The Hydrogeomorphological Impacts of Artisanal Aggregate Mining on Alluvial Streams and Fluvial Landscape of the Rusine Subwatershed in Northern Rwanda.

Nicolas Dos Santos

McGill University

Department of Geography

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Abstract

Sand and other aggregates are the most extracted natural resources worldwide, surpassing fossil fuels. Sand is key for building materials such as concrete, which is required to meet growing infrastructure needs. Increasing global demand for sand has in turn put pressure on environmental systems such as the rivers where sand is mined. In Rwanda, artisanal sand, and other aggregate mining in the north of the country significantly influences the region's river morphodynamics, and fluvial landscapes. Artisanal small-scale mining or ASM practices studied in this thesis take the form of floodplain mining and in-channel mining which are displayed in the Rusine and Nyabugogo River respectively. Using high-resolution satellite imagery and in- situ measurements taken during fieldwork in June 2023 in mined river segments, this thesis documents significant river alterations caused by artisanal mining practices. The obtained data from in situ morphological assessments provide information on the morphology and process response of the two rivers from ASM. Spatial imagery is used as a visual aid to determine the change in fluvial structure and morphology based on previously obtained high-resolution images. Quantifying between different styles of artisanal mining ranging from extensive floodplain mining to riverbed mining. Results indicate that floodplain mining activities 1) increases erosion and incision of the riverbed, 2) causes channel widening through the increased presence of open stagnant water pools that erode to widen the channel, 3) river straightening, 4) heterogenous river reaches and, 5) leads to an alteration of the Pool-Riffle Sequence. We can attribute that floodplain mining processes changes the overall morphological structure of fluvial systems to solely depend on anthropic alterations rather than natural processes. In-channel mining processes lead to significantly less impacts on the fluvial landscape were limited to increased incision and riverbank erosion stemming from in-channel mining activity.

Résumé

Le sable et les autres agrégats sont les ressources naturelles les plus extraites dans le monde, dépassant les combustibles fossils. Le sable est essentiel pour les matériaux de construction tels que le béton, qui est nécessaire pour répondre aux besoins croissants en matière d'infrastructures. L'augmentation de la demande mondiale de sable a, à son tour, exerce une pression sur les systèmes environnementaux tels que les rivières où le sable est extrait. Au Rwanda, l'extraction artisanale de sable et d'autres agrégats dans le nord du pays influence considérablement la morphodynamique des rivières et les paysages fluviaux de la région. Les pratiques d'exploitation minière artisanale à petite échelle (ASM) étudiées dans cette thèse prennent la forme d'une exploitation minière sévère dans les plaines alluviale et d'une exploitation minière simple dans le lit des rivières, comme le montrent respectivement les rivières Rusine et Nyabugogo. En utilisant l'imagerie satellite à haute résolution et les mesures in situ prises pendant le travail de terrain en juin 2023 dans les segments de rivière minés, ce projet documente les altérations significatives de la rivière causées par les pratiques minières artisanales. Les données obtenues à partir des évaluations morphologiques in situ fournissent des informations sur la morphologie et le processus de réponse des deux rivières à l'exploitation minière artisanale. L'imagerie spatiale est utilisée comme aide visuelle pour déterminer le changement de la structure fluviale et de la morphologie sur la base d'images à haute résolution obtenues précédemment. La quantification des différents styles d'exploitation minière artisanale, allant de l'exploitation extensive de la plaine alluviale à l'exploitation du lit de la rivière. Les résultats indiquent que les activités minières sévères 1) augmentent l'érosion et l'incision du lit de la rivière, 2) provoquent l'élargissement du chenal par la présence accrue de bassins d'eau stagnante ouverts qui s'érodent pour élargir le chenal, 3) le redressement de la rivière, 4) des tronçons de rivière hétérogènes et, 5) conduisent à une altération de la séquence de bassins et de ruisseaux. Nous pouvons affirmer que les processus d'exploitation minière sévères modifient la structure morphologique globale des systèmes fluviaux, qui dépendent uniquement des altérations anthropiques plutôt que des processus naturels. Les processus miniers simples ont un impact nettement moindre sur le paysage fluvial et se limitent à une augmentation de l'incision et de l'érosion des berges résultant d'une simple activité minière dans le lit de la rivière.

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Contribution of Authors

This thesis is the original work of the author Nicolas Dos Santos which has created the entirety of this manuscript. All chapters 1 through 7 have all been solely written and created by the author Nicolas Dos Santos. The reference of the work “ Towards a Holistic Understanding of Artisanal Aggregate Mining in Rwanda” shows the collaboration between Dr. Mette Bendixen, Dr. Lars L. Iversen, Dr. Moussa Twizere, Dr. Ke Huang, Dr. Maurice Mugabowindekwe, Placide Habinema and Nicolas Dos Santos. This co-authored work reflects the collaborative work accomplished during the field campaign accomplished in the summer of 2023.

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List of Abbreviations

ASM: Artisanal and Small-Scale Mining

DEM: Digital Elevation Model

dGPS: differential Geographic Positioning System

PPK: Post-Processing Kinematic

PRS: Pool-Riffle Sequence

RSA: Rwanda Space Agency

SSA: Sub-Saharan Africa

UNEP: United Nations Environment Programme

WWF: World Wildlife Fund

Chapter 1. Introduction

1.1Scientific Rationale

Sand constitutes the most demanded natural resource, now surpassing fossil fuels and biomass based on shares of material use by mass (Zhong et al., 2022). In tandem with growing population trends, sand is required to accommodate the expanding needs for housing and infrastructure leading to an increase in the demand for sand globally. Aggregates like sand play a critical role in the global economy has it is the key ingredient for construction material such as concrete, electronics, pharmaceuticals and more (Bendixen et al., 2021). Nations across the Global South are seeing a sizeable rise in their demand for sand. Sub-Saharan African (SSA) countries are projected to front the overall growth in the sand market (Zhong et al., 2020). Zhong et al. (2020) claim that the largest increase in the demand for sand will take place in Eastern and Western Africa with projected levels of demand growing by up to 500% by 2060.

Although sand is mined to a far greater extent than most other minerals, very little data exists to document the amount of sand extracted every year (Krausmann et al., 2009). One reason for this issue is introduced by Torres et al. (2017) mentioning that sand is a "common pool" resource, meaning that it is accessible to anyone because extraction is only monitored on large quantities of sand exportation and importation. The authors mention that the communal use of natural resources like sand is prone to a tragedy of the commons (Torres et al., 2017). This tragedy of the commons would be exemplified by greedy extraction attitudes that have no regard for long-term environmental impacts as well as the rampant illegal extraction activity and trade due to a lack of proper enforcement and governance (WWF, 2018). Combining the growing demand in addition to what Torres et al., (2017) and the WWF (2018) show, sand extraction can outpace natural sand replenishing rates and introduce a global sand scarcity issue (Bendixen et al., 2019;

Torres et al., 2017, Peduzzi, 2014) and according to recent studies, demand trends are likely to cause a sand shortage as early as 2050 (Sverdrup et al., 2017).

The extraction of aggregates occur with impacts on the environment (Peduzzi, 2014). Globally, sand mining is deemed to be one of the main stresses impacting rivers and their related ecosystems (Koehnken et al., 2019).

River mining processes take many forms and greatly differ within their potential environmental and morphological impacts. Extraction methods can be of an artisanal nature where the five most common practices are highlighted by Rentier & Cammeraat (2022), channel wide instream excavation, wet and dry pit excavation or pit mining, bar excavation and bar skimming. Certain methods required the use of heavy machinery such as dredgers and excavators such as wet pit excavation due to the extraction occurring under the water table (Padmalal & Maya, 2014). Dry pit excavation can also use heavy machinery but can also be conducted through the simple use of shovels and buckets from residents forming what is known as artisanal mining. The use of machinery and more advanced technologies, forming industrial mining extract sand and other aggregates from a river can be very destructive due to the increase in size and amount of material extracted. Due to the overall larger scope of industrial mining, it often can overlook artisanal practices and the related impacts to this informal extraction practice.

Within Sub-Saharan Africa, artisanal sand and aggregate mining is one of the main non-agricultural activities that enables a spur of employment and income (Macháček, 2020). Its importance within Sub-Saharan Africa poses important threats to many aspects of population well-being such as socio-economic parameters, child and women labor conditions, the illegality and danger of artisanal mining in certain areas (Macháček, 2020). However, little attention is attributed to the environmental drawbacks of such practices as evidenced in the scarce scientific literature or only based on location specific studies (Bendixen et al., 2023). It is only very recently that the field of research on sand and aggregate mining has gained traction within the scientific communities. Much of the work focuses on the extraction practices and their environmental impacts on local biospheres (Bendixen et al., 2023). Previous research on ASM tend to focus upon gold and heavy mineral mining rather than sand and alluvial aggregates.(Byizigiro et al., 2015; Bruno et al., 2020; Dethier et al., 2023). Sand and aggregate mining are linked to a complex web of environmental factors such as degradation, disruption of natural hydrological processes, loss of soil through increased erosion stemming from artisanal mining practices. (Koehnken et al., 2019; Rentier & Cammeraat, 2020). Therefore, the impacts related to artisanal sand and aggregate mining practices reveal to be complex and span across several facets that remain to be studied accordingly.

Two main types of artisanal small-scale mining occur within Rwanda's fluvial system: severe floodplain mining and simple in-channel mining (Figure 1). Floodplain mining practices are observable in the Rusine River and smaller scale rivers. It is characterized by severe manipulations of the entire fluvial landscape including floodplains and active channel. In-channel mining focuses on riverbed excavation only and does not interfere with any other fluvial landforms. The focus of floodplain mining exceeds in-channel mining manipulation using the active floodplain for mineral excavation. Floodplain mining is an opportunistic form of mining that will extract any area where available sand and aggregate is accessible. The use of ad-hoc methods such as damming, the digging of new channels, floodplain entrenching will be used in order to maximize excavation on the fluvial landscape. Miners target depositional landforms of the fluvial landscape such as point bars and the entirety of the floodplain at the expense of fluvial stability and fertile soil available for subsistence agriculture. In-channel mining is observable in the Nyabugogo River notably, but in other larger scale rivers. The processes of in-channel mining refer only to the excavation of the riverbed for sand. The cluster of the impacts will therefore be noticeable within the active channel rather than throughout the entirety of the fluvial landscape. Visual cues of the in-channel mining are minimal and do not reflect a significant alteration of the landscape.

Figure 1: Photo of Floodplain Mining in the Rusine River (left) and in-channel Riverbed Mining in the Nyabugogo River (right) in 2023

Rwanda has one of the highest population densities with 503 residents per sq. km (National Institute of Statistics of Rwanda, 2023) in Africa and rapidly growing national economy exerts pressure on the sand and other aggregate resources of the country to further develop and promotes the country's economic expenditure. Increasing demand for sand and gravel will inevitably create added stresses on Rwandan fluvial systems. This work will help to bridge certain knowledge gaps regarding the impacts of artisanal. This study will be separated into two different sections, first starting by the morphological evolution of the Rusine River from 2000 to 2023 though a geospatial analysis of its channel pattern through time and space, looking also at floodplain migration and land use changes through time. The same geospatial analysis will be applied to the Nyabugogo River with the exception of floodplain migration and land use change as they both remain very similar throughout the entire studied period. The second part of this research will discuss the field campaign where in-situ field data gathering and morphological assessments of artisanal mining practices in the Rusine River using dGPS, hydrological measurements and river style analysis.

This research tries to further the understanding of the impacts of ASM on river systems but also on the fluvial landscape including floodplains, which no direct knowledge has been created on the impacts of ASM on floodplains (Bruno et al., 2020).

1.2 Research Objectives

The primary goal of this research is to characterize and depict the impacts of artisanal sand and aggregate mining on the fluvial morphological functions of river systems in Rwanda by focusing on mined river segments of the Rusine and Nyabugogo. This research will have a site-specific analysis that will provide a deeper understanding of two different types of ASM occurring in the Rusine and the Nyabugogo, where one river undergoes severe floodplain ASM, and the second experiences more simple in-channel practices, respectively. This approach will determine the relationship between mining and fluvial morphology based on two different types of artisanal mining observed throughout the field campaign.

The main research question that drives this study is led by the hydrogeomorphological impacts that arise from mining within a river system and congruently in the floodplain. Therefore, the main question this research will focus on is: (1) how does artisanal sand and aggregate mining influence hydrogeomorphological settings in rivers in Northern Rwanda? By analyzing the overall changes within the morphology of the study area, this research will seek to understand how the fluvial landscape responds to such anthropogenic disruption by answering (2) what are the active changes to the fluvial landscape that accompanies artisanal mining in fluvial areas?

The main objectives following this research question will be to understand how artisanal mining impacts fluvial systems and how it alters the physical fluvial landscape at a site-specific scale. In order to answer such questions, this research aims to observe the relationship between artisanal small-scale mining to site specific morphological functions such as pool-riffle sequencing, amplitude and wavelength of the meanders of the studied rivers. This includes not only the hydrological functions within the studied systems but also the overall change within the observable fluvial landscape that results from artisanal mining operations based on a landform-based analysis. This research's scope aims to analyze two contexts of ASM occurring in a small very shallow stream as the Rusine which will make up the majority of the analysis of this project. Visits to the Nyabugogo serves as additional work to understand how ASM occurs on larger rivers with increased discharge, depth that could become an obstacle to processes linked to ASM such as scooping sand and alluvial sediments from the riverbed. The Nyabugogo exhibits a different type of ASM to the Rusine where the manipulation of the system remains minimal and does not entail mining action on the floodplain. As the Rusine remains the main focus of this research, work on the Nyabugogo will become a source of comparison between mining activity occurring in the Rusine River and the Nyabugogo River.

Chapter 2. Background

2.1 Literature Review

Understanding sediment supply and where the sand is sourced from is critical to quantify how sand has becomes a scarce resource and how sand mining impacts the environment. The predominant environments for sand extraction consist of aquatic environments, rivers, lakes, and coastal areas. Fluvial and limnological landscapes are key areas within sand and aggregate mining efforts across the globe. Aquatic environments are prioritized since they provide sediment such as sand from the erosive processes that enable natural sediment supply. Fluvial processes create sand grains that possess greater bonding attributes for the use in cement. The angularity in the shape of the sand grain contrasts to the smoother surface of grain stemming from aeolian erosive processes (Zhong et al., 2022). Yamei & Lihua (2017) studied the differences between construction-grade sand in contrast to desert sand referring to sand nurtured by aeolian processes. Desert sand is deemed to have a smooth, round shape while construction sand has an irregular, flat, angular characteristics that are profitable for cementation processes (Yamei & Lihua, 2017). Mining practices in developing countries mostly relies on small-scale mining, especially in the African Great Lakes region conglomerating Rwanda, Tanzania, Burundi, Kenya, Uganda, and the Democratic Republic of Congo (Macháček, 2020). Knowing that construction sand stems from aquatic environments and depositional landforms, a variety of studies have focused on how sand mining impacts the physical environment.(Kondolf, 1997; Brown et al., 1998; De Leeuw et al., 2010; Padmalal et al., 2010; Dang, Umeda & Yuhi, 2014; Huang et al., 2014; Koehnken et al., 2019; Hackney et al., 2020; Pilkey et al., 2022; Rentier & Cammeraat, 2022) Fluvial aggregate and sand mining constitutes an intricate web of consequences that impact multiple aspects of the fluvial environment. Landscape changes become significant when we introduce ASM or artisanal small-scale mining. The latter sections of the literature review will look upon the anthropogenic impacts on fluvial landforms, it will mention the already known morphological impacts of ASM and will provide an overview of the sand and aggregate use in Rwanda.

2.1.1 Anthropogenic Impacts on Morphological Landforms

Artisanal mining distinguishes itself from industrial mining efforts by legal parameters and functions. The lack of regulations and informal nature of ASM brings distinct changes to morphological features within alluvial channel morphology that are highlighted by Jones (2001) as three categories that describe how ASM influences: human-made relief, human-induced relief, and human-modified relief. Based on the African Great Lakes region, these categories were created to understand the anthropogenic influence on relief resulting from anthropogenic geomorphic processes (Byizigiro et al., 2015) such as mining in alluvial channels. Any form of mining effort involves the removal of material from geomorphic structures that are featured within a particular landscape. This region englobes seven lakes that are in the heart of the Congo and Nile basins. This area spans over the countries of Uganda, Tanzania, Rwanda, Kenya, Eastern side of the RDC and Burundi (Macháček, 2019) and are all characterized by the amplitude of ASM and its importance within local economies. Certain mining processes will result in a variety of landscapes and landforms that fall under one of the three categories (Jones, 2001) as contextualized by Byizigiro et al. (2015). The workers claim that mining offers better financial opportunities where the pay is categorized as high in comparison to local standards (Cook et al., 2014). Therefore, impacts on the landscape and the environment will increase in severity as more and more workers and residents will focus on mining rather than agriculture since agricultural revenue are on the decline forcing residents to find alternative sources of income (Gervasio & Lopes, 2003).

When looking at human-made landforms, a specific purpose underlies mining efforts projects, rarely would there be mining activity without a specific goal driving it. In the case of mining, Jones (2001) exemplifies the efforts of removing material to mine resources found underneath the surface, hence creating new anthropogenic landforms such as pits and trenches (2001). Such landform distinguishes themselves by being artificial depressions within the landscape (Byizigiro, 2015). Such depressions are created for excavation purposes that are often left behind without any proper rehabilitation plan afterwards (Macháček, 2020). Intense mining activities lead to the creation of pit walls (Jones, 2001; Byizigiro et al., 2015; Macháček, 2020). These walls are characterised by an over-steepened slope that is highly prone to collapse via mass-movement events or increased erosion on the barren surface. Within human-made landforms, the deposition sites are often observed as series of piles of sediment near the excavation sites.

Human-induced landforms stem from the geomorphic processes happening in places and times that are completely dependent of anthropogenic activities (Jones, 2001). In ASM sites, we would observe geomorphological processes in pits, trenches and other human-made landforms that emerge from ASM practices. For example, erosion rills can occur in pits and pit walls stemming from surface runoff. This will cause these features to expand and a new gullying process to occur in the landscape. The intensification in the formation of gullies can subsequently lead to the development of badlands (Byizirgiro & Biryabarema, 2008). Other human-induced landforms usually occur in areas with slopes, where disturbances from ASM can destabilize upper portions of a slope which can create cracks. In Rwanda, which experiences two rainy seasons, increased precipitation can cause seepage within those cracks which lead to further destabilization of the slopes leading to failure and therefore mass movement events within the mined areas (Macháček, 2020). Such landslides then disrupt the overall geometry of the initial slope by the addition of material at the base of the slope and therefore increasing the slope angle at the head of the slope (Varnes, 1984).

The primary mechanism that actively produces human-modified landforms is the disruption within the hydrological balance of a system (Jones, 2001). Deforestation and vegetation removal is imperative to ASM activities, which can alter the hydrological budget of a tributary. A global study conducted by Wilkinson & McElroy (2007) investigated the changes in alluvial deposition that arise from human activities, and finds that in higher Strahler's order tributaries, alluvium accumulation stemming from anthropogenic events becomes the most important geomorphological process to quantify sediment erosion and deposition. Kondolf and Piégay (2016), without directly relating their findings to Jones geomorphological landscapes, claim that sedimentation episodes that are caused by human activity such as deforestation and mining can be severe enough to initiate channel and floodplain aggradation events that are preserved within the alluvial record.

All three landforms are actively related to ASM processes. Despite the sparse literature, there is an agreement that ASM is a potent agent of geomorphological change. However, in the realm of ASM, very little governance and responsibilities are instated to mitigate the environmental consequences. Due to the poor environmental monitoring in ASM, geomorphological changes in the landscape can become substantial especially within fluvial landscapes.

2.1.2 Known Morphological Impacts of Artisanal Small-Scale Mining on Fluvial Systems

The practice of mining or the removal of sediments from a river system impact the local and downstream environment and morphology. The severity of such impacts will be directly dependent of the amount of excavation. Important issues arise when the removal of sediment surpasses the natural replenishment rates (Hackney et al., 2020).

Sand mining in fluvial landscapes is an important agent of change and has a multitude of repercussions on fluvial morphology (Pilkey et al., 2022). Riverbed excavation can create nick points and excavation pits that migrate upstream from the processes of head cutting leading to an increase in the amount of sediment being transported (Kondolf, 1997). The creation of nick points and excavation pits increases the erosive power of the stream. As the excavation pit and nick point migrate upstream at distances up to 11 km (Kondolf, 1997), sediment will deposit at the bottom of the excavation pit. Following this sediment pile, the flow becomes starved from sediments, therefore, increasing the available energy left for erosion. As the river carries less sediment, the erosive power increases (Koehnken et al., 2019). Certain techniques used for riverbed sand extraction like pit excavation are known to deepen and widen the riverbed resulting in induced undercutting of the riverbank, leading to bank failure, and increasing the riverbed width (De Leeuw et al., 2010; Rentier & Cammeraat, 2022). A study conducted in the Mekong River demonstrates that riverbed excavation directly triggers bed lowering which leads to bank instability (Hackney et al., 2020). Other instances of channel widening due to sand mining was found in the Ozark Plateau in the United States (Brown et al., 1998).

The erosive forces and consequences of mining are often the central argument within the literature regarding the impacts of mining within fluvial systems, where incision rates are directly impacted by river sand mining. Koehnken et al (2019) argue the increase of channel incision to be the most prevalent and common impact on river systems. Many studies reveal that channel incision can vary greatly and is site-specific; Common incision levels range from 0.5m to 3.5 as described by Dang, Umeda & Yuhi (2014). However, levels of incision can reach up to 10m and in extreme cases, incision levels can surpass the 30-meter mark as seen in the Bachang River in Taiwan (Huang et al., 2014). In contrast to the “hungry water mechanism” (Kondolf, 1997) channel incision leads to a narrowing of the channel due to bank erosion that is initiated by an over-steepening of the riverbanks (Koehnken, 2019).

River sand mining also changes the overall structure of sediments found within the rivers (Koehnken et al., 2019). Padmalal et al. (2010) discovered that river sand mining in southern rivers of India has led to an increase in sediment grain coarseness, as most fine sediments were removed due to sand mining activity upstream. Here, point bars that were once characterized only by sand-sized material are now characterized by gravelly sand due to the removal of fine particles upstream. (Padmalal et al., 2010).

Other impacts on the fluvial geomorphology are noted by Pilkey et al. (2022), who finds that sand mining has implications for water level fluctuations which can increase instances of flooding but also a reduction of the water table. A reduction of the river water table leads to a lowered water table in surrounding areas (Rentier & Cammeraat, 2022). It can lead to certain stratigraphically elevated aquifers not being replenished which leads to secondary issues in agriculture, fisheries, and available water supplies. Here the authors describe secondary issues as impacts that are seen due to alterations of channel morphology. This does not aim to reduce the severity of secondary issues, but instead to link sand mining-related morphological impacts to biotic processes in fluvial landscapes. Other described impacts relate to bank erosion, where impacts are seen on levees and floodplains which can increase the vulnerability to floods (Pilkey et al., 2022). Other noted implications are relevant to delta formation and retreat., which due to the limited renewal and supply of sediments, Pilkey et al. (2022) describe that deltas are retreat in rivers that are known to be mined.

While understanding that these impacts is beneficial to further understand how ASM and river mining impacts the natural environment, reports by the United Nations Environment Programme (UNEP) and World Wildlife Fund (WWF) call out for further research in the field to get a holistic understanding of how ASM mining influences natural functions of an ecosystem.

2.1.3 Sand in Rwanda

Across Sub-Saharan Africa, drivers for sand mining were identified that increase the demand and simultaneously exert pressure on this resource. Bendixen et al. (2023) highlight population growth as one of the two main drivers of sand mining in Sub-Saharan Africa (SSA). Population growth across the continent requires the development of more infrastructure such as housing, schools, roads, and healthcare facilities to support the increasing number of people adding pressure on the built environment and, sand is a key ingredient to support the growth of the built environment in SSA. Livelihood subsistence is the second most important driver of sand mining (Bendixen et al., 2023). Economic instability represents a significant issue for most sand miners as poverty and lack of employment opportunities lead to an increase in people participating in sand mining activities (Mensah, 1997). Hence, sand mining offers an economic opportunity for residents to develop a new livelihood and earn an income.

Rwanda is a country rich in natural resources and minerals (REMA, 2011). Sand is found in most regions, except the Eastern province, readily available for extraction. Sand plays an important role within the country for glass production, filtering for water plants and as construction materials. One of the great deficiencies within the Rwandan market is the production and availability of glass (MINICOM, 2007). The Geological Survey of Rwanda has been leading an ongoing investigation of the presence of sand deposits since 1974 and has identified several types scattered across the country. Some sand deposits sites lie inland from “the quartzite of Sakinnyaga and from the alteration of Kigali and Butare granites" (MINICOM, 2007). Other deposits are found along riverine environments. The ministry is emphasizing two large sand deposits that would open the possibility for locally produced glass due to the large extent of sand available within both deposits. The Mukungwa-Masango deposit is the largest out of both and has an estimated 2,160,000 tons of sand available and the Karundura-Kirimbi reserve holds respectively an estimated 985,000 tons of exploitable sand (MINICOM, 2007, p.116). Therefore, the possibilities for sand mining in Rwanda are opening and will boost local economies though future jobs and sustain locally produced products.

2.1.4 Summary

Artisanal mining in SSA has yet to become a central aspect of research amongst the scientific community. Previous work on river sand and aggregate mining demonstrates certain impacts based on industrial mining action to fluvial geomorphology and landscape changes. Much of the existing work addresses the environmental impacts and the changes in the physical environment on a larger scale analysis as seen in the research done in the Great Lakes region (Byizigiro, 2015; Yamei & Lihua, 2017; Macháček, 2020). Research also focuses on larger mining operations rather than artisanal practices with a scope on larger mining operations rather than on site-specific artisanal mining areas. With Rwanda having a strong commitment to develop the country into an upper-middle income country by 2035 (Bendixen et al., 2024), the overall growth of the country will rely heavily on the extraction of sand and other aggregates creating immense pressures on the local aggregate resources which will mostly take shape as artisanal mining. Artisanal mining will support the economic growth of the country and will support poverty alleviation (World Bank Group, 2017). It is critical to highlight that Rwanda has yet to be the focus of study on sand, gravel and crushed stone mining in a Sub-Saharan African context.

Chapter 3. Study Area

3.1 Regional Settings and Hydrological Landscape

Rwanda is a landlocked country situated in Sub-Saharan Africa sharing its borders with Burundi, Tanzania, Uganda, and RDC. Rwanda is home to over 13,700,000 residents with a population density rising over 500 people per sq.km. (National Institute of Statistics of Rwanda, 2023). The country lies within the Congo and Nile River watersheds (Macháček, 2020). The Congo basin covers roughly 33% of the total landmass of Rwanda and drains 10% of the water in Rwanda, while the Nile Basin takes up 67% and drains 90% of the total water within Rwanda's water systems (Macháček, 2020). Rwanda shares its water through smaller tributaries of both major rivers with other countries that form the "water tower" of the Nile Basin. Major rivers of Rwanda are separated between both basins.

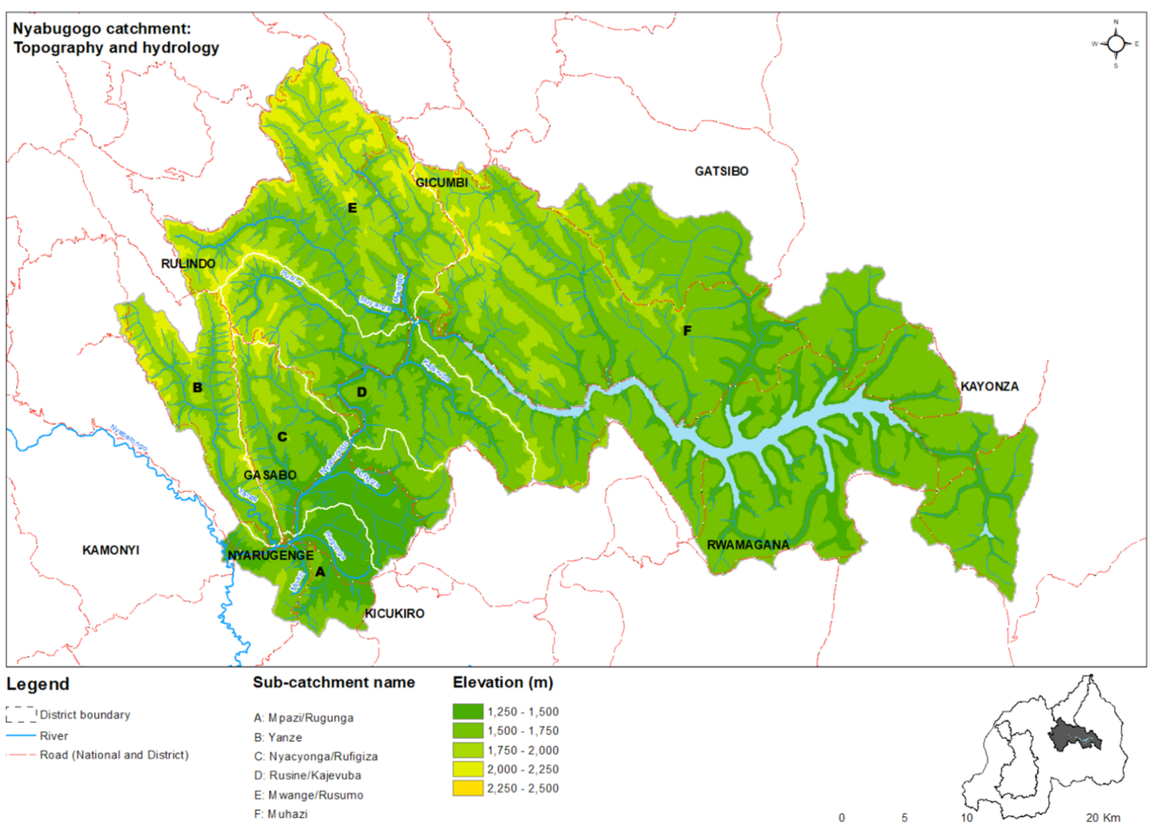

Figure 2. The Nyabugogo Catchment (REMA, 2018)

The Nyabugogo catchment spans the eastern, central, and northern territories of Rwanda, where its main source stems from Lake Muhazi, some80 km in length from east to west (Munyaneza et al., 2013). The catchment hosts the densest population and urbanised areas in the country as it includes Kigali City, while still being home to several rural and remote areas (Umugwaneza et al., 2021). The Nyabugogo River is found in the Albertine Rift Montane Forests as well as the Victoria Basin Forest-Savanna ecoregions (MoE of Rwanda, 2018). The Nyabugogo is a tributary of the Nyabarongo and joins the Nyabarongo River near the capital city of Kigali at roughly 1360 m elevation. The highest point of the catchment is at 2,280 masl in the Northern Province. The river is a second order channel fed by its tributaries the Mwanga, Muyanza, Kajevuba, Yanze and Rusine River (NWRMP/MINIRENA, 2014).

Situated in the District of Rulindo, at the northern tip of the Nyabugogo catchment lies the Rusine River. The Rusine is an alluvial river with a total length of 12.07km and a sub-catchment spanning across 54.07km^2. The Rusine is classified as a headwater stream of 3rd order feeding a second order stream, the Nyabugogo. The Rusine headwater stems from the Buberuka Highlands agro-ecological zone and flows into the central plateau of Rwanda. The average long-term discharge of the river is 0.36 m3/sec with seasonal variabilities during both dry and wet seasons. Part of the Rusine River constitutes a dedicated mining area owned by a private corporation, Rutongo Mines LTD. The vast majority of mining projects owned by Rutongo Mines are centrally located in Rwanda in the District of Rulindo (Kazindu et al., 2020). The company has large scale mining license that spans over five notable sectors in the district of Rulindo including the sector of Masoro and notable the Cyinzuzi sector where the Rusine River is located (Kazindu et al., 2020).

3.1.1 Climate

Rwanda lies within a tropical climatic zone (Siebert et al., 2019). Due to its proximity to the equator, the country has two wet seasons, with one spanning from March to May, and the second from September to December (Siebert et al., 2019). Rwanda's precipitation patterns are highly dependent on movements of the Inter Tropical Convergence Zone (ITCZ). Rwanda's precipitation averages between 1000mm to 1200mm per year varying on the location; the highlands in the North and West receive more precipitation than the savannahs and lowlands in the East (Uwihirwe et al., 2020). Rwanda is located at high elevations where mountainous regions dominate the western and central portion of the territory. The east and south have less topographical relief and are mainly occupied by savannas and lowland swamps (Rwanda State of Environment and Outlook: Summary for Decision Makers, 2009).

3.2 Study Sites

The main sites for this research are located along the Rusine River in the Nyabugogo catchment, where field surveys and remote sensing analyses were conducted at four specific locations. All studied sites of the Rusine River are shown in Figure 3 across the 16, 420m studied of the Rusine River. The western side of the Rusine River was not analyzed in the scope of this research due to restricted access which is shown in red in Figure 3. Both rivers are classified as meandering streams with sinuous bends. A second site was studied in the Nyabugogo River as additional work. The two sites were chosen to allow for a better understanding of the mining processes across different morphological fluvial conditions and across different mining intensities. Two rivers exhibit differences in river order and size, confinement, style, and mining process and enables the assessment of how sand and aggregate ASM varies across different fluvial landscapes and how the morphological impacts differ between the two.

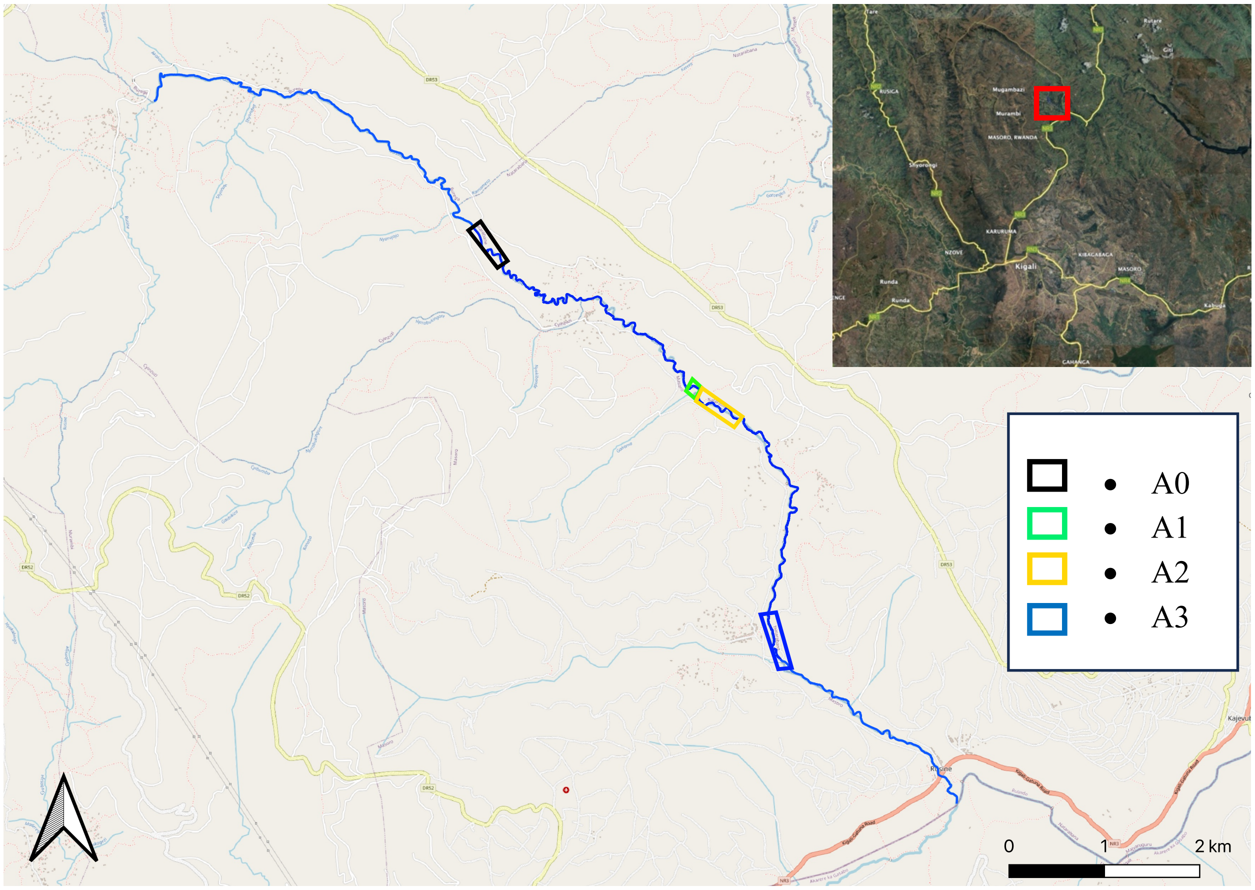

Figure 3. Study Sites on the Rusine River

3.2.1 Upper Rusine River Site A0

The first site, classified A0, is located at (-1.761361°, 30.052405°). This site is one of the only areas on the channel where no active mining is occurring. This site was previously mined from 2013 to 2015 according to high-resolution satellite imagery obtained from Google Earth that featured signs of ASM, which will be discussed at a further instance. This site demonstrates the possibilities of potential restauration at a local scale due to its vegetation covered riverbanks that go all the way down to the stream. Together with growing vegetation, no clear erosional features were observed. The river at this site behaves completely different from other reaches in the surrounding areas. The river segment observed at A0 is classified as a straight river reach in comparison to any other sites located on the Rusine River which could be due to previous mining happening in previous years as highlighted during the spatial survey prior to fieldwork. This river reach is also unique to the rest as it is the only one impacted by the presence of a road bridge that crosses over the river. Debris has collected under the bridge which forms a temporary dam which has consequences on hydraulic structure of the river (Wang et al., 2019).

3.2.2 Downstream Sites A1, A2, A3

Sites A1, A2 and A3 are located downstream of A0 (-1.771276°, 30.067573°), (-1.778896°, 30.075854°), (-1.802569°, 30.081741°) respectively. All exhibit intensive ASM with a particular focus on coarser aggregates like gravel and TIN at A1 and A2. Site A3 demonstrates a clear evidence of sand mining. Site A1 is characterized by a multitude of secondary and tertiary channels within the floodplain. Mining at this site seemed to focus on gravel and coarser sediments based on field observations of a delegation of labour between men and women where men will extract the material from the river and will pass it on to women and children to break the coarser material into finer material. The floodplain is scarred by leftover mining pits adjacent to the river. These pits fill up during the wet seasons and remain stagnant during the dry season. Site A2 indicates the largest fluvial manipulation out of all sites chosen. This area served as the main site of research for this project due to the overall scale of impacts to the fluvial landscapes. The Rusine river flows within a largely unconfined to semi-confined valley with very little limitations to movement within the Rusine Valley at site A2 in particular. The river flows parallel to the DR53 road north of the Rusine Valley.

3.2.3 Site B1 in Nyabugogo River

Site B1 is located roughly 5 km downstream of the confluence of the Rusine and Nyabugogo rivers (-1.846170°, 30.097148°). The scale of ASM operations on the Nyabugogo River target sand from the riverbed rather than coarser materials. The site demonstrates a significant difference in anthropogenic river manipulation as seen in sites A1 to A3. Far less mining occurs on the riverbank and floodplain, rather a the mining efforts focus on the riverbed. Sites B1 to A1, A2 and A3 all have steep riverbanks with significant erosion patterns. This river flows through an unconfined valley where the floodplains are wide and are commonly used for rice cultivation adjacent to the NR3 Kigali-Gatuna Road.

Chapter 4. Methods

A wide range of methods can be utilized to study a landscape and may depend on the complexity of the landscape and therefore in-situ readings of the landscape are a critical to geomorphological research. Due to the high complexity and lack of proper understanding of the relationship between ASM and rivers morphological response, fieldwork and geospatial observational analyses of the landscape were the most appropriate way of interpreting the ASM landscape in fluvial systems. The analysis of 23 years of historical satellite imagery and fieldwork provides a thorough understanding of the geomorphological setting of the Rusine River and Nyabugogo River which are under the pressure of ASM. It is important to tie theoretical and conceptual fluvial morphology principles and compare them to in-field settings (Fryirs & Brierley, 2012). This method entailed the identification of fluvial landforms and their spatial relationship with ASM features like pits, trenches, dams and more. This allows us to understand the disturbance response of the river systems, which in the context of this research, aims to understand the relation between ASM and the geomorphological response of the studied rivers.

4.1 Geospatial Overview

4.1.1 Introduction

Geospatial and temporal analyses of the ASM landscape allow us to gain a deeper understanding of the distribution of ASM across the Rusine and Nyabugogo River. An investigative approach to ASM gives critical information regarding the signs and evidence of how ASM is conducted in all studied sites and its prominence within the fluvial landscape. It provides important information regarding the overall fluvial landscape of the watershed through the analysis of fluvial behaviour and fluvial landforms across a larger scale than the site-specific analysis of fieldwork efforts. It also enables quantitative analysis of meander bends, meander amplitude and wavelength that will elucidate meander complexity and the overall response of a river to active ASM.

The methods section is divided in three parts describing the spatio-temporal investigation of ASM of the Rusine and Nyabugogo River which governed the overall site selection process; the quantification of fluvial processes through measurements and calculations aimed at understanding the fluvial landscape at pre- and in-mining stages; and, the mapping approach.

4.1.2 Site Selection

Artisanal and small-scale mining is widespread across Rwanda. Thousands of mining sites can be found around the multiple rivers and lakes of the country. As sand and aggregate mining mostly occur around aquatic environments, and the scope of this research being to understand the impacts of river systems, the search for potential sites was confined the investigation of fluvial areas within the vicinity of Kigali City and its surroundings. An investigative approach to fluvial geomorphology, allows us to understand the spatial pattern of ASM on fluvial systems in Rwanda and the impacts of mining of the rivers over multiple areas in the country. The main focus area was the Nyabugogo basin due to its proximity to Kigali city and ease of access via car transportation. The process of studying the distribution of ASM mines across the Nyabugogo basin was accomplished using the satellite imagery provided freely available through Google Earth Pro. The search was done by finding and depicting signs of active sand or aggregate mining using a series of proxies that serve to establish a relationship between each site and ASM activity. The proxies used must be visible by the satellite imagery therefore each proxy must be large enough to be identified properly. The proxies combined signs of anthropogenic disruptions to the fluvial landscape, human presence, and disturbances to river morphology such as bank erosion, unnatural behaving fluvial systems. ASM is done without the use of heavy machinery therefore dredgers and other extractive machinery are often not present. During the process of ASM, material extracted from the rivers is deposited in circular piles usually on the riverbank or nearby to await transportation. The most evident clue from satellite imagery is the presence of such piles appearing in the landscape (Figure 4). Such piles can remain present for only a few hours but up to a few weeks and months depending on demand and truck passage. Another landform that appears in areas where ASM is practice are circular pits creating small depressions adjacent to the river. These pits are scars of the mining practices.

Figure 4. Proxies of ASM across the Nyabugogo Watershed (Google Earth Pro, 2024)

The material found in piles is then loaded onto vehicles, most often dump or haul trucks, by sand loaders using small spades (Lalèyè et al., 2020). Therefore, the process of identification of sand and aggregate mines must include the presence of trucks or tire tracks left by such trucks. Moreover, a key factor in the identification of ASM is unnatural morphological landforms stemming from anthropic disturbances. In Figure 3A, multiple signs of anthropogenic disturbances are present throughout the landscape. First, the riverbank demonstrates cutbanks that have been dug creating an irregular riverbank that is highly susceptible to mass movements due to its high slope angle and complete removal of vegetation. Rapid changes in fluvial style from meandering to braiding or the opposite also appears in areas where river ASM occurs.

The presence of anthropogenic proxies such as the presence of trucks, tire tracks, mining pits and sand or alluvial piles dictates the potential research areas. All areas where these proxies were found were investigated upon arrival in the country to narrow down to the chosen sites in the Rusine and Nyabugogo River.

4.1.3 Archival Satellite Imagery Analysis

By analyzing satellite imagery dating to before the start of ASM in the Rusine and Nyabugogo River I establish the presence of the anthropogenic proxies to estimate when ASM started at the study sites, thus creating a separation between periods before mining and in-mining periods. As ASM is heavily practiced in all study sites, as confirmed during field campaign in the summer of 2023, knowledge gained from in-situ methods was used to establish the impacts of ASM and compare to what can be observe in high-resolution satellite imagery.

Through high-resolution satellite imagery found through Google Earth and Satellite Worldview-3 acquired from the Rwanda Space Agency, dating back to year 2000 till present, we can establish migration patterns, meander complexity, channel width changes and understand the morphological responses to ASM. The year of 2008 marks when ASM started in the Rusine River based on the first ASM evidence observable in the imagery. From the Nyabugogo River imagery, 2006 was established as the start of ASM in this area. A series of calculations, measurements (refer to subsection 4.1.5) and mapping (subsection 4.1.6) of the morphometrical parameters of fluvial migration, amplitude, wavelength, sinuosity, fluvial path, and style were made to gain an understanding of the undisturbed pre-mining fluvial morphology and the in-mining morphological response of both rivers.

Archival satellite imagery analysis also served as a tool to conduct analysis of river corridor management practices focusing on hydrogeomorphological processes to identify areas prone to avulsion or cut-off. Basic concepts of hydrogeomorphological analysis focus on channel mobility (Biron et al., 2014) with a particular attention to avulsion risks. From historical imagery, fluvial migration behaviour can be assessed and used to establish the geomorphological integrity of both studied rivers.

4.1.4 Data

The images used for this project span from the period 2000 to 2023. High-resolution satellite imagery was obtained from the Rwanda Space Agency (RSA) for 2008 and 2019. These images have a 50cm spatial resolution, with Red Blue Green spectral bands, with a radiometric resolution of 8 bit from the WorldView-3 sensor. The imagery from 2008 and 2019 were used to develop a floodplain migration map (Figure 9). The latest satellite imagery provided by Google Earth Pro coincides with the field campaign of June and July of 2023. All data used for the geospatial calculations were manually generated using the measurement tools from ArcGIS 10.1 and Google Earth Pro.

4.1.5 Governing Equations

This research uses several calculations and measurements to quantify the changes in the fluvial landscape, i.e., indexes of sinuosity, channel migration, channel amplitude and wavelength. These metrics indicate the morphodynamics of the studied river and provide information regarding the complexity of the meander bends in the studied river segments. This will allow a comparison between the natural behaviour of the river prior to the anthropogenic disturbances of ASM. The equations necessary to analyze both rivers morphological structures are their sinuosity, migration rate, amplitude, and wavelength.

Sinuosity index measurements taken over multiple years allow us to identify the changes within the sinuosity of the channel and is calculated by dividing the channel length along the centerline by the valley length (Wilzbach & Cummins, 2008). The meandering nature of both streams requires us to quantify the sinuosity index over time to provide information regarding their morphological response to ASM through the changes in sinuosity.

SI = Channel length/ Straight-Line Valley Length (Petts & Amoros, 1995)

Floodplain migration rates will allow for quantification of the lateral change/movement of the floodplain due to ASM processes. From observation gathered from fieldwork, many obstacles are built into the river system that diverts flow and leads to vastly changing river behaviour impacting the active floodplain. Such calculations will show how much the Rusine River moves under no ASM pressure and conversely with ASM pressure. The migration rate will be calculated as:

EQ1.

$$R_m = \frac{A}{L}/y$$

Where R_m is the rate of migration expressed in sq. km, A represents the area of the change polygon, L is the length of the centerlines used to represent the river path and y equates to the number of years (Giardino & Lee, 2011). Due to the high degree of disturbance response in the Rusine river, manual digitization of the active floodplain boundaries is preferred over automated and modelling methods to quantify floodplain changes. Due to the anthropic alterations of the riverbanks such as the trenching of new meanders in the floodplain, an automated method of centerline generation would become inaccurate and would not depict the true centerline of the main channel.

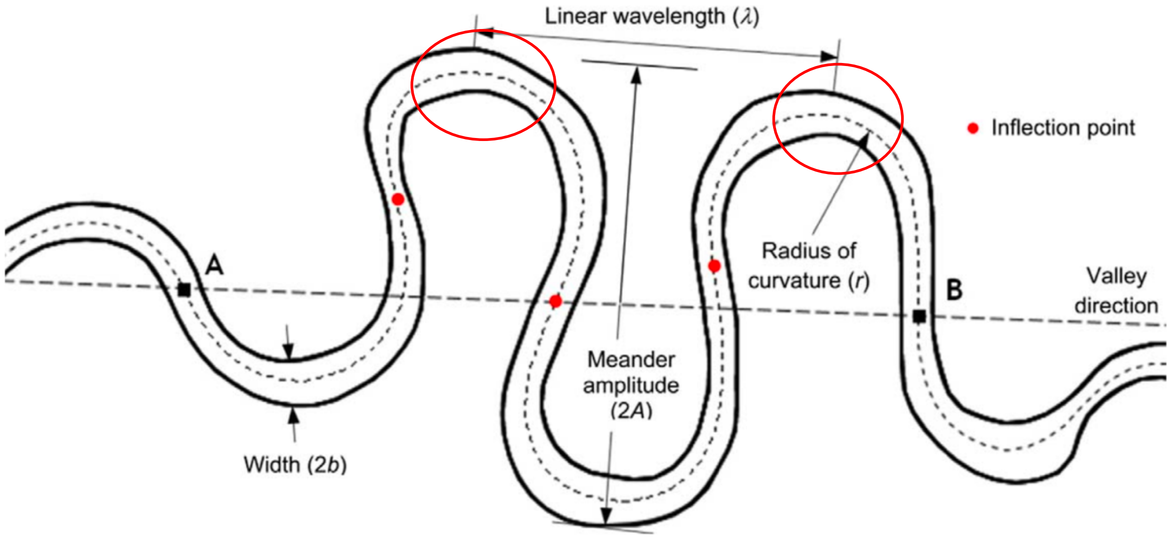

Figure 5. Meander Conceptual Model (Gueneralp & Marston, 2012))

Wavelength and amplitudes of the meanders are crucial to understanding the planform evolution of a meandering river. Wavelength and amplitudes are an important factor to quantify meander sinuosity (Gueneralp & Marston, 2012). In this research, linear wavelength is measured at the apexes of two successive bends highlighted by the red circles (Figure 5).

This conventional approach to wavelength calculations is only applicable to river segments that possess opposing sinusoidal meanders (Reinfields & Bishop, 1998). In the case of straighter river segments, where sinuosity levels are low, the wavelength is measured from inflection points. Such points mark the location at which the curvature of the meander transitions from one bend onto the next opposing one. In certain cases, although it may differ between each one, wavelength can be related to the root square of the discharge as power functions of the form:

EQ 2.

$$\lambda_L \sim c\, Q^{1/2} = c \sqrt{(Q)}$$

Where c is an empirical coefficient varying on the characteristics of the river. On average, total linear wavelength of a meander is usually between 10 to 14 times the channel width of a meandering river.

Amplitude is measured by the distance of a meander along the valley axis. It is calculated at the maximum displacement from the valley axis to sinuous axis as Figure 4 demonstrates. As for wavelength, amplitude is related to the square root of the discharge where k represents the empirical coefficient similar to EQ. 2, and Q refers to discharge:

EQ 3.

$$A_m \sim k\, Q^{1/2} = k \sqrt{(Q)}$$

Wavelength and amplitude are important to consider when looking at the overall stability of a channel. Rivers will demonstrate a degree of regularity in their morphology through their wavelength and amplitude. The regularity of simple opposing sinusoidal meanders that appear in meandering systems are a clear indicative of a river reaching equilibrium which is related to external factors like discharge. This explains the relationship between the square root of the discharge of a river to the calculation of wavelength and amplitude. If the river remains at equilibrium, the overall meander morphology will not be altered as it moves through time and space or through its migration pattern. However, a change in allogenic or anthropogenic controls as ASM can cause a shift in equilibrium, therefore, a change in meander morphology (Trenhaile, 2016).

4.1.6 Mapping

To gain the necessary data to run the equations, a significant mapping effort was needed to trace the fluvial path, floodplain progression and develop a thorough analysis of the interaction between ASM and the changes in fluvial morphology. The first step in this process is the georeferencing of satellite imagery gathered from Google Earth and digitization of the channel centerline and floodplain. The georeferencing process is used to analyze imagery from different years using the same Google Earth tile and/or high-resolution satellite imagery provided by the Rwanda Space Agency (RSA). High-resolution imagery was acquired from Maxar by the Rwanda Space Agency (https://space.gov.rw/). This imagery has a 50cm spatial resolution with an 8-bit radiometric resolution from the WorldView-3 Sensor and was acquired in 2019. A series of tiles were mosaicked to portray the entirety of the study sites in the Rusine River, spanning from sites A0 to A3.

Following site selection, analysis of the fluvial landscape was undertaken of the designated study area via high-resolution satellite imagery and geographic information systems processing is done. Publicly available data were gathered from the Rwanda Water Resources Board Geospatial Portal (https://www.geoportal.rwb.rw) and of a 10m Digital Elevation Model (DEM) (https://geonode.rbis.ur.ac.rw) to model slope across site A2. The geoportal provided layers such as the river network, waterbodies, and catchment levels. River network data were available at the Rwanda Water Resource Board and the Ministry of Environment of Rwanda.

A topographical analysis was used to extract the river network and understand the setting of the study area. Geospatial processing was utilized to analyze the fluvial style of the Rusine River as well as to gather information regarding hydrological and morphological characteristics prior to fieldwork. The assessment of fluvial style is done to understand the morphodynamics of a particular reach and to understand the response to sediment starvation or excess following mining processes. This assessment of fluvial style will be further discussed in the latter portion of the methodology. The area was delimited by the boundaries set of the catchment level 1 layer provided by the Rwanda Geoportal. The 10m x 10m DEM file had to be mosaicked by merging all of the DEM files together before clipping to the catchment level. The delineation of the topographical map was then be used to distinguish slope throughout the catchment. An analysis of the study area's topography allowed for an assessment of how the topography of the terrain controls river characteristics and behavior (Brierly & Fryirs, 2005). In this case, the DEM was critical in creating slope data for the land surface flow direction model, to create baseline data for multiple aspects of the fluvial morphology of Nyabugogo watershed. It will also establish basic morphological characteristics of the river such as floodplain extent which can be translated into possible behaviors of the streams.

Digitization of the river's centerline was accomplished using the edit function from ArcMap 10.1, where manual digitization was used to portray the most accurate centerlines of the Rusine and Nyabugogo rivers. The centerlines were digitized over the entire length between site A0 and A3, which marks the beginning and end of the study sites of the Rusine River and was also digitized at the site specific scale of 500 meters across each site to assess local variations of the sinuosity. To assess the floodplain spatio-temporally, a manual digitization of the floodplain at site A2 was done, following the same method used to digitize the river centerline based on elevation changes between the river floodplain to the edge of the bank wall. Site A2 was selected due to the availability of high-resolution imagery from RSA. This is done for the minimum and maximum available years of satellite imagery available from the RSA, i.e., 2008 and 2019. The year of 2015 was used an intermediate study year between 2008 and 2019. In 2015, the limits of the active floodplain were visible enough to digitize in contrast to other years with available imagery from Google Earth Pro. Site A2 was chosen based on the quality of data available from the Worldview-3 Sensor imagery. Site A1 and A3 showed gaps between tiles that did not accurately represent the entirety of the floodplain at each site.

4.1.7 River Corridor Analysis

This study applies river corridor management analysis which relies on understanding hydrogeomorphological processes to determine areas that show signs of erosion leading to avulsion through natural fluvial processes. This concept has been described under various names, from erodible corridors (Piégay & al., 2005) to freedom space (Biron et al., 2014). Areas prone to avulsion are determined by detecting erosion traces (Biron et al., 2014) using high-resolution satellite imagery to identify meanders that are likely to avulse in the near future. A meander neck with a width of less than four times the channel width is considered a high cut-off risk meander (Biron et al., 2014). River corridor management allows the establishment of a predictability factor for river behaviour under no ASM influences.

4.2 Morphological Assessment/Fieldwork

This research is based on in-situ assessments conducted in Rwanda over the summer of 2023 of the qualitative and quantitative morphological assessments of the Rusine and Nyabugogo rivers to understand landform changes and fluvial processes.

4.2.1 Field Methods and In-Situ Assessments

In-situ data gathering focused on the Rusine River, (A0, A1, A2, A3) where the initial measurements taken were cross sections of the Rusine River floodplain and channels. dGPS points were collected using an Emlid Reach RS2 differential GPS allowing a 1-2cm precision to determine topographic relief such as steepness of the riverbank, the length of the floodplain, incision of the riverbed, localized morphological features such as point bars, mid-channel bars on braiding segments and marking anthropogenic manipulations of the river for ASM purposes. The points were measured perpendicularly to the direction of the valley and flow of the river to obtain a cross section of the entirety of the floodplain starting at the older fluvial terrace, which is also located at the highest topographic level in the terrain and ending at the opposite end of the transect at that same terrace. Individual dGPS point measurement were collected based on a feature-based analysis rather than equidistant measurements, allowing for the inclusion of as many details and smaller elevation fluctuations as possible in the floodplain and channel. It also allows the marking of anthropogenic influences spanning from improvised dams to hand dug meanders to pits and sediment deposition sites. Cross-section data collection was conducted at multiple section across the Rusine River with a particular focus on site A2 due to the severity of the mining effort at this specific site. These measurements are then compared next to each other to assess the profile of the floodplain between heavily mined areas such as site A2 and recovering sites like site A0. Each point was then post-processed to obtain a FIX resolution where each point has an accuracy of 1-2 cm.

Basic hydrological measurements were taken in the field including river depth, width, and velocity in order to calculate discharge. River depth was measured using a one-meter ruler placed on the riverbed at the thalweg or deepest and fastest flowing portion of the river and comparing the surface level of the river to the increments of the meter. The ruler was placed parallel to the flow of the river to avoid accumulation on the meter's flat surface. Multiple depth measurements were averaged from the same location to gain a mean river depth at the thalweg for each measurement location which have been marked with the differential GPS. River width was measured using a tape measure across the river from bank to bank.

Flow velocity measurements were taken using an Owens River Hydroprop meter. Five propeller transit times were collected at each site to estimate a mean velocity measurement. This meter determines flow velocity by measuring the transit time it takes for the hydro propeller to travel across the entire axis, therefore a faster transit time equals a faster flowing river. Individual velocity measurements were taken at different, using a combination of the 0.6 method and the two-point method, or otherwise called the three-point method (Waugh & Fenwick, 1979), therefore measuring at 0.2, 0.6 and 0.8 of the river depth as indicated in Figure 6.

These methods are drawn from multiple studies and field observations over time that have provided scientists with consistent and accurate results (Buchanan & Somers, 1969). The combination of methods ensures maximum accuracy in the field with the equipment that is available. All results gathered from both methods of current meter gauging are then averaged to calculate the overall arithmetic mean velocity of the entire water column. The arithmetic mean velocity of all three points is then used within discharge calculations. In cases where flow measurements may not be possible due to the size of the meter, but our hydropropeller was small enough not to interfere with the surface and bed of the river during measurements at 0.2 and 0.8 depth

measurements.

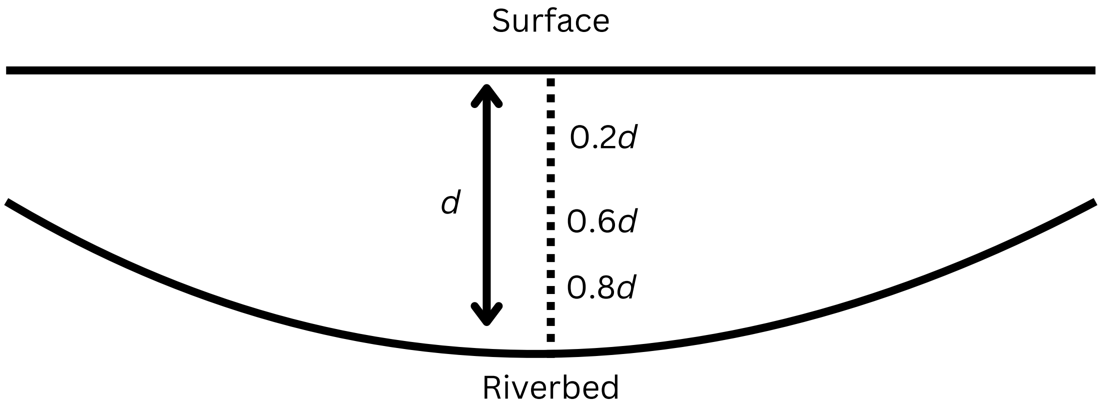

Figure 6. Velocity Depth Measurements Methods Used in the Rusine River

In order to convert propeller transit time in seconds to velocity in cm/sec, a calibration equation is provided:

EQ. 4

$$V = \left(0.0277 + \frac{3.2805}{T}\right)100$$

Where V defines velocity in cm/sec and T is the measured time for the propeller to make full transit of the axis. Both numerical values are constants provided from the calibration chart of the hydro propeller. This equation was used to generate all velocity measurements gathered in the field campaign on the Rusine River.

Using measurements gathered in the field, it is now possible to calculate discharge using:

EQ 5.

$$Q = wdv$$

Where Q is the discharge in m^3s^{-1}, w stands for the width of the studied channel, d refers to the depth and v is the measured velocity of the stream in m/s.

A field survey was conducted in the studied river segments of the Rusine River to identify pool and riffle sequencing formations within the channel. This was done by a simple walkthrough of the river to identify bed undulations. Since the field campaign was conducted during the dry season, water levels were very low and enabled surveying of the riverbed. This method enabled a fast and simple way to determine the length of the riffles and pools, as well as their sequencing order. It provides a greater analysis to identify other external factors that can influence Riffle-Pool sequencing such as improvised dams, active mining on the riverbed other processes common to ASM in the Rusine River.

During the field campaign, river behaviour was analysed by looking for river change or "a wholesale change in the river type" (Fryirs & Brierley, 2012, pp.21). Wholesale changes in the river types relate to the complete shift between the established river style to another one that differs completely from the original. This is done by a walkthrough on the river to capture photographic evidence of behavioural change, or a change due to a disruption upstream. This allows us to understand whether a threshold has been exceeded by a disturbance in the fluvial system.

Chapter 5. Results

This section focuses on and introduces the variety of different data measured and analyzed in this thesis to describe the morphological parameters. To obtain an historical overview of the last 20-years of river evolution, geospatial analyses were conducted. These are supported by in-situ analyses collected through fieldwork. In-situ methods were used for ground-truthing and physical measurements of selected morphological parameters of the Rusine River such as river geometry, basic hydrological measures of velocity and discharge and Pool-Riffle sequencing. Section 5.1 focuses on the entirety of the geospatial analysis on the Rusine River. Section 5.2 shows the additional work done on the Nyabugogo River to provide a contrast between severe floodplain ASM practices and in-channel riverbed mining. Since the work of the Nyabugogo River does not reflect the main focus of this study, land use change was not accounted for in the analysis and no apparent changes in the land use was detected between 2000 and 2023.

5.1 Morphological Evolution of the Rusine River from 2000-2023

Pre-mining imagery provides key information regarding fluvial behaviour before any anthropogenic manipulations of both rivers. The oldest imagery available from Google Earth dates from the year 2000. Imagery from 2000 acts as the baseline for comparing pre-mining and in-mining periods of the river. In 2000, no mining had yet taken place in the Rusine River, and cropland dominated the landscape surrounding the Rusine River, making up the majority of the Rusine River's floodplain and the valley hills surrounding the river. Throughout the valley, patches of forested and shrub areas compose the other main land cover types of the Rusine Valley. However, the Rulindo district has been under mining initiatives since the 1930s as part of the Rutongo Mining area (Kazindu et al., 2020). While no mining occurred directly on the Rusine river in 2000, ASM activity did take place within the district, such as along tributaries of the Rusine, which lie outside of the study area.

In 2000, the Rusine River remained under natural control as no signs of active mining. The river meanders with varying degree of sinuosity, as shown in Section 5.1.4. The change in sinuosity level varies at a larger scale due to the local variability of each meander's age and progression through its cycle at each site, whether it has just avulsed or cut off, leaving behind an oxbow. Identifying meander scrolls and paleo-channel marks in the landscape allows the estimation of the progression of meanders in the valley. However, due to the highly vegetated and cropland-dominated landscape, certain palaeohydrological features of the Rusine are dissimulated within these land uses. The channel size contrasts severely with what the Rusine River currently exhibits. Prior to ASM activities, the Rusine River had an arithmetic mean river width of ≈1.2 meters using an equidistant measurement of width every 100m of the river length in each studied reach of the Rusine River. During fieldwork, the river's width was measured again at all sites and showed an arithmetic mean width of ≈5.37m reflecting an increase in the overall width of the channel (Refer to Table 5). In 2000, the size of the river was minimal; its appearance was barely noticeable due to its creek-like origin and it share no common attributes other than its style to what is observable during on-going ASM. The earliest evidence of mining appears in 2008, where tire tracks, alluvial piles and small mining pits are observable from high-resolution satellite imagery. Between 2000 and 2008, no satellite imagery is available. Thus, a conservative estimate would assume that mining activity does start in 2008. The imagery from 2008 show active mining that left a small imprint on the land in contrast to 2023 which shows that the active mining activity is recent. Within the dedicated field sites, several mining pits cutting in to the floodplain had filled with water from the river or precipitation are creating standing water on the adjacent banks of the river, as shown in Figure 7.

Figure 7. Open Mining Pits at Site A0 (RSA, 2019)

It is assumed that ASM practices in 2008, were very recent due to the minor morphological disturbances seen across the fluvial landscape of the Rusine River in comparison to the impacts observed in 2023.

Applying river corridor management to a complex multilobed meander located at site A2 in the Rusine River (-1.776067, 30.072059) for the year 2000 shows a very high cut-off hazard (Figure 7). The meander's neck width is less than four times the channel width, meaning that in this meander, there is a cut-off risk in the second sinusoidal loop of the meander, where both opposing segments are very close to one another. Before the first inflection point of the meander, the outside bank pushes towards the opposing segment, where the erosive action of the river will connect both segments and leave the remainder of the meander to be cut off via a chute channel. Figure 7 shows the high-risk meander and highlights the potential cut-off area. Since there is a large time gap between both images, the resulting cut-off process in the high-resolution satellite imagery 2008 may not directly relate to the predicted cut-off. However, it does portray the compound loop's avulsion and further river migration through the river's erosive functions. We observe the paleo-channel that progressed between the initial fluvial path taken from June 2000 and the cut-off event between this date and July 2008. The avulsion of the compound loop indicates that the channel continued to erode the outside banks, pushing the apex of the last lobe of the meander prior to avulsion.

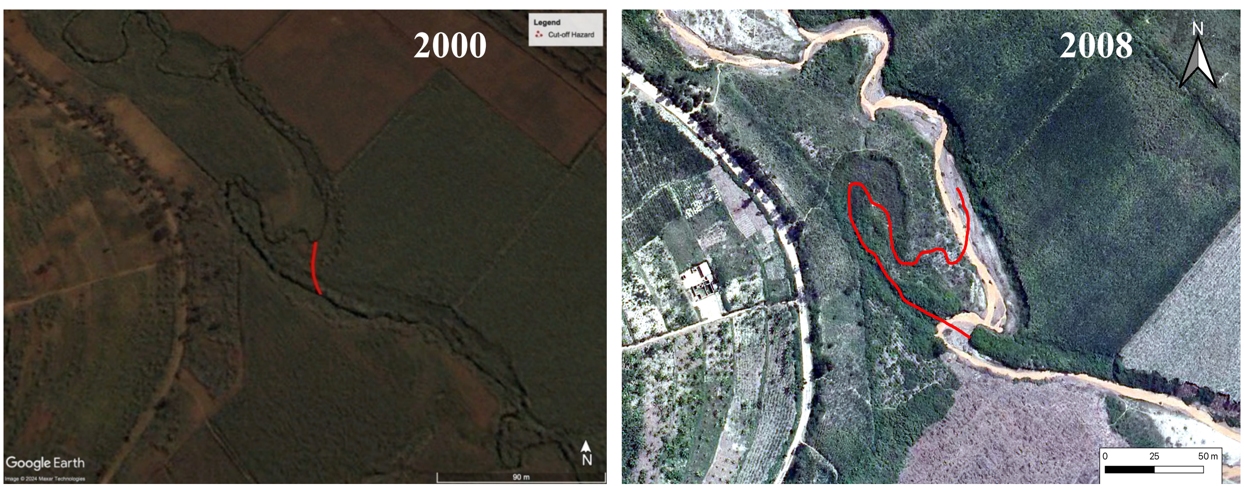

Figure 8. Cut-off Hazard in the Rusine River (Google Earth Pro, 2024)

In Figure 8, we see that the cut-off event occurred directly at the neck of the initial meander, therefore cutting off the entire meander identified from the year 2000. No signs of erosion prevention measures are evident at this meander to reduce the erosion impact on the cropland of the Rusine Valley.

5.1.1 Channel Pattern Measurements of the Rusine River

The primary morphometrical analysis of both studied rivers, incorporating wavelength, amplitude, and sinuosity parameters, are significant as they provide a crucial understanding of flow and channel patterns over the project's studied reaches. The index was calculated for each site (A0, A2, A3) for every analyzed year between 2000 and 2023. The entirety of the eastern part of the Rusine River and the site-specific reaches for all studied sites of the river were measured to assess local variations at a site-specific scale for the individual study sites. Site A1, due to the braiding occurring at the site, is deliberately excluded from sinuosity and hydrological measurements. It is also to note that available imagery from the RSA for 2008 and 2019 is not used to measure channel patterns and sinuosity due to the numerous gaps in the tile mosaic of the river and only spans up to site A0 which prevents an accurate measurement of the sinuosity index of the river.

Sinuosity measurements were conducted at the reach level for the sites visited during fieldwork and along the full river extent to visualize local differences in sinuosity. The larger-scale sinuosity measurements agglomerate the distance between the head of the Rusine River and its mouth when flowing into the Nyabugogo River. For wavelength and amplitude, this research focuses on a particular meander at site A2. The knowledge of active mining at this site led to the choice of this meander and the knowledge of important ASM impacts on the fluvial landscape, which portrays a floodlpain ASM style. Figure 9 shows the meander progression from 2000 to 2023 over four instances of the studied meander at site A2 with an overlay of the fluvial path from the year 2000 and each precedent year. The meander was measured from apex to opposing meander apex for the amplitude and from apex to seconding apex for wavelength measurements. All measurements from 2000 to 2023 at each site and of the entire river extent are shown in Table 1. Table 2 shows all amplitude and wavelength measurement targeting site A2.

In the Rusine River, clear downward trends of sinuosity at the large-scale level during the active mining period are observable. At the site-specific scale, dramatic decreases in sinuosity are observed due to the protrusion of flow directly through the floodplain originating from intense digging and increased erosion seen in the river. In the case of site A2, there is a gain of sinuosity in 2023 which can be explained by the entrenching of new meanders outside of the active floodplain. Trends also show that there is a steady decline in meander amplitude levels and a net gain in meander wavelength. Such phenomenon depicts the overall straightening of the river. The fluvial path will follow riverbed and pit mining that tend to occur toward the center of the active floodplain. The widening of the meander structure through increasing wavelength measures and decreasing amplitude levels translates to river straightening due to severe floodplain mining. The overall impacts of the ASM of channel pattern are more evident at the site-specific scale. The overall analysis of the Rusine River from head to mouth reveals the agglomeration of the mining efforts downstream of site A0 from 2012 to present day. The variability of sinuosity indexes is pronounced from A0 down to the river mouth with more significant changes in sinuosity values.

Table 1: Sinuosity Indices of the Rusine River

	A0	A2	A3	River Totality
SI 2000	1.226	1.427	1.453	1.52
SI 2012	1.111	1.534	1.364	1.429
SI 2018	1.144	1.137	1.214	1.455
SI 2023	1.243	1.305	1.115	1.467

Table 2: Amplitude and Wavelength of the Selected Meander at Site A2

λ_L 2000 (m)	λ_L 2012 (m)	λ_L 2018(m)	λ_L 2023(m)
99.9	75.4	153.9	164
A_m 2000 (m)	**A_m 2012 (m)**	**A_m 2018 (m)**	**A_m 2023 (m)**
74	74.1	37.2	58.8

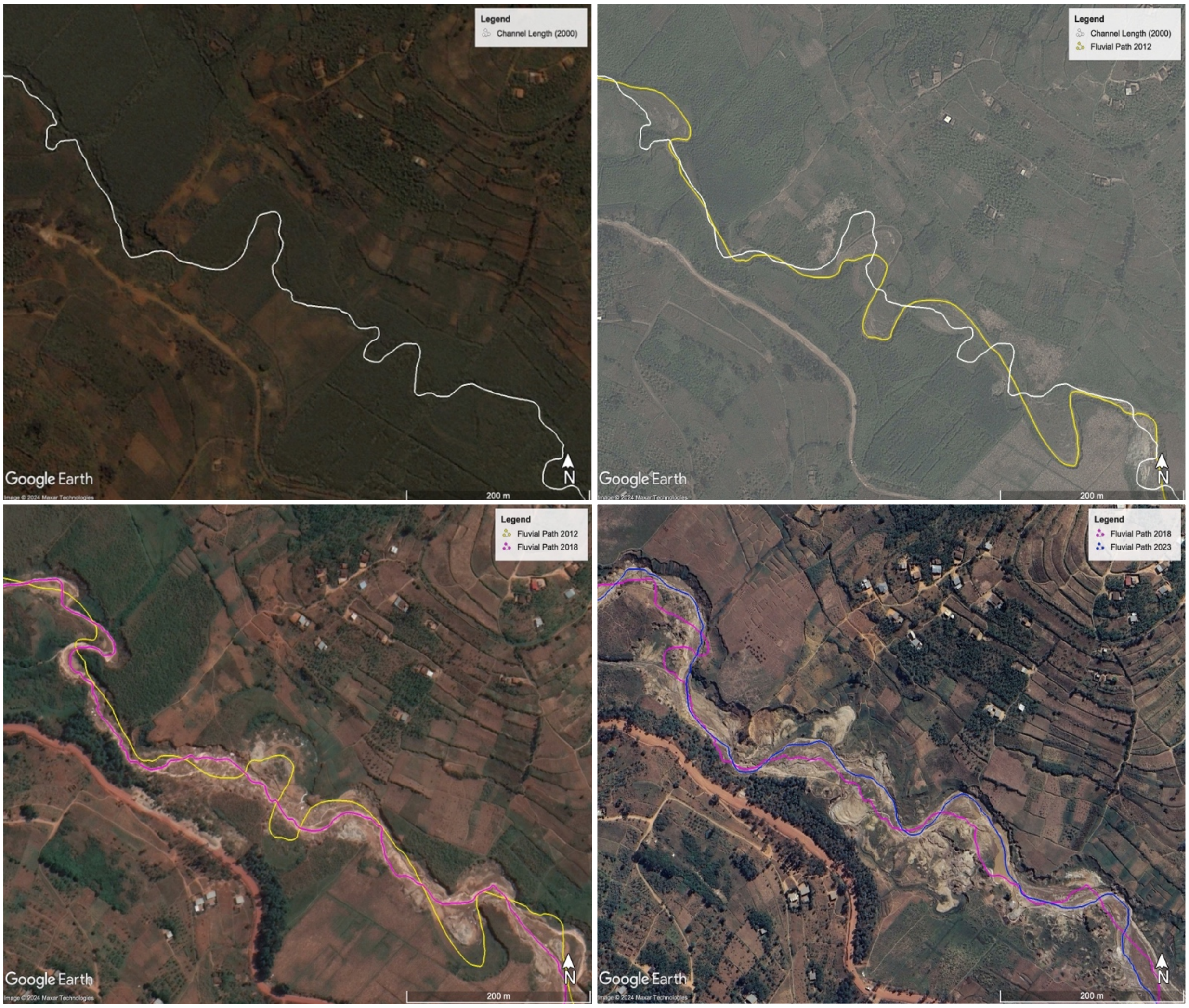

Figure 9. Fluvial Path Progression at Site A2 from 2000 to 2023 (Google Earth Pro, 2024)

5.1.2 Floodplain Migration of the Rusine River

Floodplain ASM include practices that target not only the river itself, but also excavate the riverbanks. The active digging of the active floodplain boundaries results in a significant increase in the active floodplain area and a reduction of the available fertile soil for subsistence agriculture by residents of the Rusine River. Protrusion of the floodplain takes many shapes during ASM, such as entrenching new channels and excavating the available sand and aggregates constituting the scarp between the active floodplain and ancient floodplain. These practices cause the enlargement of the active floodplain due to the addition of new secondary channels in the entrenched channels. Water flow in the new entrenched channel provides new erosion potential on previously unavailable areas within the enlarged floodplain. New meanders formed by the digging action of miners enable fluvial processes to extend the active floodplain, adding to anthropic manipulations of the floodplain.

With high resolution satellite imagery available from site A2 in year 2008 and 2019 (Rwanda Space Agency) it is possible to address floodplain migration over both years to visualize and quantify the changes occurring from ASM on the active floodplain. Figure 10 demonstrates the growth of the active floodplain over 11 years at site A2 which is the most disturbed site by ASM. Figure 10 represents imagery with available slope data from the Rwanda Space Agency in 2019 for 2008 and 2019.

In this example, the active floodplain area in 2008 was 0.014964 sq. km; through ASM incorporating tactics such as new channel entrenching and scarp wall mining, the active floodplain grew to 0.023695 sq. km in 2019 or 158.34% increase or 0.008731sq. km per year. The river path of the Rusine River at site A2 shows that from 2008 to 2015, active floodplain growth resembles and depends on the migration of the river through its freedom space. The migration of the Rusine at site A2 shows that the active floodplain migrates following meander progression. Under natural circumstances, river migration and meander cycles would cause this growth in the active floodplains; however, since 2019, the relationship has been inversed where by the active floodplain has grown due to anthropic activities. Morphometrical measurements of the Rusine indicate that at site A2, the river is straightening, where amplitude levels are significantly diminished, and wavelength measurement increased. Without ASM, such morphological changes could lead to a halt in active floodplain progression. Figure 10 shows that in 2019, the active floodplain continued to grow and relies no longer on the erosional action of the river.

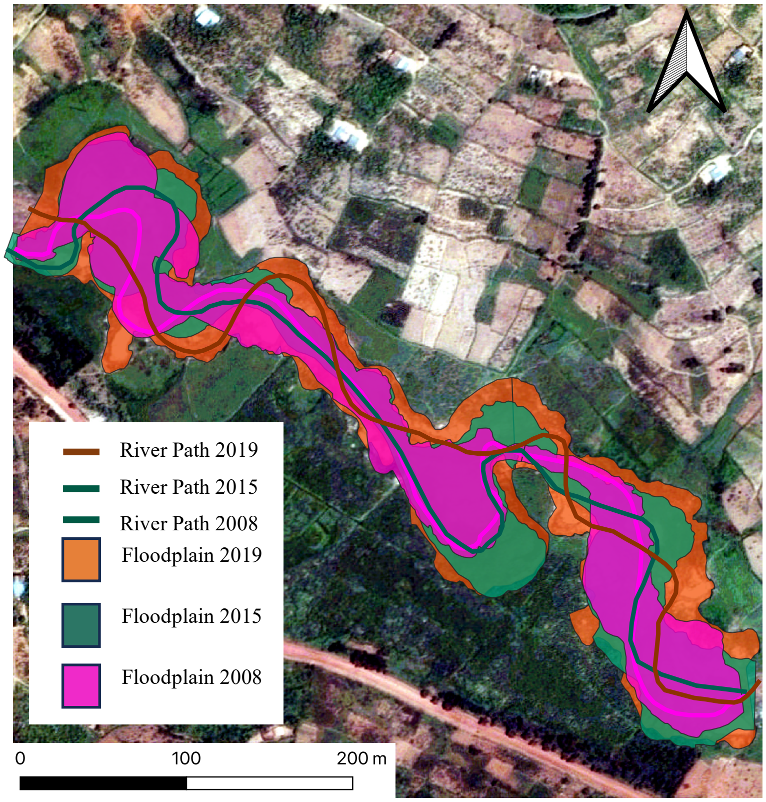

Figure 10. Change Detection for Floodplain and Fluvial Migration at Site A2 from 2008 to 2019

5.1.3 Land use Change in the Rusine River

The Rusine Valley hosted limited land use prior to the ASM activity occurring in 2008, i.e., cropland, forest and shrubland. According to field accounts, cropland surrounded sites A1 and A2 for cultivating primarily sweet potatoes. Site A0 and A3 are mostly located in forested areas and shrubland in the pre-mining stages. The introduction of ASM in the Rusine River coincides with deforestation, which is dominant in highly vegetated forest and shrubland areas such as sites A0 and A3. Deforestation of such sites leads to a transition from previously forest to new cropland. The enlargement of the active floodplain through ASM practices enabled the introduction of new crops within the active floodplain. At site A0, the active floodplain, landuse during periods of active mining, transitions from a dense forest patches to bare land with no dominant vegetation cover to a sweet potato farming patch. Cropland introduction in the valley occurred at the same time as mining occurred, leading to a connection between ASM and the increased agriculture in the Rusine Valley, as seen at sites A0 and A3. Previously farmed areas, such as sites A1 and A2, however, suffer from soil erosion due to severe floodplain mining in the adjacent river. However, sporadic, and small patches of cropland appeared in previously mined areas. Site A2 shows that residents of the valley use previously entrenched or dug areas, and the newly available area in the active floodplain is planted with sweet potatoes as a nature-based solution enabling recovery of the mined landscape.

The increasing presence of mining over time shows significant alterations within the land use of the Rusine River. The mining activities extends rapidly throughout the Rusine River. A quantification (Table 3) of the percentage of actively mined channel length across the entirety of the studied segment of the river reveals that mining presence across the river increases rapidly from 2012 and continues to intensify today. Results from the quantification of the mining activity across the Rusine River show a significant increase at every studied year. This upward trend in mining activity show that ASM will continue to take more space as time progresses.

Table 3: The Distribution of ASM Across the Rusine River

Rusine River	**2012**	**2018**	**2023**
Meters mined	4991	7873	8995
% of mining	31.18	48.31	54.77

5.2 Morphological Evolution of the Nyabugogo River from 2000 to 2023

The undisturbed meander progression of the Nyabugogo River is highly dynamic and stable, where through time, meander cut-offs in areas that are likely to avulse. The dominance of natural processes rather than anthropogenic processes is crucial for understanding the river's morphological functions and enables the prediction of channel erosion and avulsion patterns. In the Nyabugogo River outside meander bank erosion occur where the channel follows its natural path through time in the active floodplain, creating tighter meander loops, increasing meander amplitude, and reducing wavelength between successive meander bends (Figure 11). This process unfolds until a cut-off occurs when the meander exceeds its threshold and returns to equilibrium via the avulsion or cut-off of the channel throughout the active floodplain. Figure 11 serves as a conceptual model to demonstrate meander progression observed in undisturbed meandering rivers in dark blue at the earliest stage and dark grey at the latest stage. It highlights how the Nyabugogo River moves along its active floodplain when no mining occurs in the river.

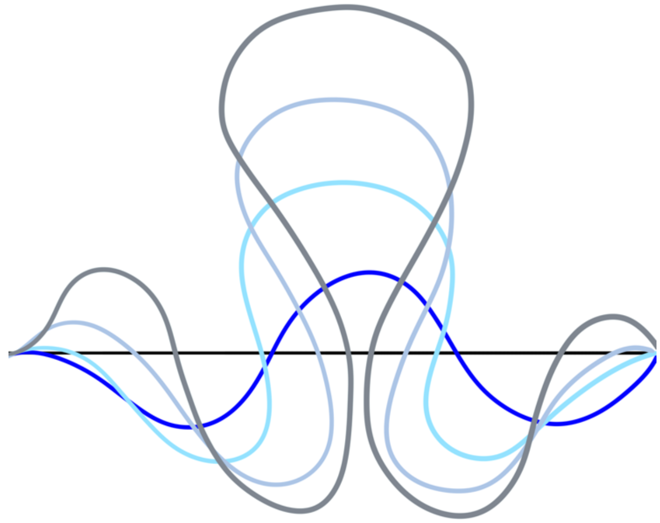

Figure 11. Meander Progression Model

The Nyabugogo river can move freely within its floodplain limits as it has no obstruction across its corridor following Kline & Cahoon (2010). Figure 12 shows a cut-off hazard area at site B1 in the year 2000; the compound loop's first sine wave shows tendencies towards avulsion due to the sharp curvature of the meander bends. Through the erosive action of the river, both outer bends of the meander will avulse together over time as the river continues to migrate laterally. Both opposing channel sections erode oppositely, eroding towards one another. By natural morphological processes the identified meander will cut off naturally at the first meander iteration of the compound loop at both inflection points.

In Figure 12, I verified the meander at a later stage to determine if erosion stresses exceeded its resistance threshold, leading to a cut-off of the meander. Figure 10 also shows the next available imagery possible of the selected meander, showing the original fluvial path in 2000 by the digitized red line overlayed on satellite imagery of the same meander in 2006. In 2000, the river's channel width was ≈3.8 meters, and the meander neck of the meander's initial lobe was 13 meters, less than four times the channel width. The overlay clearly illustrates the river cut-off at the predicted area. The avulsion occurs at the first lobe of the initial meander that forms this multilobed meander. The absence of any significant anthropic activity is a key factor, as it allows, under the right circumstances, to see how fluvial action and determines river migration.

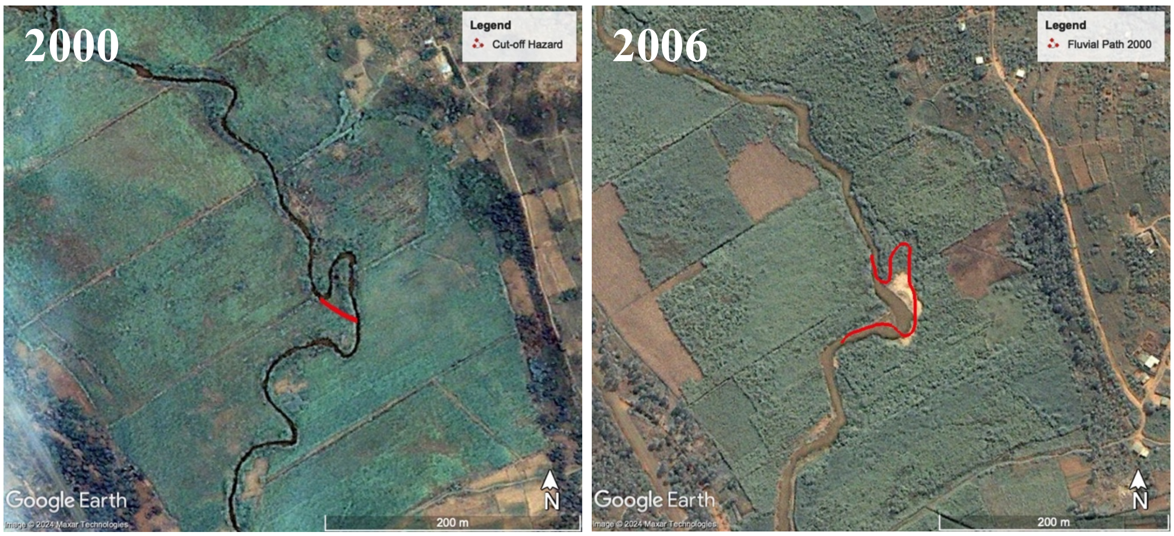

Figure 12. Cut-off Hazard in the Nyabugogo River (Google Earth Pro, 2024)

This analysis shows that the river moves predictably following river corridor management practices and allows us to predict future shifts in river migration and erosion when the river is undisturbed. The morphological function of the Nyabugogo, under no stress from ASM, remains dependent on natural processes for its behaviour and landforms. No erosion mitigation measures had been implemented at this specific site in the river, as the fluvial migration would have been significantly different. The interpretation of site B1 in 2000 demonstrates no active risks related to erosion due to the unconfined reach of the river.

Both rivers share similar attributes in their respective pre-mining era; they demonstrate active meandering processes leading to an amalgamation of complex meanders. Both meanders analyzed also demonstrate similar erosive patterns that can be predicted through river corridor management practices. Under natural controls, both rivers behave in ways expected from a fluvial geomorphological point of view and fit previous knowledge on fluvial style and behaviour in unconfined valleys.

5.2.1 Channel Pattern Measurements of the Nyabugogo River

Site B1 in the Nyabugogo River primarily undergoes riverbed mining, resulting in a less pronounced morphological response to mining activities. Figure 13 provides a comprehensive view of the area investigated over a 500-meter valley-length segment, including an overlay of the precedent and earliest fluvial path identified over each year of study to facilitate a comparative analysis between each year. Table 4 provides an overview of all morphometrical measurements of the Nyabugogo River.

The river shows, contrary to what is observable in the Rusine River, an increase in amplitude levels and a decrease in wavelength revealing that meanders at site B1 are progressing in natural manner where it would be expected to have an overall tightening on the meander bends. A sharp decrease in sinuosity occurs between 2000 to 2006 which is explained by the cut-off of a compound meander. After the cut-off event, sinuosity levels increase over time.

Table 4: Sinuosity Indexes of Site B1 In the Nyabugogo River

	B1		B1		B1
SI 2000	1.721	**λ_L 2000 (m)**	79.9	**A_m 2000 (m)**	47.4
SI 2006	1.332	**λ_L 2006 (m)**	108.6	**A_m 2006 (m)**	50.8
SI 2012	1.39	**λ_L 2012 (m)**	99.1	**A_m 2012 (m)**	56.3
SI 2018	1.411	**λ_L 2018 (m)**	97.7	**A_m 2018 (m)**	66.6
SI 2023	1.374	**λ_L 2023 (m)**	91.2	**A_m 2023 (m)**	76.6

Through in-channel ASM procedures, the Nyabugogo River demonstrates a tightening of meander sequencing, indicating the progression of the meander through its erosion cycle, accompanied by an increase in amplitude and a decrease in wavelength measures. This relationship between meander progression and ASM presents a trend that is distinct from that of the Rusine River, underscoring the unique impact of riverbed mining on the Nyabugogo River's morphometrics.

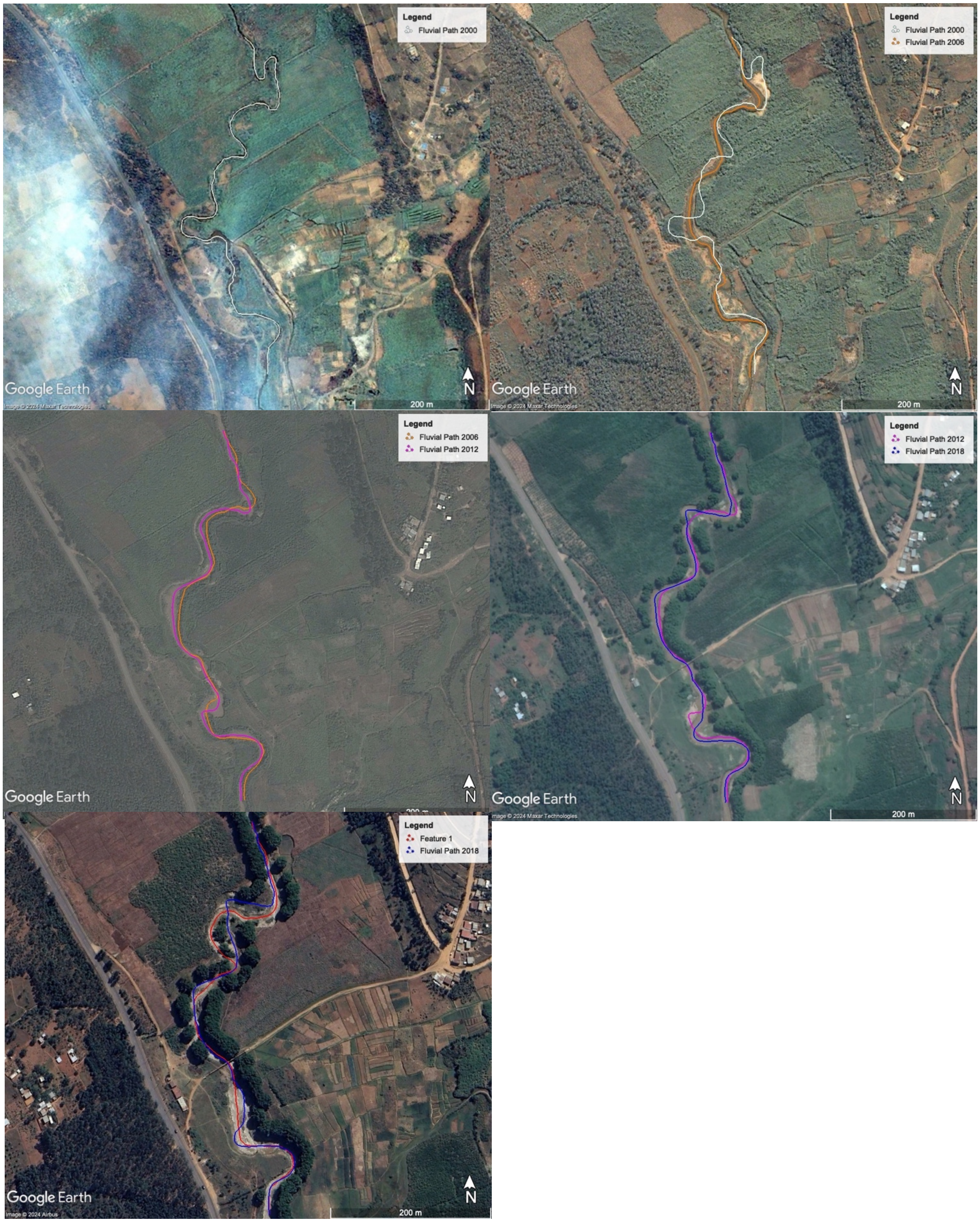

Figure 13. Fluvial Path Progression at Site B1 from 2000 to 2023 (Google Earth Pro, 2024)

5.3 Fieldwork Morphological Assessment

This section focuses on the field data obtained during the 2023 field campaign. The measurements taken reflect sections of the river that are actively mined (A2) and non-actively mined (A0). In-situ measurements were made of flow, discharge and Pool-Riffle sequencing and changes in river styles. All data gathering during fieldwork was obtained in the Rusine River.

5.3.1 dGPS Cross-Section Profiles of the Rusine River

dGPS measurement of cross section profiles reveal the prevalence of very steep and high riverbank walls along the Rusine River. Seven profiles were gathered and show undulating surfaces throughout the floodplain that reflect positive and negative landforms that stem directly from mining. Moreover, the cross-sections are used to identify the presence of the main and secondary channels present in the floodplain. Negative landforms were pits, trenches, and incision of the riverbed, while positive landform often took form as mid channel bars located in the channel, splitting the stream into secondary channels in braided reaches. Other positive landforms seen in the studied reaches were rock accumulated in piles and alluvial deposition. Cross sections profiles were gathered at sites A0 and A2 to compare an active mining site to a non-active site. Four cross sections profiles were taken at site A2 and three at A0 as shown in the satellite imagery from 2023 depicted in Figure 14. The left image represents site A0 and the right, site A2 where the red line depicts the location of the hand-made dam. All measurements were post-processed to correct the dGPS data using a kinematic processing (PPK) type due to the Rover being in movement during the data collection.

Figure 14. dGPS points collected on the Rusine River in July 2023 (Google Earth Pro, 2024)

In the mined areas, steep riverbank walls are observed on each side. These walls can reach heights of between 3 to 6 meters with gradients varying from 21.4% and 21.5% at the minimum to 42.76% and 49.7% slope at the steepest calculated inclines. The slope was calculated using the ellipsoidal height (meters) measured at the top of the floodplain where the initial dGPS measurement of a cross section was taken, and the height measured at the lowest point of the initial slope. In several instances, slope could not be measured due to the over incline of the riverbank wall at over 90° overarching over the river that occur from fluvial erosion leading to undercutting. When the river stands at bank full, the erosive action of the river causes the erosion of the top portion of the riverbank leading to a towering overhanging riverbank wall. Figure 15 highlights all of the cross-sections taken by the dGPS to measure slope change overall relief in the Rusine River floodplain. The red circles indicate where the river flows, meaning that if there is only one circle, this section of the river only exhibits a singular main channel. If there are multiple circles, the cross-section then shows that this section of the river has a multi-threaded channel.

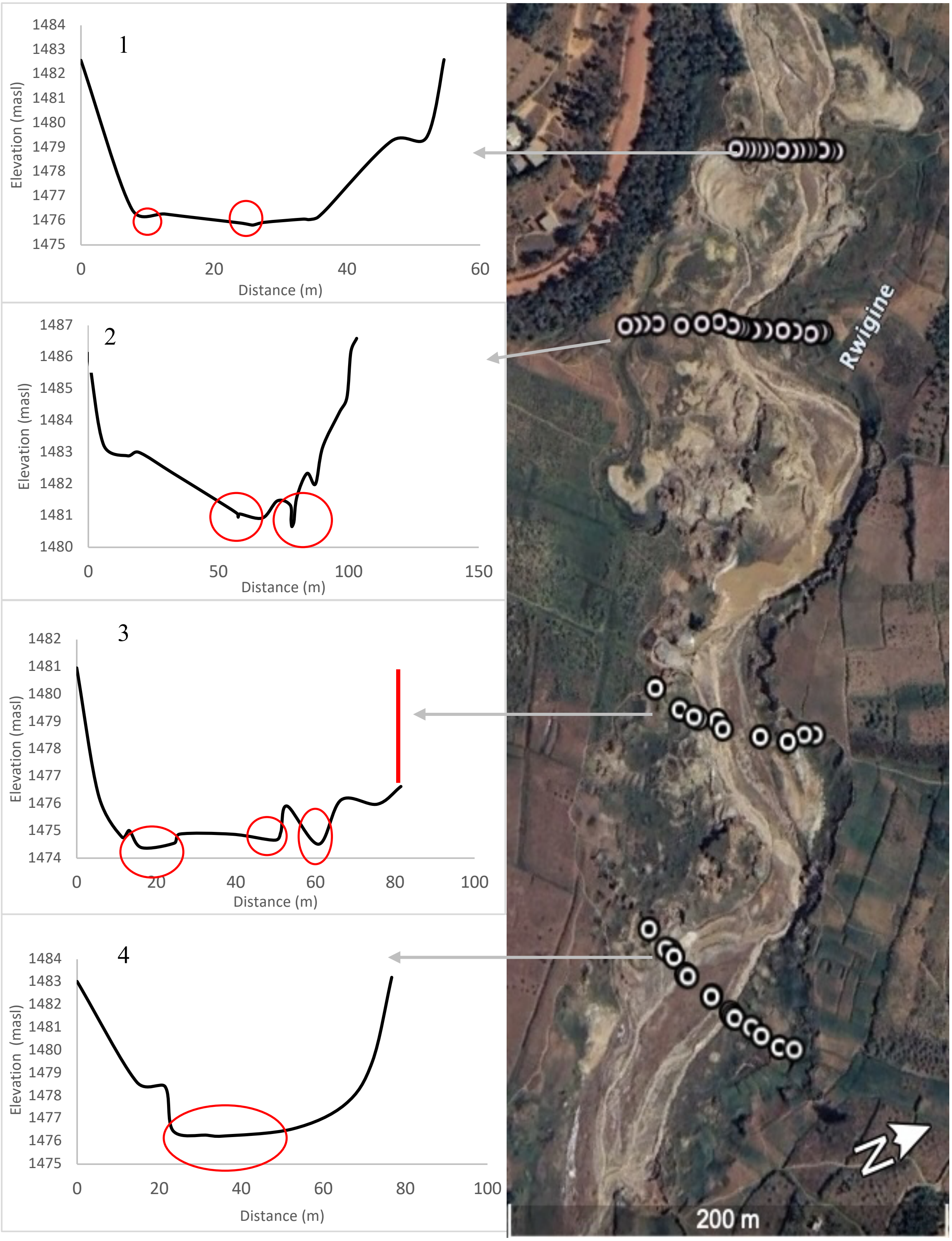

Figure 15. Cross-sections of Site A2 on the Rusine River Collected in July 2023.

Cross-section profile 3 demonstrates a situation where an overhanging bank wall is present indicated by the red line on the cross section in Figure 15. The rapid changes in relief at the bottom of the cross-sections are explained by the presence of secondary channels and mid channel bars that occur in heavily mined areas (Figure 14). It can therefore be established that mining causes an increase in incision rates in mined rivers. Increased incision rates also affect secondary channels which is reflected in cross-sections 2 and 3. Cross-section 4 is the only instance where only one channel is visible in the freedom space. Cross section profile 4 is also the only cross section that experiences the downstream effects of an upstream temporary man-made (or people-made) dam that diverts the channel away from its natural fluvial path. A hand-dug meander diverts the previous main channel to flow out of the freedom space and rejoin the main channel roughly 50 meters after the dam. In cross section 4, we observe a 1.954 m drop in the profile representing the hand dug meander rejoining the main freedom space of the Rusine. The following section of the cross-section profile is a flat lying area where the abandoned main channel has little to no effect on the relief of the floodplain due to the absence of any potential energy that could lead to incision. The second surveyed area was site A0 which was a previously mined section of the Rusine River and now remains undisturbed. Site A0 portrays a gentler slope gradient where the slopes of the riverbank are mostly covered in vegetation rather than bare soil. Calculated slope gradients within the three measured cross-section profiles range from 12.81% to 19.44% and extending to 26.77% representing a decrease from the profiles taken at site A2. No overhanging riverbank walls are present at site A0. The overall relief of the cross-sections are significantly smoother with less positive and negative variations throughout the floodplain. Only one main channel is present at site A0 and does not have braiding tendencies as observed in mined areas, therefore no observable repeating dips seen in the cross-sections at site A2 occur at A0. The riverbanks at site A0 are mostly occupied by shrubs, trees, and tall grass, that is adjacent to sweet potato fields which lie on a flatter surface (Figure 16).

The cross-section measured at the non-actively mined area shows gradual slopes with less angularity in its relief leading to a much smoother cross-section line without any signs of acute erosion (Figure 17). Channel incision is less significant at this site and the marked channels are shallower and wider than the channels at site A2. Individual information for each dGPS point collected is presented in Appendix A.

Figure 16. Photo of Site A0 Recovered from ASM Impacts, July 2023

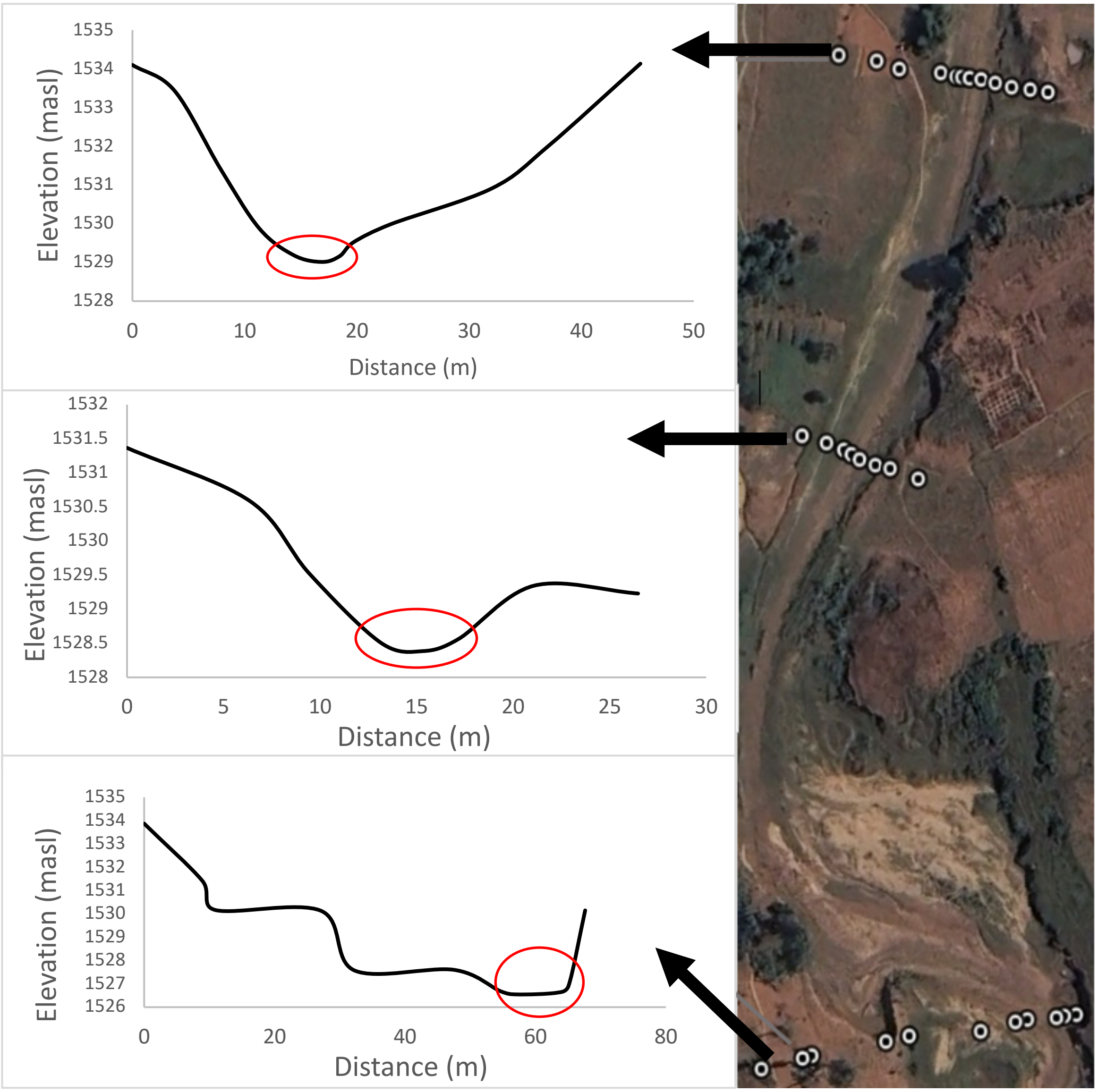

Figure 17. Cross-sections of Site A0 in the Rusine River Collected in July 2023.

5.3.2 Riffle-Pool Sequencing of the Rusine River

Theory of Riffle Pool structure claims that the sequence is linked to planform geometry and can be scaled to the channel width. Therefore, in a meandering system it is expected to see pools forming throughout a meander or at its apex, riffles are usually shallower and tend to occur in straight segments of the river or in the cross overs (Church and Jones, 1982; Keller & Melhorn, 1978). Pools are usually characterized as wider and deeper than the subsequent riffles The Riffle-Pool sequencing is observed in the Rusine River and compared to theoretical morphological knowledge of riffle and pool placement within a meandering stream. In heavily mined segments of the river, an alteration of the morphological parameters of pools and riffles occurs. For the section, a pool-riffle sequence is referred as a PRS unit or Pool-Riffle Sequencing Unit.

Site A0 demonstrates a normally occurring pool and riffle sequence throughout the length of the site. The pool-riffle sequencing at A0 reflects the theory of PRS (Pool-Riffle Sequence) structuring in a meandering stream, where pools are found at meander apexes and riffles are located in crossovers sections or straight-aways. In mined areas such as site A2, PRS units are changed where longer riffles and shorter pool segments are discernible. In those areas, the undulations in the riverbed tend to be flattened out in riffles leading to an overall flatter riverbed. Anthropogenic induced scouring of the riverbed and high velocity where incision rates and hungry water mechanism are in action lead to deeper riffles. An instance of disruption in the downstream PRS units is the man-made dam located at site A2. This dam causes a complete interruption in the sequencing of pools and riffles in the river. With damming of the river, a retention pond is created. An increase in depth from 29 cm to over 150 cm in depth is observable at the dam and at the neck of the entrenched meander detouring the river flow away from the dam. dGPS points were not collected at this location due to the sizeable depth of the channel causes by the dam. The entrenched human-made meander adjacent to the dam has a homogenous riverbed with no major observable differences in riverbed undulations within the entrenched section and therefore no recognizable PRS unit in the human-made meander.

Site A3 shows the largest variations in riverbed undulations between riffles and pools, however, the location of pools demonstrates that ASM can lead to a change in PRS structures.

Floodplain ASM at site A3 causes the river to straighten across the entirety of the site leading to both pools forming in cross-over sections. The PRS structure at site A3, in 2023, reflects the sequencing observable in a straight river segment rather than in meandering stream. The pool in the second PRS unit of site A3 is heavily influenced by the passage of trucks across the river. The frequent passage of trucks through the river forces an abrupt depression of the riverbed and increase in channel width at the intersection of the river and the dirt road used for truck crossing which is uncharacteristic of the overall morphological structure of site A3. Both riverbed depth and channel width double in contrast to the other measurements at the closest riffles surrounding the pool. The exertion of pressure on the riverbed from the passage of trucks leads to the formation of what is defined as 'a forced pool' (Montgomery, 1995) where the controls of the PRS Unit are no longer depending on fluvial processes but rather an external force.

5.3.3 Flow Velocity and Discharge of the Rusine River

Velocity and discharge measurements vary greatly along mined and non-mined segments of the Rusine River during low flow period of the year. Table 5 show all measures taken at each PRS Units along the studied sites on the Rusine River. The measurements were separated in between each site where two PRS units were identified to gather data on. Further downstream, the analysis of a man-made meander is done to show how the river engages with an anthropogenic diversion from its natural path. PRS units were not measured on the Nyabugogo due to its sizeable depth and discharge which posed a potential threat to safety.

Table 5: Pool-Riffle Sequencing Measurement Across the Rusine River.

	Depth (cm)	Width (cm)	Velocity (cm/sec)	Discharge (m3/sec)
A0				
Pool 1	21	383	65.85	0.529
Riffle 1	27	198	81.81	0.308
Pool 2	21	472	45.87	0.457
Riffle 2	18	212	81.81	0.437
A2				
Riffle 1	28	275	91.91	0.707
Pool 1	27.5	401	62.85	0.678
Riffle 2	17	348	80.32	0.475
Pool 2	29	378	51.51	0.564
Hand-Dug Meander				
Neck of Meander	36	1172	37.67	1.576
Meander Apex	17	225	117.47	0.449
Paleo-channel	16	159	57.17	0.317
Confluence	14.2	507	124.27	0.894
A3				
Riffle 1	14	256	71.113	0.255
Pool 1	38.5	529	42.057	0.856
Riffle 2	21	239	142.365	0.714
Pool 2	30.1	698	44.774	0.937

Site A0 shows a non-active mining area, where similarities are evident in the velocity and discharge measurements between the morphological entities of the river. Through depth sampling of the initial riffle, we observed that the depth over which the riffle occurs is deeper than the pool downstream at the meander apex where flow significantly reduces. We can attribute this phenomenon to a scour hole, forming from highest energy flows happening to during both wet seasons and that site A0 follows a dam that was built under a vehicle overpass, therefore the immediate section following the dam is starved of any upstream sediment causing increased incision of the bed. Overall, very little local variations occur in flow velocities in the studied riffles at a non-mined site. Greater variabilities of flow velocity are observed in deeper segments or the pools of the non-mined segments. The main difference observed were the width of the channel at each PRS iteration where the initial sequence was deeper but narrower and the second PRS unit was shallower but wider. The increase in channel width compensates for the loss of depth in the channel planform area.

The following velocity and discharge measurement were taken at site A2 both upstream of an improvised dam and at certain point around it to highlight the impacts of this dam on flow. Heavy mining is occurring directly upstream of the first PRS unit at site A2 which could also lead to scouring holes forming downstream due to the alteration of flow parameters and sediment transport capability. The second measured PRS unit is located directly downstream of the first unit. This unit is impacted by the presence of an improvised dam downstream that creates a retention pond prior to the channel diversion effort that displaces the flow of the river outside of its natural freedom space through the intermediate of a hand-dug channel that meanders in the cropland and rejoins the paleo-main channel shortly after. This pond then acts as a very large pool within the PRS unit which differs completely from what is observed in natural settings and even in mined settings where no damming occurs. From in-situ analysis, pools observed in the Rusine River tend to be shorter and riffles tend to be very long in contrast to what occurs in natural settings of a meandering river. However, the dam inverts this tendency at site A2 and causes a shift in the sequencing in the main channel which has been diverted. This pond starts with a swift drop in the riverbed due to increased turbulence from the presence of the dam. An attempt was made to measure depth and velocity at the deepest portion of the pond, however, contrary to any morphological forms of the Rusine River, depth increased to over 150cm as water level reached higher than shoulder height while wading across the pond. At the far corner of the pond, a backwater effect is present that would skew velocity measurements.

The following velocity measurements were taken within the hand dug meander and at the paleo-main channel that still flows due to leaks from the improvised dam. This series of measurements allow us to understand the impact that the change of flow direction has on the flow dynamic of the river. The initial measures of flow velocity were taken at the neck of the entrenched meander. The following velocity measurements were taken at the apex of this landform which exhibits very rapid flow due to an important quantity of water exiting the dammed pond. Measurements were also taken within the ancient, dammed channel. Water still flows due to imperfection within the mud and rock structure of the dam and therefore, significant leakages occur that keep the ancient challenge active, but significantly weakened. The fastest flowing water occurs at the confluence of both new and paleo channel due to the downhill flowing water coming from the hand-dug meander.

Site A3, sitting at the confluence of one of the Rusine's tributary, has been heavily mined since the year 2000. This site shows important changes in riverbed undulations between the different pools and riffle sequences. The last pool measured at site A3 shows changes in the channel planform being influenced by the passage of trucks that collect sand from nearby mining sites which is then suggested to significant increase in width and depth depending on the number of trucks passing by every day.

5.3.4 River Style Change In the Rusine River

Artisanal Small-Scale Mining is an important agent of change within the fluvial landscape and is directly linked to the changes in fluvial style that occurs. First, over the study period of the Rusine River in mining periods, certain reaches of the river change from a meandering style to a braiding style. This phenomenon typically occurs directly downstream of a severely mined river segment (Figure 18). This sudden change in style occurs throughout the fluvial landscape and commonly appears in a straight away riffle section following a meander apex.

According to satellite imagery, the highlighted braided reach at site A1 (Figure 17) remains

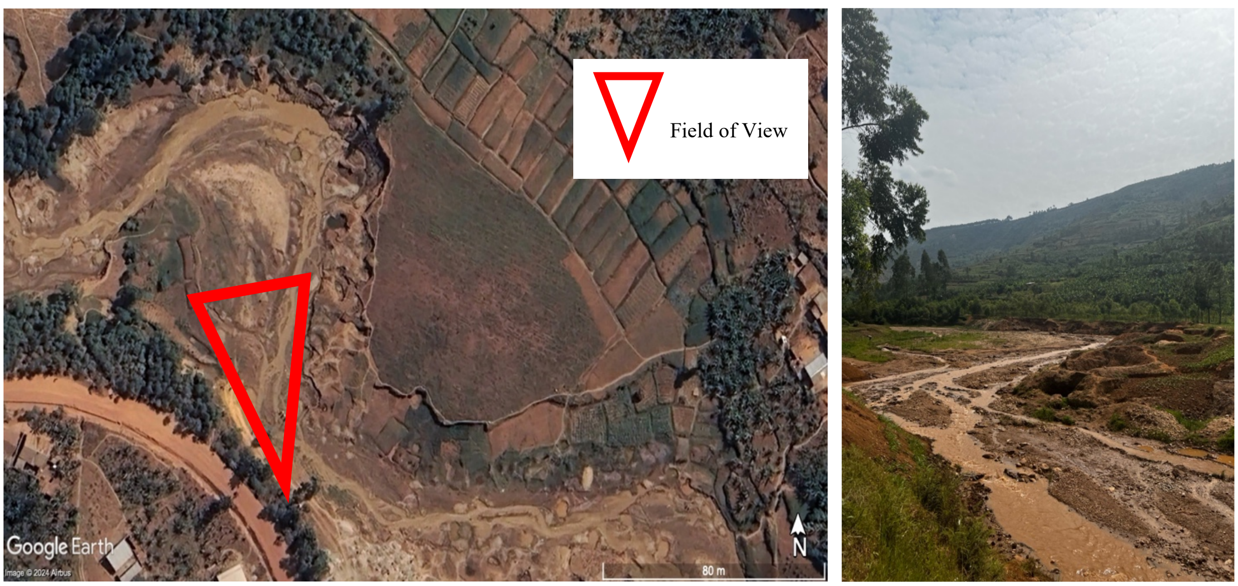

Figure 18. Braided Section of the Rusine River Following Heavy ASM Action (Google Earth Pro, 2024)

a single thread channel in August 2022. In July 2023, allowing one dry season to pass, the river segment starts to braid, and multiple secondary channels appear adjacent to the river with fine sand and clay-rich sediments mid-channel bars. Once braiding is initiated, it will respond to ASM upstream, as seen in the Rusine tributary mined before 2000. Through the repeated branching of the watercourse stemming from ASM practices, the development of a braided system changes the river style of specific river reaches depending on the anthropogenic action taken on the river through ASM.

The intensive removal of coarser material like gravel and sand upstream prevents the deposition of material downstream and reduces cohesiveness of the riverbanks. With less sediment available for transport, there is a relative increase in energy available for active erosion. Therefore, the erosive power of the river increases downstream of heavily excavated areas. The increased erosive action causes the banks to erode rapidly and create a wider, a less stable channel that avulses within its planform creating a braiding channel segment due to the restriction of helical flow preventing the meandering process. Through extensive mining upstream for over 20 years, a braiding system formed which could be a sign of the long-term anthropic disturbance response of the Rusine River or other smaller scale rivers to extensive ASM (Figure 19).

Figure 19. Braided Tributary of the Rusine River in 2024 (Google Earth Pro, 2024)

Pit mining creates negative features throughout the Rusine and Nyabugogo fluvial landscape. Pits are mined adjacent to the active channel or on point bars and creates undulations in the active floodplain and are often left abandoned. The abandoned pits will create a new ephemeral beading stream next to the active channel. Prior to pit capturing, overflowing pits will connect via an ephemeral stream that flows in between abandoned mining pits. The overfilling and linkage between the pits by an ephemeral stream create a beading channel style that flows adjacently to active channels. In turn, the active floodplain now populates a multi-thread channel rather than a single thread channel. The creation of beading ephemeral channels may occur on both sides of the river and lead to the addition of multiple secondary and tertiary channels within the active floodplain. Through the erosive action of a river, these ephemeral channels will eventually connect with the main channel leading to channel widening. This process often occurs in point bars where a beading chute channel forms along the neck of the meander. The cutting action of the point bar occurs in both studied rivers where the formation of a chute channel will accelerate the morphological processes of both rivers leading to a rapid meander cut-off and formation of oxbows within the active floodplain.

Chapter 6. Discussion

Throughout the Rwandan ASM landscape, several styles of mining are used in fluvial systems. Floodplain mining processes occur in the active riverbed and the floodplain, whereas in-channel mining focuses directly on the stream riverbed and disregards any anthropic action on the floodplain.

In this section, I will address and discuss the following questions: (1) How do artisanal sand and aggregate mining influence the hydrogeomorphology in the Rusine and Nyabugogo Rivers in Northern Rwanda?;and, (2) What changes are observed in the fluvial landscape accompanying artisanal mining? In this section, I will link the impacts of ASM in the Rusine and Nyabugogo Rivers to their fluvial dynamics and floodplains, aiming to establish and understand the relationship between ASM activity and fluvial morphology. The first section will focus on the floodplain mining style in the Rusine River, followed by a discussion on the morphological processes in response to in-channel mining processes on the Nyabugogo River. Following this section will be an overview of the impacts of each form of mining on the fluvial landscape. Lastly, I will discuss future steps and recommendations introducing new management practices to alleviate morphological stresses on both rivers and mitigate the impacts of ASM on the fluvial landscape. This section will also serve as a conceptual model to understand the morphological changes of the rivers caused by ASM. It will establish a cause-and-effect statement for significant morphological anomalies observed throughout this research.

Two main types of riverbed mining influence the Rusine River: channel-wide instream mining and pit excavation (Rentier & Cammeraat, 2021). Whether it is 'severe floodplain' or 'simple in-channel' mining, sand and aggregate extraction are mostly occurring from the riverbed. However, with floodplain mining, the practices extend beyond the floodplain, and targets the the riverbed and depositional landforms. The process of riverbed mining causes an interruption in the river's natural flow due to the removal of material, which causes morphological changes to the channel planform. The first type of mining occurs during the dry season as the active floodplain becomes available with very shallow water levels, and the river not operating at bank full levels. Pit excavation relies on simply removing sand and aggregates from the riverbed or floodplain, causing an open pit to be formed. These mining pits have various depth and size ranging usually from ≈1m to 2m in width. In the Rusine, mining pits appear adjacent to the active channel, becoming highly likely to be captured by the stream once the river is flooded during rainy seasons. The process of pit capturing, and thus enlargement of the river, is a critical aspect of the mining activities that explains the significant increase in riverbed width. During periods of rain and high-flow regimes, the sediment separating the open pit from the river collapses, capturing the open pit (Haghnazar & Saneie, 2019; Rentier & Cammeraat, 2021). This capturing process occurs throughout all areas where active ASM takes place in the Rusine River.

Periods of intense mining also cause abrupt changes in river style throughout the Rusine River. Site-specific analyses reveal that the river style changes frequently over time and space in heavily mined reaches from meandering to braiding. Before any mining activity in the region, the Rusine River was a meandering river throughout its entire length with little to no variability within its confinement levels, style, and width. Roughly 15 years later after mining activities were introduced and increased in extent, the river shows segments of varying confinement due to river entrenching, and decreased sinuosity. A shift in the fluvial style from meandering, braiding, and straight and beading at a site-specific level is caused by the practices involved in floodplain mining.

6.1 Floodplain Mining and Fluvial Morphology

The impacts of floodplain mining efforts on the Rusine River in Northern Rwanda involve an array of changes brought to the morphological functions of the river and its landscape. Floodplain ASM drives important changes to morphological landforms and processes exclusive to the severe floodplain form of artisanal mining and are responsible for varying degrees of disturbance responses of the river. Man-made constructions and deliberate flow redirection through the construction of temporary dams and hand-dug channels become essential agents of change in the river's morphodynamics. Artisanal mining also leaves scars on the landscape, such as pits and trenches, that become significant variables to changes in fluvial style and channel planform.

6.1.1 Floodplain Mining and Riverbank Excavation

Different approaches to river artisanal mining yield distinctive features and impacts along mined rivers. Severe floodplain forms of mining as introduced in the Rusine River case present unique landforms and geomorphological impacts. These anthropogenically induced landforms are attributed to significant floodplain and channel excavation without regards the removal of cropland or other surrounding land uses. Mining impacts of ASM in the floodplain reveals that the natural erosive action of the river no longer has significant leverage on the migration of the active floodplain during heavy mining areas of the river. Growth of the active floodplain occurs through processes attributed to ASM such as floodplain entrenching and scarp excavation. The detachment between natural processes and floodplain migration is attributed to the rapidity and volatility of these mining methods which can often leads to an important change in the overall morphology of the floodplain.

Through temporal analysis of high-resolution satellite imagery, fluvial migration and meander progression controls the active floodplain size as shown in Figure 10. Under natural circumstances, the active floodplain will expand via the migration of the river and its meander progression cycle. From the geomorphological heritage of the Rusine River, the active floodplain boundaries coincide with the apex maxima of the meanders. Therefore, the river's meander amplitude guides the lateral expansion of the floodplain in undisturbed systems as shown on Figures 10 and 11. In pre-mining, the growth of the river's freedom space or active floodplain is solely linked to natural processes. The interpretation of the historical imagery in pre-mining stages follow river corridor management practices which allows us to determine a predictability factor within a non-mined river from basic morphological knowledge and fluvial migration under natural controls that shape the fluvial morphology. The mining stage of the Rusine River's show that floodplain mining processes override natural controls of floodplain progression during periods of intensive mining throughout the entirety of the floodplain. An example linking the disconnection between natural morphological controls of the river and the river morphology is through the decrease in sinuosity observed in the Rusine River: The straightening of the river is explained by the elongation of the meander sine wave and the shortening of the overall amplitude of each meander iteration. However, contrary to the decrease in sinuosity and meander amplitude, the active floodplain expands, as seen in Figure 10. The continuous growth of the active floodplain is explained by the current mining action in the floodplain where scarp excavation artificially expands the floodplain and the entrenching of annex channels within the cropland rather than fluvial migration. Thus, focusing on the active floodplain parameters to understand the river's response to ASM would skew the interpretation due to the inverse relationship between active floodplain progression and river migration. Therefore, ASM practices in the Rusine River show anthropogenic control surpassing the natural morphological control threshold which are in accordance with Byizirgiro et al (2015) which show similar impacts in opencast mining areas.

The mining processes associated with floodplain ASM diminishes natural controls due to its dominance and faster acting processes than naturally occurring geomorphological processes. The possibility to predict future movement of the river is difficult as it depends on which mining practices are taking place, and where these are occurring. Due to the opportunistic and often unsystematic nature of ASM, modelling the river for floodplain management becomes obsolete. The lack of planning, guidance, and management of ASM can therefore not incorporate any form of predictability within the short term and long-term morphological changes brought by ASM.

6.1.2 Flow Interruptions Caused by the Construction of Man-Made Dams

Diversion of the river flow path is a common practice to easily access new mining zones throughout the active floodplain in the context of the Rusine River. In certain areas where higher river discharge creates difficulties for mining process, miners will create dams and dig a new path for the river to flow in. The dam located at site A2 exemplifies this behavior. Damming causes several changes to the hydrological structure of the river, which is essential in causing significant changes in the pool-riffle sequencing structure of the river. Pool-riffle bedforms are critical to overall channel stability due to their physical function of reducing the potential energy loss per unit of mass of water (Keller & Melhorn, 1978). Therefore, a disruption in the pool-riffle sequencing of a river as seen at the dam at site A2 where significant shifts on the riverbed occur due to the establishment of a dam leading to a destabilization of the riverbed and overall stream in which ties directly to Keller & Melhorn (1978) findings.

Bridges and dams obstruct a river's natural flow and shifts the sediment balance downstream (Montgomery et al., 1995). Such manipulation of the river causes anomalies in the hydrological functions of the river and lead to complete changes in the morphological and erosive processes of the river when combined with ASM activities. Assessing the metrics for the pools and riffles studied in the field campaign, in multiple cases, certain riffles are deeper than pools, and we assess that the riffles are significantly longer in 2023 compared pre-mining periods, in tandem with long cross-over sections of the river between riffles and pools. This notion ties to the river straightening action of ASM within the Rusine River. The deeper riffles at sites A0 and A2 contrasts the expected bed undulations in a meandering system, where riffles should be shallower (Trenhaile, 2016). Riffles deeper than their following pool as seen in Table 5, align with a forced pool-riffle sequencing causing flow convergence and divergence and leads to scouring of the riverbed (Montgomery et al., 1995). Forced pool formation in the Rusine is common due to the extensive digging action and extraction of material from the riverbed at low-flow stages, mimicking any other form of obstruction that depresses the riverbed. The observed increase in depth of the riffles is interpreted to be caused by anthropic or artificial degradational scouring that links the removal of sediments from the riverbed, causing the lowering of the river through human action rather than sediment transportation. Similar attributes of this scouring effect on the riverbed are observed at site A0, where the initial PRS unit riffle is deeper than its subsequent pool. The first riffle at site A0 is located immediately downstream of a bridge where debris causes a partial obstruction flow. Therefore, with very little sediment transportation due to sediment clogging at the bridge, the downstream riffle gets deeper through a contraction scour process. Sediment starvation is linked to both the debris and bridge pillars, creating a sediment barrier and a small mining sector operating upstream, increasing scouring and incision.

River damming is essential for miners to access certain areas of the river that can otherwise be difficult to access. River segments with higher discharge will cause sand and finer sediments to fall off their shovels when being scooped up from the riverbed, decreasing the amounts of sand and aggregates collected. The miner's adaptation mechanisms are to create dams to stop water inflow to a specified area, which will then be redirected elsewhere via a new artificial channel dug by the miners. At site A2, an improvised dam made of rocks, mud, and bamboo interrupts the main channel of the Rusine River and redirects it through a much narrower hand-dug channel, freeing the downstream section for mining as seen in Figure 14. Observations made in the field reveal a progressively deeper pool prior to the neck of the hand-dug meander. The halt of flow of the river causes the riverbed to become progressively deeper. The dam creates another forced pool-riffle sequence through the obstruction of flow, which causes a convergence of flow at the dam, leading to an increase in turbulence within the pool and increasing scouring of the riverbed (Figure 20) (Montgomery et al., 1995). Figure 20 reflects observations made in the field which explain the sharp depression of the riverbed at the man-made dam; the scouring at the dam sharply increases the riverbed depth from 29 cm in the main channel prior to the retention pond to depths above 150cm in the pool that sits at the man-made dam at site A2.

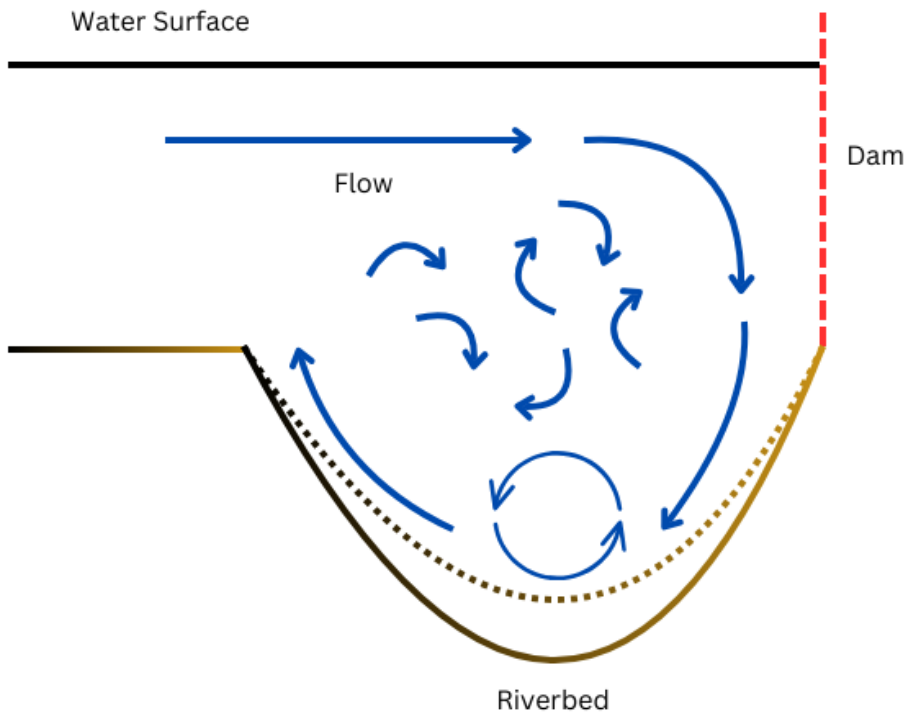

Figure 20. Model of Flow Turbulence Caused by Dam in the Rusine River

The dam will not only impact the immediate, local river morphology, but will also influence riverbed morphology downstream. The retention of sediments will inhibit sediment starvation of the main channel, leaving an increasing amount of energy previously dedicated to sediment transportation. A shift in sediment supply balance can increase available kinetic energy in the river, elevating the erosion potential of the riverbed. Furthermore, it can lead to increased incision in the stream and is responsible for the increased incision of all channels downstream of the bridges following the cross-sectional measurements of the river seen in Figure 14.

ASM processes shape the hydrological functions controlling riffle-pool sequencing in the Rusine River. Alterations of the flow path explain the irregularities occurring in the pools and riffles. Fluvial interruptions, such as the studied dam and bridge at sites A2 and A0, respectively, are important factors explaining why the observed pools and riffles do not match conceptual frameworks of riffle-pool morphology and exhibit, unique morphological characteristics throughout the river.

6.1.3 Instream Riverbed Excavation in Floodplain ASM Practices in the Rusine River

The Rusine exhibits a high density of mining pits throughout its floodplain and at the studied sites, as seen during fieldwork and throughout the historical imagery studied from 2008 to 2023. During floodplain ASM activity, the Rusine River width depends on the creation of mining pits adjacent to the river that erode during high-flow seasons, leaving the riverbed to widen through time. The growth of the active floodplain allows for the increase in pit mining adjacent to the active channels which will only lead to an increasing riverbed width after every mining season. Instream mining for sand and aggregates also results in an increase in river depth and increase in riverbank steepness as observed in the Rusine and the Nyabugogo River. This response has been observed by Lai et al, (2014) and Hackney et al (2020) in China and the Mekong River in Vietnam, respectively. The relationship between the physical properties of the riverbed and mining processes are apparent within the cross-section at site A0 and A2. Actively mined channels show numerous incised secondary channels and steep gradients of the scarp wall which is explained by floodplain ASM processes such as scarp excavation and pit mining. The slope gradient increase and the incised riverbed in the cross-sections indicate that mining causes sediment starvation and migration of the sediment balance (De Leeuw et al., 2010). The removal of aggregates and sand from the riverbed causes an upstream shift in the sediment balance of the river to make up for the loss of material downstream, causing increased erosion of the riverbed and riverbank which explains the incised appearance of the riverbed from the cross-section profiles at site A2 and follows what De Leeuw et al (2010) show in their research in China. Therefore, riverbed lowering occurring in the Rusine River, occurring away from any structures obstructing flow, is explained by miners removing material from the riverbed and the following feedback mechanism, shifting sediment supply balance upstream to counteract the anthropic forces changing the riverbed morphology and sediment availability. The removal of sediments causes an increase in potential erosive energy in the river, resulting in an increase in riverbed incision. As the amount of sediment available for transport continues to decrease, the "hungry water mechanism" proposed by Kondolf (1997) is triggered as part of the incision action of mining on the actively mined channels which will become increasingly prominent .

A combination of anthropic and natural processes shapes the overall fluvial morphology of the riverbed, as seen in the pit-capturing process. Moreover, the morphological changes appearing on the Rusine River are attributed to ASM processes, as an increasing majority of the morphological controls have shifted to become dependent on the intensity of mining activity present in the region.

6.1.4 River Style Change

A common occurrence in the Rusine Valley is the creation of braided or multi-threaded river segments in heavily mined areas. A multi-threaded reach only appears downstream or in areas where floodplain artisanal mining occurs for an extensive period of time, such as sites A1 and A2. In the case of the Rusine River, the branching and braiding style is explained by the aggregate mining that removes coarser sediments, such as gravel, from the river which increases the shear strength of the active riverbanks. Under natural circumstances, a shift from meandering to a braided system occurs when there is an increase in slope and, most importantly, high amounts of coarser sediments.

The removal of coarser bed material from ASM, causes finer clay-like sediment and sand to make up the majority of the available sediment in the river. These finer sediments flow downstream of mined areas during sediment removal, and through transportation, the sediment gradient reduces through mechanical erosion in the form of abrasion (Barman et al., 2019). The sediments will then get deposited downstream in other mined or previously mined areas where the active floodplain and channel planform is wider due to bank cutting, pit capturing and heavy floodplain mining processes. Sand mining is known to increase the natural processes of sediment transport (Padmalal & Maya, 2014) and removal of the armoured layer (Melton, 2009).

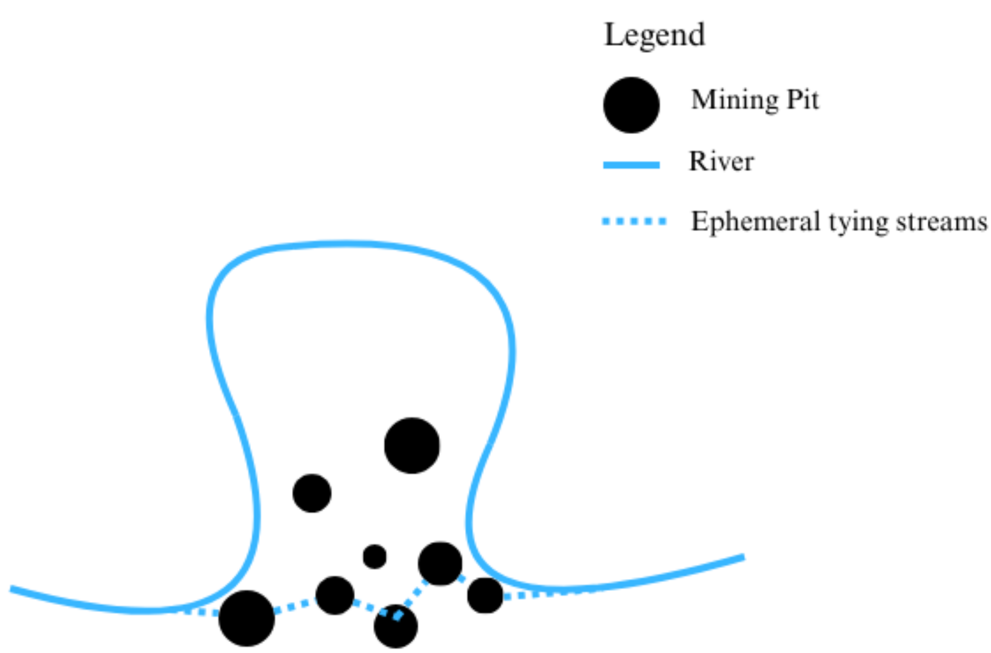

Figure 21. Model of Impacts of Pit-Mining on Point Bars

Consequently, with the removal of coarser sediment through aggregate mining and fine sediment deposition, the banks become highly erodible with little to no lateral constraints. They will avulse depending on fluctuations of flow velocity and discharge. Erodible streams will prevent helical flow from occurring, and the banks will erode instead (Easterbrook, 1993). Riverbed mining incorporates a significant anthropogenic influence on the erosive processes (Macháček, 2020) and causes shifts in sediment characteristics, leading to a lesser degree of material cohesion and becoming easily erodible during higher flowing periods, creating branches into the watercourse.

The acceleration of morphological processes from ASM can also reduce meandering and lead to a decrease in overall sinuosity from premature meander cut-offs. Pit mining practices occurring on point bars lead to the early creation of a chute channel avulsing a meander. The open pits left from mining eventually fill up with river water during high-flow periods and connect through a small ephemeral stream that longitudinally ties mining pits together, creating a secondary channel close to the neck of the meander at the inflection point and continues to fill up through the fluvial input. These pits will then erode, creating a chute channel in the form of a beading system that will cut off the meander and straighten the river (Figure 21). Such process is observed in Figure 22. The red box demonstrates where the meander was cut-off from pit mining.

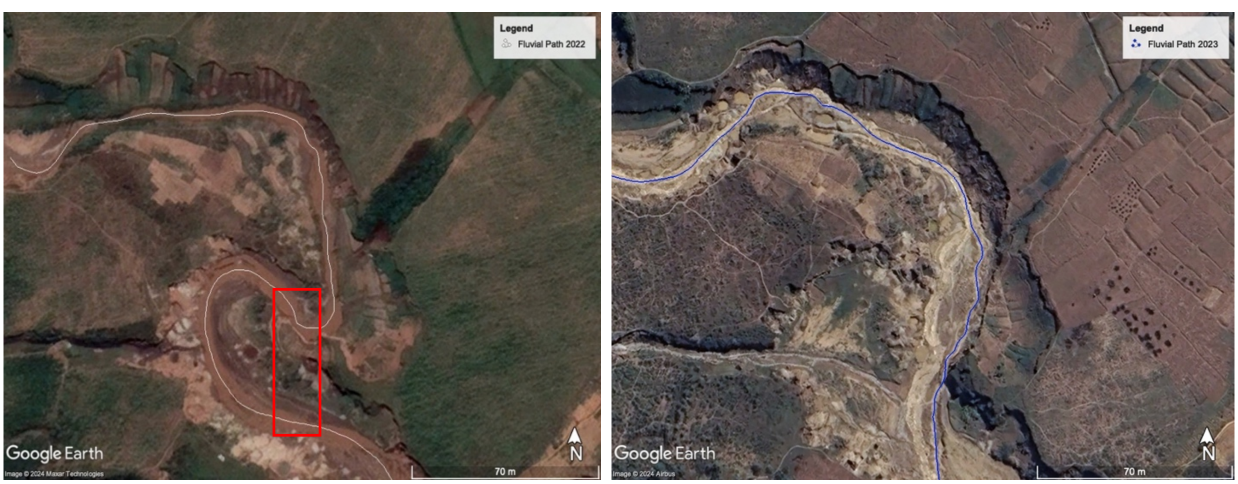

Figure 22. Results of Pit Mining on a Point Bar seen in the Rusine River from July 2022 to July 2023 (Google Earth Pro, 2024)

The Rusine River also shows clear signs of river straightening, with a continuously decreasing sinuosity index at the site-specific scale. Certain cases show that the river changes from a meandering to a straight reach. River straightening occurs due to a change in the morphological control of the fluvial path. The creation of depressions or entrenching in the active floodplain induces the river to follow the path of least resistance and ultimately follows the mining pattern. Examples include the premature cut-off of point bars due to mining activity, and floodplain mining, which leads to a straighter river segment throughout the Rusine Valley (Figure 22). The combination of this process and sediment sorting, leading to less stable channels, explains the contrast in fluvial styles throughout the Rusine River and the abrupt transition from a homogeneous river to a series of heterogeneous reaches that occur under floodplain ASM practices.

6.2 In-channel Mining and Fluvial Morphology

In-channel mining processes influence instream and riverbank morphology by solely focusing on riverbed extraction. In-channel riverbed mining leads to a series of morphological landforms that remain within the instream portion of the channel and does not impact the overall floodplain morphology of the river.

6.2.1 In-channel Mining in the Nyabugogo River

Sediment extraction in the Nyabugogo River reflects a simpler form of ASM where impacts on the river's morphological landforms are limited compared to floodplain mining practices. During field observations, the majority of the visible impacts of riverbed mining appear to occur on the riverbanks. Through similar processes seen in the Rusine River, riverbanks steepen and undercut during the excavation of the riverbeds. The over-steepening banks result from a shift in sediment supply balance shifts to account for the sediment deficiency in the active mining sites. Such shifting sediment supply balance is known to increase erosion rates, thus amplifying erosive action on riverbanks (De Leeuw et al., 2010). Excess excavation of the riverbed is known to lead to the overall lowering of the riverbed, which will cause unstable riverbanks (Hackney et al., 2019), which are present throughout the Nyabugogo River. Similar to the Rusine River, an increase in potential erosive energy occurs due to the removal of material from the riverbed following the hungry-water mechanism (Kondolf, 1997), leads to undercutting and acceleration of the geomorphological processes in the Nyabugogo River, and ultimately the collapse of riverbanks which widens the channel as per with previous literature on river sand mining (Rentier & Cammeraat, 2021). As a response to the in-channel ASM practices, the riverbed is expected to lower, in accordance with previous work on the effects of river sand mining (Dang et al., 2014; Huang et al., 2014; Yuhi et al., 2014; Koehnken et al., 2019; Rentier & Cammeraat, 2021). Bank collapse acts similarly to pit capturing to increase channel width, as observed in the Nyabugogo however no open pits were observed adjacent to the Nyabugogo river. Pit mining is only performed on the point bars of the meandering stream.

The analysis of the migratory path of the Nyabugogo River reveals that the river does not migrate nearly as much as the Rusine River due to ASM activity. In-channel mining causes significantly less fluvial behaviour volatility, and hydrogeomorphological parameters change compared to mining activity in the Rusine River. The lack of anthropogenic landforms other than eroded riverbanks show that in-channel ASM impacts on the Nyabugogo target only the riverbed, riverbanks, and sediment supply balance. Through the same period studied from 2000 to 2023 as the Rusine River, the Nyabugogo remains a homogenous river with varying forms of meanders and sinuosity levels that remain constant after the start of ASM activity in the river. It is critical to acknowledge the nuance between the different types of mining and what constitutes river sand and aggregate mining as the results from this research show.

6.3 Fluvial Landscape Changes

6.3.1 Floodplain Mining Induced Landscape

The impacts of ASM on fluvial morphology extend beyond the hydrological and morphological processes of the river. The anthropogenic interaction between floodplain mining activity and the fluvial environment yields a transition between a naturally controlled fluvial ecosystem to an anthropogenic landscape where most of the ecosystem controls are now dependent on human action. ASM is known to have important impacts on "naturally occurring geomorphological processes" (Macháček. 2020, pp.17) and with the analysis of the evolution of the Rusine River, it is evident that it is also responsible for creating new landforms that differ completely from the ones naturally occurring in a fluvial landscape. During the field campaign, in many instances was the fluvial environment so severely manipulated that it depicted a moon-like landscape. This description is used to highlight the crater-like formations in the floodplain and the rugged look of the Rusine River valley. New landforms that do naturally occur in fluvial ecosystem are spread across the valley which can result from an acceleration of geomorphological processes occurring naturally. In the case of the Rusine River, the creation of a new fluvial landscape ties to badlands formation (Byizirgiro et al., 2015). Badlands are "deeply and densely dissected accelerated erosional landforms often developed on unconsolidated or poorly cemented materials. They are generally characterized by steep, unvegetated slopes, a high drainage density and high erosion rates" (Coratza, 2021, pp. 1). Many factors influence the creation of badlands; it is agreed that physical, chemical, lithological, topographical, seasonal, and anthropogenic factors are the main drivers of badlands formation. Under factors external to ASM, anthropogenic factors of badlands are associated with deforestation, agricultural land abandonment and land reclamation efforts (Caraballo-Arias et al., 2014). Badlands often occur in vegetation-deprived areas that typically stem from mass wasting events or difficult climatic conditions (Alexander, 1980). However, the Rusine River experiences deforestation and transitions from densely vegetated areas, as seen in 2000, to a barren landscape in 2023 due to ASM throughout the valley. The creation of badlands in the active floodplain of the Rusine stems from the morphological features associated with the practice of artisanal mining, such as gullies, pits, trenches, and pit walls (Dušková et al., 2014). These features are wholly present in the Rusine River fluvial landscape; they occur in place and time depending on anthropogenic activity (Jones, 2001). As mining activity progresses through time, the development of these new features amplifies. The overall landscape of the river in 2000 was seemingly untouched yet still influenced by natural factors such as flooding through time prior to the capture of the satellite imagery. However, no such geomorphological landforms like badlands occurred in the basin other than in actively mined areas, such as the unnamed tributary of the Rusine. Therefore, this research is in accordance with previous literature on ASM as being responsible for creating a human-induced landscape in the Rusine River through floodplain ASM practices where the geomorphic processes happening in places and times that are completely dependent on anthropogenic activities (Jones, 2001). Thus, ASM causes the formation of geomorphic features seen in the fluvial landscape to depend on ASM rather than on natural processes. These observations explain the anomalies seen in erosional patterns, PRP sequences, changes in river style, fluvial migration, impacts on the active floodplain and all identified geomorphological features that this research intends to understand.

6.3.2 Fluvial Landscape Changes from In-channel Mining Processes

In-channel mining is a practice that remains fundamental to sand and aggregate mining. It is often combined with other mining practices, as observed in the Rusine River, leading to imbalances in the landscape. When in-channel mining is the only mining process conducted, the disturbances on the fluvial landscape are smaller than with floodplain mining areas. As in-channel mining targets only riverbed extraction, the acute impacts are primarily observed within the channel planform rather than throughout the active floodplain or ancient floodplains. The anthropogenic action outside of the active channel has impacts stemming from the deposition of sand and aggregate piles and the soil erosion caused by the passage of trucks to transport the extracted material. The visual impacts of ASM on the Nyabugogo River are found in the depositional features of the river and on the riverbanks. Similarly to the Rusine River, pit mining and bar skimming occur on point bars, which serves as the only exception of ASM processes that stand out from in-channel mining practices in the Nyabugogo River. The creation of opposing depressions in the point bar through pit mining causes the acceleration of chute channel formation and, therefore, meander cut-off. Pit mining happens in the sparse mid-channel bars, which is observable in the Nyabugogo at low flow. Pit mining is done on mid-channel bars that serve two purposes, one of extraction and the other as an intermediate for sediment transportation to the riverbank (Figure 23). The extraction of material from the mid-channel bars causes them to be removed from the fluvial landscape after all materials are mined from the bar. Through the erosive action of the river, the bar will be washed away. These impacts are important and bring notable changes to the fluvial landscape; however, they differ from floodplain mining impacts. The natural morphological parameters and processes of the Nyabugogo remain the most important controlling factor of the river's behaviour and the overall fluvial landscape. These observations and impacts of in-channel mining are consistent with Jones' (2001) notion of a human-modified landscape. Due to riverbed excavation, the changes to the hydrological balance of the Nyabugogo River lead to sediment deficiencies. The system then falls out of equilibrium and impacts riverbank stability as sediment supply imbalances cause an increase in riverbank erosion, leading to undercutting and floodplain aggradation. In rivers with higher discharges, the sedimentation episodes caused by ASM are severe enough to cause a substantial increase in erosion.

6.4 Next Steps and Recommendations

The environmental and hydrogeomorphological impacts of ASM practices in Rwanda are substantial and complex. This research agrees with the call for further research to better understand the drivers and effects of ASM practices. The establishment of proper management strategies are essential to mitigate impacts on the environment and on the livelihoods of miners (Bendixen et al., 2024).

Figure 23. Photo of Mined Mid-Channel Bar in the Nyabugogo River in July 2023

6.4.1 Land Use Change and Recovery

The geomorphological footprint of ASM shapes the fluvial landscape of Rwanda through the expansive measures taken for sand and aggregate extraction. However, previously mined sites have shown encouraging recovery over time. The case of site A0 demonstrates the ability of a site to recover from intensive mining activity naturally. Site A0 was actively mined from 2008 to 2020 while also incorporating the construction of a bridge at the site. After ASM was ceased, the site was left untouched without anthropogenic interactions. The site remains untouched and shows signs of natural restoration from floodplain ASM practices. This restoration method is based on a process-based restoration which focuses on natural fluvial processes such as erosion, flow paths, sediment transport, nutrient cycling and all other naturally occurring processes that make the river's ecosystem (Beechie & Bolton, 1999). Moreover, process-based restoration directly targets the correction of anthropogenic disruptions of the natural fluvial processes in order for a river to move along its recovery trajectory with little to no interventions (Beechie et al., 2010). In the case of site A0, its abandonment led to the site recovering naturally through fluvial processes and relates to the idea that the river can "heal itself" (Beechie et al., 2010). Flooding events cause deposition downstream of the bridge, leading to gentler riverbank slopes. Figure 15 shows the restoration potential and revegetation of the active floodplain and riverbanks. In three years, the site recovered to natural-like forms with a stable, single-thread channel resembling the pre-mining era of the Rusine River. The successful recovery of the site also promotes the reinstitution of agriculture within the active floodplain, severely hindered during the heaviest mining period at site A0 from 2017 to 2018. The integration of cropland on previously mined land is a known practice in other parts of the world such as in Morocco (N. Noorbhai, personal communication, May 20, 2024). Considering these observations, this research argues for promoting site recovery through a temporary cessation of mining or a process-based restoration approach to prevent irreparable morphological changes to the river. Natural morphological and fluvial processes will restore initial equilibrium and fluvial style similar to non-mined areas in the valley. Site A0 is an example applicable to the rest of the Rusine River and to rivers of similar order, size, discharge, and fluvial pattern.

In the Nyabugogo River, the increased width and discharge of the river from ASM processes combined with the increased erosional energy created by the shift in sediment balance will inevitably lead to critical erosional events on the riverbanks, leading to channel width increase and riverbank destabilization. To mitigate these effects, nature-based solutions are already being implemented to stabilize riverbanks. The use of bamboo as bank stabilizers and as step ladders are utilized in multiple mining sites on the Nyabugogo River to mitigate active erosion, prevent bank collapse, and help miners get in and out of the river, preventing further erosion and increasing the productivity of miners through lessening the amount of time used to get in and out of the river. Bamboo has been planted and grows on the riverbanks adjacent to mining sites (Figure 24) acting as erosion mitigation. Such prevention measures are simple and naturally sustainable, as bamboo is one of the fastest growing and highest yielding renewable resource (Kindu & Mulatu, 2010; Nduwamungu & Musengimana, 2015). Multiple bamboo species are native to Rwanda such as *bambusa oreobambos* and *Yushania Alpina* (Nsanzirwimo, 2007), however multiple other indigenous bamboo species are found throughout the country such as *Bambusa vulgaris.* Revegetation efforts by planting new patches of bamboo on riverbanks can therefore become a viable solution to prevent soil erosion and mitigate impacts of ASM on the riverbanks and due to the abundance of native bamboo species in the country

Mining presents a tempting incentive for residents of the Rusine Valley due to the growing financial opportunity that arise from mining but can however come with the trade-off which prioritizes mining over agriculture. It is important to acknowledge the economic relevance of ASM throughout the African landscape as it employs over 2.5 million people in Sub-Saharan Africa and serves a crucial role in poverty alleviation efforts and supports development through infrastructure

Figure 24. Photo of Bamboo used as Erosion Mitigation and Step Ladder for Miners in the Nyabugogo River in July 2023.

and innovation (Hilson & Maconachie, 2020). ASM represents also one of the fastest growing economic sectors in Sub-Saharan Africa as one of the most significant "rural nonfarming economic activity" (Hilson & Maconachie, 2020, p. 126). ASM can act as a primary source of income while still being an alternative source. Agricultural output is declining in Sub-Saharan Africa due to increasingly difficult climatic conditions (Gervasio & Lopes, 2003) and is forcing residents of rural African areas such as the Rusine River to seek a new source of income rather than solely focusing on agricultural yields. It is therefore critical for residents to align these two livelihoods together of agriculture for subsistence and mining for its cash income potential.

The impacts of ASM are still relatively unknown and many aspects of the field have yet to be studied in the context of Rwanda. Further research should focus on the impacts of ASM on fluvial physiochemical parameters, focusing on total dissolved sediments (TDS), pH, and turbidity, and conductivity to assess the overall suitability of water for uses such as drinking, irrigation and aquatic habitat quality (Kumar & Prabhahar, 2012). An environmental health approach focusing on the impacts of ASM on miners and surrounding communities to understand how ASM may lead to health complications through water contamination or increase presence of dust and other particles that miners can breathe. This approach can highlight the relationship between ASM and the introduction of contaminants in the river (Akanwa et al., 2020), such as heavy metals like mercury. A biological assessment and inventory of aquatic ecosystems and biomass could also reveal important information on the impacts of ASM on marine species found in rivers and the overall biotic impacts of fluvial-based ASM in Rwanda. This research proposes a particular attention on the relationship between the impacts of ASM on the possible degradation of aquatics natural resources such as fish and drinkable water. This would highlight other impacts from ASM that stand apart from physical degradation of rivers. These would contribute to a better understanding of the broader environmental and social impacts of ASM practices and sand and aggregate mining. Additional research would correspondingly add to the advancement of the field and respond to the call for action by the WWF (2018).

Chapter 7. Conclusion

The impacts of ASM practices in fluvial environments will continue to expand as the demand for sand and other aggregates rises following the expected rise in population across the African continent (Bendixen et al. 2023). Eastern and Western Africa is expected to see the largest demand increase (500%) by 2060 (Zhong et al., 2020). Hence, further mining efforts will be undertaken within fluvial ecosystems to supply the increasing demand, jeopardizing the morphological structure of rivers throughout Sub-Saharan Africa. This research aimed to understand the impacts stemming from the practice of artisanal and small-scale mining on the morphology of mined rivers in Rwanda using a geospatial and in-situ analysis. A morphological impact assessment of fluvial structure and function was conducted to quantify the impacts created by severe/floodplain mining and in-channel mining.

The findings of this research show that the interaction between ASM and fluvial morphology is intricate and dependent on the type of mining occurring within a river. Mining practices in the Rusine River are classified as floodplain mining due to the extension of mining efforts outside of the active channel. Floodplain mining in the Rusine River causes significant shifts channel morphology. Notable impacts are changing meander migration and complexity, increased incision rates, channel widening, bank cutting, and increased slope of pit walls and scarps which agree with previous literature on the subject (Dang et al., 2014; Huang et al., 2014; Yuhi et al., 2014; Byizigiro et al., 2015; Koehnken et al., 2019; Rentier & Cammeraat, 2021). However, no literature shows changes in meander wavelength, amplitude, and changes in river style due to the intense ASM action and impacts on the pool-riffle sequencing as shown in this study. Moreover, the results show that floodplain ASM causes a shift within the fluvial landscape towards a badlands landscape. This shift initiates from the deforestation, gullying and creation of deep pits throughout the active floodplain. In terms of the in-channel mining studied in the Nyabugogo River, the impacts generated from this style of mining do not entrain the severity of impacts caused by floodplain mining. Notable impacts relate to increased incision rates due to shifts in sediment supply balance leading to bank instability.

ASM influences the morphological controls of rivers by depleting the dependence of fluvial processes on natural controls. Rather, anthropogenic action will define the fluvial landscape. In severely mined rivers, the main morphological controls are fully dependent on the mining action taking place leading to a human-induced landscape (Jones, 2001). In-channel mining modifies the landscape rather than dictating the morphological controls of the river. Thus, these mining practices over time creates a human-modified landscape based on modifications brought to the hydrological balance creating visible impacts on the riverbed and on the riverbank (Jones, 2001).

The impacts of ASM on rivers remain an understudied topic that will require an increasing effort over time as the demand for materials such as alluvial, sand, and other aggregate found in riverine environments continues to increase as society is wholly dependent on such resources. Further research is required to synthesize the ramifications of ASM outside of the mining sites and develop new initiatives to promote safer, less destructive methods of mining.

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Annex A

Site A0 dGPS Points

Name	Longitude	Latitude	Distance (m)	Ellipsoidal Height (m)	Origin	Easting RMS	Northing RM!	Elevation RM	Lateral RMS	Antenna height	Antenna height units	Solution stat	Averaging start	Averaging end	Samples	PDOP	CS name
TR1.1	30.0531145	-1.7622396	0	1534.1	Global	0.04	0.011	0.008	0.041	1.934	m	FIX	2023-06-28 05:30:46.2 UTC-04:00	2023-06-28 05:30:56.2 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.2	30.053084	-1.7622553	3.75	1533.434	Global	0.011	0.013	0.008	0.017	1.934	m	FIX	2023-06-28 05:31:33.6 UTC-04:00	2023-06-28 05:31:43.6 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.3	30.0530524	-1.7622724	7.87	1531.404	Global	0.015	0.005	0.009	0.016	1.934	m	FIX	2023-06-28 05:32:04.6 UTC-04:00	2023-06-28 05:32:14.6 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.4	30.0530225	-1.7622843	11.3	1529.878	Global	0.007	0.006	0.008	0.009	1.934	m	FIX	2023-06-28 05:32:29.4 UTC-04:00	2023-06-28 05:32:39.4 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.5	30.0529968	-1.7622948	14.35	1529.189	Global	0.009	0.012	0.008	0.015	1.934	m	FIX	2023-06-28 05:32:54.6 UTC-04:00	2023-06-28 05:33:04.6 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.6	30.0529772	-1.7623057	16.85	1529.013	Global	0.005	0.004	0.008	0.006	1.934	m	FIX	2023-06-28 05:33:24.4 UTC-04:00	2023-06-28 05:33:34.4 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.7	30.0529641	-1.7623125	18.45	1529.16	Global	0.017	0.028	0.008	0.032	1.934	m	FIX	2023-06-28 05:33:42.0 UTC-04:00	2023-06-28 05:33:52.0 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.8	30.0529546	-1.7623181	19.72	1529.526	Global	0.005	0.007	0.008	0.009	1.934	m	FIX	2023-06-28 05:34:13.6 UTC-04:00	2023-06-28 05:34:23.6 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.9	30.0529266	-1.7623298	23.05	1529.991	Global	0.005	0.009	0.008	0.011	1.934	m	FIX	2023-06-28 05:34:35.2 UTC-04:00	2023-06-28 05:34:45.2 UTC-04:00	51	1.2	WGS 84 / UTM zone 34S
TR1.10	30.0528576	-1.7623699	32.01	1530.911	Global	0.008	0.01	0.008	0.013	1.934	m	FIX	2023-06-28 05:35:02.2 UTC-04:00	2023-06-28 05:35:12.2 UTC-04:00	51	1.2	WGS 84 / UTM zone 34S
TR1.11	30.0528139	-1.7623833	37.03	1532.001	Global	0.009	0.014	0.008	0.017	1.934	m	FIX	2023-06-28 05:35:25.8 UTC-04:00	2023-06-28 05:35:35.8 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR1.12	30.0527486	-1.7624166	45.25	1534.133	Global	0.005	0.005	0.008	0.008	1.934	m	FIX	2023-06-28 05:35:58.8 UTC-04:00	2023-06-28 05:36:08.8 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR2.1	30.0532987	-1.7629363	0	1531.366	Global	0.014	0.017	0.008	0.022	1.934	m	FIX	2023-06-28 05:38:48.0 UTC-04:00	2023-06-28 05:38:58.0 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR2.2	30.0532441	-1.7629523	6.39	1530.581	Global	0.009	0.006	0.008	0.011	1.934	m	FIX	2023-06-28 05:39:15.0 UTC-04:00	2023-06-28 05:39:25.0 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR2.3	30.0532176	-1.7629638	9.45	1529.52	Global	0.006	0.005	0.008	0.008	1.934	m	FIX	2023-06-28 05:39:41.4 UTC-04:00	2023-06-28 05:39:51.4 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR2.4	30.0531871	-1.7629729	13.16	1528.505	Global	0.027	0.011	0.008	0.03	1.934	m	FIX	2023-06-28 05:40:05.0 UTC-04:00	2023-06-28 05:40:15.0 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR2.5	30.0531689	-1.7629746	15.33	1528.385	Global	0.007	0.005	0.01	0.008	1.934	m	FIX	2023-06-28 05:40:32.0 UTC-04:00	2023-06-28 05:40:42.0 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR2.6	30.0531528	-1.7629766	17.19	1528.566	Global	0.006	0.006	0.009	0.008	1.934	m	FIX	2023-06-28 05:40:53.2 UTC-04:00	2023-06-28 05:41:03.2 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR2.7	30.0531188	-1.7629857	21.07	1529.344	Global	0.01	0.007	0.009	0.012	1.934	m	FIX	2023-06-28 05:41:16.4 UTC-04:00	2023-06-28 05:41:26.4 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR2.8	30.053073	-1.7630023	26.47	1529.23	Global	0.011	0.006	0.008	0.012	1.934	m	FIX	2023-06-28 05:41:36.6 UTC-04:00	2023-06-28 05:41:46.6 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR4.1	30.0536448	-1.7639541	0	1533.871	Global	0.008	0.007	0.009	0.01	1.934	m	FIX	2023-06-28 06:02:26.0 UTC-04:00	2023-06-28 06:02:36.0 UTC-04:00	51	1.2	WGS 84 / UTM zone 34S
TR4.2	30.0536988	-1.7638934	8.94	1531.41	Global	0.007	0.006	0.009	0.009	1.934	m	FIX	2023-06-28 06:02:58.6 UTC-04:00	2023-06-28 06:03:08.6 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR4.3	30.0537105	-1.7638795	10.92	1530.164	Global	0.005	0.012	0.009	0.013	1.934	m	FIX	2023-06-28 06:03:20.0 UTC-04:00	2023-06-28 06:03:30.0 UTC-04:00	51	1.2	WGS 84 / UTM zone 34S
TR4.4	30.0538128	-1.7637777	27.13	1530.13	Global	0.005	0.006	0.01	0.008	1.934	m	FIX	2023-06-28 06:03:57.8 UTC-04:00	2023-06-28 06:04:07.8 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR4.5	30.0538438	-1.7637439	32.23	1527.576	Global	0.006	0.016	0.008	0.017	1.934	m	FIX	2023-06-28 06:04:28.4 UTC-04:00	2023-06-28 06:04:38.4 UTC-04:00	51	1.2	WGS 84 / UTM zone 34S
TR4.6	30.0539515	-1.7636589	47.46	1527.602	Global	0.01	0.006	0.009	0.011	1.934	m	FIX	2023-06-28 06:04:56.2 UTC-04:00	2023-06-28 06:05:06.2 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR4.7	30.0539968	-1.7636072	54.64	1526.683	Global	0.004	0.006	0.009	0.008	1.934	m	FIX	2023-06-28 06:05:22.2 UTC-04:00	2023-06-28 06:05:32.2 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR4.8	30.0540131	-1.7635905	57.17	1526.546	Global	0.005	0.004	0.008	0.006	1.934	m	FIX	2023-06-28 06:05:48.2 UTC-04:00	2023-06-28 06:05:58.2 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR4.9	30.0540571	-1.7635559	63.33	1526.621	Global	0.01	0.007	0.009	0.012	1.934	m	FIX	2023-06-28 06:06:13.4 UTC-04:00	2023-06-28 06:06:23.4 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S
TR4.10	30.0540677	-1.7635448	65.07	1526.914	Global	0.009	0.008	0.009	0.012	1.934	m	FIX	2023-06-28 06:06:41.8 UTC-04:00	2023-06-28 06:06:51.8 UTC-04:00	51	1.2	WGS 84 / UTM zone 34S
TR4.11	30.0540852	-1.7635298	67.62	1530.148	Global	0.007	0.006	0.008	0.009	1.934	m	FIX	2023-06-28 06:08:11.2 UTC-04:00	2023-06-28 06:08:21.2 UTC-04:00	51	1.1	WGS 84 / UTM zone 34S

Site A2 dGPS points

Name	DESCRIPTION	LONG	LAT	Distance	Ellipsoidal height	Origin	Easting RMS	Northing RMS	Elevation RMS	Lateral RMS	Antenna height	Antenna height units	Solution status	Averaging start	Averaging end	Samples	PDOP	CS name
TR1.1	top	30.0772381	-1.7792891	0	1482.563	Global	0.017	0.011	0.010	0.020	1.934	m	FIX	2023-07-06 05:27:17.2 UTC-04:0	2023-07-06 05:27:27.2 UTC-04:0	51	20.9	WGS 84 / UTM zone 35S
TR1.2	bottom	30.0772026	-1.7793482	7.636	1476.476	Global	0.006	0.005	0.014	0.008	1.934	m	FIX	2023-07-06 05:28:38.6 UTC-04:0	2023-07-06 05:28:48.6 UTC-04:0	51	4.4	WGS 84 / UTM zone 35S
TR1.3	paleochannel	30.0771899	-1.7793929	12.666	1476.267	Global	0.008	0.007	0.011	0.011	1.934	m	FIX	2023-07-06 05:29:53.0 UTC-04:0	2023-07-06 05:30:03.0 UTC-04:0	51	10.6	WGS 84 / UTM zone 35S
TR1.4	main wet	30.0771496	-1.7794871	24.001	1475.898	Global	0.012	0.009	0.011	0.015	1.934	m	FIX	2023-07-06 05:30:47.0 UTC-04:0	2023-07-06 05:30:57.0 UTC-04:0	51	10.6	WGS 84 / UTM zone 35S
TR1.5	main wet middle	30.0771381	-1.7794995	25.785	1475.815	Global	0.009	0.006	0.010	0.011	1.934	m	FIX	2023-07-06 05:31:13.2 UTC-04:0	2023-07-06 05:31:23.2 UTC-04:0	51	10.7	WGS 84 / UTM zone 35S
TR1.6	main wet end	30.0771335	-1.779515	27.558	1475.927	Global	0.007	0.005	0.010	0.009	1.934	m	FIX	2023-07-06 05:31:55.0 UTC-04:0	2023-07-06 05:32:05.0 UTC-04:0	51	11	WGS 84 / UTM zone 35S
TR1.7	sec wet	30.0771124	-1.7795634	33.393	1476.059	Global	0.011	0.015	0.010	0.019	1.934	m	FIX	2023-07-06 05:32:21.0 UTC-04:0	2023-07-06 05:32:31.0 UTC-04:0	51	11.1	WGS 84 / UTM zone 35S
TR1.8	sec wet mid	30.0771097	-1.7795703	34.22	1476.038	Global	0.009	0.006	0.010	0.011	1.934	m	FIX	2023-07-06 05:32:57.0 UTC-04:0	2023-07-06 05:33:07.0 UTC-04:0	51	11.2	WGS 84 / UTM zone 35S
TR1.9	sec wet end	30.0771032	-1.7795804	35.53	1476.121	Global	0.006	0.007	0.010	0.009	1.934	m	FIX	2023-07-06 05:33:35.0 UTC-04:0	2023-07-06 05:33:45.0 UTC-04:0	51	11.4	WGS 84 / UTM zone 35S
TR1.10	far hill start	30.0770962	-1.7795905	36.873	1476.461	Global	0.006	0.005	0.010	0.007	1.934	m	FIX	2023-07-06 05:34:02.4 UTC-04:0	2023-07-06 05:34:12.4 UTC-04:0	51	11.6	WGS 84 / UTM zone 35S
TR1.11	far hill mid	30.0770389	-1.7796602	46.634	1479.252	Global	0.007	0.007	0.012	0.010	1.934	m	FIX	2023-07-06 05:34:40.4 UTC-04:0	2023-07-06 05:34:50.4 UTC-04:0	51	22.9	WGS 84 / UTM zone 35S
TR1.12	far hill mid 2	30.077014	-1.7797011	51.934	1479.406	Global	0.009	0.012	0.017	0.015	1.934	m	FIX	2023-07-06 05:35:04.8 UTC-04:0	2023-07-06 05:35:14.8 UTC-04:0	51	1.4	WGS 84 / UTM zone 35S
TR1.13	far hill top	30.0769955	-1.7797179	54.559	1482.587	Global	0.007	0.014	0.011	0.016	1.934	m	FIX	2023-07-06 05:35:38.6 UTC-04:0	2023-07-06 05:35:48.6 UTC-04:0	51	24.2	WGS 84 / UTM zone 35S
TR1.14	far hill top	30.0769955	-1.7797195	54.559	1482.594	Global	0.007	0.011	0.010	0.013	1.934	m	FIX	2023-07-06 05:36:43.0 UTC-04:0	2023-07-06 05:36:53.0 UTC-04:0	51	26	WGS 84 / UTM zone 35S
TR2.1	top	30.075422	-1.7777013	0	1486.115	Global	0.010	0.006	0.012	0.012	1.934	m	FIX	2023-07-06 07:26:10.2 UTC-04:0	2023-07-06 07:26:20.2 UTC-04:0	51	4.5	WGS 84 / UTM zone 35S
TR2.2		30.0753959	-1.7777472	5.84	1483.235	Global	0.008	0.009	0.011	0.013	1.934	m	FIX	2023-07-06 07:26:52.6 UTC-04:0	2023-07-06 07:27:02.6 UTC-04:0	51	1.2	WGS 84 / UTM zone 35S
TR2.3	rock pile	30.0753645	-1.7778246	15.058	1482.887	Global	0.011	0.011	0.011	0.016	1.934	m	FIX	2023-07-06 07:27:27.2 UTC-04:0	2023-07-06 07:27:37.2 UTC-04:0	51	5.3	WGS 84 / UTM zone 35S
TR2.4	rock pile	30.0753367	-1.7778548	19.439	1482.996	Global	0.008	0.009	0.012	0.012	1.934	m	FIX	2023-07-06 07:27:46.0 UTC-04:0	2023-07-06 07:27:56.0 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.5	rock pile	30.0752814	-1.7779574	32.344	1482.348	Global	0.010	0.021	0.013	0.023	1.934	m	FIX	2023-07-06 07:28:19.8 UTC-04:0	2023-07-06 07:28:29.8 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.6	paleo channel	30.0751974	-1.778086	49.329	1481.484	Global	0.008	0.009	0.012	0.012	1.934	m	FIX	2023-07-06 07:29:09.2 UTC-04:0	2023-07-06 07:29:19.2 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.7	wet main	30.0751678	-1.7781502	57.127	1481.070	Global	0.014	0.022	0.011	0.026	1.934	m	FIX	2023-07-06 07:29:50.4 UTC-04:0	2023-07-06 07:30:00.4 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.8	wet main mid	30.0751657	-1.7781536	57.569	1480.951	Global	0.013	0.020	0.011	0.024	1.934	m	FIX	2023-07-06 07:30:11.0 UTC-04:0	2023-07-06 07:30:21.0 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.9	wet main end	30.0751596	-1.778156	58.139	1481.052	Global	0.009	0.020	0.012	0.022	1.934	m	FIX	2023-07-06 07:30:53.2 UTC-04:0	2023-07-06 07:31:03.2 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.10	mid channel bar paleo channel	30.0751135	-1.7782207	66.901	1480.925	Global	0.007	0.008	0.012	0.010	1.934	m	FIX	2023-07-06 07:31:48.4 UTC-04:0	2023-07-06 07:31:58.4 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.11	mid channel bar 2	30.0750986	-1.778272	72.633	1481.466	Global	0.012	0.012	0.012	0.017	1.934	m	FIX	2023-07-06 07:32:14.8 UTC-04:0	2023-07-06 07:32:24.8 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.12	mid channel bar 2 end	30.0750814	-1.7783137	77.592	1481.328	Global	0.007	0.008	0.011	0.011	1.934	m	FIX	2023-07-06 07:32:42.8 UTC-04:0	2023-07-06 07:32:52.8 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.13	main channel 2 wet	30.07508	-1.7783161	77.896	1480.840	Global	0.006	0.004	0.012	0.007	1.934	m	FIX	2023-07-06 07:33:22.6 UTC-04:0	2023-07-06 07:33:32.6 UTC-04:0	51	8.4	WGS 84 / UTM zone 35S
TR2.14	main channel 2 wet mid	30.0750816	-1.7783202	78.211	1480.653	Global	0.008	0.005	0.011	0.010	1.934	m	FIX	2023-07-06 07:33:45.2 UTC-04:0	2023-07-06 07:33:55.2 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.15	main channel 2 wet end	30.075076	-1.778325	78.979	1480.804	Global	0.011	0.010	0.011	0.015	1.934	m	FIX	2023-07-06 07:34:32.6 UTC-04:0	2023-07-06 07:34:42.6 UTC-04:0	51	1.2	WGS 84 / UTM zone 35S
TR2.16	main channel 2 wet end	30.0750752	-1.7783365	80.131	1481.591	Global	0.009	0.005	0.014	0.011	1.934	m	FIX	2023-07-06 07:41:24.2 UTC-04:0	2023-07-06 07:41:34.2 UTC-04:0	51	1.3	WGS 84 / UTM zone 35S
TR2.17	main channel 2 wet end	30.0750564	-1.7783661	84.011	1482.331	Global	0.008	0.009	0.011	0.012	1.934	m	FIX	2023-07-06 07:41:54.4 UTC-04:0	2023-07-06 07:42:04.4 UTC-04:0	51	1.3	WGS 84 / UTM zone 35S
TR2.18	paleo	30.0750363	-1.7783885	87.263	1481.997	Global	0.007	0.007	0.010	0.010	1.934	m	FIX	2023-07-06 07:42:26.8 UTC-04:0	2023-07-06 07:42:36.8 UTC-04:0	51	1.2	WGS 84 / UTM zone 35S
TR2.19		30.0750155	-1.7784052	90.018	1483.153	Global	0.009	0.012	0.011	0.015	1.934	m	FIX	2023-07-06 07:42:55.4 UTC-04:0	2023-07-06 07:43:05.4 UTC-04:0	51	1.2	WGS 84 / UTM zone 35S
TR2.20		30.0749893	-1.7784566	96.392	1484.247	Global	0.016	0.024	0.011	0.029	1.934	m	FIX	2023-07-06 07:43:16.6 UTC-04:0	2023-07-06 07:43:26.6 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.21		30.0749718	-1.7784775	99.371	1484.737	Global	0.010	0.019	0.011	0.022	1.934	m	FIX	2023-07-06 07:43:35.2 UTC-04:0	2023-07-06 07:43:45.2 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.22		30.0749656	-1.7784895	100.867	1486.166	Global	0.011	0.011	0.011	0.016	1.934	m	FIX	2023-07-06 07:43:57.6 UTC-04:0	2023-07-06 07:44:07.6 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.23		30.0749534	-1.7785056	103.09	1486.591	Global	0.006	0.009	0.010	0.011	1.934	m	FIX	2023-07-06 07:44:15.4 UTC-04:0	2023-07-06 07:44:25.4 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S

Site A2 dGPS Points Section 2

Name	Longitude	Latitude	Distance	Ellipsoidal height	Origin	Easting RMS	Northing RMS	Elevation RMS	Lateral RMS	Antenna height	Antenna height units	Solution status	Averaging start	Averaging end	Samples	PDOP	CS name
TR1.1	30.0770101	-1.7797342	0	1483.022	Global	0.008	0.014	0.008	0.016	1.934	m	FIX	2023-06-28 06:55:11.0 UTC-04:0	2023-06-28 06:55:21.0 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR1.2	30.0771266	-1.7796712	14.52	1478.608	Global	0.008	0.010	0.007	0.013	1.934	m	FIX	2023-06-28 06:58:44.4 UTC-04:0	2023-06-28 06:58:54.4 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR1.3	30.0771704	-1.7796242	21.415	1478.411	Global	0.008	0.010	0.007	0.013	1.934	m	FIX	2023-06-28 06:59:08.8 UTC-04:0	2023-06-28 06:59:18.8 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR1.4	30.077182	-1.7796093	23.415	1476.457	Global	0.016	0.005	0.008	0.017	1.934	m	FIX	2023-06-28 07:00:22.4 UTC-04:0	2023-06-28 07:00:32.4 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR1.5	30.0772174	-1.7795356	31.669	1476.272	Global	0.004	0.005	0.008	0.007	1.934	m	FIX	2023-06-28 07:01:30.8 UTC-04:0	2023-06-28 07:01:40.8 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR1.6	30.0772551	-1.7795305	35.199	1476.229	Global	0.006	0.007	0.008	0.009	1.934	m	FIX	2023-06-28 07:03:24.0 UTC-04:0	2023-06-28 07:03:34.0 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR1.7	30.0773391	-1.7793915	52.543	1476.549	Global	0.009	0.006	0.008	0.011	1.934	m	FIX	2023-06-28 07:04:28.0 UTC-04:0	2023-06-28 07:04:38.0 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR1.8	30.0773982	-1.7792898	65.281	1477.623	Global	0.007	0.010	0.008	0.012	1.934	m	FIX	2023-06-28 07:05:01.4 UTC-04:0	2023-06-28 07:05:11.4 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR1.9	30.0773997	-1.7792138	71.934	1479.497	Global	0.011	0.005	0.008	0.013	1.934	m	FIX	2023-06-28 07:05:33.0 UTC-04:0	2023-06-28 07:05:43.0 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR1.10	30.077416	-1.7791727	76.667	1483.204	Global	0.004	0.005	0.007	0.006	1.934	m	FIX	2023-06-28 07:06:11.8 UTC-04:0	2023-06-28 07:06:21.8 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR2.1	30.0778342	-1.7801221	0	1480.961	Global	0.013	0.010	0.007	0.017	1.934	m	FIX	2023-06-28 07:17:04.4 UTC-04:0	2023-06-28 07:17:14.4 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.2	30.0779281	-1.780085	5.46	1476.312	Global	0.012	0.011	0.008	0.016	1.934	m	FIX	2023-06-28 07:18:03.2 UTC-04:0	2023-06-28 07:18:13.2 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR2.3	30.0779402	-1.7800713	11.346	1474.774	Global	0.008	0.011	0.007	0.014	1.934	m	FIX	2023-06-28 07:20:08.2 UTC-04:0	2023-06-28 07:20:18.2 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR2.4	30.077969	-1.7800674	13.194	1475.010	Global	0.006	0.008	0.008	0.010	1.934	m	FIX	2023-06-28 07:20:53.0 UTC-04:0	2023-06-28 07:21:03.0 UTC-04:0	51	1	WGS 84 / UTM zone 35S
TR2.5	30.0780424	-1.7800498	16.297	1474.385	Global	0.023	0.014	0.008	0.027	1.934	m	FIX	2023-06-28 07:22:09.4 UTC-04:0	2023-06-28 07:22:19.4 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.6	30.0780538	-1.7800435	24.514	1474.549	Global	0.010	0.004	0.007	0.011	1.934	m	FIX	2023-06-28 07:22:36.6 UTC-04:0	2023-06-28 07:22:46.6 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.7	30.0781549	-1.7799764	25.934	1474.882	Global	0.012	0.007	0.008	0.014	1.934	m	FIX	2023-06-28 07:23:11.8 UTC-04:0	2023-06-28 07:23:21.8 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.8	30.0781551	-1.7799768	39.16	1474.875	Global	0.005	0.003	0.008	0.006	1.934	m	FIX	2023-06-28 07:26:31.0 UTC-04:0	2023-06-28 07:26:41.0 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.9	30.0782373	-1.779926	49.826	1474.659	Global	0.015	0.006	0.008	0.016	1.934	m	FIX	2023-06-28 07:27:23.6 UTC-04:0	2023-06-28 07:27:33.6 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.10	30.078263	-1.7799159	51.298	1474.952	Global	0.011	0.007	0.008	0.013	1.934	m	FIX	2023-06-28 07:28:07.8 UTC-04:0	2023-06-28 07:28:17.8 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.11	30.0783172	-1.7798648	52.879	1475.906	Global	0.006	0.005	0.008	0.008	1.934	m	FIX	2023-06-28 07:28:36.6 UTC-04:0	2023-06-28 07:28:46.6 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.12	30.0782499	-1.7799215	60.807	1474.511	Global	0.007	0.007	0.008	0.010	1.934	m	FIX	2023-06-28 07:29:23.8 UTC-04:0	2023-06-28 07:29:33.8 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.13	30.0783604	-1.7798375	66.4755	1476.134	Global	0.007	0.007	0.008	0.010	1.934	m	FIX	2023-06-28 07:30:04.2 UTC-04:0	2023-06-28 07:30:14.2 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.14	30.0784233	-1.7797827	75.534	1475.975	Global	0.008	0.007	0.008	0.011	1.934	m	FIX	2023-06-28 07:30:36.0 UTC-04:0	2023-06-28 07:30:46.0 UTC-04:0	51	1.1	WGS 84 / UTM zone 35S
TR2.15	30.0784522	-1.7797269	81.477	1476.623	Global	0.005	0.006	0.009	0.008	1.934	m	FIX	2023-06-28 07:31:12.2 UTC-04:0	2023-06-28 07:31:22.2 UTC-04:0	51	1.2	WGS 84 / UTM zone 35S