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POLYTECHNIQUE MONTRÉAL
affiliée à l'Université de Montréal

Numerical Modeling of Channelization Impacts on Hydrodynamic and Floods: Case of Okanagan River

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
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Numerical Modeling of Channelization Impacts on Hydrodynamic and Floods: Case of Okanagan River

présenté par **Meriam BOUBAKRI**
en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
a été dûment accepté par le jury d'examen constitué de :

Tew-fik MAHDI, président
Ahmad SHAKIBAEINIA, membre et directeur de recherche
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DEDICATION

À mes parents, à mes deux soeurs,
La famille c'est là où la vie commence et où l'amour ne finit jamais.

À mon mari,
Avoir un partenaire qui nous soutient est une véritable chance pour surmonter les défis de la vie, briller et réussir.

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Lastly, I extend my heartfelt appreciation to my parents, my two sisters, and my husband, who have been my steadfast pillars of support. Their unwavering encouragement, patience, and understanding provided me with the strength to navigate and overcome the challenges encountered during this journey.

RÉSUMÉ

La linéarisation des rivières est une pratique courante d'aménagement des cours d'eau qui consiste à retirer artificiellement les courbes naturelles d'une rivière, ce qui entraîne une diminution de sa sinuosité. Bien que ces activités anthropiques aient offert certains avantages, une inquiétude croissante émerge quant aux impacts potentiellement négatifs sur l'hydrodynamique, la géomorphologie et l'environnement des systèmes fluviaux. Cependant, notre compréhension du lien entre le redressement des rivières et ces conséquences, ainsi que la quantification précise de ces impacts, reste limitée. Cela souligne la nécessité de recherches approfondies sur les effets du redressement des rivières. Cette recherche étudie et quantifie numériquement l'impact du redressement des rivières sur l'hydrodynamique des flux et les conditions d'inondation. Elle repose sur un modèle hydrodynamique bidimensionnel (2D) à profondeur moyenne appliqué à divers scénarios de flux avec et sans linéarisation de la rivière. L'étude de cas concerne le cours d'eau redressé de la zone Oliver de la rivière Okanagan en Colombie-Britannique, qui a été soumise à des inondations fréquentes ces dernières années. La méthodologie utilisée dans cette recherche met l'accent sur les conséquences directes des inondations dans les sections redressées, afin de répondre à la question de la causalité entre les récents événements d'inondation extrême et la linéarisation de la rivière. L'aspect hydrodynamique de la recherche implique la simulation des caractéristiques du flux, notamment les changements de l'étendue des plaines inondables et les risques d'inondation. En quantifiant les réponses du comportement de la rivière à la linéarisation, les résultats confirment les impacts négatifs de la linéarisation à long terme sur les aspects hydrodynamiques, les modèles de flux et l'étendue des plaines inondables. Le modèle pré-linéarisation a montré une plus grande stabilité, avec moins de variations prononcées de la vitesse et des niveaux d'eau comparativement au modèle post-linéarisation sous les mêmes conditions hydrologiques, pour les sections en amont et en aval du cours d'eau de la zone Oliver. Bien que l'efficacité de la linéarisation des rivières pour le contrôle des inondations ait été confirmée par un avantage temporaire et localisé au milieu du cours d'eau redressé près de la zone urbaine. Cette analyse souligne les défis hydrodynamiques et de risque d'inondation posés par la linéarisation des rivières, mettant en évidence l'importance d'une évaluation minutieuse des processus d'ingénierie fluviale.

Mots-clés : linéarisation des rivières, hydrodynamique, inondation, modèle numérique.

ABSTRACT

Channelization is a common river engineering practice that involves artificially removing the natural meandering bends of a river, resulting in a decrease in sinuosity. Although these anthropogenic activities have offered certain benefits, there is a growing concern about the potential negative impacts on hydrodynamics, geomorphology, and the environment of river systems. However, our understanding of the connection between river straightening and these consequences, as well as the precise quantification of these impacts. This underscores the need for comprehensive research on the impacts of river straightening. This research numerically studies and quantifies the impact of river straightening on the flow hydrodynamics and flooding condition. It is based on a two-dimensional (2D) depth-average hydrodynamic model applied to flow various scenarios with and without river channelization. The case study is the channelized Oliver stream of the Okanagan River in British Columbia which has been subject to frequent floods recent years. The methodology applied in this research emphasizes direct flood consequences in straightened sections and further downstream to answer the question of causality between recent extreme flood events and river channelization. The Hydrodynamic aspect of the research involves the simulation of flow characteristics including changes in floodplain, flood extent, and flood risk. By quantifying the responses of river behavior to channelized river, the results confirme the negative impacts of channelization on long-term to hydrodynamic aspects, flow patterns and floodplain extends. The pre-channelization model demonstrated greater stability, with less pronounced variations in velocity and water levels compared to the post-channelization model under the same hydrological conditions, for both upstream and dowstream locations of the Oliver stream. While, a temporary and localized benefit of channelization was clear in the middle of the stream near urban area for water levels confirming the effectiveness of channelization for flood control. This analysis underscores the hydrodynamic and flood risk challenges posed by channelization, emphasizing the importance of careful evaluation in river engineering processes.

Keywords: Channelization, hydrodynamic, flood, numerical model.

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CHAPTER 1 INTRODUCTION

1.1 Context

Hydrodynamic modeling plays a critical role in advancing the understanding of water systems and their behavior under varying conditions, making it an indispensable tool for tackling some of the most pressing global challenges. In the field of flood risk management, hydrodynamic models have become essential for simulating water flow during extreme events, providing accurate predictions of flood extents, depths, and velocities. These models help identify flood-prone areas, enabling the design of more effective mitigation measures, such as flood defenses and floodplain management strategies [12]. The integration of morphodynamic processes into hydrodynamic models further enhances their utility by simulating sediment transport, erosion, and deposition during flooding events, which are crucial for understanding how floodwaters interact with riverbeds and coastal environments [13]. The study of sediment dynamics in rivers and reservoirs, for example, is critical for the design and management of flood control infrastructure and for optimizing the operation of dams [14]. As the effects of climate change intensify, hydrodynamic modeling becomes even more vital in assessing the impacts of altered precipitation patterns, rising sea levels, and shifts in hydrological cycles. These models allow scientists to simulate future scenarios under various climate change projections, providing valuable insights into how climate-induced changes will affect flood risks, water quality, and ecosystems [15]. For instance, the increased frequency and intensity of extreme weather events, such as intense storms and floods, can be better predicted using hydrodynamic models, allowing for proactive mitigation strategies [16]. Additionally, these models are crucial in coastal areas, where rising sea levels and storm surges present growing risks to vulnerable communities and ecosystems. Hydrodynamic models can simulate the impact of such changes, helping to design adaptive strategies for infrastructure resilience and ecosystem preservation [17]. In regions affected by ice, hydrodynamic modeling is indispensable for understanding ice dynamics, including ice formation, movement, and breakup. These processes are particularly relevant in cold-climate regions where ice affects river navigation, hydropower operations, and the structural safety of infrastructure [18]. Hydrodynamic models can simulate the formation of ice jams and predict their impact on water flow and flooding, which is especially important for managing ice-related hazards during spring thaw [19]. Furthermore, the combination of hydrodynamic and morphodynamic models can provide valuable insights into the interaction between water and ice, which is essential for the design of infrastructure that can withstand ice-induced damage and for managing seasonal water flow fluctuations [20]. Beyond these applications, hydrodynamic modeling also plays a significant role in topographic and ecological studies. Water flow is influenced by the topography of the land, including riverbeds, floodplains, and coastlines, and hydrodynamic models help to simulate these interactions. For instance, changes in the topography of a riverbed due to sediment deposition or erosion or human activities can have long-term effects on water flow patterns and flood risks [21]. The ability to model these interactions allows for better planning and management of flood risk in areas where land-use changes or natural processes are altering topographical features. Moreover, hydrodynamic models are vital for studying ecological systems, particularly freshwater ecosystems, by simulating how changes in water flow, sediment transport, and water quality affect aquatic habitats. These models are essential for assessing the impacts of human activities, climate change, and land-use changes on biodiversity and ecosystem services, guiding conservation efforts [22]. By integrating ecological variables, hydrodynamic models help predict the effects of flow regime alterations on species populations, ecosystem structure, and the overall health of freshwater ecosystems [23]. In conclusion, hydrodynamic modeling is an indispensable tool for understanding the complex interactions within water systems, from flood risk management to the impacts of climate change, ice dynamics, and ecological health. The integration of morphodynamics, topographic features, and environmental processes into these models enhances their predictive power and ability to guide sustainable water resource management. As computational capabilities improve, hydrodynamic models will become increasingly accurate and capable of addressing the growing range of challenges posed by human activities and natural events. Their role in informing policy, infrastructure development, and environmental conservation will continue to expand as we face a future of unpredictable and complex water-related challenges.

1.2 Problematic

Watercourses are fluvial systems that have complex and variable spatio-temporally responses to change [24,25]. Additionally, certain rivers are more susceptible to change than others. Waterways are subjected to natural evolution over time under the influence of climatic, tectonic, and lithological origins [24, 26]. However, previous studies have demonstrated that anthropogenic activities can induce alterations on Earth comparable to certain great natural events affecting various locations, natural systems, and with varying degrees of intensity [27–29]. This extends to rivers, where human activities such as reservoir's construction [27–30], bank revetment and land-use [31] have led to significant changes on the total area and dynamic behavior of the channel [32–34]. One seriously impactful aspect of these activities is river channelization, encompassing all fluvial channel engineering initiatives aimed to adjust and simplify the geometry bed of the watercourse [10, 11]. Channelization has been a prevalent practice for the past century in rivers worldwide, especially employed to enhance agricultural productivity, to control floods, to improve drainage, to facilitate navigation, to reduce bank erosion or to relocate roadway construction [9, 11, 35]. Many countries adopt this engineering process, particularly in the United States with the Missouri [36–38] and Mississippi rivers [11, 39–41], in Great Britain [42, 43], in Denmark [44], and in the Carpathians [45]. Channelization refers to the modification of natural river channels which are basically sinuous through artificial cutoffs along the meandering river stretch. While it has historically been viewed as an essential tool for managing watercourses, the practice of channelizing rivers and streams has become increasingly problematic due to its wide-ranging environmental impacts and its long-term sustainability concerns. One of the key issues associated with channelization is the alteration of natural hydrodynamic and morphodynamic processes. By straightening, deepening, or widening rivers, channelization disrupts the natural flow regime, which can lead to increased erosion, sedimentation, and the degradation of water quality [46]. This disruption can have severe consequences for both aquatic ecosystems and human infrastructure, as altered water flows may exacerbate flooding in some areas while reducing the natural replenishment of sediments in others, such as floodplains and deltas [47]. Moreover, channelization often leads to the destruction of habitats for many species. Natural river channels support a wide range of biodiversity by providing varied habitats, such as wetlands, riparian zones, and meanders. When rivers are channelized, these critical habitats are typically lost or degraded, leading to the decline of many aquatic species [48]. Fish populations, for example, are particularly vulnerable to the removal of meanders and natural flow patterns, as these features are essential for spawning, migration, and feeding. Furthermore, the rigid confinement of the river in a channelized form can limit the river's ability to accommodate fluctuating water levels, a crucial process for maintaining ecological balance and supporting biodiversity [49]. Channelization also poses significant challenges in the context of climate change. As the frequency and intensity of extreme weather events increase, the modified river systems may become more prone to problems such as higher water velocities, erosion, and sediment transport. These modifications can exacerbate the impacts of flooding and reduce the resilience of river systems to climate-induced changes [17]. The lack of natural floodplains and wetlands, which typically absorb excess water during floods, can worsen the effects of extreme rainfall events and storm surges. Furthermore, the loss of natural flood mitigation capacity may necessitate even more artificial interventions, leading to a cycle of increasing reliance on costly and unsustainable infrastructure solutions. In addition to the environmental impacts, channelization can also have socio-economic consequences. While it often provides short-term benefits such as flood protection and improved navigation, these gains may come at the expense of long-term ecological and economic costs. The loss of ecosystem services, such as water purification, groundwater recharge, and biodiversity, can result in a decline in local resources that communities rely on for agriculture, fishing, and recreation [23]. Additionally, as climate change continues to alter river dynamics, the infrastructure designed to control river flow may become inadequate or even counterproductive, requiring costly retrofits or replacements [50]. In conclusion, while channelization may offer immediate benefits for flood control, navigation, and land development, its long-term environmental, ecological, and socio-economic consequences present significant challenges.

This study focuses on the Oliver region of the Okanagan River, located in the southern part of the river's watershed, to analyze the hydrodynamic changes associated with channelization. By comparing pre- and post-channelization conditions, this study aims to provide a more comprehensive understanding of the river's response to human interventions and quantify the effects of these changes on velocity, water levels, and floodplain dynamics.

The structure of this report is as follows: **Section 2** reviews the relevant literature on river channelization, its positive and negative impacts discussed in previous studies. **Section 3** outlines the methodology employed in this study. It details the data collection process, the setup and calibration of the numerical model, the simulation results, and a comparative analysis of hydrodynamic characteristics and floodplain dynamics under pre- and post-channelization conditions. Additionally, it includes a discussion of the variations in velocity and water level on pre- and post-scenarios to analyze and interpret the impact of channelization on these variables. Finally, **Section 4** concludes the report and offers recommendations for future research in the Okanagan River and similar systems.

CHAPTER 2 LITERATURE REVIEW

This chapter is dedicated to the literature review. The first section addresses fluvial systems and hydrosystems, the second explores meandering systems, the third focuses on the channelization process, and the fourth discusses methods for investigating fluvial processes.

2.1 Fluvial system and Hydrosystem

Fluvial system and hydrosystem are two concepts developed for the systematic study of the dynamics of rivers and their associated spaces. The first, appeared in the early 1960s [51, 52] and formalized in the late 1970s [3] is defined as the particular arrangement of morphological entities (channel, flood plain) within a watershed. It highlights the links between the upstream/downstream organization of these entities and the flows existing between them. This system has a mainly longitudinal dimension dictated by the evolution of the hydrological slopes which divide it into three subsets (Figure 2.1).

- Sediment production areas are marked by dominance of steep slope erosion processes (energy-dense).
- Transition zone with reduced slope and balance between erosion and sedimentation.
- Deposition zone with low slopes where sedimentation processes dominate (less available energy).

The limited vertical relationships of this approach led to the beginning from the 1990s to the emergence of the hydrosystem concept [4]. It is based on the integration of the alluvial plain as an ecological complex consisting of spatial units nested and connected by flows [53]. This approach takes into account the multi-directionality of material and energy exchanges between the different units. The Commission has also adopted a proposal for a Directive on the protection of the environment. It allows to detail the lateral exchanges between the river and its floodplain, but also vertical with the water table. This approach also brings a dynamic character to the system by introducing a temporal dimension. Streams are then considered as systems that evolve in four dimensions in space and time (Figure 2.1).

The combination of these two approaches is necessary for the study of a body of water. Indeed, the river hydrosystem is a complementary subset of the river system, which allows to better understand the multiple exchanges between the river and its close environment. The river system widens the scale of analysis and makes it possible to locate the sector studied in a global system. It offers a better interpretation of river dynamics in their relationship with environmental and societal changes that affect the watershed [54]).

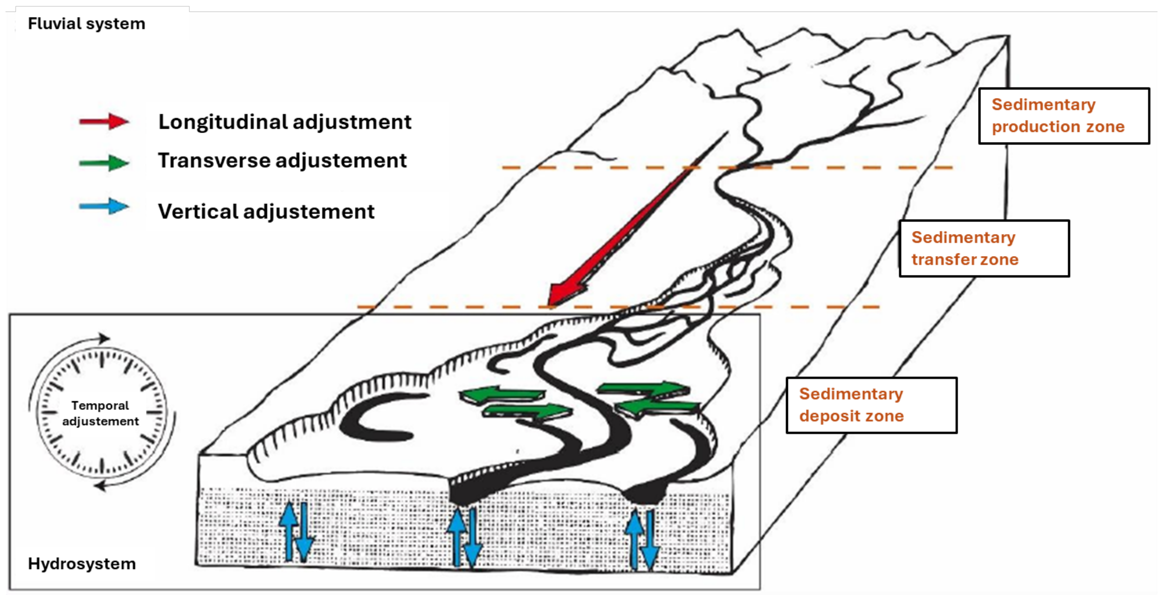


Figure 2.1 Representation of the river system and the Hydrosystem (modified from [3, 4])

2.2 Meandering systems

Water transport models the landscapes crossed through channel structures that dig and fill the valleys. These are important factors in the geomorphology of our landscapes, but also those of other planets such as Mars where traces of paleo-channel systems have been found [55, 56], evidence that there was water on this planet, as on Titan [57]. In continental context, rivers govern the sharing of water resources and for a long time also the division of territories. Rivers have been shaped according to human needs, they were channeled, barred, by geotechnical works, at the expense of their natural need for space for migration and overflow, with sometimes dramatic consequences. Backwaters promote ecosystem development [58]. They also resist erosion due to their clay nature. Understanding these systems has therefore been the heart of urban and agricultural planning topics for centuries. Thus, they contribute little by little to the formation of the substrate or, more precisely, the pile of sediments on which they evolved. Indeed, the study of meandering systems requires a sedimentary profile that requires variation in temporal and spatial scales as well as geological and sedimentary analyzes to fully understand it [5]. The profile of these channels varies with the interaction of various factors (e.g., distance to source, hydrodynamics, erodibility of meander belt) [59, 60]. A simplified illustration of the succession of the different profiles of channel systems along the transport of water and sediments is proposed in Figure 2.2.

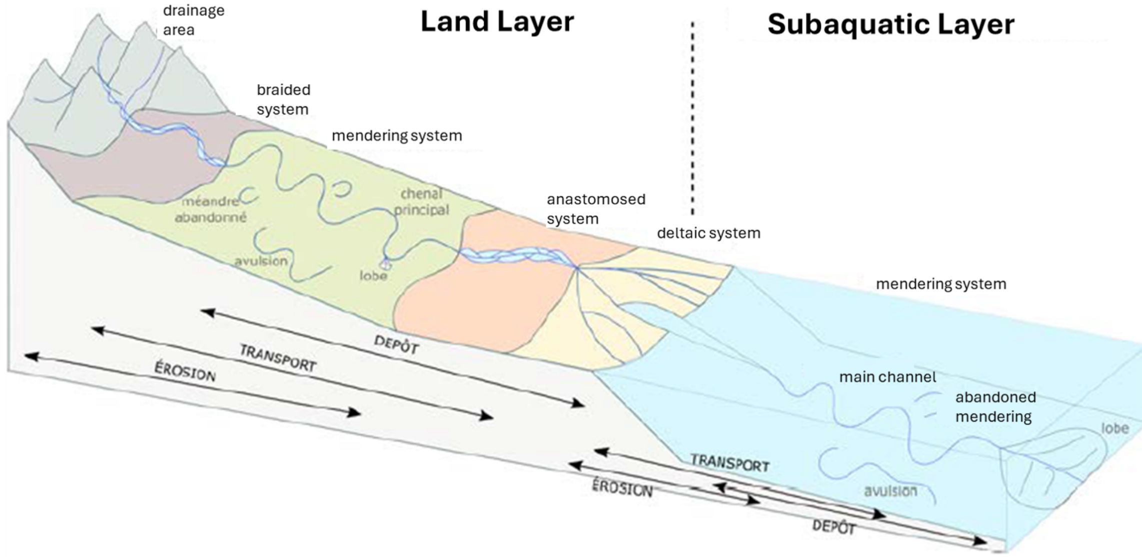


Figure 2.2 General scheme of the contexts of alluvial deposits from the draining zone to the submarine plains (modified from [5])

Water transport begins at altitude with the draining area corresponding to the catchment area. The channels are rather straight, the main process is erosion, so there are mainly rocky river beds. A little further downstream with a decreasing slope, braid systems are characterized by a higher sediment load than their ability to deposit suspended particles in the current. The channels are therefore unstable and intersected by multiple movable internal bars. Then, the system refocuses on a single more sinuous channel. It draws meanders in the flood plain. In addition to the main channel, other structures can also be observed in this one such as old meanders isolated from the main channel, called abandoned meanders, or old trajectories cut off from the current system by an avulsion. The meanders evolve in space and time, due to the deposition on the internal edge of suspended sediments and erosion on the external edge (Figure 2.3) [5, 61].

Near its opening, the system can again divide into several relatively straight channels that form a delta. This stage is characterized by a high rate of deposition at the outlet in the sea. Underwater channels can also form under the force of more or less continuous and sediment-laden submarine currents [62]. These have a strong geomorphological resemblance to continental meandering systems (Figure 2.4).

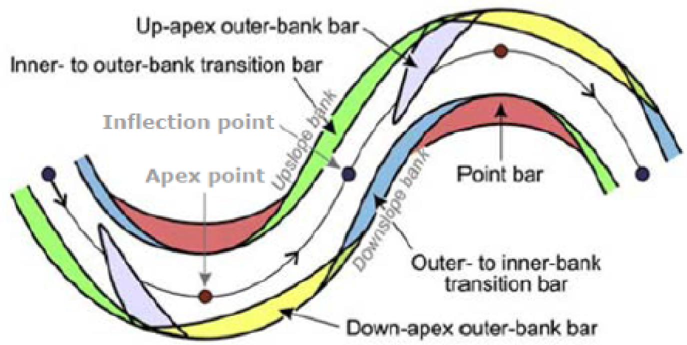


Figure 2.3 Erosion and deposition through channel migration. (According to [6])

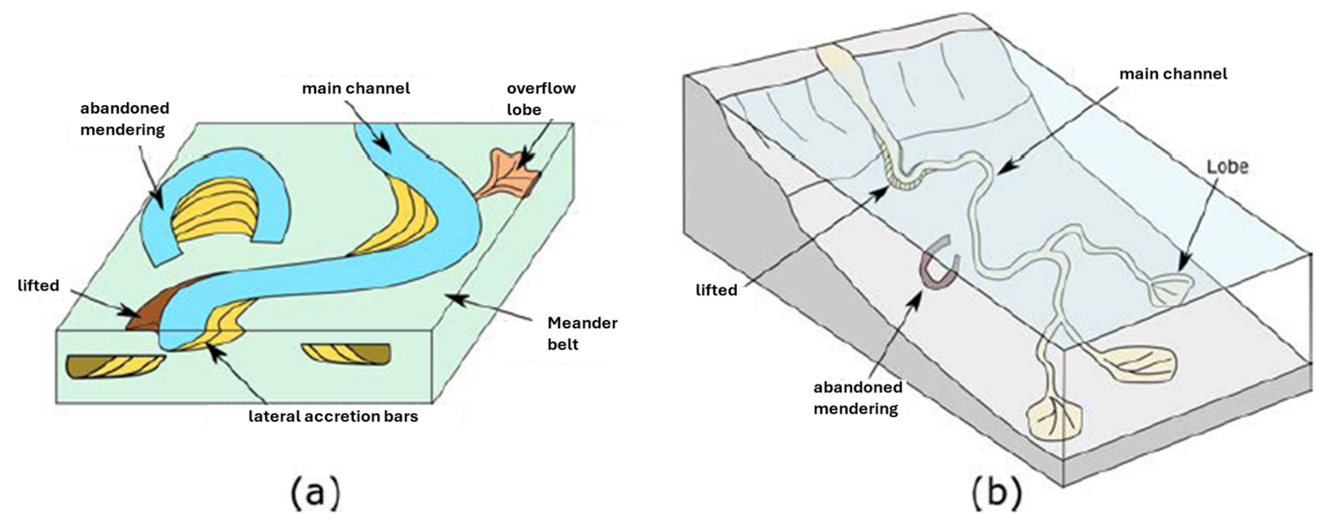


Figure 2.4 Diversity of sedimentary structures found similarly in a b-fluvlatile or turbiditic context. (Modified from [7])

They develop the same structure in meanders with a lateral extension and downstream of the trajectory, and a vertical component by system aggradation. Abandoned meanders can also be observed, as avulsions, side lobes and sand bars [63]. Mutti and Normark [64] were the first to use the term turbidity channel to evoke the perennial conduit that carries sediment at the bottom of the slope. For others, turbidity currents are dense gravity currents with non-cohesive behaviour and without direction preference nor spatial organization [65]. The main differences between turbidity and river Meandering systems concern the physical and hydrodynamic process at the origin of the phenomenon. The sedimentary contribution is also more discontinuous in submarines than in continental domains. Several studies have concluded that, in comparison with the fluviatile meandering channel, the turbidity meandering channel migrates more vertically than laterally. Abandoned meanders are rarer, as are crevice lobes. Vertical stacking is predominant on lateral continuity of geological bodies [63]. Nevertheless, despite differences in size and probability of occurrence of events, the two types of systems are very close geometrically. They present the same structures despite physically different processes [5].

2.3 Channelization

2.3.1 Channelization Process

The process of channelization involves engineering interventions to modify river systems, aiming to streamline their flow, simplify geometry, and enhance predictability for specific purposes such as navigation, flood control, and agricultural productivity. These changes typically include redirecting flows, altering riverbed shape and slope, and removing natural meanders to increase slope and accelerate water movement [8, 10]. While these interventions have historically provided benefits such as improved drainage and reduced local overflows during floods [11], they have also caused significant ecological and geomorphological consequences. Channelization has been a prevalent practice worldwide, with notable examples in the United States, Europe, and other regions. Large-scale projects, such as those on the Mississippi and Missouri rivers, sought to improve transportation and agricultural productivity but resulted in severe ecological damage, including wetland loss, reduced biodiversity, and degraded water quality [66, 67]. Similarly, post-World War II channelization in Europe, including the Carpathians, aimed to enhance agricultural productivity and flood management but led to habitat loss, increased flood risks, and decreased ecosystem resilience [42, 45]. The engineering process typically involves artificial cutoffs along meandering stretches to shorten river length and reduce sinuosity (Figure 2.5). These changes increase slope and flow power, enhancing erosive capacity and leading to channel incision. This incision can propagate upstream, disrupting the river system, while downstream sedimentary deposition elevates the channel bed [8]. Artificial bank stabilization, a common component of channelization, prevents natural sediment replenishment, exacerbating incision and simplifying flow patterns, which homogenizes habitats and reduces ecological diversity [4].

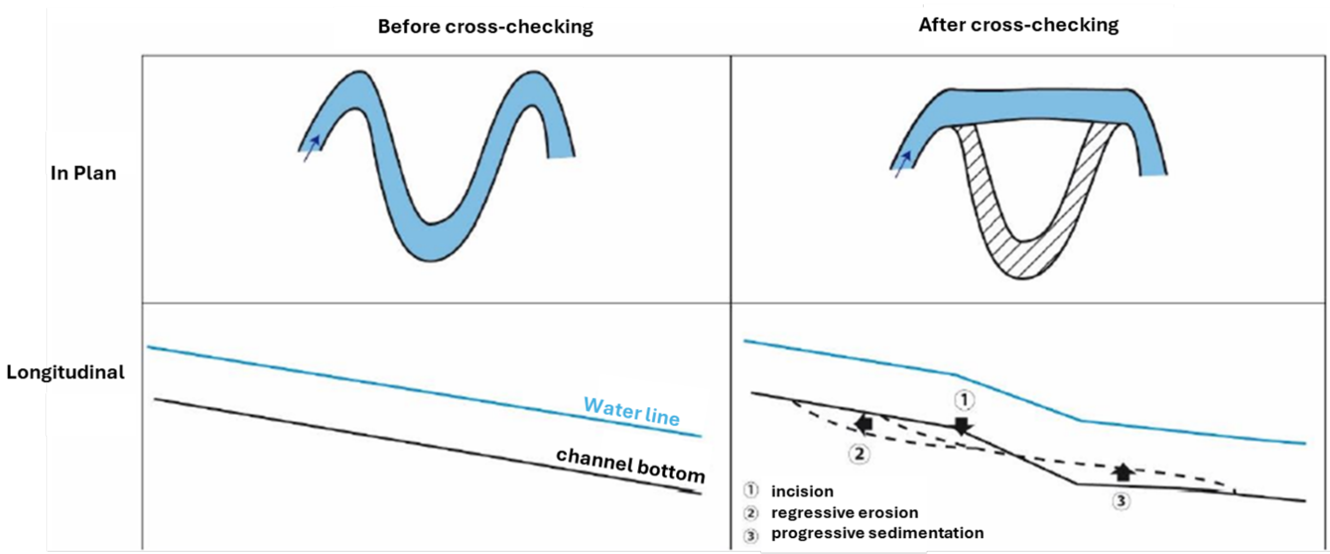


Figure 2.5 Meander cut and consequence on the long profile (modified from [8])

2.3.2 Types of Channelization

Channelization is a broad concept that encompasses all the development of [10]. It refers to interventions that are assumed to increase the flow rate by modifying the trace, cross geometry, slope, and roughness of a river. Longitudinal and transverse stabilization structures (e.g. thresholds), as well as actions to maintain the bed and riparian vegetation (e.g. cleaning, dredging), usually accompany these interventions to limit erosive processes channel-induced. Channel-type developments address human use of the floodplain (or major bed) and depend on the interaction between natural features of rivers and human activities (e.g., agricultural uses, urbanization, use of the driving force of water). In watercourses of medium size (between 5 and 30 meters wide), these facilities allow local control of floods, erosion of the banks and the bottom, land sanitation, fish enhancement, recreation, irrigation or pollution control. These multiple and sometimes competing uses result in a certain moderation of the effects of the developments. However, following catastrophic events (eg floods of rare frequency), rivers are urgently needed without planning or concern for the ecological consequences on their entire course. In addition, such as protecting residents from flooding is one of the main objectives and that most of the rivers are located nearby housing, all of the developed areas eventually become contiguous and the channel of the total stream. There are many classifications that distinguish the different types of channels according to their objectives and impacts on the diversity and dynamics of the environment [9,11]. All take into account in part the work of correction of the bed, stabilization works, and maintenance of the vegetation of the banks. The typology of Brookes [9] and its adaptation by Wasson [10] remain the most precise and frequently used in Europe (Figure 2.6).

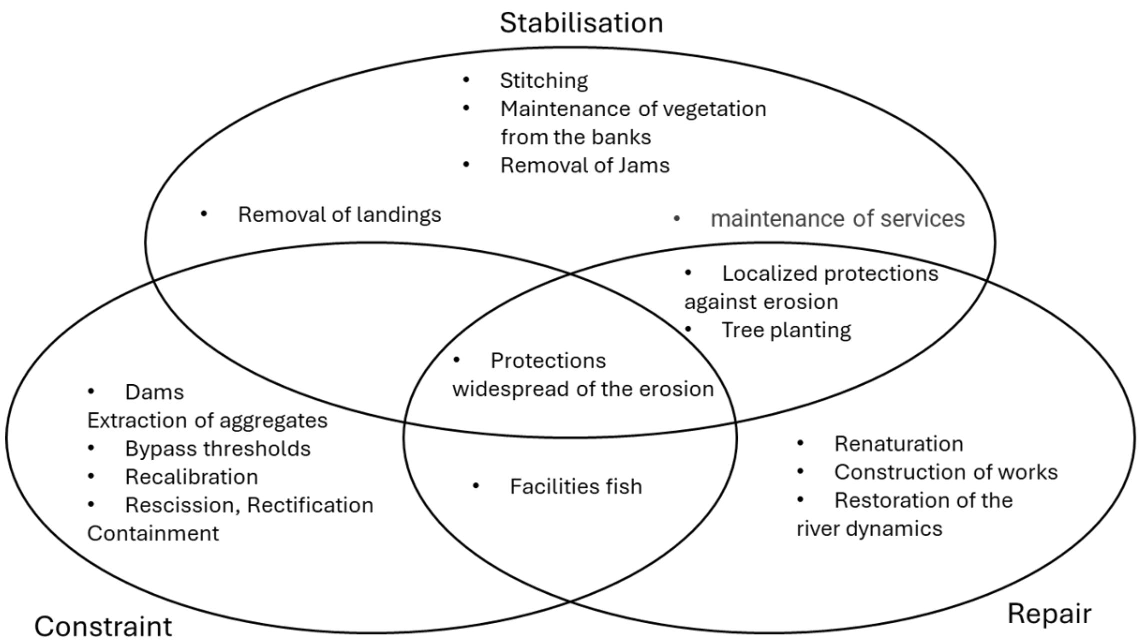


Figure 2.6 Typology of human channelization interventions affecting the physical running water environment. (According to [9, 10]).

2.3.3 Methods of Channelization

The methods most frequently used to achieve this objective are reviewed in detail by Brookes [9, 11]. This author distinguishes 5 major types of interventions (Figure 2.7).

a. recalibration

The goal is to increase the discharge capacity of minor bed flood flows. This recalibration is usually done by widening and deepening the channel. The ideal profile would then be the one with the best capacity for the minimum excavation. Beds between unprotected earth banks are often cut into trapezoidal sections to improve bank stability.

b. realignment, rectification

This type of channelization aims to shorten a portion of meandering or meandering rivers, by making artificial crossings of the elbows. This is usually done at the scale of a sinuosity but can also be done on a long meandering segment and concern all the inflections of the path.

c. containment

Damming, whether localized or extensive, is intended to protect the riparian lands of the stream from flooding and to increase the hydraulic capacity of the high water bed. At the same time, these dams can be used to protect agricultural or urbanized areas from erosion phenomena related to dynamic adjustment of rivers.

d. bank guards

In most cases, the protection of banks carried out in various ways and with different materials are implanted in the concavities of the sinuosities, where the major phenomena of erosion in high waters develop. This category may include localized developments such as cobs. The ecological impact depends a lot on the techniques and materials used.

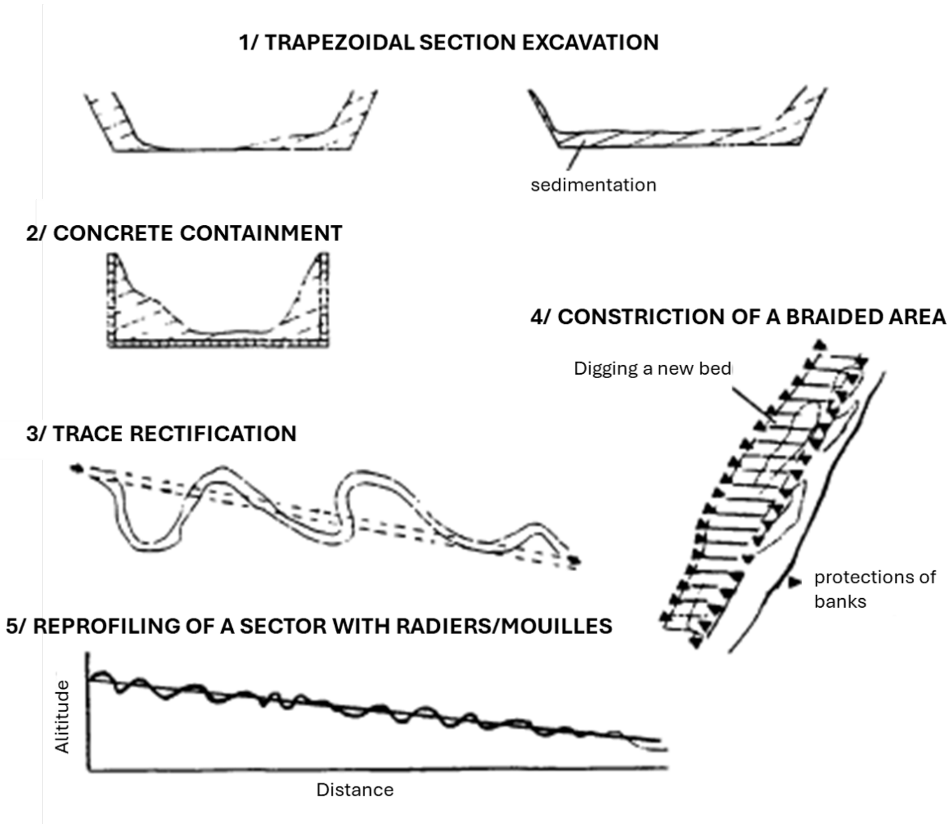


Figure 2.7 Examples of river developments (modified from [11])

2.3.4 Impacts of channelization

River channelization is a process that alters the natural morphology and dynamics of rivers to create a more predictable, linear flow. This involves modifying the river's course, shortening its length, and reducing its sinuosity to redirect the flow around obstacles, straighten meanders, and increase the slope of the riverbed [68–70]. The increased slope enhances the stream's energy, thereby elevating its capacity for erosion and sediment transport. These modifications are often implemented to optimize water management, mitigate flooding, or support agricultural and urban development. However, the steeper slopes associated with channelization amplify the river's power and erosive potential, leading to channel incision. This process involves the downward cutting of the riverbed, which can propagate upstream and destabilize large portions of the river system. Upstream incision not only alters sediment transport dynamics but also disrupts the surrounding ecosystems. Conversely, downstream sections may experience sediment deposition due to the sediment surplus carried by the modified flow. This deposition can raise the channel bed, potentially altering water flow and flooding patterns [8]. Channelized rivers often involve artificialization of their banks to prevent erosion. This includes reinforcing banks with concrete, riprap, or other materials. While these measures stabilize the channel, they also eliminate natural bank processes, such as sediment contribution and vegetation growth. This lack of natural sediment input further exacerbates channel incision and reduces the river's ability to maintain its geomorphological balance. Additionally, artificial banks hinder ecological connectivity, reducing the diversity and quality of aquatic habitats [4]. The homogenization of flow patterns caused by channelization often leads to a loss of habitat heterogeneity, severely impacting aquatic species and ecological processes. The oversizing of river cross-sections is another common feature of channelization, designed to increase the channel's hydrological capacity during flood events. Larger cross-sections can accommodate higher water volumes, reducing local overflows and flood risks in specific areas. However, this increased capacity can have adverse downstream consequences. By accelerating water flow, oversized channels contribute to the concentration of floodwaters downstream, potentially exacerbating flooding in lower-lying areas. Furthermore, the increased flow velocity can erode downstream habitats and further disrupt sediment transport [11]. The long-term ecological and environmental costs of river channelization are significant. By simplifying river morphology and flow dynamics, channelization disrupts natural sediment transport, alters hydrological regimes, and diminishes the ecological integrity of river systems. Aquatic habitats are particularly vulnerable, as the loss of meanders, natural banks, and habitat diversity reduces their ability to support a wide range of species [68, 69]. In turn, this has cascading effects on ecosystem services, including water purification, flood regulation, and biodiversity conservation. In conclusion, while river channelization provides certain short-term benefits, such as flood control and land optimization, its long-term impacts on river systems and ecosystems are overwhelmingly negative. The trade-offs associated with these modifications highlight the need for more sustainable river management practices that balance human needs with ecological preservation. In this context, a preliminary synthesis was proposed in the work of Graves et al. [1], addressing the "advantages and drawbacks" impacts of channelization on the hydromorphology and ecology of watercourses (Table 2.1). This synthesis has since been modified and supplemented with additional bibliographic elements published in subsequent studies [38, 71–74].

Table 2.1 Summary of the hydro-morphological and ecological impacts of river thresholds (modified from [1])

Impact	**Drawbacks**	**Advantages**
Impacts on liquid flow	- Strong reduction in the speeds in the upstream retention. - Homogenization of flows and over-representation of lenticular facies. - Greater downsizing in short-circuited sectors. - Increased risk of flooding upstream in case of threshold mishandling.	- Control of water levels that can limit the rapid spread of flows downstream during small floods. - Natural irrigation of grassland in valley bottom more frequent.
Impacts on solid flow	- Restricted blocking of coarse sediment transport if regular maintenance of the hold or poor management of the threshold. - Regular silting (fertilization) of the meadows in the valley.	- Morphological adjustment of bed geometry: stabilization of longitudinal and transverse profiles. - Reduction of upstream erosion and sediment transport.
Morphological impacts	- Regressive upslope depletion if blocking of sedimentary transit. - Significant sedimentation in alluvial plains and formation of terraces. - Adjustment of bed geometry to new solid flow conditions: risk of progressive erosion downstream (bank erosion, bed incision). - Risk of shorted channel contraction (reduction in width and depth).	- Stabilization of longitudinal and transverse profiles. - Reduction of upstream erosion and sediment transport.
Piezometric impacts on the alluvial aquifer	- Elevated water table roof upstream, increasing flood risks. - Reduced channel-surface connectivity in case of bed backfill. - Reduction in water filtration and productivity.	- Increase in the level of the alluvial water table. - Limitation of leaching effects and better aquifer stability.
Ecological impacts	- Ecological fragmentation and barriers to fish migration. - Habitat standardization and potential emergence of invasive species. - Reduction of vegetation and destabilization of riparian zones.	- Development of wetlands and spawning areas. - Increase in fish abundance and stability of riverbanks.

Despite their intended benefits, channelization projects have underscored the long-term costs of these interventions. Wetland loss and reduced biodiversity in the United States and Europe highlight the need for restoration initiatives to mitigate past damage and promote resilient ecosystems in the face of environmental pressures [66, 68]. Due to the significant damage caused by channelization during the time and the high recurrence of flood events, many studies [1, 38, 71–75] have employed a variety of investigative methods to examine the impacts of channelization on river systems in different aspects (e.g., sediment transport, riverbank erosion, morphodynamic, land cover, ecological, flood events,...). For example, Graves et al. [1] and Conesa-García et al. [71] used a combination of field surveys, hydrodynamic modeling, and remote sensing data to assess changes in river morphology post-channelization. These methods helped identify alterations in sediment transport and flow patterns. In their studies, Padovan, Cockburn, and Villard [72] also integrated physical measurements and hydraulic modeling to explore the relationship between channelized river features and flood risks, emphasizing the spatial variability in these impacts. On the other hand, Li, Gao, and Wu [73] employed computational fluid dynamics (CFD) models to simulate the hydrodynamics of channelized rivers, providing insight into flow patterns and the evolution of riverbanks. Similarly, Jerin et al. [38] and Li et al. [74] used a mix of remote sensing techniques, such as LiDAR and satellite imagery, alongside traditional field surveys to examine post-channelization river dynamics and associated flood risks. The combination of these approaches offers a comprehensive understanding of the complex processes at play, though a notable gap remains in assessing pre-channelization conditions, which could provide valuable comparative insights.

2.4 Methods of investigating fluvial processes

Understanding fluvial processes requires integrating multiple investigative methods, each offering unique insights that complement one another for a comprehensive analysis of river dynamics.

2.4.1 Physical observations

Physical observations, which are a fundamental approach, involving direct measurement and assessment of river morphology, hydraulic characteristics, and sediment dynamics. Techniques such as surveying river cross-sections, measuring flow velocities, and analyzing sediment transport rates are key to identifying erosion, deposition, and channel migration [75]. For example, Roy and Sahu [75] used detailed physical measurements to assess how land cover affects channel form in headwater streams. Mihu-Pintilie et al. [76] similarly employed channel profiling and sediment sampling to improve urban flood hazard assessments. These physical methods provide the essential data that informs subsequent modeling efforts and ensures the accurate representation of real-world conditions.

2.4.2 Field assessments

Field assessments play a crucial role in gaining a deeper understanding of local-scale fluvial processes by systematically sampling on-site. These include water quality measurements, sediment analysis, discharge monitoring, and vegetation surveys, offering valuable ground-truth data to validate remote sensing findings and model predictions. For instance, Mihu-Pintilie et al. [76] used field data to enhance urban flood hazard mapping by incorporating sediment deposition and vegetation impacts. Similarly, Urzica et al. [77] utilized field measurements to evaluate sedimentation dynamics in reservoirs, supporting model outputs for flood control strategies. These assessments provide real-time data necessary for interpreting processes influencing river systems, such as sediment transport, erosion, and vegetation growth.

2.4.3 Remote sensing technologies

Remote sensing technologies, including LiDAR, aerial imagery, and satellite data, enable large-scale monitoring of river systems, offering high-resolution mapping and tracking of river morphology, floodplains, and sediment transport. These technologies are critical for both cross-sectional and temporal studies of river dynamics. For example, Mihu-Pintilie et al. [76] used LiDAR data to improve urban flood hazard mapping, demonstrating the power of remote sensing in predicting fluvial processes. Urzica et al. [77] also employed satellite imagery to assess floodplain changes in the context of reservoir management. Remote sensing supports long-term studies, as evidenced by Roy and Sahu [75], who used satellite data to track river evolution over decades. These technologies provide crucial data for understanding changes in river morphology, sediment deposition, and floodplain evolution, contributing to effective flood management and conservation efforts.

2.4.4 Numerical modeling

Numerical modeling plays a central role in synthesizing data from physical methods, field assessments, and remote sensing to simulate and predict river behavior under varying conditions. Computational models like HEC-RAS, MIKE 21, and SWAT allow researchers to replicate complex hydrodynamic and sediment transport processes. These models simulate flood inundation, sediment deposition, and channel morphological changes, providing insights into how rivers respond to natural events and human interventions. Brunner [78] demonstrated the utility of HEC-RAS in assessing river hydraulics and simulating the effects of channelization, offering critical data for flood management. Similarly, Quiroga et al. [79] used 2D HEC-RAS to simulate flood dynamics in the Bolivian Amazon, illustrating the adaptability of models to diverse river systems. Numerical models rely on calibrated parameters, such as flow rates, sediment transport capacities, and channel roughness, to generate accurate predictions. For example, Urzica et al. [77] applied 2D HEC-RAS to assess the flood control capacities of multi-reservoir systems in Romania, validating their models with field data and providing reliable predictions for flood management. These models not only simulate current conditions but also project future scenarios, incorporating variables like climate change and land use alterations to predict how rivers will evolve under different stressors. Such capabilities are essential for long-term river system planning, especially in the face of climate change. For instance, Mihu-Pintilie et al. [76] used numerical models to predict urban flood events, aiding in flood mitigation and floodplain management. Moreover, numerical modeling supports river management decisions, simulating interventions such as dam operations or channel restoration. Brunner [80] and Quiroga et al. [79] showed how these models optimize mitigation measures for flood risks and sediment management. Additionally, numerical models can simulate the effects of land cover, vegetation, and agricultural practices on river systems, as demonstrated by Roy and Sahu [75] and Mihu-Pintilie et al. [76], offering insights into sediment transport and water quality. These models are vital for comprehensive river basin management, blending scientific understanding with practical solutions for sustainable water resource management. Numerical modeling is grounded in the governing equations of fluid dynamics, primarily the Saint-Venant equations for shallow water flow, which describe the conservation of mass and momentum in river systems. These equations, in combination with sediment transport models, enable the simulation of flow, sediment transport, and riverbed evolution, providing a robust framework for analyzing and predicting river dynamics.

2.4.5 Saint Venant 2D model

a. Principle

In many free-surface flow problems, the flow equations vary little in the vertical direction, allowing the use of two-dimensional flow equations. This two-dimensional form is derived by integrating the Navier-Stokes equations under the assumptions of constant density and hydrostatic pressure in the vertical direction (from the bottom to the surface). The vertically integrated components of the velocity vector are expressed as:

$$u = \frac{1}{h}\int_{z_b}^{z_s} U dz \tag{2.1}$$

$$v = \frac{1}{h}\int_{z_b}^{z_s} V dz \tag{2.2}$$

b. Continuity equation

The integration of the continuity equation according to the vertical gives:

$$\int_{z_b}^{z_s}\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z}\right) dz = 0 \tag{2.3}$$

Using the Leibnitz rule:

$$\begin{aligned}\int_{z_b}^{z_s}\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z}\right) dz = &\frac{\partial}{\partial x}\int_{z_b}^{z_s} U dz - U(x,y,z_s)\frac{\partial z_s}{\partial x} + U(x,y,z_b)\frac{\partial z_b}{\partial x} \\ &+ \frac{\partial}{\partial y}\int_{z_b}^{z_s} V dz - V(x,y,z_s)\frac{\partial z_s}{\partial y} + V(x,y,z_b)\frac{\partial z_b}{\partial y} \\ &+ W(z_s) - W(z_b) = 0\end{aligned} \tag{2.4}$$

Taking into account the hypothesis of impermeability:

$$\frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} + \frac{\partial z_s}{\partial t} + \frac{\partial z_b}{\partial t} = 0 \tag{2.5}$$

Where $h = z_s - z_b$
Thus,

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \tag{2.6}$$

ou sous la forme :

$$\frac{\partial h}{\partial t} + \mathrm{div}(h\bar{u}) = 0 \tag{2.7}$$

The continuity equation above can also be written in the form

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{2.8}$$

c. Equation of motion quantity

With the hydrostatic pressure hypothesis, the equation of the quantity of motion is written as follows:

$$\frac{\partial U}{\partial t} + \frac{\partial(U^2)}{\partial x} + \frac{\partial(UV)}{\partial y} + \frac{\partial(UW)}{\partial z} = \frac{\partial}{\partial x}\left[\rho g(z_s - z)\right] + \frac{\partial}{\partial z}\left(\tau_{xx} + \tau_{xy}\right) \tag{2.9}$$

- Terms as a function of time

$$\int_{z_b}^{z_s} \frac{\partial U}{\partial t} dz = \frac{\partial}{\partial t} \int_{z_b}^{z_s} U dz - U(z_s)\frac{\partial z_s}{\partial t} + U(z_b)\frac{\partial z_b}{\partial t} \tag{2.10}$$

- Advection term

$$\int_{z_b}^{z_s} \frac{\partial U}{\partial x} dz = \int_{z_b}^{z_s} U' dz' - U(z_s)\frac{\partial z_s}{\partial x} + U(z_b)\frac{\partial z_b}{\partial x} \tag{2.11}$$

$$\int_{z_b}^{z_s} \frac{\partial U}{\partial y} dz = \int_{z_b}^{z_s} UV dz = U(z_s)\frac{\partial z_s}{\partial y} + U(z_b)\frac{\partial z_b}{\partial y} \tag{2.12}$$

Using the expression of UV for example:

$$\frac{\partial}{\partial y} \int_{z_b}^{z_s} UV dz = \frac{\partial}{\partial y} \left(\int_{z_b}^{z_s} (u + U - u)(v + V - v) dz \right) = \frac{\partial}{\partial y} \int_{z_b}^{z_s} uv dz + \frac{\partial}{\partial y} \int_{z_b}^{z_s} (U-u)(V-v) dz \tag{2.13}$$

Same for UW:

$$\int_{z_b}^{z_s} \frac{\partial UW}{\partial z} dz = U(z_s)W(z_s) - U(z_b)W(z_b) \tag{2.14}$$

- Pressure gradient

$$\int_{z_b}^{z_s} \frac{1}{\rho} \frac{\partial}{\partial x} \Big(pg(z_s - z) \Big) dz = -hg \frac{\partial z_s}{\partial x} \tag{2.15}$$

- Term of diffusion

$$\frac{\partial}{\partial x} \Big(\tau_{xx}^{(e)} + \tau_{xx}^{(v)} \Big) + \frac{\partial}{\partial y} \Big(\tau_{xy}^{(e)} + \tau_{xy}^{(v)} \Big) + \frac{\partial}{\partial z} \Big(\tau_{xz}^{(e)} + \tau_{xz}^{(v)} \Big) \tag{2.16}$$

In a horizontal plane, let us define the stress tensor τ_e, referred to as effective or equivalent, which includes both viscous and turbulent stresses. The components of the effective stress in a horizontal plane can be expressed as:

$$\tau^{(e)} = \begin{bmatrix} \tau_{xx}^{(e)} & \tau_{xy}^{(e)} \\ \tau_{yx}^{(e)} & \tau_{yy}^{(e)} \end{bmatrix} \tag{2.17}$$

Additionally, two terms τ_{bx} and τ_{sx} appear, representing the x-axis components of shear stresses acting at the free surface or the bed, respectively. These components are defined as:

$$\tau_{bx} = \frac{1}{\cos(\alpha_b)} N_b \Big(\tau^{(v)} + \tau^{(i)} \Big)_b \tag{2.18}$$

and

$$\tau_{sx} = \frac{1}{\cos(\alpha_s)} N_s \Big(\tau^{(v)} + \tau^{(i)} \Big)_i \tag{2.19}$$

N_b and N_s are unit vectors normal to each surface, while α_b and α_s are the angles between the normal vectors and the vertical axis. Considering the calculations of the various terms in an integrated momentum balance, the integrated momentum equation on the x-axis is expressed as:

$$\frac{\partial hu}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = -gh\frac{\partial z_s}{\partial x} + \frac{1}{\rho}\Big(\tau_{sx} - \tau_{bx}\Big) + \frac{\partial}{\partial x}\Big(h\tau_{xx}^{(e)}\Big) + \frac{\partial}{\partial y}\Big(h\tau_{xy}^{(e)}\Big) \tag{2.20}$$

$$\frac{\partial hv}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hv^2)}{\partial y} = -gh\frac{\partial z_s}{\partial y} + \frac{1}{\rho}\Big(\tau_{sy} - \tau_{by}\Big) + \frac{\partial}{\partial x}\Big(h\tau_{xy}^{(e)}\Big) + \frac{\partial}{\partial y}\Big(h\tau_{yy}^{(e)}\Big) \tag{2.21}$$

2.5 Conclusion

The purpose of this thesis is to analyze the hydrodynamic behavior of the river under pre- and post-channelization conditions. Thus, we have chosen the numerical modeling method for hydraulic analysis, as it provides a reliable framework for simulating river dynamics, flood risk, and water surface elevations. A numerical model is developed to simulate and understand the river's response to the channelization process over time and space. Compared to previous studies, this thesis explores two key innovations simultaneously: the quantification of channelization impacts on hydrodynamic conditions and flood risks, as well as the analysis of these impacts in the river's pre-channelization state.

CHAPTER 3 NUMERICAL MODELING OF CHANNELIZATION IMPACTS ON HYDRODYNAMIC AND FLOODS

3.1 Introduction

This approach overlooks the spatio-temporal complexities of channelization, particularly the contrasting hydrodynamic effects on flood extents in both pre- and post-channelized scenarios. To address this limitation, a numerical model is developed to integrate both pre- and post-channelization conditions, enabling a comprehensive investigation of river channelization. It is essential to analyze these aspects to determine whether the observed impacts are solely attributed to channelization and to improve the understanding of river dynamics and flood behavior. This method was applied to the Oliver stream within the Okanagan River watershed, where we quantified the effects of channelization on velocity and water level propagation along the channelized stream. Finally, we compared floodplain extents before and after channelization, examining their relationship with hydrodynamic factors to provide a more accurate assessment of channelization impacts.

3.2 Study area

The Okanagan River is a tributary of the Columbia River, extending approximately 185 kilometers through southern British Columbia and north central Washington. The Okanagan Valley measures roughly 20 kilometers in width. Originating from Okanagan Lake in Penticton, British Columbia (BC), the river flows into the Columbia River at Brewster, Washington (WA). It connects the cities of Penticton, BC, and Omak, WA, and drains the scenic Okanagan Country, a plateau region east of the Cascade Range and north and west of the Columbia River, which includes the Okanagan region of British Columbia. Since the mid-1950s, the Canadian portion of the river has been channelized, reducing its total length by half. These engineering projects were implemented by the government of British Columbia to improve flood control and navigation [81]. The channelization of the Okanagan River has significantly reduced the quantity and quality of its natural aquatic and riparian habitats. This alteration contributed to record-setting high flows and flooding in the Okanagan Valley in 2017, followed by high flows in 2018 [82]. This study focused on analyzing only the Oliver region located in the southern Okanagan Basin between Vaseux Lake and Osoyoos Lake (Figure 3.1), with an approximate length of 35 km and an average width of 50 meters. Other streams of the Okanagan river were not considered, as they have undergone restoration projects involving re-meandering and re-connecting to return them to a natural state. As a result, 84% (30 km) of the Oliver stream has been channelized, straightened, narrowed, and dyked, severely impacting the health of the river. Currently, only 16% (5 km) of the river remains in a natural (3 km) or semi-natural state (2 km) exactly at the upstream of the Oliver region [83]. The primary driver of channelization in this region is the critical dependence on freshwater resources to support key industries, including agriculture (notably orchards and vineyards) and tourism. Known as the "Wine Capital of Canada," the region relies heavily on these sectors, as well as the presence of two world-class golf courses [84].

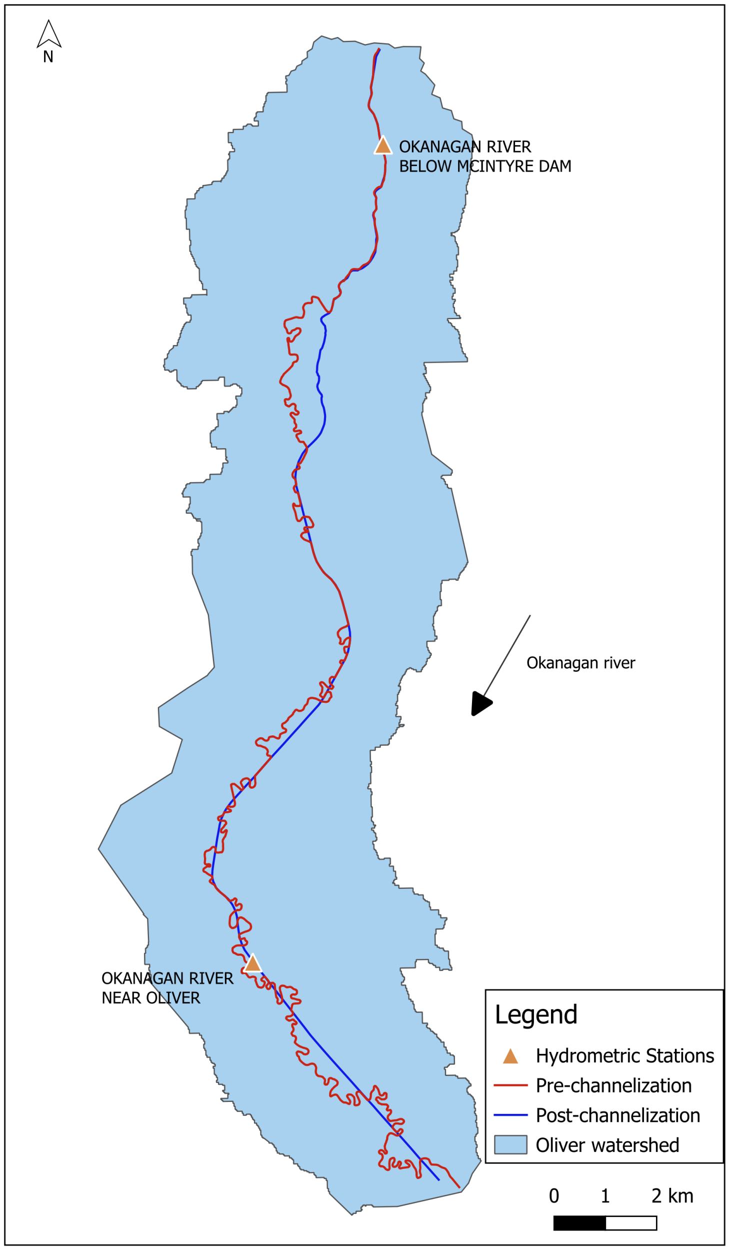


Figure 3.1 Study river reach (Lower Okanagan River)

3.3 Methods

3.3.1 Data

3.3.1.1 Geometric data

To conduct 2D modeling, a significant and accurate volume of spatial data (e.g., terrain model, bathymetric model, roughness coefficient) and hydrological data is required. Starting with geometry shape of the river reach before and after channelization. Since the channelization of this river dates back to the 1950s, no satellite data from that period are available for analysis. The oldest Landsat satellite imagery (Landsat 5), which provides large-scale historical satellite data, only dates back to 1985. Additionally, digitized aerial photos of Canada available on the Geoindex platform do not cover the study area, further limiting access to historical spatial data. Therefore, the shapes of the stream pre- and post-channelization were obtained from the OpenStreetMap database (consulted in 2024) (Figure 3.2). Indeed, during the channelization works on the Okanagan River, the meanders were left in place but disconnected from the straightened channel, which helped regenerate the meander geometry shape before channelization in QGIS (version 3). The flow path data were derived by manually digitizing polylines on-screen in QGIS. Three main lines were delineated: the left and right bank lines, and the centerline of the stream.

Figure 3.2 Manual creation of geometry shape of the river reach in QGIS

HEC-RAS 2D modeling requires a terrain model that includes bathymetry, as the accuracy of this terrain model directly affects the accuracy of the 2D modeling approach. Due to the unavailability of a Digital Terrain Model (DTM), we merged the region's DEM (Geobase 2023) with bathymetry data by modifying cross sections in the 1D modeling framework to incorporate the channel bathymetry. Manual integration of bathymetry data can serve as a solution. Before this step, we obtained data to create 1D cross sections from the bathymetry profile included in the report of [81] where the bathymetry measurements correspond to the thalweg. The bathymetry data was constructed as a continuous profile for the main channel and adjacent floodplains, with a resolution of approximately 10 m. The DEM data was used to model the topography of the riverbanks and floodplain. The combined bathymetry elevation for the study reach and its floodplain were created for both cases pre- and post-channelization. These bathymetry data were interpolated on the 1D cross sections (30 cross sections with 1-km intervals) to construct the required model geometry. The river has a meandering shape pre-channelization, which requires a higher number of cross sections to ensure accurate interpolation. This is because the complex curvature of the river cannot be accurately represented with fewer cross sections, and adding more sections helps capture the detailed geometry of the channel and its variations. Thus, the bathymetry data of river shape pre-channelization were interpolated with over 80 cross sections with 300 m intervals.

In HEC-RAS 2D modeling, bathymetry is a key factor influencing flow simulations, yet its accuracy is often limited by the method used for data collection. In this research, as the bathymetry is constructed from in-situ measurements at discrete cross-sections, it introduces uncertainty due to spatial interpolation errors, vertical measurement inaccuracies, and temporal variability in riverbed morphology ([85], [86]). These uncertainties affect water surface elevation (WSE) predictions, flow velocity estimations, and floodplain mapping, potentially leading to miscalculations in flood risk assessment ([87] , [88]).

3.3.1.2 Hydrometric data

Hydrometric data on daily flow rates and water levels, used as boundary conditions in the model and for calibration purpose, were obtained from Water Survey Canada (WSC 2024) [2] hydrometric stations (Table 3.1). The stations include the Okanagan river below Mcintyre dam station 08NM247 (at the upstream) and the Okanagan river near Olivier station 08NM085 (at the downstream) (Figure 3.1). Figure (Figure 3.3) shows the daily variation of discharge and water level in one of the Okanagan river near Olivier station (at the downstream) between 1 January 2011 and 31 December 2023. The daily mean flow rate of the stream of Okanagan river below Vaseux Lake (the upstream boundary of the study reach) during the 2012–2023 period is $11.31 m^3 s^{-1}$. The daily mean water level of the Oliver stream of Okanagan river above Osoyoos Lake (the downstream boundary of the study reach) during the 2012-2023 period is 1 m. The region generally experiences mild winters compared to other parts of Canada. Winter temperatures typically range from just below freezing to around -5°C, although extreme lows can occasionally occur and the cold season (below zero) extends from around December to April. In summer, average daily temperatures are around 25–30°C, with peaks reaching over 35°C during heatwaves.

Table 3.1 Hydrometric Stations Characteristics (WSC 2024) [2]

Station Name	**Years**	**Station Number**	**Data Availability**	**Latitude**	**Longitude**	**Schedule of Operations**
OKANAGAN RIVER BELOW MCINTYRE DAM (upstream station)	2012-2023	08NM247	Flow and Level	49°15’24" N	119°31’40" W	Continu
OKANAGAN RIVER NEAR OLIVER (downstream station)	1944-2023	08NM085	Flow and Level	49°06’52" N	119°33’59" W	Continu

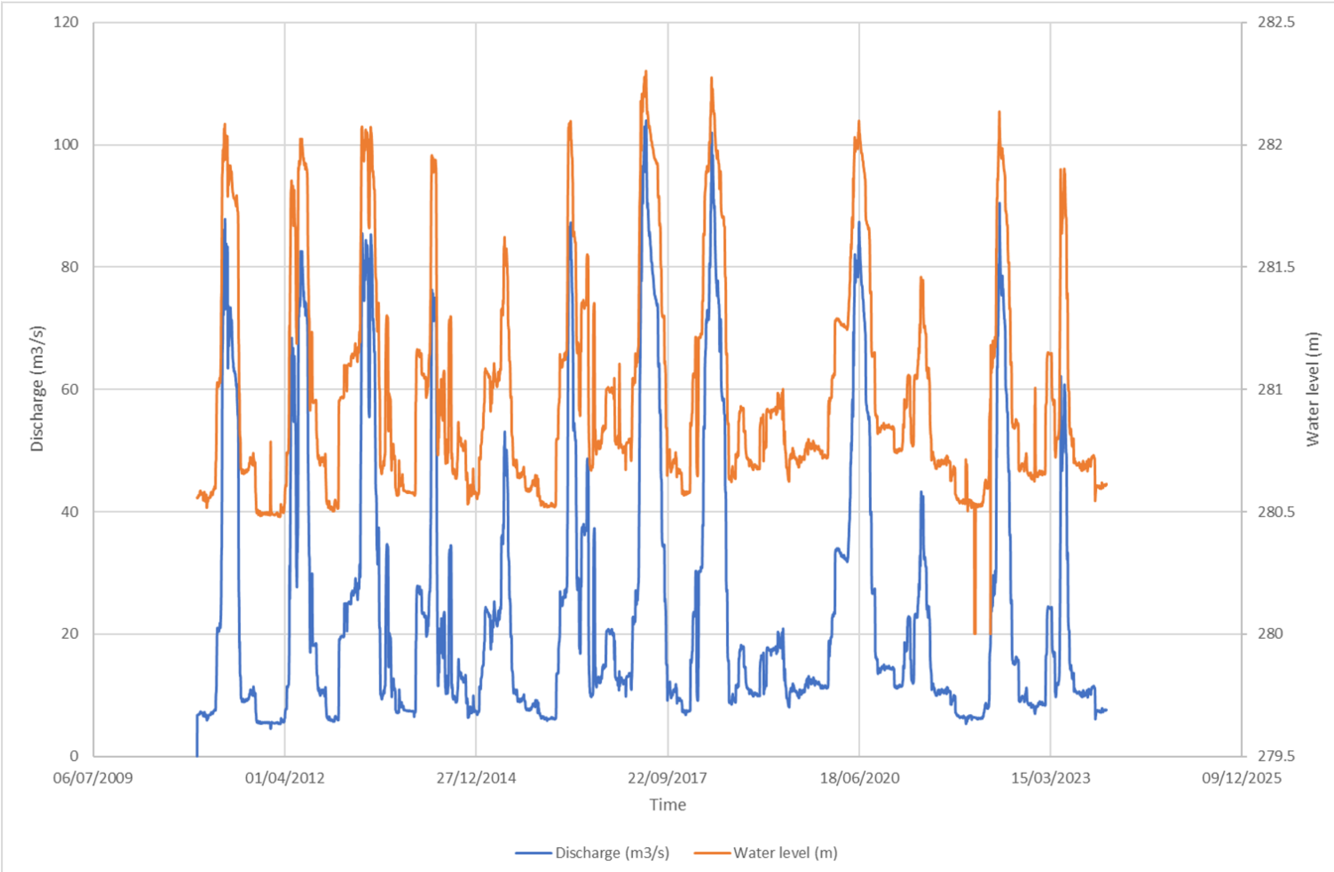


Figure 3.3 Daily variation of discharge and water level in one of the Okanagan River near Olivier station (at the downstream)

3.3.1.3 Frequency analysis

To simulate flood scenarios in HEC-RAS, we need hydrograph of extreme events. The historical data from the downstream station (2012–2023) covers only 11 years, which is insufficient to assess extreme floods with high return periods (25, 50 and 100 years). Generating synthetic hydrographs in HEC-HMS allows for a probabilistic approach using IDF curves and watershed characteristics, ensuring a more comprehensive representation of rare flood events. Additionally, return period hydrographs (25, 50, and 100 years) provide a standardized basis for flood risk assessment, whereas historical records may lack major flood events. This approach improves the reliability of hydraulic modeling in HEC-RAS, ensuring better floodplain evaluation. We first perform a flood frequency analysis on historical data followed by determining flood (Q) with different frequencies using IDF curves and the Gumbel distribution to calculate discharge peaks. Then generate three extreme flood hydrographs for 25-, 50-, and 100-year return periods using HEC-HMS (version 4). This process involved calculating flow peaks based on frequency analysis, where we tested three different probability distributions: Gumbel, Normal, and Log-Normal. The Gumbel distribution was ultimately selected, as it yielded the smallest error margin (0.054) compared to the other two distributions. We introduced in HEC-HMS, flow peaks calculated using the Gumbel distribution, IDF curves and other watershed-specific input parameters (Curve Number, time of concentration, time lag,..). The Curve Number (CN) was automatically computed within QGIS, ensuring accurate land-use and soil-type classifications for runoff estimation. The final step involved calibrating the generated hydrographs using historical hydrographs from the downstream station. These historical records featured wider base flows, which provided a reliable reference for adjusting the HEC-HMS simulated hydrographs, ensuring consistency with observed flood behavior in the study area. However, the hydrological model introduced additional uncertainties, as the generated hydrographs of extreme flood were created in HEC-HMS. These uncertainties propagate into the hydraulic modeling step in HEC-RAS, potentially affecting the accuracy of floodplain extent and water level predictions in the subsequent simulations. Figure 3.4 shows a calibrated hydrograph of extreme flood for 25 year return period using HEC-HMS.

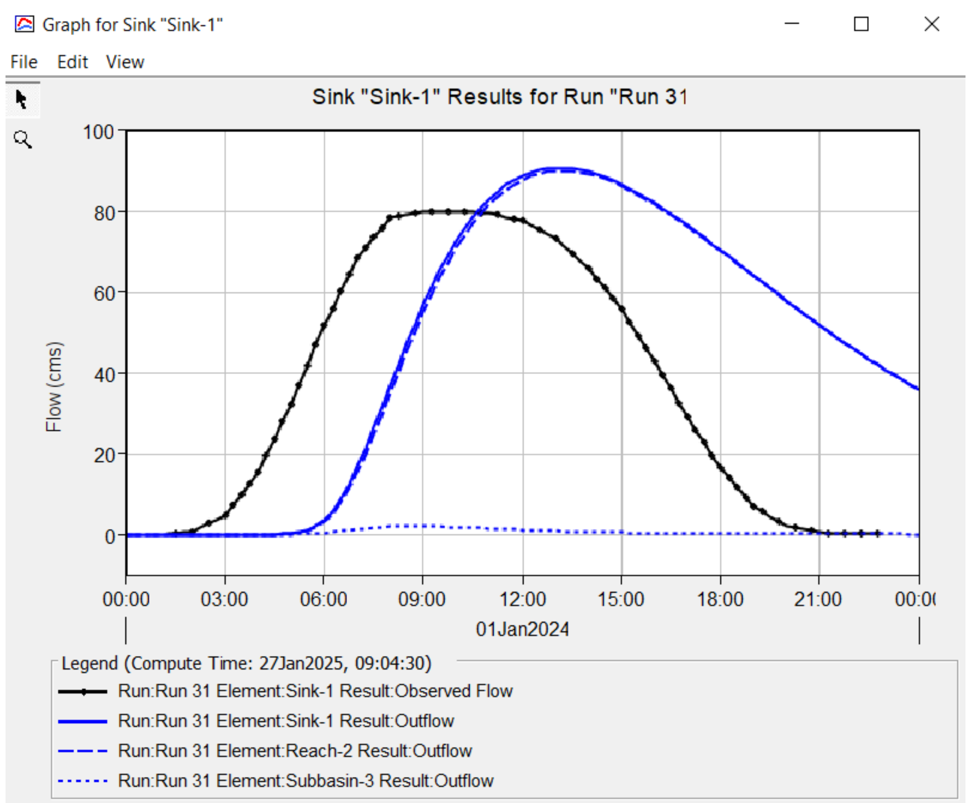


Figure 3.4 Calibration of hydrograph of extreme flood in HEC-HMS (25 year return period)

3.3.2 Numerical model

3.3.2.1 Model characteristics

In this study, we have chosen numerical modeling method for fluvial investigations, as it provides a reliable framework for simulating river dynamics, flood risk, and water surface elevations. Among the most widely used tools for hydraulic analysis, several commercial software exist, such as MIKE 21, TUFLOW, and TELEMAC-2D, which offer high-resolution hydrodynamic modeling but require costly licenses. We initially considered IRIC (Nays2DH), a Japanese open-source tool, due to its free availability and user-friendly interface. However, as IRIC is still in development, it primarily supports low-resolution free surface flow simulations and is more efficient for small-scale synthetic cases rather than complex natural river systems. Despite being continuously developed, HEC-RAS is a widely validated and recognized hydraulic modeling tool, offering flexibility in simulating 1D and 2D river dynamics, flood risk, and hydraulic structures ([87], [89]). Its free license, broad user support, and regular updates ensure accessibility and adaptability for research applications [90]. Additionally, HEC-RAS has been successfully applied in numerous flood studies, demonstrating its reliability in water surface elevation predictions and floodplain mapping ([91], [88]). Given these advantages, HEC-RAS was ultimately chosen for this work.

HEC-RAS—Hydrologic Engineering Center River Analysis System, developed by the Hydrologic Engineering Center (HEC), United States Army Corps of Engineers (USACE) in Davis, California, USA, has the capability to simulate flood inundation event, flows in river and complex fluvial systems while considering hydrodynamic aspects and sediment transport depending on the type of simulation selected, the module used and the selected configuration. The modeling process uses three different methods: one-dimensional (1D) steady/unsteady flow model, two-dimensional (2D) unsteady flow model, coupled 1D-2D modeling and 3D numerical models. [92, 93] Unlike 1D modeling, which assumes uniform flow along cross sections, the 2D feature generates flood models in both spatial dimensions, X and Y, with flow variability over time. The advantage of using 2D modeling is that this method captures the changes in water elevation when a flood wave propagates as well as the spatial variations in flow velocity, direction, and water levels, making it more appropriate for cases that consider dam/levee break flood waves, large floodplains, backwater efforts, urban environments [77, 93]. Therefore, due to the complex flow patterns in this study region with meandering river shape before channelization and wide floodplains after channelization, we adopted the 2D hydraulic modeling as the most suitable method for quantifying the responses of river behavior to channelization using HEC-RAS software (6.0 version). Overall, HEC-RAS software integrated 2D algorithm enables the analysis of water propagation over a predefined surface by solving unsteady flow capabilities with two different equations: the Saint–Venant equation (Equation 3.1) also called full momentum equation or the 2D diffusive wave equations (Equations 3.2 and 3.3) [76, 77, 79].

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \tag{3.1}$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -n^2 pg \frac{\sqrt{p^2+q^2}}{h^2} - gh\frac{\partial \zeta}{\partial x} + pf + \frac{\partial}{\partial x}\left(\frac{h\tau_{xx}}{\rho}\right) + \frac{\partial}{\partial y}\left(\frac{h\tau_{xy}}{\rho}\right) \tag{3.2}$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) = -n^2 qg \frac{\sqrt{p^2+q^2}}{h^2} - gh\frac{\partial \zeta}{\partial y} + qf + \frac{\partial}{\partial y}\left(\frac{h\tau_{yy}}{\rho}\right) + \frac{\partial}{\partial x}\left(\frac{h\tau_{xy}}{\rho}\right) \tag{3.3}$$

where h is the water depth (m), p and q are the specific flow in the x and y directions ($\mathrm{m^2\,s^{-1}}$), respectively, ζ is the surface elevation (m), g is the acceleration due to gravity ($\mathrm{m^2\,s^{-2}}$), n is the Manning's Roughness coefficient ($\mathrm{m^{-1/3}\,s}$), ρ is the water density ($\mathrm{kg\,m^{-3}}$), τ_{xx}, τ_{yy}, and τ_{xy} are the components of effective shear stress, and f is the Coriolis coefficient ($\mathrm{s^{-1}}$). When the diffusion wave mode is selected, the inertial terms of the momentum are neglected [77]. To ensure numerical stability of the model, the time step was defined according to the Courant–Friedrichs–Lewy condition [77, 93], as shown in Equation 3.4:

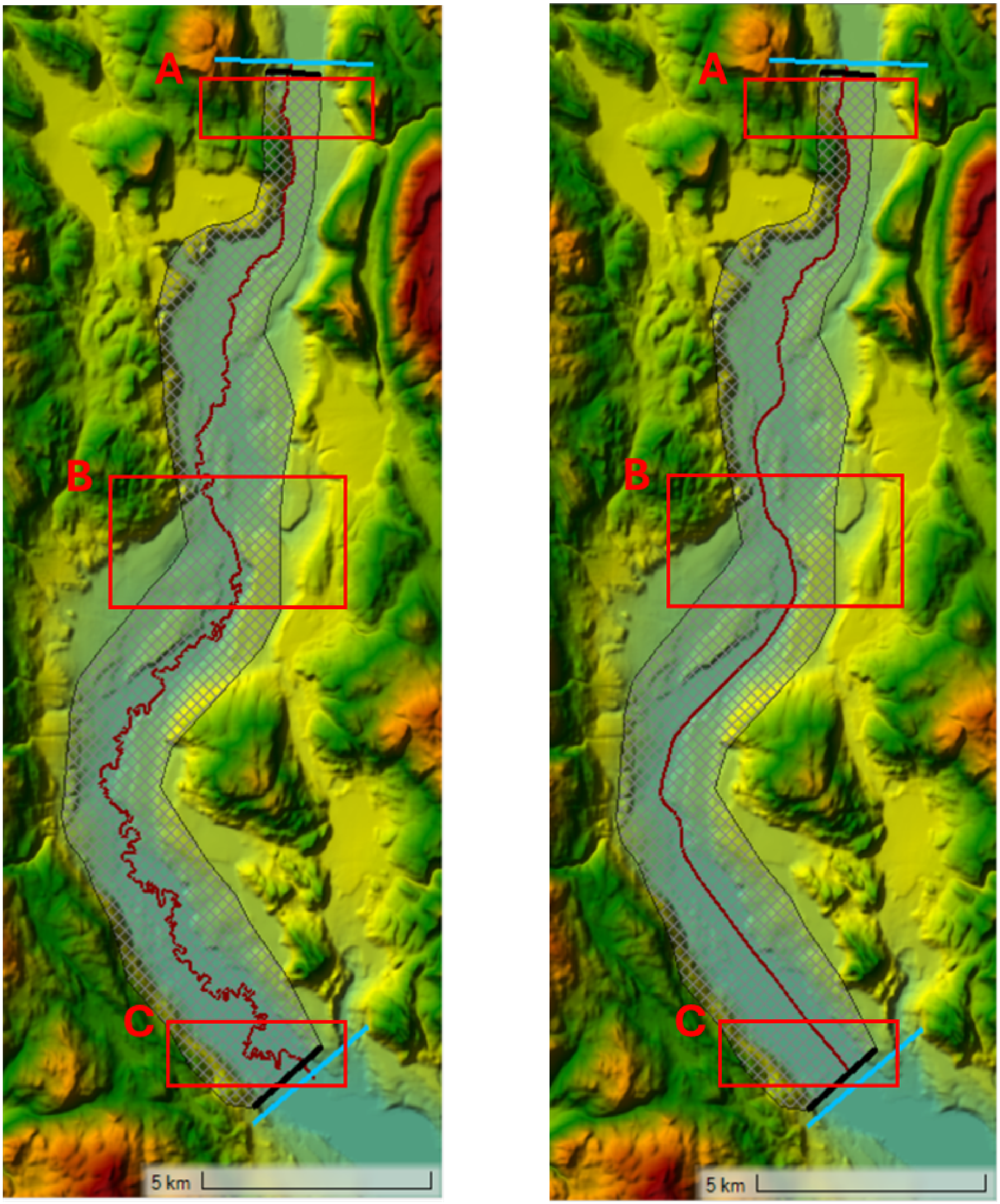
$$C = \frac{V\Delta T}{\Delta x} \leq 1.0 \quad (\text{avec } C_{\max} = 3.0) \quad \text{ou} \quad \Delta T \leq \frac{\Delta x}{V} \quad (\text{avec } C = 1.0) \tag{3.4}$$

where C is the Courant number, V is the velocity ($\mathrm{m\,s^{-1}}$), ΔT is the time step (s), and Δx is the grid cell size (m).

3.3.2.2 Model setup

The model geometry was generated in Rasmapper and HEC-RAS editor using the DTM to represent the ground surface. Rasmapper was used to create a computational mesh at 20 x 20 m spatial resolution on the entire study area for both river shape (pre- and post-channelization). Mesh refinement was integrated through the breakline crossing the centerline of the river at 5 x 5 m spatial resolution with 24 cells to cover the 50 m width of the Okanagan river. The final mesh contained over 263596 cells (for geometry post-channelization) and about 324818 cells (for geometry pre-channelization) including three to eight faces.

The present study set two external boundary conditions to flow the hydrograph at the upstream and the normal depth at the downstream. The hydrographs for calibration step represent the observed discharge entering the river and the simulation domain. While, the hydrographs for scenarios of extreme floods for the respective return periods (25, 50, and 100 years) were generated using HEC-HMS software by introducing flow peaks calculated using the Gumbel distribution, IDF curves and other watershed-specific input parameters (Curve Number, time of concentration, time lag,..). The external downstream boundary condition was set to normal depth and the friction slope was estimated near the outlet of the simulation domain. Due to the insufficient number of hydrometric stations along the study stream, with only two available stations—one upstream and one downstream, it was not possible to derive more detailed boundary conditions from observed data. Therefore, the observed data from the downstream station (OKANAGAN RIVER NEAR OLIVER, 08NM085) were used for model calibration, ensuring consistency in the simulation setup. As a result, observed water level data from this station were employed to manually calibrate the simulated water levels, as the limited number of stations in the study region restricted the availability of real-time hydrodynamic measurements. The computational mesh grid and the boundary conditions (external) built in the HEC-RAS model to simulate extreme floods scenarios in Oliver region are presented in Figure 3.5 below. The calibrated model was run between 27 April 2017 00:00 and 7 July 2017 00:00 with a computational interval of 5 sec and model interval of 10 min for model performance and calibration. All other HEC-RAS unsteady computation options and tolerances were set to default. In addition to the flow hydrograph, it is crucial to introduce an energy slope that distributes the discharge along the cells integrating the boundary; the distribution is determined using the specified slope and the pre-processed hydraulic properties of individual cells. A slope of 0.001 mm-1 was applied due to the study area's conditions.



(a) Pre-channelization (b) Post-channelization

Figure 3.5 Geometry (A: upstream below Vaseux Lake, B: middle near urban areas, C: downstream near Osoyoos Lake)

3.4 Results and discussion

3.4.1 Calibration

The calibration of Manning's roughness coefficient (n) was conducted separately for two distinct hydraulic models, each corresponding to the river's geometry pre- and post- channelization. These manual calibrations were based on the temporal variation of water levels observed at the OKANAGAN RIVER NEAR OLIVER hydrometric station. For the post-channelization model, Manning values for the main channel ranged from 0.025 to 0.04, with increments of 0.005. In contrast, the pre-channelization model, representing the river's meandering shape, utilized Manning values ranging from 0.03 to 0.04, with increments of 0.01. These values were applied uniformly along the river for both models. The calibration process revealed an optimal post-channelization Manning value of 0.025, producing reliable simulation results with strong statistical performance (correlation coefficient of 0.984 for water levels). However, the calibrated Manning value required for the meandering shape pre-channelization was optimized by 0.03 which reflects the increased hydraulic resistance inherent in natural, sinuous channels (correlation coefficient of 0.96 for water levels). Meandering rivers typically have more complex flow paths, greater variability in channel geometry, and enhanced surface roughness due to vegetation, sediment deposits, and irregular bank profiles. These factors contribute to higher energy dissipation and flow resistance, necessitating larger Manning values to accurately simulate the river's behavior. Conversely, the channelized river's simplified and straightened geometry reduces flow resistance, allowing for lower Manning values. This reduced roughness reflects the minimized interaction between the flow and channel boundaries, as well as the absence of natural obstructions such as vegetation and point bars. Figure 3.6 details the calibration outcomes.

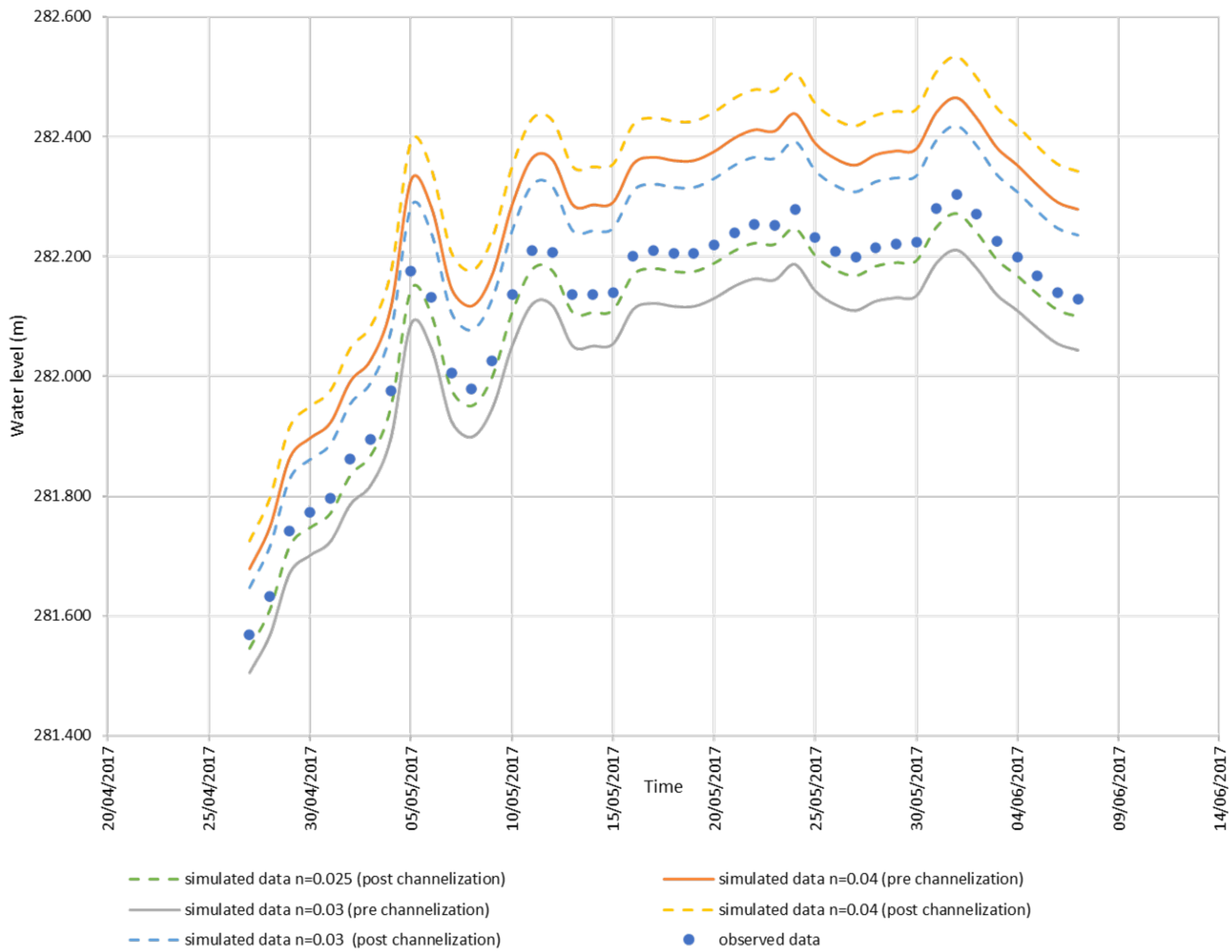


Figure 3.6 Observed vs. simulated stage hydrographs at OKANAGAN RIVER NEAR OLIVER hydrometric station

3.4.2 Channelization impacts on hydrodynamic and floods

3.4.2.1 Spatial water level variation

Figure 3.7 represents the scenario of 100-year return period, that matches with the most extensive floodplain. A comparison of floodplain extents before and after channelization reveals significant differences across the three locations: upstream, middle, and downstream. In the upstream zone which remains natural, the floodplain extent is larger after channelization compared to the pre-channelization scenario. This increase in floodplain extent is mainly due to the increase in water levels observed after channelization. In the middle zone, the floodplain extent is smaller after channelization, confirming a temporary and localized effectiveness of channelization for flood control in this urban-area. However, at the downstream location, while the floodplain extent before channelization is larger than after, the comparison is challenging due to bathymetry incertitude issues caused by manual creation. The channelization process, by straightening and narrowing the river, reduces flow resistance and increases flow velocities, which consequently elevates water levels during flood events [11,94]. The higher water levels enable floodwaters to spread farther into adjacent areas, thereby expanding the inundation zone. The increased extent of floodplain poses increased risks to ecosystems in inundated areas (upstream and downstream), it can unintentionally amplify them by increasing the spatial extent of flooding, particularly during extreme flood events such as the 100-year return period scenario.

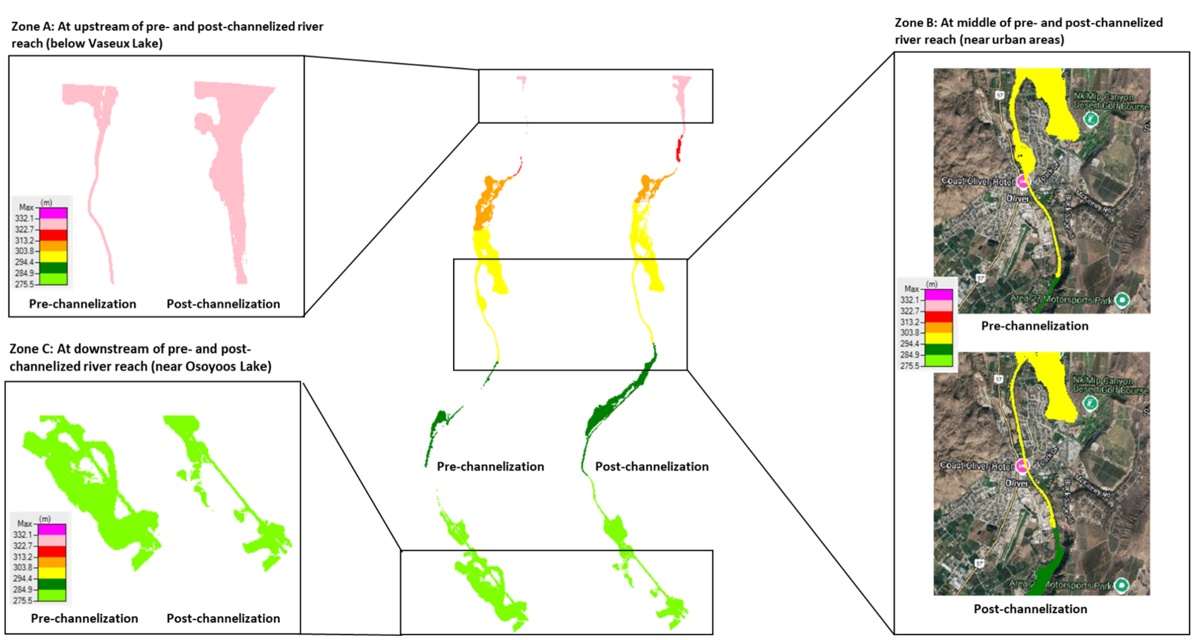
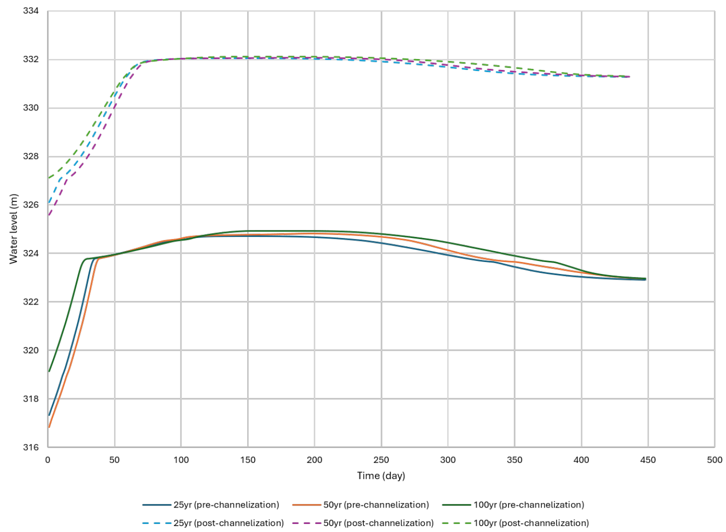


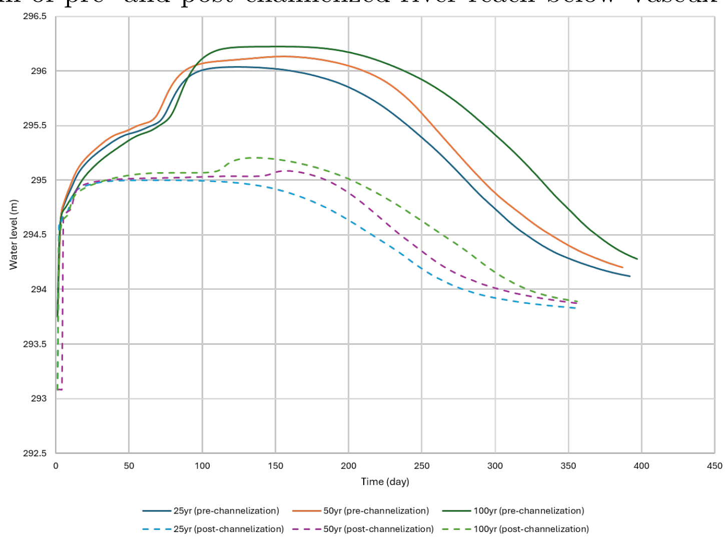
Figure 3.7 Spatial water level variation of pre- and post- channelization (100-yr return period)

3.4.2.2 Temporal water level variation

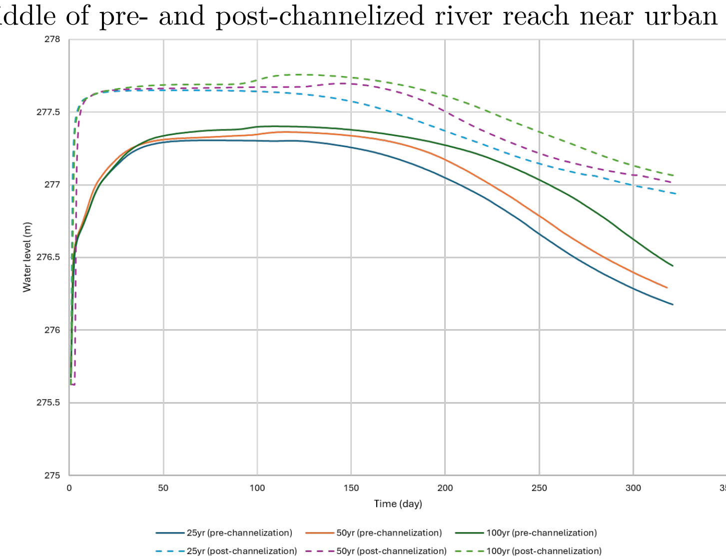
The variation of water level along the river, measured at three distinct locations—upstream near Vaseux Lake, middle near a city, and downstream below Osoyoos Lake, exhibits significant changes under different return periods of 25, 50, and 100 years (Figure 3.8). Before channelization, water levels decrease from upstream to downstream due to natural river characteristics such as friction, sediment deposition, and channel morphology, which dissipate energy and reduce water levels along the course of the river [24]. After channelization, the upstream section, which remains natural, shows increased water levels comparable to its pre-channelization state. This can be attributed to the fact that the remaining natural segment still retains vegetation and natural channel geometry, enhancing resistance and leading to localized elevation of water levels. The increased water level in the upstream section results in a more extensive floodplain due to the greater water volume being retained in the natural section, causing expanded inundation areas [11]. In the middle section, post-channelization water levels decreased due to the straightened channel for all three return periods. These significant flow changes due to channelization near urban areas, reduce flood extents and risks [95]. Downstream, the water level post-channelization is higher than pre-channelization values. The channelized section downstream effectively transports high-discharge floodwaters, increasing water levels and expanding the floodplain area. These interpretations emphasize the drawbacks of channelization, as the straightened sections can increase flood risks by reducing natural floodplain storage and elevating peak flows, thus expanding inundation areas [34, 96, 97].



(a) At upstream of pre- and post-channelized river reach below Vaseux Lake (Zone A)



(b) In the middle of pre- and post-channelized river reach near urban areas (Zone B)



(c) At downstream of pre- and post-channelized river reach near Osoyoos Lake (Zone C)

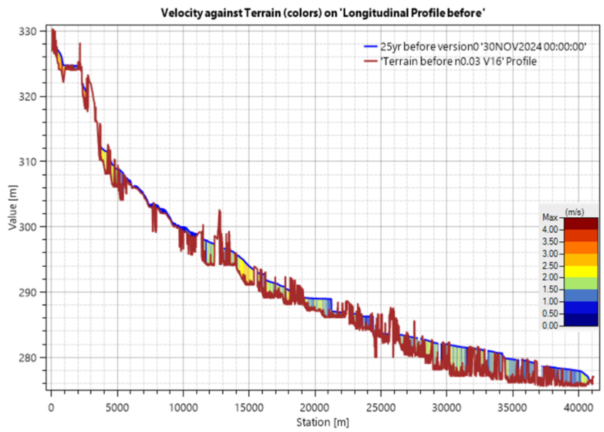
Figure 3.8 Water level variation of pre- and post-channelized river reach (25yr, 50yr and 100yr return period scenarios)

3.4.2.3 Spatial velocity variation

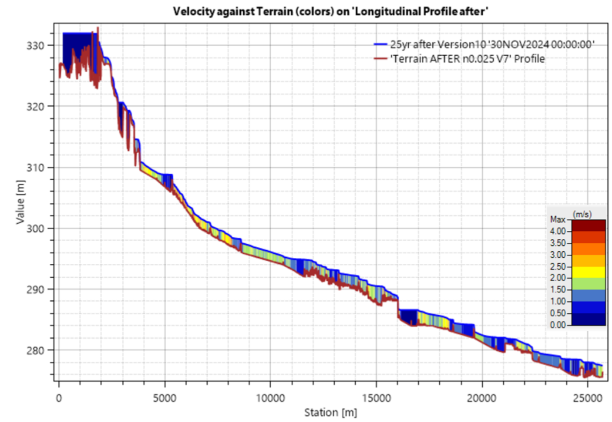
The spatial variation of flow velocity for pre- and post-channelization scenarios under the same return periods (25-, 50-, and 100-year) demonstrates a consistent pattern of higher velocities in the post-channelization scenarios compared to the pre-channelization ones (Figure 3.7). This increase in velocity after channelization can be attributed to the reduction in channel roughness and the straightening of the river course, which reduce energy losses due to friction and increase flow efficiency [98]. By removing meanders and smoothing the riverbed, channelization facilitates a more uniform and rapid movement of water, effectively enhancing the hydraulic capacity of the river to transport floodwaters.

However, while these changes may appear beneficial in terms of reducing localized flooding risks, they come with significant drawbacks. Higher flow velocities increase the erosive power of the river, leading to heightened risks of bank instability, scouring, and increased sediment transport downstream [99]. These processes can destabilize riparian zones, resulting in habitat loss for vegetation and wildlife and potential damage to nearby infrastructure. Furthermore, the increased sediment load often results in deposition downstream, which can reduce the capacity of downstream channels and exacerbate future flooding risks.

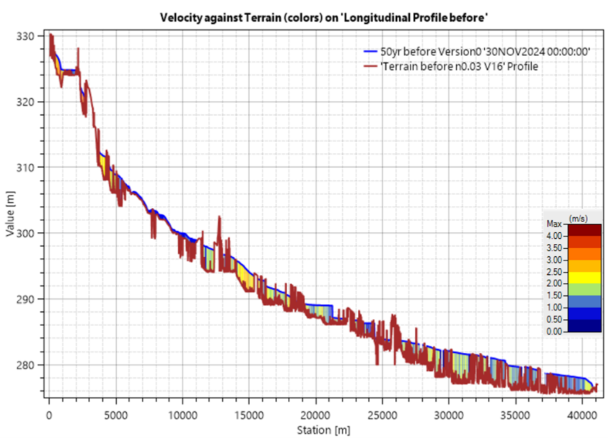
Additionally, elevated velocities disrupt aquatic ecosystems by altering the physical characteristics of river habitats, increasing stress on aquatic species that depend on slower, more stable flow regimes [11]. The intensified flow also reduces the natural floodplain storage capacity, as water is transported more rapidly downstream, bypassing opportunities for infiltration and natural attenuation [94]. This reduction in storage capacity not only diminishes the river's natural flood mitigation functions but also amplifies flood risks in downstream areas. Therefore, while channelization may offer short-term gains in flood conveyance, its long-term impacts on river stability, ecosystems, and downstream flood risks highlight the need for integrated management approaches that consider both hydrological and ecological consequences.



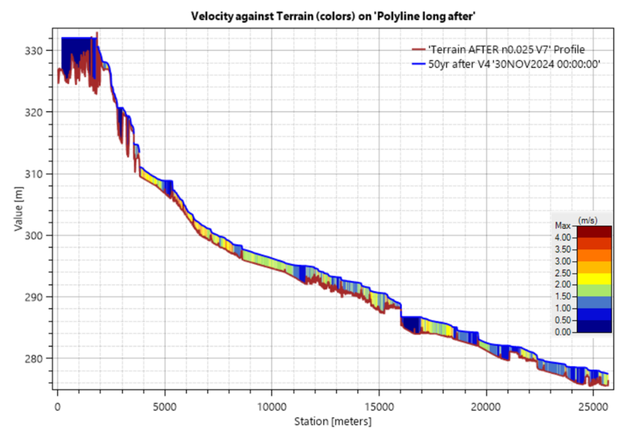
(a) Pre-channelization senario (25yr return period)



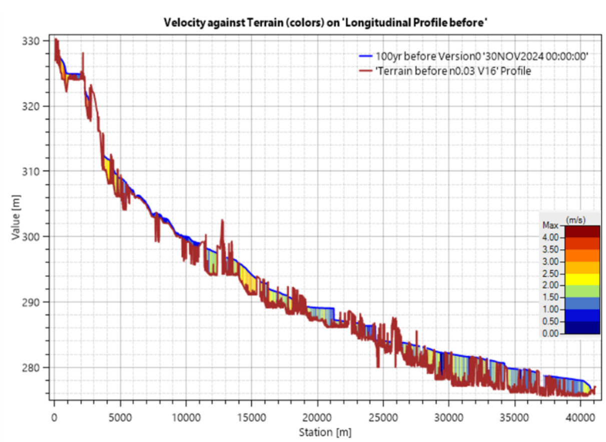
(b) Post-channelization senario (25yr return period)



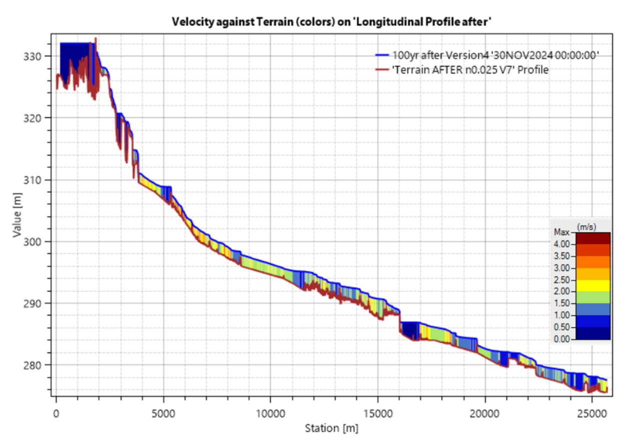
(c) Pre-channelization senario (50yr return period)



(d) Post-channelization senario (50yr return period)



(e) Pre-channelization senario (100yr return period)



(f) Post-channelization senario (100yr return period)

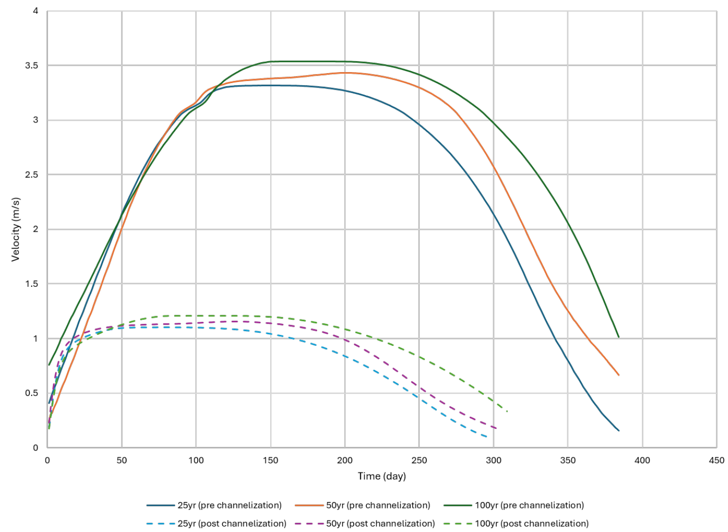
Figure 3.9 Spatial velocity variation of pre- and post-channelized river reach (25yr, 50yr and 100yr return period scenarios)

3.4.2.4 Temporal velocity variation

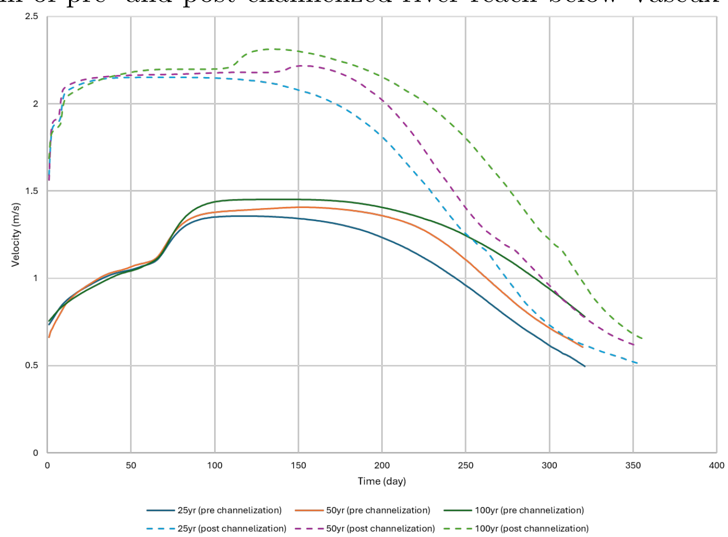
The variation of flow velocity over time at three distinct locations—upstream near Vaseux Lake, middle near a city, and downstream below Osoyoos Lake—illustrates notable changes under different return periods of 25, 50, and 100 years (Figure 3.10). Before channelization, velocity generally decreases from the upstream location towards the downtown section. This decline is primarily due to the natural river's friction and obstructions, as noted by Knighton [24]. Natural features in this section, including vegetation and natural channel geometry, contribute to higher flow resistance and energy dissipation, leading to reduced velocities, even under high-return-period flood conditions.

After channelization, the upstream section, despite remaining natural, shows lower peak velocities compared to pre-channelization, highlighting a temporary and localized benefit of channelization. The middle section near urban areas displays more pronounced velocity patterns than the upstream section. This increase in velocity can be attributed to the engineered channels designed to minimize resistance through smoother, straighter paths with fewer obstructions, facilitating efficient water flow [100]. Differences in velocity peaks across return periods are particularly evident in the downstream section, where channelization enhances the transport of high-discharge floodwaters, thus underlining the potential risks of downstream flooding and overbank flows that could severely impact floodplains.

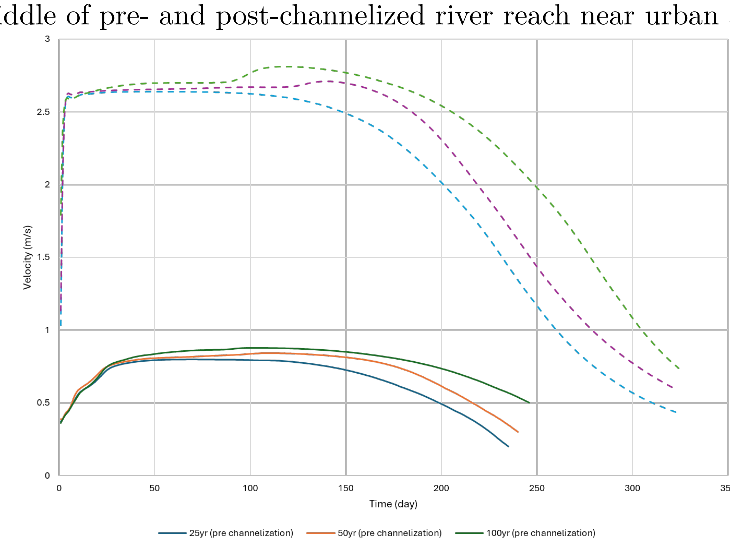
For each return period, increased peak flows result in higher velocities, especially post-channelization, where channelized sections manage these extreme flows effectively. These observations align with previous studies, demonstrating that higher return periods correspond with amplified discharge and velocity, which are further exacerbated by the effects of channelization [34, 96]. Overall, the natural upstream section illustrates the advantages of flow resistance in mitigating velocity increases during extreme events. Conversely, the channelized downstream section underscores the intensified hydraulic response under high-return-period floods. These interpretations are grounded in hydraulic principles, emphasizing that channelized sections, while designed to handle higher flows with increased velocity, can exacerbate flood risks by reducing natural floodplain storage and increasing downstream peak flows [34, 97].



(a) At upstream of pre- and post-channelized river reach below Vaseux Lake (Zone A)



(b) In the middle of pre- and post-channelized river reach near urban areas (Zone B)



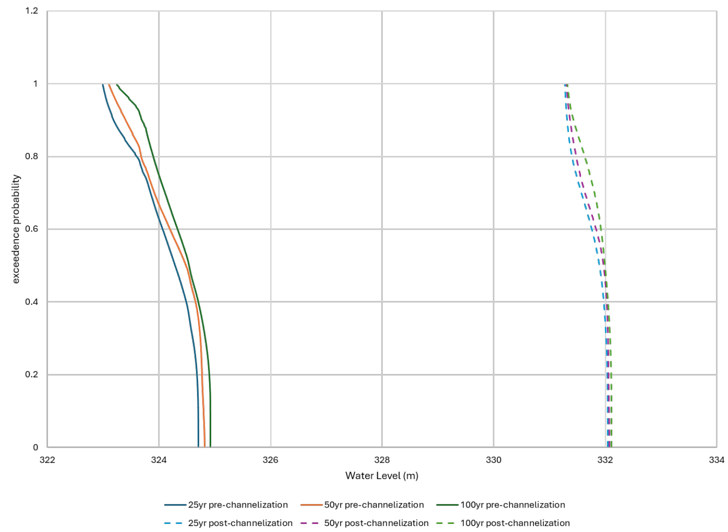
(c) At downstream of pre- and post-channelized river reach near Osoyoos Lake (Zone C)

Figure 3.10 Velocity variation of pre- and post-channelized river reach (25yr, 50yr and 100yr return period scenarios)

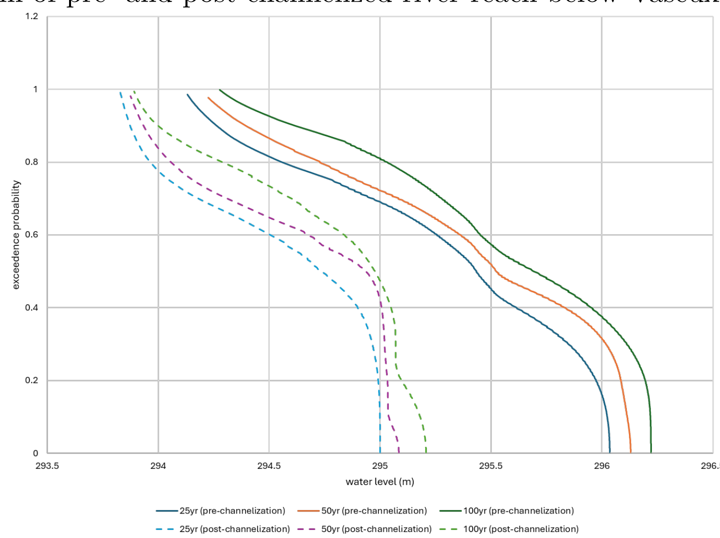
3.4.2.5 Exceedance probability

Analyzing exceedance probability is essential in quantifying flood risks as it allows for the determination of the likelihood of different flood events occurring within a specific time frame. This analysis helps in understanding the frequency and severity of potential floods, which is crucial for effective flood management and mitigation strategies [101]. It provides a probabilistic measure of flood hazards, enabling the development of appropriate infrastructure and emergency response plans to protect urban populations and assets [102].

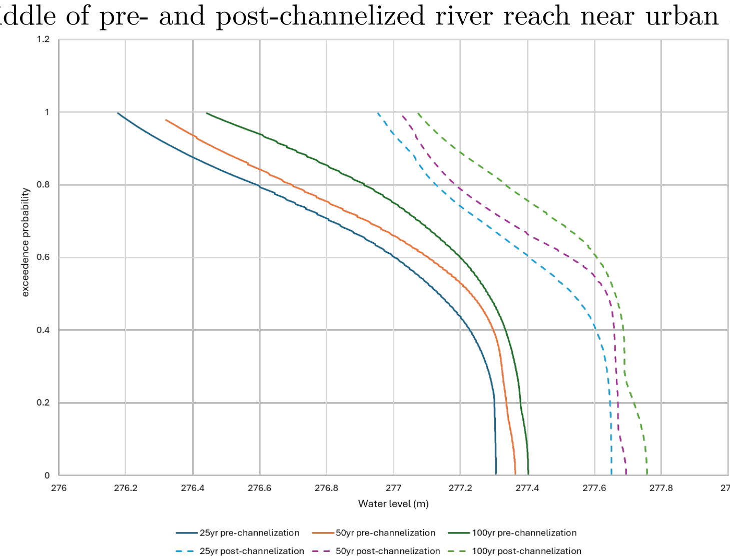
The analysis of the exceedance probability figures for upstream, middle, and downstream locations pre- and post-channelization, for 25-, 50-, and 100-year return periods, reveals distinct hydrological patterns. In the upstream section, the curves exhibit less pronounced curvature overall, with pre-channelization curves being more pronounced than post-channelization curves, indicating relatively stable water level distributions and the dampening effect of channelization. In the middle section, the curves are the most pronounced, especially for pre-channelization, reflecting significant changes due to channelization, particularly near urban areas. This suggests that channelization might have altered flow characteristics in such a way that, while aiming to control flooding, it has inadvertently increased water levels and flood risks, exacerbating the extent of flood-prone areas. Urban areas tend to have higher surface runoff due to impervious surfaces, such as roads and buildings, which prevent water from infiltrating the ground [103]. This increases the potential for flooding in these areas, making them critical for detailed flood risk assessment. Downstream, the curves display moderate curvature, with pre-channelization curves again being more pronounced, indicating a gradual stabilization of flow as the river approaches a larger water body, like Osoyoos Lake. The reduced curvature post-channelization across all locations confirms the smoothing effect of channelization on flow dynamics, but this smoothing effect could also contribute to a rise in water levels, thereby enlarging the potential flood areas, as channelization tends to concentrate and accelerate the flow of water, limiting natural floodplain functions. This pattern of increased water levels due to channelization aligns with the findings of studies such as those by Matalas [104] and Ward [99], who highlight the unintended consequences of channelization in certain areas, such as reduced floodplain storage capacity, elevated water levels, and a higher potential for flooding in areas previously protected. Furthermore, the more pronounced curvature of pre-channelization curves suggests greater variability and flood risk, consistent with the observations of Leopold et al. [98], who noted that natural channels often exacerbate flow extremes due to less regulated conditions. The downstream effects of channelization reflect the complex interplay of increased flow rates and the limited capacity of downstream areas to accommodate such changes.



(a) At upstream of pre- and post-channelized river reach below Vaseux Lake (Zone A)



(b) In the middle of pre- and post-channelized river reach near urban areas (Zone B)



(c) At downstream of pre- and post-channelized river reach near Osoyoos Lake (Zone C)

Figure 3.11 Exceedance probability of pre- and post-channelized river reach (25yr, 50yr, and 100yr return period scenarios).

3.5 Conclusion

This chapter confirmed the negative impacts of the channelization process on hydrodynamic conditions and floodplain extents, particularly in the Oliver region of the Okanagan River. Numerical modeling was developed to analyze and quantify these effects by comparing pre- and post-channelization hydrodynamics. The results demonstrate that post-channelization conditions lead to increased water levels and flow velocities, expanding the floodplain extent in both upstream and downstream locations. In contrast, the pre-channelization state exhibits greater hydrodynamic stability, with less pronounced variations in velocity and water levels, even under peak flows with return periods of 25, 50, and 100 years. While a localized flood control benefit was observed in the middle section near urban areas, where water levels temporarily stabilized, downstream instability increased, affecting floodplain distribution. These findings underscore the trade-offs of channelization, emphasizing the need for sustainable river management strategies that balance flood protection with long-term hydrodynamic stability.

CHAPTER 4 CONCLUSION

4.1 Summary of Works

In this thesis, the challenges associated with the engineering process of channelization were addressed, focusing on the long-term negative impacts of channelization on hydrodynamic aspects and flood risks. To analyze and understand these issues, a numerical modeling approach was developed. Numerical modeling serves as a robust method for understanding the hydraulics of fluvial systems. Through this approach, both pre- and post-channelization models were used to quantify the hydrodynamics, flow patterns, and floodplain extents of the river.

Chapter 3 highlighted the negative impacts of channelization on the river under different conditions (25-year, 50-year, and 100-year return periods). The pre-channelization model demonstrated greater stability, with less pronounced variations in velocity and water levels compared to the post-channelization model under the same hydrological conditions. This analysis underscores the hydrodynamic and flood risk challenges posed by channelization, emphasizing the importance of careful evaluation in river engineering processes. The velocity and water level variation are different for pre- and post conditions for the three locations. For upstream, the velocity was lower in the post condition compared to the pre condition, while the velocity variation in middle and downstream locations was higher in the post condition compared to the pre condition. This indicates that channelization can significantly alter flow dynamics along the river's course, leading to localized increases in energy and changes in sediment transport mechanisms. These alterations can have long-term implications for the stability of the river system and its ecological functions. Water level variation for upstream and downstream zones was higher in the post-channelization condition than in the pre-channelization. However, in the middle zone, the floodplain extent is smaller after channelization, confirming a temporary and localized effectiveness of channelization for flood control in this urban area. Generally, lower water levels and higher velocities are expected along the channelized reach. This discrepancy in upstream and downstream zones could be attributed to specific local factors such as channel geometry, flow resistance, and bed roughness in the modeled sections. The interplay between increased velocities and water level changes highlights the complex nature of channel adjustments post-channelization. The flooded area in the post-channelization condition aligns closely with the locations of removed meanders, indicating a direct relationship between morphological changes and floodplain dynamics. By straightening the river and reducing its natural sinuosity, channelization has effectively altered the spatial distribution of floodwaters, potentially increasing flood risks in adjacent areas. In conclusion, the findings of this thesis underscore the importance of incorporating a holistic understanding of river dynamics into channelization projects.

4.2 Limitations

The advantage of the numerical modeling developed in this thesis is its ability to quantify hydrodynamic responses for both pre- and post-channelization scenarios. This confirms the long-term negative impacts of the engineering practice of channelization in this case study. However, it is essential to test the model in multiple case studies to further validate its applicability and reliability. Several limitations of the study should be acknowledged. Assumptions were made regarding the bathymetry, which may not fully capture the true variability of the riverbed. The impact of climate change on flow regimes was not considered, which could have significant implications for the long-term applicability of the findings. Additionally, the downstream effects of the linearized sections were not investigated, potentially overlooking cumulative impacts on the broader river system. A lack of field measurements for model validation further constrains the robustness of the results. These assumptions and limitations may influence the study's outcomes. For example, rivers tend to adjust their morphology (bed and banks) to compensate for increased energy resulting from higher velocities. Over time, this natural adjustment process may reduce the observed velocity increases to their original conditions. Understanding these dynamic feedback mechanisms is crucial for developing sustainable river management practices that account for both immediate and long-term impacts of engineering interventions.

4.3 Future Research

To improve the method proposed in this thesis, several avenues are suggested. First, it would be valuable to test synthetic cases with river meanders of varying curvature angles. Second, it could be advantageous to include additional case studies (e.g., the Daaquam River and English River). Currently, only hydrodynamic aspects and flow patterns have been studied. Incorporating morphodynamic aspects such as sediment transport would enhance the precision of quantifying the impacts of channelization on rivers. Third, the use of 3D numerical modeling could be more interesting. Fourth, by addressing the highlighted limitations and integrating additional considerations such as climate change and downstream impacts, future studies can further refine the predictive accuracy of numerical models and contribute to more sustainable river engineering solutions.

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