www.whatcomcounty.us/DocumentCenter/View/69516/Nooksack-River-Sediment-Pilot-Project-Analysis-2013.