Czech University of Life Sciences Prague

Faculty of Economics and Management

Department of Water Resources and Environmental Modelling

Study Program: Environmental Modelling

Master's Thesis

Algorithm-Assisted Reconstruction of Hydrologically Correct Noachian Valley

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Thesis title

Algorithm-Assisted Reconstruction of Hydrologically Correct Noachian Valley Networks

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Objectives of thesis

Review water history on Mars as well as previous valley mapping campaigns and methods, regional paleo-hydrological studies and modelling.
Valley network and subbasin algorithm-assisted mapping campaign.
Determination of hydrological proxies (valley width, incision depth, subbasin area, eroded material) of mapped subbasins.
Comparison of the proxies in order to reveal the cause of valleys formation in such period on Mars and the relatively contribution to the overall outflow.

Methodology

Currently available datasets of Martian valley networks are unusable for hydrological applications because they do not reflect the best resolution imagery and in many cases don't make hydrological sense (lack of connectivity, basin-wide coverage, etc.). An updated valley network and basin dataset based on algorithmic and manual delineation (utilizing MOLA DEM, THEMIS-IR Night, CTX Mosaic) can improve our ability to model past hydrological processes. Review part will be focused on overview of water history on Mars as well as previous valley mapping campaigns and methods, regional paleohydrological studies and modelling. Practical part will consist of valley network and subbasin algorithm-assisted mapping campaign; determination of hydrological proxies (valley width, incision depth, subbasin area, eroded material) of mapped subbasins; and comparison of the proxies in order to reveal the cause of valleys formation in such period on Mars the relatively contribution to the overall outflow.

The proposed extent of the thesis

50-60 pages

Keywords

Mars hydrology, Noachian era, Mapping campaigns, geomorphology

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Recommended information sources

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Declaration

I declare that I have worked on my master's thesis titled "Algorithm-Assisted Reconstruction of Hydrologically Correct Noachian Valley " by myself and I have used only the sources mentioned at the end of the thesis. As the author of the master's thesis, I declare that the thesis does not break any copyrights. With my own signature, I also declare that the electronic version is identical to the printed version.

In Prague on 31th of March 2023 Islam Gomaa

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Algorithm-Assisted Reconstruction of Hydrologically Correct Noachian Valley

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Abstract: Understanding the hydrology of Mars has been a channelling topic for several decades, yet it is critical to know the history of this planet. The Noachian period, which occurred on early Mars, is thought to have been a time of significant water activity. Thus, studying the hydrology of Noachian valleys can provide insights into the early history of Mars and the conditions that may have existed on the planet during this time. This thesis aims to contribute to our understanding of the role of water in shaping the surface of Mars. The valleys and channels observed on Mars today are thought to have formed due to the flow of water. However, reconstructing the hydrology of these features can be challenging, due to the limited data available and the complexity of the processes involved. The thesis presents a novel approach for reconstructing the hydrology of Noachian valleys using algorithm-assisted mapping campaign and data from past and current Mars missions. As the Current available datasets of Martian valley networks are unusable for hydrological applications because they do not reflect the best resolution imagery lead to lack of connectivity, basin-wide coverage, etc. Therefore, an updated valley network and basin dataset based on algorithmic and manual delineation (utilizing MOLA-DEM, THEMIS-IR Night, CTX Mosaic) can improve our ability to model past hydrological processes. This thesis presents a study of the valley network in the Terra Cimmeria region of Mars, with the aim of improving our understanding of the planet's hydrology and geology. It applies morphometric analysis to investigate the morphologies and characteristics of the valley network. The results show flowing water led to soil erosion played the primary role for the valley formation in this area, and that the updated valley network provides a more comprehensive and accurate picture of the valley network on Mars. While sapping only played a secondary role in valley formation in this region. These findings support the hypothesis that Mars had a much warmer and wetter climate, with a much thicker atmosphere. The study also identifies areas for further research, including the need for more detailed mapping and modelling of Martian hydrology using more higher spatial resolution datasets and the application of advanced analysis techniques. The findings of this study have important implications for future missions to Mars and contribute to our understanding of the planet's potential for supporting life.

Keywords: Mars hydrology, Noachian era, Mapping campaigns, geomorphology

Algoritmem asistovaná rekonstrukce hydrologicky správného údolí noachijského stáří

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Abstrakt: Porozumění hydrologii Marsu bylo klíčovým tématem již několik desetiletí, nicméně je kritické znát historii této planety. Noachské období, které se odehrálo na rané Marsu, se předpokládá, že bylo obdobím významné vodní aktivity. Studium hydrologie noachských údolí tak může poskytnout informace o rané historii Marsu a podmínkách, které na této planetě v té době mohly existovat. Tato práce si klade za cíl přispět k našemu porozumění roli vody při utváření povrchu Marsu. Údolí a kanály, které dnes na Marsu pozorujeme, se předpokládá, že vznikly vlivem toku vody. Rekonstrukce hydrologie těchto útvarů však může být obtížná kvůli omezeným dostupným datům a složitosti procesů zapojených do jejich vzniku. Práce představuje nový přístup k rekonstrukci hydrologie noachských údolí pomocí algoritmus-asistovaného mapovacího programu a dat z minulých a současných misí na Marsu. Aktuálně dostupné datové soubory sítí údolí na Marsu nejsou použitelné pro hydrologické aplikace, protože neodrážejí nejlepší rozlišení obrazových dat, což vede ke snížení konektivity, celoplošnému pokrytí atd. Proto aktualizovaný soubor dat sítě údolí a pánví na základě algoritmické a manuální delineace (použití MOLA-DEM, THEMIS-IR Night, CTX Mosaic) může zlepšit naši schopnost modelovat minulé hydrologické procesy. Tato práce představuje studii sítě údolí v oblasti Terra Cimmeria na Marsu s cílem zlepšit naše porozumění hydrologii a geologii této planety. Používá morfometrickou analýzu k prozkoumání morfologií a charakteristik sítě údolí. Výsledky ukazují, že proudící voda vedla k erozi půdy a hrála primární roli při tvorbě údolí v této oblasti a aktualizovaná síť údolí poskytuje komplexnější a přesnější obraz sítě údolí na Marsu. Sapping hraje pouze sekundární roli při tvorbě údolí v této oblasti. Tyto zjištění podporují hypotézu, že Mars m

Klíčová slova: hydrologie Marsu, Noachova éra, mapovací kampaně, geomorfologie

Table of Content

1 Introduction

The study of water on Mars is important for understanding the evolution of its surface and atmosphere, and its potential for habitability. The presence of water in liquid phase on Mars is considered to be one of the key factors for the potential of past or present microbial life (Horneck, 2008). The discovery of water-carved features such as valley networks, channel networks, and outflow channels, as well as the detection of subsurface water ice, has led to the hypothesis that Mars once had a much warmer and wetter climate, with a much thicker atmosphere (Head et al., 2022). Additionally, the study of the distribution and stability of water on Mars can provide information about the planet's past and current climate, as well as its potential for future human exploration and colonization. Furthermore, the study of water on Mars can provide insights into the broader context of water in the solar system, and its potential to support life on other planets.

Thus, understanding the hydrology of Noachian valley networks can provide insights into the early history of Mars and the conditions that may have existed on the planet during this time. However, our understanding of the distribution and movement of water during this period is limited. The Noachian period, which occurred approximately 3.5 billion years ago, is thought to have been a time of significant water activity on Mars (Victor R. Baker, 2001). The valleys and channels observed on the planet today are thought to have formed due to the flow of water and understanding the hydrology of these features knowledge about the early stages of the planet and the environmental conditions that may have prevailed during that period. Unfortunately, reconstructing the hydrology of Noachian valleys is challenging due to the limited availability of data, degradation of the observed landforms by impacts and weathering and the complexity of the processes involved. Despite these difficulties, the history of water on Mars is diligently researched as it stands as an important topic of planetary science for several reasons.

First, water is a fundamental requirement for life as we know it. The presence of water on a planet is therefore an important factor in the search for life beyond Earth. The history of water on Mars is therefore of interest to astrobiologists, who are studying the potential for Mars to have supported life in the past or present (Jakosky, 2020; Knoll & Grotzinger, 2006). Second, the presence and movement of water on a planet can have a significant impact on its geology and surface features. The valleys, channels, and other features observed on Mars are thought to have been formed by flowing water and understanding the history of these features can provide insights into the geologic history of the planet. Finally, studying the history of water on Mars can help us better understand the climate and atmospheric conditions that have existed on the planet over time. Water is a key component of the planet's climate system and understanding how water has cycled on Mars can provide clues about the planet's past climate and atmospheric conditions.

In addition, the Martian surface contains numerous landforms such as outflow channels, polar ice caps and dry riverbeds that suggest extensive past activity of liquid water and ice (Costard et al., 2002; Victor R. Baker, 2001). These landforms indicate that the planet may have had more humid climate in the past, compare to the current climate which is cold and dry (Head et al., 2022). The densities of impact craters on the surface allow scientists to divide the planet's history into three stratigraphical periods: the Noachian epoch, the Hesperian epoch, and the Amazonian epoch. Water and ice were active on the surface during all these periods, and researchers are interested in understanding the mode, timing, and long-term cycling of water in surficial processes on Mars.

Regarding the Martian climate, the surface of Mars is currently extremely cold and dry, with a thin atmosphere that contains only small amounts of water vapor. At the land's surface, the atmosphere is over hundred times less dense than on Earth. Water vapor from the north polar ice cap sublimates and moves to the south pole during the northern spring and summer, but this pattern reverse in the northern autumn and winter. Water currently plays a minor role in shaping the surface of Mars compared to the role it plays on Earth, and wind is the most continuously active surface-modifying process on the planet (Victor R. Baker, 2001).

Finally, one of the critical methods to study Martian water cycle and history is regional palaeohydrological studies. These have provided valuable insights into the past water flow patterns on Mars, helping to piece together the planet's hydrological history. Further studies, utilizing a variety of methods, will be needed to continue to refine our understanding of the planet's water history and its potential implications for the potential for life on Mars.

2 Objectives and Methodology

2.1 Objectives

The main focus of this diploma thesis is to update valley network and basin dataset based on algorithmic and manual delineation. The work aims to develop a hydrologically correct valley network and basin dataset for a specific region on Mars. This will be achieved through an algorithm-assisted mapping campaign utilizing high-resolution datasets, such as MOLA-HRSC DEM, THEMIS-IR Night, and CTX Mosaic. Because the current available datasets of Martian valley networks do not reflect the best resolution imagery and in many cases don't make hydrological sense (lack of connectivity, basin-wide coverage, etc.). This work could be utilized for hydrological applications and improve the quality of the pervious Martian hydrological models. The mapping campaign will focus on the thalwegs and subbasins in a specific watershed emptying into the northern lowlands at 5.2169 S, 132.8592 E. The research will determine hydrological proxies, such as valley width, incision depth, subbasin area, and eroded material, for each subbasin and compare them to reveal the relative contributions to the overall outflow. The goal is to improve our understanding of past hydrological processes on Mars by creating a more accurate and hydrologically correct valley network and basin dataset.

2.2 Methodology

Therefore, the following methodological steps have been chosen:

- Review the water history on Mars, previous valley mapping campaigns and methods, and regional paleohydrological studies and models.
- Run hydrological model for the area of interest using high resolution dataset of MOLA-HRSC DEM.
- Emphasis on mapping and thalwegs and subbasin in the watershed emptying to the northern lowlands at .2169 S, 132.8592 E
- Determine the hydrological proxies, such as valley width, incision depth, subbasin area.
- Use proxies to reveal the cause of valleys formation in such period on Mars and the relatively contribution to the overall outflow.

3 Literature Review

In order to conduct this study, this review chapter focuses on the history of water on Mars, previous valley mapping campaigns and methods and regional paleohydrological studies and modelling. As such, this section will give the theoretical background and essential concepts on these topics.

3.1 Overview of water history on Mars

The history of water on Mars is a complex and fascinating topic that has been the subject of much scientific study. Early observations of the planet, made by telescopes and flyby missions, revealed the presence of polar ice caps and spectral signatures of minerals indicative of past water activity(Carr, 1987; Jakosky, 2020). These observations sparked interest in the possibility that water may have once flowed on the surface of Mars. More recent missions, such as the Mariner 9 and Viking orbiters, provided detailed images of the Martian surface and revealed the presence of valleys, channels, and other features that are thought to have been formed by flowing water (Victor R. Baker, 2001). These features suggest that Mars may have had a more humid climate in the past, with liquid water on its surface.

3.1.1 Sings of surface water and ice on Mars

There are many signs of subsurface water and ice on Mars, including landforms indicative of permafrost and ground ice, as well as unique crater morphologies and volcanic features thought to be related to water and ice. These features suggest that Mars has had a complex history of water and ice activity, with water and ice interacting with volcanism in various ways. Some of the youngest volcanic landscapes on the planet are thought to be closely associated with cataclysmic flood channels and volcanic lava flows, and the morphology of Olympus Mons, one of the largest known volcanoes on Mars, may be indicative of water/ice volcanic interactions (Lane & Christensen, 2000). These findings provide important insights into the past and present hydrological conditions on Mars.

There are many signs of surface water on Mars, including valley networks that are thought to have formed through groundwater sapping processes, as well as outflow channels with characteristics similar to those created by cataclysmic flooding on Earth (Williams et al., 2000). Some of these valleys and channels are thought to be relatively young, indicating that water has played a role in shaping the Martian landscape more recently than previously thought. According to NASA Ames Research Centre, these outflow channels are formed in early Amazonian (3.37–1.23 Ga) and Middle Amazonian (1.23–0.328 Ga) (Rodriguez et al., 2015). There is also evidence for past lakes and standing bodies of water on the planet such as Jezero crater where scientists believe there was a lake around 500 meters deep 3.5 billion years ago as shown in figure 3.1, as well as for water-related erosion and sedimentation (Goudge et al., 2018; Gulick, 2001). These findings suggest that Mars may have had a more humid climate in the past, with liquid water present on the surface. However, the precise nature and extent of this water activity is still the subject of ongoing research and debate.

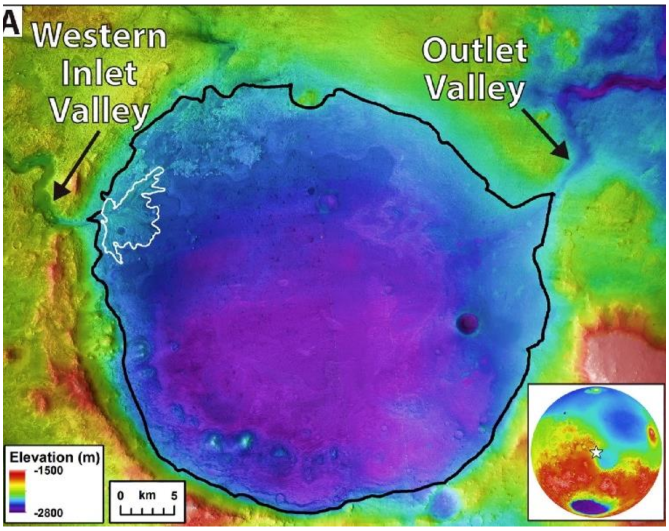

Figure 3.1: Jezero crater paleolake. Overview of the paleolake basin (centered at ~18.4°N, 77.7°E). Black outline indicates the minimum basin breach level. White outline indicates the western delta deposit (Goudge et al., 2018).

In addition, Glacial ice has been observed on Mars in various forms, including landforms that resemble terrestrial glacial features such as cirques, horns, and moraines, as well as more recent features like crevasse-like fractures and lobate debris aprons (Victor R. Baker, 2001). These features have been found in the mountainous uplands near the Argyre and Hellas impact basins, as well as in the northern fretted terrain and valleys draining to Hellas (Head & Pratt, 2001). The presence of glacial features on Mars raises questions about the climate and conditions that may have existed on the planet in the past. However, the scale of the climate changes necessary to account for glaciation on Mars has led some researchers to express scepticism about the existence of glacial ice on the planet. Further study is needed to understand the origin and evolution of these features and their implications for the history of Mars.

3.1.2 Early observations of water on Mars

Early observations of water on Mars were made through telescopes and flyby missions, which provided the first glimpses of the planet's surface and atmosphere. These observations revealed several key clues about the presence of water on Mars.

One of the most prominent features observed on Mars was the presence of polar ice caps, which are made up of water ice and frozen carbon dioxide (CO_2). These ice caps were first detected in the late 1800s, and subsequent observations revealed that they grew and shrank in size with the seasons. The polar ice caps on Mars are affected by variations in obliquity, which is the tilt of the planet's rotation axis relative to its orbit. Obliquity can vary between approximately 15 and 35 degrees. When the obliquity is high, more sunlight reaches the poles, and the polar ice caps are smaller and more carbon dioxide sublimates from the caps, leading to a warming of the planet. When the obliquity is low, less sunlight reaches the poles, and the polar ice caps are larger as more CO_2 condenses and becomes solid again, leading to a cooling of the planet (Ward, 1973) . Together with seasons, variations in obliquity have played an important role in shaping the planet's climate over time. This suggested that water and CO2 were cycling through the planet's atmosphere, with some being lost to the poles and some being returned to the atmosphere through sublimation (Victor R. Baker, 2001).

In addition to the ice caps, spectroscopic observations of Mars also revealed the presence of minerals on the planet's surface that are typically formed in the presence of water. For example, spectra of the Martian surface showed the presence of hydrated minerals such as clay and sulphates, which are thought to have formed through the interaction of water with rock (Jakosky, 2020). One of the most significant discoveries made by the Spirit rover was the presence of hydrated minerals, such as sulfates, in the Martian soil. Rover missions have first landed on mars in 2004 (Morris et al., 2004). These observations provided further evidence for the presence of water on Mars in the past.

Overall, these early observations of water on Mars sparked interest in the possibility that the planet may have had a more humid climate in the past, and they laid the groundwork for more detailed studies of the planet's surface and atmosphere.

3.1.3 More recent evidence for past water on Mars

There is a wealth of evidence for past water on Mars, including observations made by more recent spacecraft missions that have provided detailed images and measurements of the planet's surface and atmosphere. Here are a few examples of this evidence:

- *Valleys and channels*: Many of the valleys and channels observed on Mars are thought to have formed due to the flow of water (Alemanno et al., 2018; Grau Galofre et al., 2020). These features can be hundreds of kilometres long and several kilometres wide, and they show features such as meanders, tributaries, and deposits of sediment that are characteristic of water erosion. In figure 3.2, an overview of Martian fluvial systems in different colours which he majority of valleys present are single diffuse segments (Alemanno et al., 2018). Most of valley netwrok are located areas from 0° to -30° latitude and to the estern part of the plant.

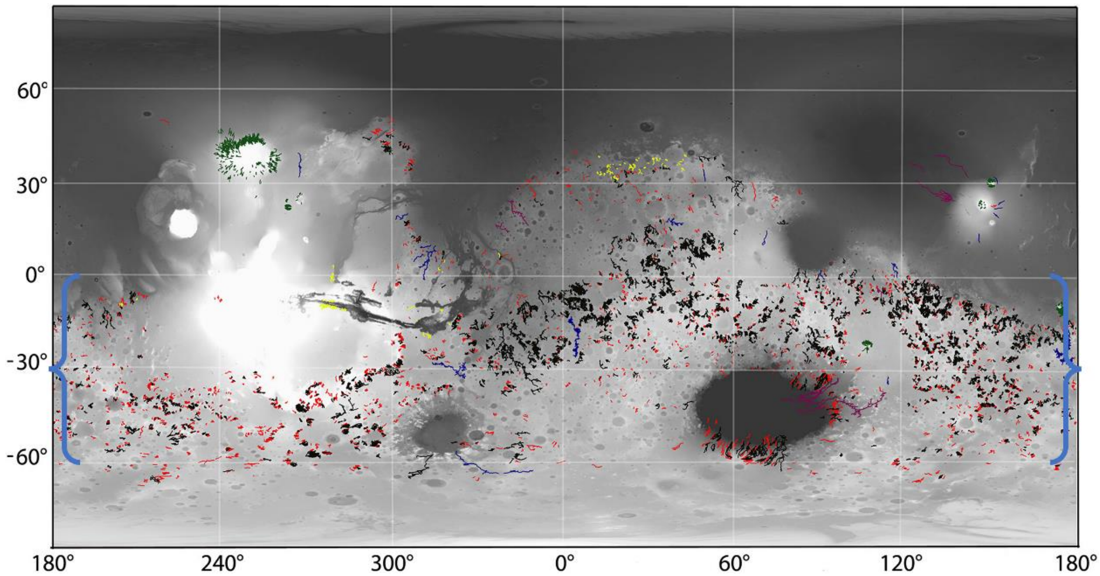

Figure 3.2: Valley networks database (black), single valleys (red), longitudinal valleys (blue), valleys atop volcanoes (green), valleys next to canyons (yellow), and tiny outflows are depicted on a map of Martian fluvial systems (pink). A grayscale MOLA topographic mosaic (Alemanno et al., 2018).

- *Lakes and lake beds*: There is evidence for the presence of lakes on Mars in the past, including the detection of sedimentary deposits and the presence of minerals that are typically formed in the presence of water. These lake beds are thought to have formed in the Noachian and Hesperian periods, when Mars is thought to have had a more humid climate (Fastook & Head, 2015).
- *Groundwater*: There is also evidence for the presence of groundwater on Mars, including the detection of minerals that are formed through the interaction of water with rock and the presence of underground aquifers (Clifford et al., 2010).

3.1.4 Hypotheses about the source and fate of water on Mars

Scientists continue to investigate Mars in order to gain a better understanding of the processes involved in the origin and fate of water on the planet. Two main key theories for origin of water are below:

- *Cometary impacts*: It is thought that water and other volatile materials may have been delivered to Mars through cometary impacts, which could have deposited water ice and other materials on the planet's surface. This hypothesis is supported by the detection of water ice on the Martian surface and the presence of minerals formed through the interaction of water with rock. There is evidence for the presence of water ice on the Martian surface, including the detection of water ice in the polar ice caps and in the subsurface at high latitudes (Senft & Stewart, 2008). However, some scientists have proposed that there is no cometary cratering. It may have been caused by a late planetary instability in the Nice

Model, a theoretical model of the early solar system (Kress & McKay, 2004; Rickman et al., 2017). According to this hypothesis, the Late Heavy Bombardment was not caused by the arrival of comets and asteroids from the outer solar system, but rather by the rearrangement of the orbits of the inner planets due to a late instability in the solar system.

- *Underground aquifers:* Another possibility is that Mars has an underground aquifer system that could have supported the flow of water on the surface in the past. This hypothesis is supported by the detection of underground water-bearing minerals and the presence of underground aquifers. The observation of small gullies connected to recent surface runoff on Mars indicate that the gullies could be formed by groundwater seepage from underground aquifers (Costard et al., 2002). As shown in figure 3.3, the bases of escarpments covered by thick accumulations of debris, while upper parts of the walls are dissected by funnels and generally have steep slopes.

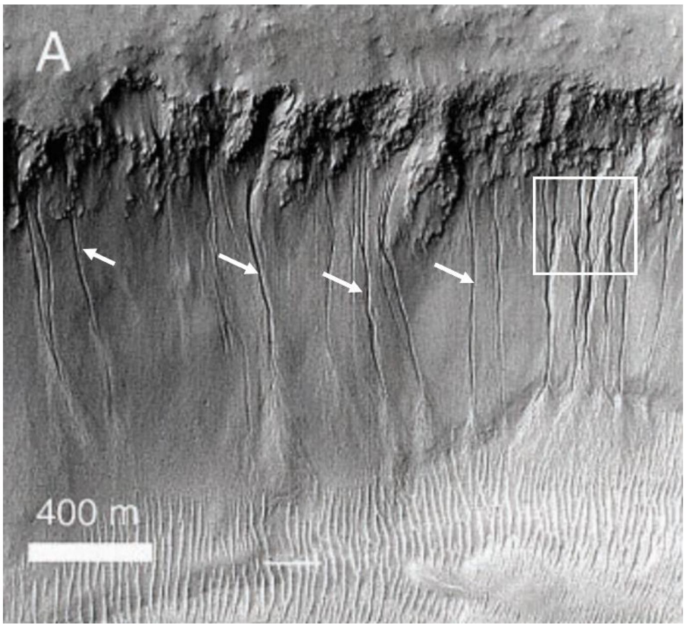

Figure 3.3: Recent gullies on Mars. Debris flows in Nirgal Vallis (MOC image M03-02290, 29.7°S, 39°W). Total length is 900 m (Costard et al., 2002).

On the other hand, there are several of the key theories of fate of water on mars are listed below:

- *Climate change:* It is possible that the history of water on Mars has been influenced by changes in the planet's climate. For example, Mars may have had a more humid and temperate climate in the past, which could have supported the flow of water on the surface. However, the planet's climate is thought to have cooled and dried over time, leading to the development of a more arid landscape (Head et al., 2022).

- *Loss to Space:* The fate of water on Mars is closely tied to the planet's weak magnetic field. Mars does not have a strong magnetic field that protects the planet from the solar wind. This causes the solar wind to strip away the planet's atmosphere, including water vapor, and this process causes the loss of water to space. This leads to water being mostly frozen in the polar caps, or exists as very thin layers of ice, or vapor. Additionally, the loss of water vapor to space can cause a thinning of the Martian atmosphere, which makes it even harder for liquid water to exist on the surface (Lundin et al., 2007). Because of the thin atmosphere and low temperatures on Mars, water ice on the planet's surface can sublimate. This process can cause the polar ice caps to shrink. Sublimation can also cause the formation of the water vapor in the Martian atmosphere, but the weak gravity and thin atmosphere, the water vapor can easily lose to space, (Dundas et al., 2015).
- *Photodissociation:* The sun's ultraviolet (UV) radiation breaks down water molecules into hydrogen and oxygen, which can then escape into space. On Mars, this process can lead to the loss of water from the planet's surface and atmosphere. As hydrogen produced by photodissociation can easily escape the planet's weak gravity and be lost to space, while the oxygen can be locked up in minerals or may also escape to space. Additionally, photodissociation can also contribute to the formation of the Martian atmosphere by breaking down the water vapor into hydrogen and oxygen, which can then become part of the planet's atmosphere (Shaposhnikov et al., 2022).

The source and fate of water on Mars is a complex and active area of research, and scientists are working to better understand the processes that have shaped the planet's water cycle and the conditions that may have existed on Mars in the past.

3.2 Previous valley mapping campaigns and methods

Valley mapping campaigns on Mars have played a significant role in understanding the history and evolution of the planet's surface. These campaigns have involved the use of various methods and technologies to map and analyse the characteristics of valleys on Mars, including their locations, sizes, shapes, and geomorphic features. These methods have included the use of remote sensing techniques, such as imaging and spectroscopy, as well as in situ measurements and field observations.

3.2.1 Description of early mapping efforts

Early mapping efforts on Mars focused on understanding the basic geology and geomorphology of the planet's surface. These efforts were driven by the desire to learn more about the history and evolution of Mars, as well as to search for evidence of past or present life on the planet.

The first successful flyby of Mars was conducted by the Mariner 4 spacecraft in 1965, which returned the first close-up images of the planet's surface. These images showed a rocky, cratered terrain similar to the Moon and provided a baseline for future mapping efforts (Leighton et al., 1965). Over the following decades, a few spacecraft missions were conducted to further explore and map the surface of Mars. The Mariner 9 spacecraft discovered evidence of past water activity on Mars when it began orbiting the planet in 1971. This evidence included valleys and channels with a morphology that suggested they had been formed by flowing water. And the Viking orbiters of the late1970s were primarily intended to support landers in their search for evidence of life on Mars. However, they also returned many images of the planet's surface, many of which had higher resolution than those taken by the Mariner 9 spacecraft (Victor R. Baker, 2001). These images provided the basis for our understanding of water and the Martian landscape for many years and helped researchers to better understand the role of water in shaping the surface of the planet.

3.2.2 Development of more advanced mapping techniques

In recent years, there have been significant developments in the mapping techniques used to study Mars. These advances have been driven by the increasing capabilities of spacecraft and instrumentation, as well as the need to address specific scientific questions and goals related to the exploration of the planet.

To start with, the Mars Global Surveyor spacecraft was launched in 1997 and began mapping the Martian surface in 1999. It was equipped with two instruments, the Mars Orbiter Camera (MOC) and the Mars Orbiter Laser Altimeter (MOLA), which provided detailed images and topographic data of the planet's surface. The MOC had a resolution of 1.4 meters per pixel, while the MOLA had a precision of better than 10 meters. These instruments allowed scientists to study Mars' landforms in greater detail, although the interpretation of these landforms still requires scientific experience and expertise (Victor R. Baker, 2001). The data is collected using instruments such as lasers and radar that measure the distance to the surface and is used to create a map of the surface elevation. These maps can be used to study the geology and geomorphology of Mars, as well as to plan future missions and landings on the planet. Global DEMs of Mars have been created using data from other missions, including the MGS and MRO, and have been used to create detailed maps of the surface of the planet.

Another important development has been the use of in situ measurements and field observations to study the Martian surface. For example, the Mars Exploration Rovers (MERs) Spirit and Opportunity, which were launched in 2003, conducted a number of field observations and measurements of the Martian surface, including the collection of rock and soil samples for analysis. NASA's Mars Exploration Rovers

(MER) were designed to traverse flat terrain with small rocks and occasional obstacles. During operations in these conditions, onboard position estimates using an inertial measurement unit and wheel encoders achieved well within a design goal of a maximum 10% error. However, the rovers were also driven on slippery slopes with inclines up to 31 degrees, requiring the use of visual odometry to maintain accurate onboard position estimates. The MER visual odometry system compares stereo images taken by the rovers' cameras to compute updates to the 6-DOF rover pose (x, y, z, roll, pitch, yaw) using a maximum likelihood estimator. It has been used during the first year of operations on Mars (Cheng et al., 2005). These observations have provided valuable insights into the composition and history of the Martian surface. In figure 3.4 shows the difference between the low-resolution imagery of Viking orbiter mission (A) in compression with the high-resolution Mars Orbiter Camera (MOC) image (Victor R. Baker, 2001).

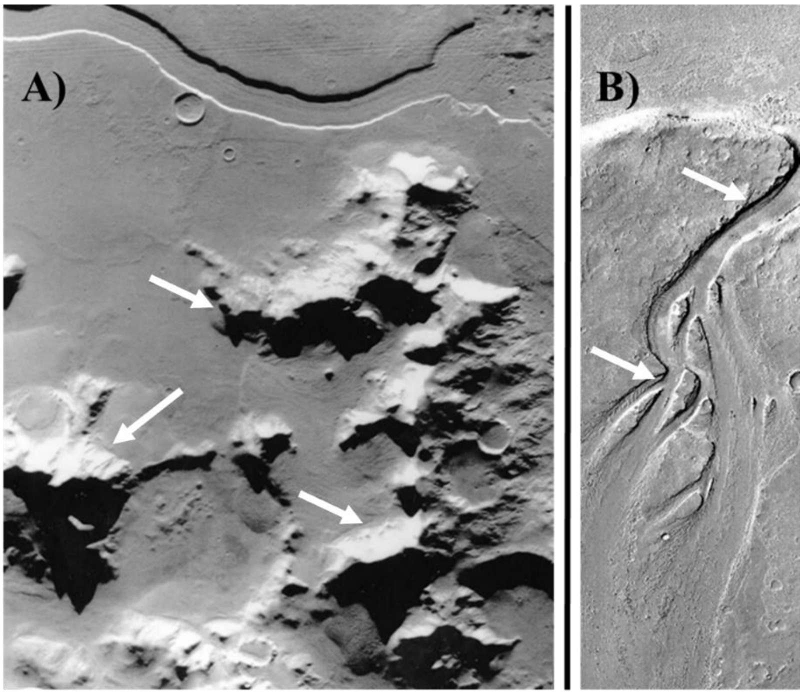

Figure 3.4: A) Glaciated terrain east of Hellas Planitia, at latitude 427 S, longitude 2527 W. This image from a Viking orbiter mission shows a scene about 1802140 km2. B) High-resolution Mars Orbiter Camera image of a fluvial channel system at latitude 7.97N, longitude 205.87 W. The scene shows an area with 4 km across (Victor R. Baker, 2001).

One key development in mapping techniques has been the use of high-resolution imaging and spectroscopy to study the surface of Mars in greater detail. For example, the Mars Reconnaissance Orbiter, which was launched in 2005, is equipped with a camera called the High-Resolution Imaging Science Experiment (HiRISE), which is capable of producing detailed images of the Martian surface with resolutions down to 25 cm/pixel. The HiRISE camera features a large primary mirror and a focal plane system that can acquire images with a high volume of data in a short period of time. It will provide detailed images of approximately 1% of the Martian surface during a two-year primary science phase, with a focus on acquiring approximately 1000 stereo pairs for topographic measurements. HiRISE will support the exploration of Mars by locating and characterizing past and potential landing sites, as well as investigating various geological and atmospheric processes on the planet. An internet website will allow users to suggest HiRISE targets on Mars and access the data collected (McEwen et al., 2007). This has enabled the mapping of features on the surface at scales that were previously unimaginable and has provided valuable insights into the geology and geomorphology of the planet.

In addition, the Thermal Emission Imaging System (THEMIS) is a camera on the Mars Odyssey spacecraft that captures images of the surface of Mars in the infrared (IR) wavelength range. THEMIS-IR is 100-m resolution thermal infrared images of Mars, which were used to identify four definitive and three probable rayed craters. The THEMIS IR mosaic is a composite image created using multiple individual images captured by the THEMIS camera, which are combined to create a detailed map of the surface of Mars. These craters are characterized by a distinct thermal contrast with their surroundings. Martian rays are typically greater than hundreds of kilometres in length and consist of densely clustered secondary craters and are thought to be a physical manifestation of high-velocity ejecta. The mechanism of spallation, which involves the ejection of meteorites from Mars due to low-shock compression, is currently the favoured explanation for the formation of Martian rays. The presence of these rayed craters suggests that they may be the most likely source craters for Martian meteorites (Tornabene et al., 2006). These images are useful for studying the geology and geomorphology of Mars, as they can reveal details about the mineralogy and temperature of the surface. THEMIS IR images are also used to identify and map surface features such as valleys, craters, and cliffs, and to study the distribution and abundance of water-related minerals on the planet. THEMIS IR mosaics have been used to create detailed maps of the surface of Mars and to study the geology and geomorphology of the planet in greater detail.

Finally, The Context Camera (CTX) is a high-resolution camera on the Mars Reconnaissance Orbiter (MRO) spacecraft that provides context images of the surface of Mars at a resolution of 6 meters per pixel. These images are used to plan and interpret observations made by other instruments on the MRO and to identify and map surface features such as valleys and craters. The CTX has a wide field of view and can capture images of large, complex features such as valleys. It has produced several mosaic images of the surface of Mars, which show the entire surface at a resolution of 6 meters per pixel and can be used to study the geology and geomorphology of Mars and identify surface features such as valleys. The CTX is operated by a team led by Malin Space Science Systems and the MRO Mars Colour Imager team and has been allocated 12% of the total MRO data return for the nominal mission (Malin et al., 2007). These images are used to help plan and interpret observations made by other instruments on the MRO, as well as to identify and map surface features such as valleys, craters, and other geomorphic features. The CTX can acquire images of a swath of ground that is 30 kilometers (km) wide, which allows it to cover a large area of the surface of Mars in a single image. It also has a wide field of view, which allows it to capture images of large, complex features such as valleys. These mosaic images can be used to study the geology and geomorphology of Mars and to identify and map surface features such as valleys and other geomorphic features.

Overall, the development of more advanced mapping techniques has greatly enhanced our understanding of Mars and the processes that have shaped its surface. These techniques will continue to play a key role in future exploration efforts on the planet.

3.2.3 key findings from previous valley mapping studies

Previous valley mapping studies on Mars have made a number of key findings. These include the identification of seven rayed craters using thermal infrared images from the Mars Odyssey Thermal Emission Imaging System (THEMIS), which are thought to be formed by high-velocity ejecta resulting from meteorite impacts. These rayed craters are young geomorphic features and are typically hundreds of kilometers in length, consisting of numerous densely clustered secondary craters (Tornabene et al., 2006). They are considered to be the most likely source craters for Martian meteorites. Other key findings include the use of the Context Camera (CTX) on the Mars Reconnaissance Orbiter (MRO) to provide context images for data acquired by other MRO instruments, observe features of interest to NASA's Mars Exploration Program, and conduct a scientific investigation of geologic, geomorphic, and meteorological processes on Mars (Malin et al., 2007). The Mars Exploration Rovers (MER) have also demonstrated a robotic Visual Odometry capability, which provides accurate knowledge of the rover's position and enables it to autonomously detect and compensate for any unforeseen slip encountered during a drive. Finally, the High-Resolution Imaging Science Experiment (HiRISE) camera on MRO has provided detailed images covering approximately 1% of the Martian surface, enabling the investigation of processes such as cratering, volcanism, tectonism, hydrology, sedimentary processes, and landscape evolution (McEwen et al., 2007).

Application of these mapping campaigns are utilized to provide details about the presence of valleys on Mars, including both smaller valleys and larger valleys known as outflow channels, suggests that water has played a significant role in the geologic history of the planet. The size, shape, and other characteristics of valleys on Mars can provide clues about the nature and history of water on the planet, including the presence of liquid water, the role of erosion and other processes in shaping the landscape, and the climate conditions that may have existed on Mars in the past. Mapping studies of valleys on Mars have used a variety of techniques, including imaging data from spacecraft, topographic data from instruments such as laser altimeters, and modelling and simulation to better understand the formation and evolution of valleys on the planet. Some previous valley mapping studies have suggested that the presence of valleys on Mars may be related to the presence of underground aquifers or other water-bearing features, while others have proposed alternative explanations for the formation of valleys on the planet.

3.3 Regional paleohydrological studies and modelling

Regional paleohydrological studies involve the examination of the past hydrological conditions of a region or area, typically through the analysis of geological and other physical evidence such as sedimentary rocks, landforms, and geochemical indicators. It is important for understanding the history and evolution of water on Mars and can provide insights into the planet's past climate, geology, and potential habitability. Modelling is often used in conjunction with paleohydrological studies to simulate and predict the behaviour of water under different conditions and to test hypotheses about the past water cycle on Mars. These studies and models can be used to inform future exploration and research efforts on the planet.

3.3.1 Overview of studies that have examined the hydrological history of specific regions on Mars

There have been numerous studies that have focused on the hydrological history of specific regions on Mars. These studies have used a variety of methods, including analysis of surface features and geomorphology, imaging and spectroscopy data, and modeling, to examine the presence and distribution of water in these regions in the past. Some key findings from these studies include the identification of past lakes and oceans, the presence of fluvial and glacial features, and the potential for underground water reservoirs. These studies have also provided insights into the environmental conditions and climatic history of Mars and have helped to inform our understanding of the planet's evolution and habitability (Clifford, 1993; Head et al., 2022).

One of the remarkable hypotheses that many scientists believe, Mars had a climate that was warmer and had more water, with a thick atmosphere during the Noachian Era. This was caused by strong volcanic activity on the planet, which created a greenhouse effect that was powerful enough to increase the temperature on Mars (Bouley et al., 2016). However, the hypothesis of a warm and wet Noachian Era has also been challenged by observations of valleys on Mars that maintain their width downstream, contrary to what happens on Earth, where valleys tend to become wider and less deep downstream. These valleys also have shallow tributaries with abrupt terminations and U-shaped cross sections, which are more characteristic of structures formed by basal sapping. This suggests that the valleys on Mars may have formed through the melting of ground ice rather than through the flow of liquid water. Further research is needed to better understand the hydrological history of specific regions on Mars (Fastook & Head, 2015).

3.3.2 Fluvial Systems

Evidence of past water flow on the surface of Mars has been observed through various features, including valley networks, longitudinal valleys, outflow channels, and valleys on volcanoes, as well as open and closed basin lakes (Erkeling et al., 2010; Gulick & Baker, 1990). It is believed that during the Noachian Era, Mars had a warmer and wetter climate due to intense volcanic activity, which led to a thicker atmosphere and greenhouse effect (Grotzinger et al., 2014). However, the hypothesis of a warm and wet Noachian has been questioned by observations of valleys with characteristics more consistent with formation through basal sapping, as well as the presence of cold-based glaciers and lobate debris aprons (Gulick & Baker, 1990). These findings suggest the potential for a range of water-related processes on Mars, including the presence of liquid water, ice, and frost. Further research is needed to fully understand the hydrological history of Mars.

One the recent effort to generate a global map of valley networks on Mars has done in 2009. A paper presents a computer-generated global map of valley networks (VN) on Mars and provides evidence for a warmer and wetter early Mars. The authors claim that the available global map of VN was incomplete and outdated because it based on Viking images. Their new map was created using a computer algorithm that analysed topographic data and identified valleys by their morphologic signature. In particular, THEMIS daytime IR data and MEGDR DEM with spatial resolution of 128 pixels/degree or about 463 m/pixel at the equator were the main two datasets for this project. The new map showed an increase in total VN length and a pattern of dissection density that suggests precipitation-fed runoff erosion as the primary mechanism of valley formation. The highest values of dissection density were found in the northern Terra Cimmeria and the Margaritifer Terra, with an average value of 0.062 km^-1, only 2.6 times lower than the value measured on Earth. The pattern of dissection is interpreted in terms of climate controlling factors (Luo & Stepinski, 2009).

Then, a study has been conducted to update the global map of Martian valley networks and examine their implications for the climate and hydrologic processes on the planet. Using higher-resolution data sets. These data sets including visible, infra-red, and topographic data were collected by NASA and the European Space Agency.

The study used the Mars Orbiter Laser Altimeter (MOLA) for high-resolution topographic data and the Thermal Emission Imaging System (THEMIS) for visible and infrared data (Hynek et al., 2010). By combining these data sets, the study was able to manually remap valleys on a global scale and identify more than eight times as many valleys as previously recorded.

The new data revealed characteristics of sustained precipitation and surface runoff indicating that groundwater processes or a transient steam atmosphere generated by impacts played, at most, a minor role. They argue that the impact hypothesis is inconsistent with the observations, particularly the inferred age of the majority of valleys. They also note that the extent of dissection and integration of networks implies long-lived surface water, and it is unclear how short-lived transient impact-generated atmospheres could produce the geological observations. The authors suggest that volcanic outgassing could have been the source of volatiles, which could have provided a substantial and long-lived atmosphere around 3.8 to 3.6 Ga ago that supported warm enough temperatures for valley formation to occur (Hynek et al., 2010).

The study found that there are more than eight times as many valleys on the surface than previously thought, and drainage densities are on average higher by a factor of 2. They also found that regions previously thought to be undissected have significant incision by fluvial processes. Most of these systems seem to have formed around the Noachian-Hesperian boundary (3.8-3.6 billion years ago). These findings imply that Mars had a long-lived period or periods of mild conditions towards the end of the Noachian epoch that supported a hydrologic cycle and potentially a biosphere, providing valuable insights into the potential for water and life on Mars. And most Martian valleys were likely formed by long-lived surface runoff from precipitation (Hynek et al., 2010). figure 3.5 presents two illustrations of the variations between the two methods. Both methods identified many of the same significant valleys, however, the authors identified many more valleys in total because the smaller valleys they found in the THEMIS and MOLA data sets may not always be noticeable in the MOLA data only used by Luo and Stepinski in 2009. This led to much longer overall valley lengths (1.68 and 2.65 times that of Luo and Stepinski, 2009), which in turn led to higher drain age densities (Hynek et al., 2010).

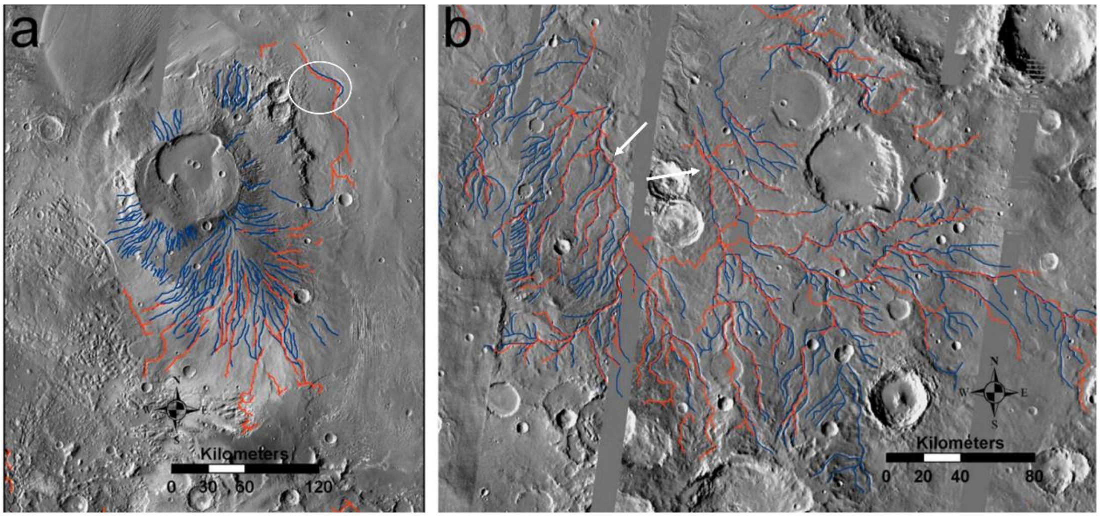

Figure 3.5: Comparisons between the manual mapping in THEMIS daylight IR and MOLA data with the automatic valley discovery by Luo and Stepinski (2009; orange) and Hynek work; blue). (a) The roughly centered Apolli-naris Patera (175°E, 9°S). (b) Valleys at 48°E and 9°N (Hynek et al., 2010).

Recently, a group of scientists from Italy and France present a detailed global map of Martian valleys, classified according to their morphology, using HEMIS daytime IR and/or CTX images, plus topographic MOLA data within QGIS software. The data set includes all valleys longer than 20 km. By combining topographic information with higher quality image data, the authors were able to map these structures at a finer scale, discovering new small valleys and more tributaries for several systems. The total length of the mapped valleys was 773,559 km, with valley networks covering 69% of this distance. The authors also estimated the age of the valleys, finding that 94% of the mapped valleys have a maximum age consistent with an origin in the Noachian period, 4% have a maximum age in the Hesperian period, and 2% have a maximum age in the Amazonian period. The total eroded volume of the mapped valley networks was estimated to be 3 x 10^14 m^3, which is in good agreement with previous estimates (Alemanno et al., 2018). The authors plan to perform further analyses of the correlation between the valleys' maximum ages and their eroded volume, and to compare their data set with other data sets of the surface of Mars in order to better understand the origin and potential habitability of the planet.

Last but not least, researchers used discordance analysis on a high-resolution valley network map of Mars to examine the effects of spatial scale. This paper presents a new approach to analyse the relationship between the orientation of valleys on Mars and the surface slope direction at different spatial scales. The study uses high-resolution images (HRSC images at a resolution of ~15 to 25 m per pixel, CTX images at a resolution of ~5 m per pixel and MOLA DEM) to manually map valleys and inverted channels in a latitudinal strip from pole to pole. The results show an increase in the density of valleys compared to previous maps, and a clear effect of scale on the conformity between valley orientation and surface slope direction. The authors find that only about 38% of valleys display conformity with topography and attribute the high discordance to a combination of valley immaturity, paleolake outburst, and possibly subglacial origin of some valley networks. The study suggests that a discordance analysis is an important step in any hydrodynamic analysis that relies on topographic information (Bahia et al., 2022).

These findings have significant implications for understanding the fluvial systems on mars, the potential habitability of Mars and the processes that shaped its surface. More hypothesis explaining the origin of these valleys is discussed in the following section.

3.3.3 Valley formation

There are several hypotheses that explain the origin of valley networks on mars. Valley formation on Mars is thought to have been caused by the erosion of surface materials by flowing water. The valleys on Mars are typically found in ancient terrains, such as the Noachian and Hesperian terrains, which are thought to be the oldest terrains on the planet. These terrains have a high density of valleys, and the valleys are found in a variety of different orientations, including east-west, north-south, and at various (Carr, 2012).

A study has conducted between two universities in Canada, University of British Columbia and University of Western Ontario, to study the valley formation on early mars. According to the authors, subglacial and fluvial erosion have contributed in valley formation on early mars. valley networks on Mars were formed by a combination of processes including fluvial, groundwater sapping, glacial, and subglacial erosion. The study uses a dataset of 10,276 individual valleys and employs a principal component analysis to classify the valleys based on their morphologies. The results of the analysis indicate that the majority of the valleys were likely formed by fluvial or subglacial erosion, supporting the hypothesis that there were ice sheets on the southern highlands of Mars during the time of valley network formation. The study also suggests that this supports the Late Noachian Icy Highlands (LNIH) climate model for early Mars (Grau Galofre et al., 2020).

The authors segment the valley datasets with six morphometric parameters to classify them based on their similarity. They used physical models of erosion by fluvial, glacial, sapping, and subglacial processes to create synthetic valley networks (SVNs) and used a principal component analysis (PCA) to understand the morphological variability of the Martian valley networks. The results of the PCA showed that most valleys best correspond to either fluvial or subglacial incision. The authors also found that 14 valley networks are best explained with fluvial erosion, 22 with subglacial erosion, 9 with glacial erosion and 3 with sapping erosion. And 18 valley networks were statistically indistinct and couldn't be classified by the PCA used (Grau Galofre et al., 2020).

Another study suggests that there is a causal link between volcanic outgassing, build-up of atmospheric pressure, and precipitation during the formation of the Tharsis bulge, the largest volcano-tectonic center on Mars, which occurred during the Noachian epoch (>3.7 billion years ago). This incident happened due to the climate change in that period. The associated transfer of mass, energy, and release of volatiles from the mantle had implications for the planet's evolution, including its climate, surface environment, and mantle dynamics. The valley networks are thought to have formed during this period, not after the emplacement of most of the Tharsis load as previously thought. This scenario is more plausible as it takes into account the early degassing and progressive depletion of volatiles in the mantle source. The study concludes by suggesting that the calculated pre-Tharsis topographic map of Mars provides a framework within which to examine the first billion years of its geological history (Bouley et al., 2016). The study also suggests that the Tharsis bulge formation caused reorientation of the planet's spin axis and that this event may have had global implications, such as affecting the distribution of surface landforms and the lack of valley networks between 30° S and 60° S from the Argyre basin to the east of the Hellas basin (Bouley et al., 2016).

Next, valley formation on Mars can also happen as a result of tectonic activity, specifically due to faulting and fracturing of the Martian surface. One study suggests that valley formation peaked during the Noachian and declined during the Hesperian and Amazonian, and is thought to have been caused by hydrothermal, deformational, and seismic-induced processes (Dohm & Tanakaa, 1999) .Tectonic activity can cause the surface to crack and create channels for water or other fluids to flow through, eroding the land and forming valleys.

Another theory for valley formation on Mars is a result of impact cratering. When an asteroid or comet impacts the surface of Mars, the energy of the impact can cause the ground to fracture and collapse, creating a depression in the surface known as a crater. The walls of the crater can also be steep, creating a distinctive circular rim around the crater. These craters can also create valleys and channels in the surrounding terrain (Brakenridge et al., 1985). The force of the impact can also cause the ground to crack and collapse, forming valleys and channels that radiate out from the crater. A study provides an overview of paleolakes found in impact craters on Mars, outlining their classification into three fluviolacustrine systems, as well as their hydrogeologic implications and potential for life to develop. It also presents a catalog of data for each of the studied impact crater lakes, including aerographic, physical, and physiographic information (Cabrol & Grin, 1999).

Furthermore, there are studies that compare the valley network on mas with the terrestrial's valleys. The valleys on Mars are typically larger than those found on Earth, and they can be several kilometers wide and hundreds of kilometers long. As, their widths range from less than 1 km to 10 km and lengths can be from less than 5 km to almost 1,000 km. The valleys on Mars also have a characteristic V-shape, which is similar to valleys formed by water erosion on Earth (Mars Channel Working Group, 1983; Penido et al., 2013). Scientists believe that the valleys on Mars were formed by water erosion because they have the same characteristics as valleys formed by water on Earth, and they are found in areas where there is evidence of past water activity (Penido et al., 2013). it's important to note that the formation of valleys on Mars might have been a result of a combination of processes, such as erosion due to flowing water, tectonics, and impact cratering.

3.3.4 Modelling approaches used to reconstruct past water flow patterns

There are several different modeling approaches that can be used to reconstruct past water flow patterns on Mars. Some examples include:

3.3.4.1 Hydrological models

These models simulate the movement of water through a landscape, taking into account factors such as precipitation, evaporation, and surface runoff. They can be used to reconstruct the flow patterns of ancient river systems and estimate the volume of water that flowed through them. One study discussed the formation of Kasei Valles, one of the largest outflow channel systems on Mars, and the evidence for water flow on the planet's surface. It is generally accepted that outflow channels formed by catastrophic fluvial activity with peak discharges of 109-1010 m3/s. However, the study finds that calculated maximum discharges for Kasei Valles, based on elevation data from the Mars Orbiter Laser Altimeter (MOLA), are much lower than previously estimated at 2-4 orders of magnitude lower (8 x 10^4-2 x 10^7 m3/s). The study also presents morphological evidence from Mars Orbiter Camera (MOC) images that supports these lower flow rates and suggests that the system formed by several fluvial episodes operating over a geologically significant period of time (Williams et al., 2000). Another study uses global-scale hydrological models to investigate the temporal evolution of Martian groundwater hydrology during the Noachian and early Hesperian epochs. The results suggest that the more active water cycle in the Noachian was caused by a greater total water inventory and high precipitation rates. The shift in the late Noachian is attributed to a net loss of water due to impact and solar wind erosion of the atmosphere, which caused the water table to retreat deep beneath the surface (Andrews-Hanna & Lewis, 2011).

3.3.4.1.1 Climate models

These models simulate the past climate of Mars and can be used to estimate precipitation and temperature patterns, which can in turn be used to infer the likelihood of past water flow. These models use data from a variety of sources such as satellite measurements, observations from rovers and landers, and measurements of the planet's geology and geomorphology. They take into account factors such as solar radiation, atmospheric circulation, precipitation, erosion, and surface temperature to reconstruct the past climate and water flow patterns (Fastook & Head, 2015). A paper, by Lunar and Planetary Institute, Houston in Texas, presents a hydrological model that considers the response of a water-rich Mars to climate change and the physical and thermal evolution of its crust. It argues that under the climatic conditions that have prevailed on Mars, the thermal instability of ground ice at low- to mid-latitudes has led to a net atmospheric transport of water from the equatorial region to the poles. The paper concludes that subsurface transport of water may have played an important role in the geomorphic evolution of the Martian surface and the long-term cycling of water between the atmosphere, polar caps, and near-surface crust (Clifford, 1993).

Here, some examples of climate models used to study water flow patterns on Mars include the Mars Climate Database (MCD), the Mars Regional Atmospheric Modelling System (MRAMS), and Early Mars Climate Models (Haberle, 1998; Millour et al., 2018; Rafkin et al., 2001). These models are used to simulate past climate conditions and water flow patterns, and to help understand the geomorphological features and the history of water on Mars.

3.3.4.1.2 Geomorphological models

These models use information about the current topography and geology of Mars to infer the processes that shaped it in the past. For example, if a channel shows signs of erosion, a geomorphological model can be used to estimate the volume of water that flowed through it. These models use data from satellite imagery and other remote sensing techniques, as well as field observations and laboratory analyses, to study the geomorphology of Martian landscapes. They can provide insight into the past processes that shaped the Martian surface, such as erosion, sedimentation, and tectonics, as well as the role of water in these processes (Norini et al., 2016). For example, geomorphological models can be used to study the formation of valley networks, channels, and other features that are indicative of past water flow, as well as to reconstruct the extent and duration of past water coverage.

In one study that used geomorphological model to map geomorphological and geological features, they study presents a Geographic Information System (GIS) algorithm for the semi-automated detection of alluvial fans from Digital Elevation

Models (DEMs). The algorithm combines spatial analysis procedures to generate maps of alluvial fans and their upstream source drainage and watersheds. It has been tested in areas with well-known alluvial fans and has been found to have high-accuracy mapping of the fan apexes and correct delineation of fan deposits (Norini et al., 2016). Possible applications of this algorithm include systematic survey of alluvial fans for geologic hazard assessment, studies on the evolution of climate, analysis of continental sedimentary environments, understanding of the interplay between endogenous dynamics and exogenous processes, and the evaluation of natural resources.

3.3.4.1.3 Numerical models

These models use mathematical equations to simulate the physical processes that shape the Martian surface. Numerical models can be used to simulate the flow of water through a landscape and can be used to estimate the timing and magnitude of past water flow events. These also known as computational models which are mathematical representations of physical systems that can be used to simulate and predict the behaviour of those systems. In the context of reconstructing past water flow patterns on Mars, numerical models can be used to simulate and analyse the hydrological processes and systems that may have contributed to the formation of features such as valley networks, outflow channels, and other evidence of water flow on the Martian surface. These models can include simulations of atmospheric processes, groundwater flow, and surface water flow, as well as the interactions between these different systems (Turbet et al., 2020). They can also incorporate data from spacecraft observations and other measurements to improve the accuracy of the simulations. It means that, numerical models used to reconstruct past water flow patterns on Mars include hydrological models, ice sheet models, and climate models.

There is a study that investigates the formation of the Noachian valley networks by using numerical model. The paper discusses the use of a hierarchy of numerical models to explore the environmental effects of very large bolide impacts on early Mars. The results show that the largest impact events recorded on Mars are characterized by a short impact-induced warm period, a low amount of hydrological cycling of water, deluge-style precipitation, and precipitation patterns that are uncorrelated with the observed regions of valley networks.

The study suggests that the impact-induced stable runaway greenhouse state is not achievable if convection and water vapor condensation processes are considered. The study also finds that large bolide impacts can produce a strong thermal anomaly in the mantle of Mars that can survive and propagate for tens of millions of years. However, this thermal anomaly is largely insufficient to keep the Martian surface above the melting point of water. The study concludes that the largest impact events are unlikely to be the direct cause of the formation of the Noachian valley networks (Turbet et al., 2020).

All these models are complementary, and the results from one model can be used to validate or constrain the results from another. It is important to note that the results from any one model must be compared to the geological context and other available data to confirm the hypothesis.

4 Data and Methodology

This chapter provides a description of the dataset used in the thesis as well as the study area. The methodology illustrates the process to update the valley network and the basins dataset by performing algorithmic and manual delineation.

The study area for this diploma thesis is one of the southern valleys on Mars. This valley is chosen for its potential to provide insight into the hydrological history of the planet and its past environments. The valley network will be characterized using high-resolution datasets such as MOLA-HRSC DEM, and CTX Mosaic, which will provide a more accurate depiction of the valley network and its features compared to previous mapping campaigns. The focus of the study will be on the subbasins that empty into northern lowlands, which will be mapped and characterized using algorithmic and manual delineation methods. The determination of hydrological proxies such as valley width, incision depth, subbasin area, and eroded material will provide a better understanding of the processes that shaped the valley network and its surroundings.

The valley network and subbasins were analysed to determine the relative contributions of different processes to the overall outflow from the watershed. This helped to reconstruct the hydrologically correct Noachian valley network and provided new insights into the early geological and hydrological history of Mars. The study also provided valuable information for future hydrological modelling efforts on Mars, as well as for comparative studies of valley networks on other planetary bodies.

4.1 Study area

4.1.1 Location

The study area in this thesis is one of the equatorial valleys on the southern hemisphere of Mars. The exact location of the valley outlet is 5.2169 S, 132.8592 E, and it is situated in the northern lowlands. As shown in figure 4.1, the valley network is within the red square extent and the blue star shape indicates the location of the valley outlet. The subbasin which includes the valley network is laid Middle Noachian highland unit. According to USGS Scientific Investigations Map the study area is in one of the highland units. The topography of this unit is characterized as uneven to rolling, with high-relief outcrops that extend hundreds to thousands of kilometers. These outcrops are commonly layered in crater walls and may be hundreds of meters to over a kilometer thick. The presence of undifferentiated impact, volcanic, fluvial, and basin materials suggests that a variety of geological processes have contributed to the formation and evolution of the area. This highland unit is extensive in the equatorial to southern highlands. In some areas, it superposes while elsewhere it is overlain with several other Martian unit. The coordinate of its centre is -47.17° N and 349.33° E (Tanaka et al., 2014a).

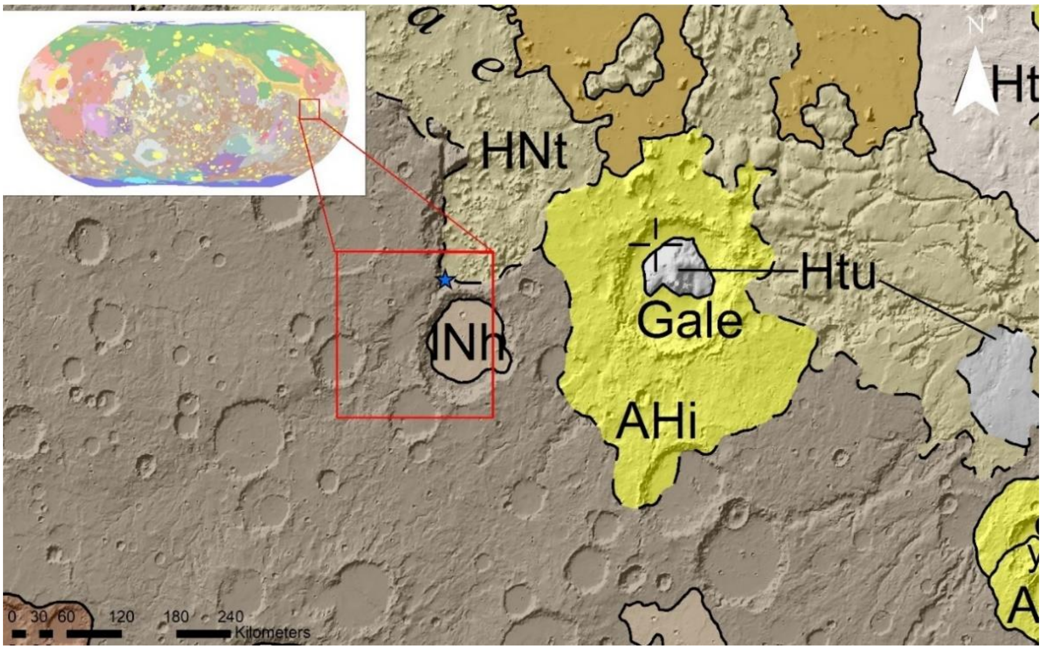

Figure 4.1: The study area exact location. This is geological map of mars not true colour map. The map layers are adopted from Tanaka map sheet (Tanaka et al., 2014a). The figure is created by ArcGIS to show the location of outlet illustrated by the blue star and network is within the extent of the red square. Also, the Gale crater is with AHi geological unit.

The Middle Noachian highland unit (mNh) dominates highland regions in areas where the Early Noachian highland unit (eNh) is scarce or absent. This unit consists of a higher proportion of sedimentary and volcanic materials, which may reflect a climate conducive to precipitation and runoff. The highlands contain at least 15 Middle Noachian impact basins larger than 150 km in diameter, including the Argyre and Isidis basins. The Isidis basin is located along the highland/lowland transition(Tanaka et al., 2014b). Although the study area is not within these basins, it is also located along the highland/lowland transition.

While the Middle Noachian highland unit found almost in all southern Mars land, The boundary of the study area in this thesis is defined as follows:

- 11.16 degrees South latitude and 128.25 degrees East longitude
- 11.20 degrees South latitude and 130.48 degrees East longitude
- 4.90 degrees South latitude and 132.15 degrees East longitude
- 5.46 degrees South latitude and 133.21 degrees East longitude.

This area represents the focus of the research and will be the main region of investigation for the analysis of the Martian valley networks. Specific coordinates were chosen to encompass the target area of interest and to ensure that the data collected within this boundary accurately represents the characteristics of the Martian valleys in this region.

Although the valley network is located within the Middle Noachian highland, the valley's outlet empties in Hesperian and Noachian transition (HNt). This is one of the transition units that has a centre of latitude 13.38° N., longitude 116.70° E. This geological unit is characterized by plains-forming deposits that are undulating to moderately rugged, with scattered low knobs and mesas of Noachian highland material. This unit borders the boundary between the highlands and lowlands in the Arcadia and southwestern Amazonis Planitiae regions and the Acidalia Mensa. The unit has a moderate density of wrinkle ridges and may contain mass-wasting, fluvial or lacustrine sedimentary materials, and possibly volcanic rocks in some places (Tanaka et al., 2014a).

4.1.2 Borders

The study area's valley network is bordered by several relevant geological units. The valley itself is located in Middle Noachian highland unit and empties in Hesperian and Noachian transition unit, but some interesting geological units as well as fractures are found near the study area. To illustrate, there is a large crater (25 km Diameter) to the east side of the valley which is classified as Late Noachian highland unit (LNh). LNh is a layer of Martian surface material that is characterized by being mostly plains-forming, although it can be rugged in places. It is estimated to be hundreds of meters thick. This unit is commonly found in highland depressions as well as in higher elevation parts of the lowlands. Also, this unit is composed of undifferentiated impact, volcanic, fluvial as well as can be locally marked by grabens or wrinkle ridges (Tanaka et al., 2014a).

Further east, Gale crater -as shown in figure 4.2 is found in an area within the Amazonian and Hesperian impact unit (Tanaka et al., 2014a). The center of the Gale craters is approximately 240 km from the center of the area of interest. One of the valleys that runs through the Gale crater is Farah valley. It is thought to be one of the most recent valleys on Mars and is believed to have formed during the Late Noachian epoch (Palucis et al., 2016).

In addition, the area of interest is part of the dichotomy boundary which separates the Martian northern lowlands from the southern highlands. The dichotomy boundary is characterized by a sudden change in elevation, with the northern lowlands being roughly 2-3 kilometers lower than the southern highlands. This boundary is thought to have been formed by a large impact event, which created the large northern impact basin and led to the formation of the dichotomy boundary (Watters et al., 2007). Moreover, the study area is within the Terra Cimmeria region which is a large region located in the highlands of Mars, near the Martian equator. It is characterized by its rugged terrain which probably formed as a result of volcanic activity and subsequent erosion (Irwin & Howard, 2002). This region is of interest to scientists because it may contain evidence of early Mars' geological and climatic history and could help to shed light on the processes that have shaped the Martian surface over time.

4.1.3 Physio-geographical characteristics

To describe the physio-geographical characteristic of the area, some spatial analysis has been done to MOLA-DEM data using ArcGIS software. Mainly, the CTX data is used to determine the different geomorphological characteristic in the study area. Other data and online platforms maybe used to enhance the quality of the analysis or check the computability of the findings.

The geological morphologies of the study area are diverse as it contains different landforms including craters, lakes, and ridges. All of them have an influence on shaping the valley network within the area of interest. in addition, there are some evidences indicting presence of ground water. Thus, the diversity of geomorphological landforms of the study area provides a rich source of information about the geological history and evolution of Mars.

The study area, as determined by MOLA-DEM data, is located within the highland region of Mars, which is reflected by its mean elevation of 794 m. Despite being situated within a relatively uniform terrain, the study area exhibits significant topographic variability, with a range of elevations spanning from -2265 m to 3021 m. This range is attributed to a combination of factors, such as the presence of craters and valleys, as well as other landforms. The low elevation regions are primarily found in the vicinity of craters and valleys, while the high elevation regions can be found on topographic features such as mesas, plateaus, and ridges. The standard deviation of the elevation is 1318.9 m, indicating that the elevation of the area varies from the mean elevation and the distribution of the elevation data is left skewed. This variability highlights the diverse and dynamic nature of the Martian landscape and its ongoing evolution over time. In figure 4.2, A histogram of elevations of the study area from MOLA-DEM.

The slope of the study area, as determined by the MOLA-DEM data, reveals interesting information about the topographical features of the area. The highest slope found in the study area is 32°, which is quite steep, and the average slope is approximately 3° with a standard deviation of 3.37°. This distribution of slopes is considered right skewed, meaning that there is a higher concentration of slopes towards low land slopes and relatively fewer slopes at the higher end. The slope of the land is a crucial factor in determining the flow of water on Mars, especially during the middle Noachian epoch when the study area was believed to have a more active hydrological cycle (Andrews-Hanna & Lewis, 2011). The slopes, therefore, play a significant role in shaping the drainage patterns, creating valleys and ridges, and forming other geological morphologies found in the study area.

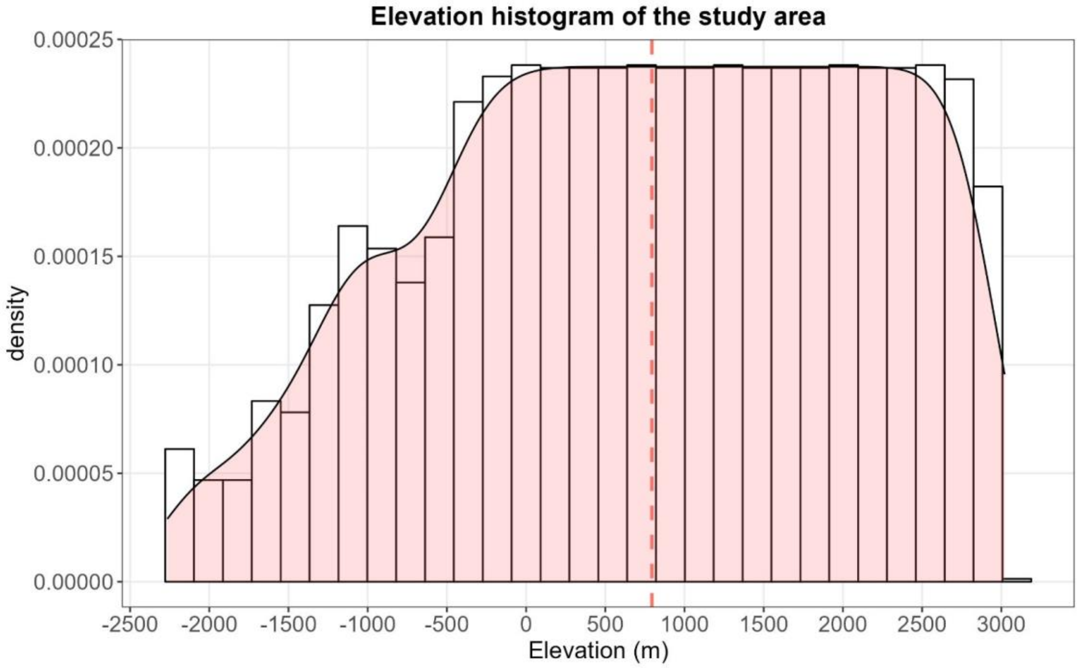

Figure 4.2: Histogram of elevation of the study area. The red dashed line refers to the mean elevation.

The slope of the study area, as determined by the MOLA-DEM data, reveals interesting information about the topographical features of the area. The highest slope found in the study area is 32°, which is quite steep, and the average slope is approximately 3° with a standard deviation of 3.37°. This distribution of slopes is considered right skewed, meaning that there is a higher concentration of slopes towards low land slopes and relatively fewer slopes at the higher end. The slope of the land is a crucial factor in determining the flow of water on Mars, especially during the middle Noachian epoch when the study area was believed to have a more active hydrological cycle (Andrews-Hanna & Lewis, 2011). The slopes, therefore, play a significant role in shaping the drainage patterns, creating valleys and ridges, and forming other geological morphologies found in the study area.

The study area is characterized by a diverse aspect, with the majority of the land oriented towards the network valley or the big craters within the area. This orientation is predominantly towards the east direction, rather than towards the west direction. This orientation of the land is in line with the main valley which drains into the northern lowland region. The aspect of the area could have implications the direction of flowing water on early Mars, particularly during the middle Noachian epoch. These environmental factors could have played a role in shaping the landscape and determining the location of various landforms within the study area.

In figure 4.3, Maps for slope and aspect are shown for the study area. On the left side a map for the aspect of the study area. On the right side a map of the slope if the study area.

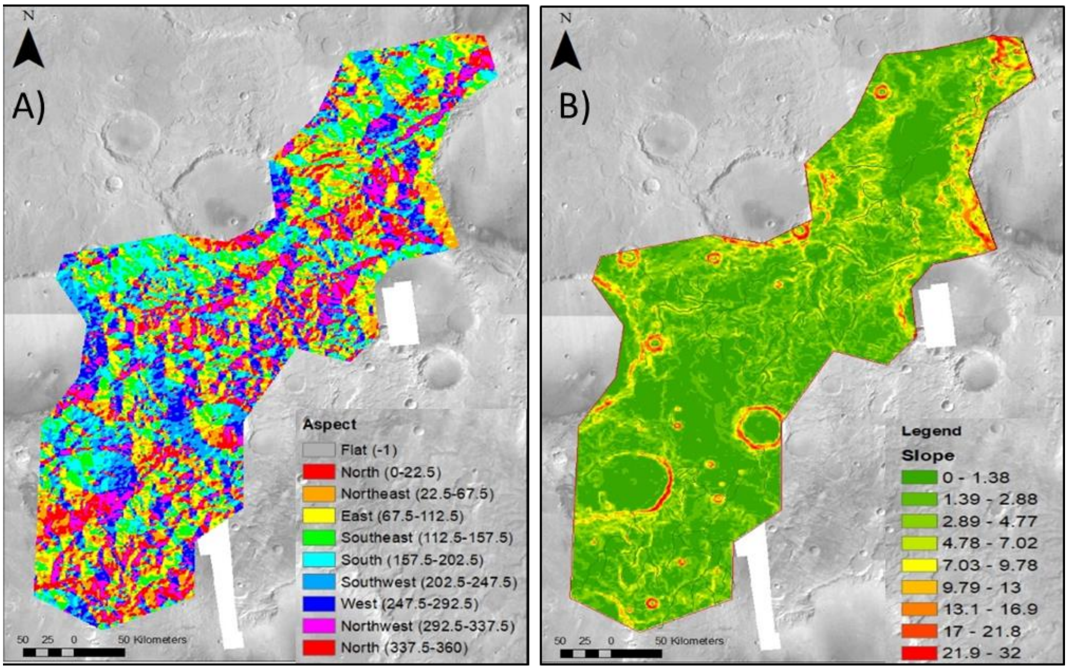

Figure 4.3: Study area: A) aspect of the study area, B) slope of the study area.

4.2 Data extraction and processing

Mapping the valley network of a study area on Mars is a complex task that requires a variety of data sources. One important aspect to consider is that these data may not be readily available and may require registration to access and download. The process of mapping the valley network involves gathering information from different sources, which may come in various formats and projections. For instance, elevation data is critical to this process, and it can be obtained from different sources, such as the Mars Orbiter Laser Altimeter Digital Elevation Model (MOLA-DEM) and the Context Camera (CTX) stereo images.

Apart from elevation data, the most recent valley network for the study area is also needed, which can be found in the database of Martian surface valley network by Alemanno in 2018. High-resolution surface images are also crucial in this process, and the CTX mosaic is an excellent source for these images. While these data are essential to delineate the watershed and map the valley network, there are additional data sources that can be used to validate the findings. For instance, Thermal Emission Imaging System (THEMIS) IR and High-Resolution Imaging Science Experiment (HiRISE) data can be used to validate and confirm the results obtained from the other data sources.

First, MOLA is adjusted to create a digital elevation model (DEM) on Mars with a pixel resolution of 463 meters per pixel. The newly released MOLA DEM version 2 offers even higher pixel resolution, with 200 meters per pixel. Researchers can conveniently obtain the data from the USGS Astrogeology Science Centre website in a .tif format, allowing them to crop the data to fit their specific study area. Once the data is downloaded and processed, the physio-geographical characteristics can be calculated, and essential hydrological functions can be performed.

Second, the Context Camera (CTX) datasets, which are available on various platforms such as NASA, offer crucial data and information for Mars researchers. Currently, these are the highest resolution images for the mars surface. The beta version of the CTX mosaic is a preliminary product generated by the Bruce Murray Laboratory for Planetary Visualization. It includes seam-corrected and seam-mapped mosaic of Mars, rendered at 5.0 m/px using Context Camera (CTX) data from the Mars Reconnaissance Orbiter (MRO). The CTX mosaic beta01 version is available for streaming via the internet and through GIS software as a Web Map Service (WMS) through ESRI. ArcMap users can import it from the website or directly from ArcMap by selecting "Add Data from ArcGIS Online..." and searching for "Mars CTX." QGIS users can download the file that contains a link to the online data. For the majority of uses, this JPEG-compressed version will be adequate (The Murray Lab - A Global CTX Mosaic of Mars, 2018). The CTX mosaic data provides a valuable resource for researchers to analyse the physiographic characteristics and hydrological functions of Mars.

Third, both HiRISE dataset and THEMIS are available online for exploration and downloading. HiRISE (High Resolution Imaging Science Experiment) is a state-of-the-art camera that has been sent to Mars onboard the Mars Reconnaissance Orbiter. This camera is the most powerful camera ever sent to another planet, with the capability of capturing images at a resolution of up to 30 centimeters per pixel. This high-resolution imaging capability has been instrumental in studying the Red Planet and has been useful in selecting landing sites for both robotic and future human exploration missions. Over the past decade, HiRISE has captured several remarkable images, including avalanches in progress, and dark flows that may or may not be briny seeps (HiRISE | About Us: Principal and Co-Investigators, 2022). Then, The Mars Odyssey THEMIS-IR Day Global Mosaic 100m v12 is a thermal map of Mars that represents the daytime infrared (IR) 100 meter/pixel mosaic generated using the Thermal Emission Imaging System (THEMIS). This version, released in 2014 by Arizona State University, has stretched and blended the original values to create a seamless and visually pleasing mosaic. The values in the mosaic are only a representation of daytime temperatures on Mars. This data set is available to the public and can be used for various research purposes.

Fourth, the CTX stereo dataset contains a digital elevation model of the Martian surface, which is available through MarsSI data processing services. After registering a request, the data can be accessed and downloaded. While there are no complete CTX stereo images of the entire Martian surface, processing can be requested for available areas. As part of this project, CTX stereo images are available for the valley network near the outlet at a resolution of 12 meters per pixel, which is four times better than the MOLA-DEM resolution. This highly precise data can be useful for obtaining accurate hydrological proxies such as valley width and incision depth.

In the following table 4.1, summary of the dataset used to accomplish this project. The table describe the variable name, sources of the data, spatial resolution as well as links to access and download the datasets.

Table 4.1: Summary of the dataset used for the project (mapping the valley network). The table contains links to access the data.

Variable	Source	Spatial Resolution	Link
DEM (digital elevation model)	MOLA-DEM (V1, V2)	463 Meter / Pixel (v1) 200 Meter / Pixel (v2)	https://planetarymaps.usgs.gov/mosaic/Mars_MGS_MOLA_DEM_mosaic_global_463m.tif https://planetarymaps.usgs.gov/mosaic/Mars/HRSC_MOLA_Blend/Mars_HRSC_MOLA_BlendDEM_Global_200mp_v2.tif
DEM	CTX stereo	12 Meter/ pixel	https://marssi.univ-lyon1.fr/wiki/Home
Images	CTX	5 Meter / Pixel	http://murray-lab.caltech.edu/CTX/
Images	HiRISE	Up to 30 cm/pixel	https://www.uahirise.org/hiwish/browse
Daytime temperatures	THEMIS-IR	100 meter/pixel	https://planetarymaps.usgs.gov/mosaic/Mars_MO_THEMIS-IR-Day_mosaic_global_100m_v12.tif

Given the complexity of the mapping process, it is important to have a clear understanding of the limitations and potential sources of error associated with each data source. Additionally, it is essential to ensure that all the data is properly integrated, processed, and analysed to produce accurate and reliable results. Ultimately, the process of mapping the valley network in the study area on Mars will provide valuable insights into the planet's geological and hydrological history, as well as inform future hydrological modelling efforts and comparative studies with other planetary bodies.

4.3 Algorithm and manual delineation

Mapping a valley network on Mars is a challenging task that requires the use of various datasets or up-to-date data. Due to the absence of the possibility of conducting field measurements on the Martian surface, it is crucial to rely on digital information that can provide an accurate representation of the topography of the planet. The delineation process of watersheds and valley networks involves two primary approaches. The first approach utilizes automatic tools and algorithms in the context of various packages, such as WhiteBoxtools. This approach has become more common in the last few decades, but the accuracy of these models is not robust, and they cannot be used as standalone outputs for further analysis, which limits their effectiveness in explaining the water history on Mars.

On the other hand, manual delineation of both valleys and watersheds is a time-consuming process, but it is the most reliable method to ensure the accuracy of the data. To enhance the accuracy of the output of the models, a combined approach is used, which benefits from the computational power of these packages and tools and the accuracy of manual delineation. This approach allows for the identification of additional features that may be missed by the automatic tools, and it also provides the opportunity to cross-check and verify the results generated by the algorithms.

4.3.1 Watershed delineation

Watershed delineation is the process of identifying and mapping the boundaries of a watershed or catchment area. This process is crucial in understanding the hydrological processes of the study area, as it allows for the identification of the sources of water and the direction of flow within the watershed. To perform watershed delineation, a variety of data sources can be used such digital elevation models (DEMs). DEMs provide a representation of the elevation of the terrain, which can be used to calculate the flow direction and accumulation of water within a given area.

The process of watershed delineation typically involves several steps, including the pre-processing of data, such as correcting elevation data, followed by the identification of pour points, which are the points where water exits the watershed. Then, a flow direction algorithm is applied to determine the direction of water flow across the terrain, and a flow accumulation algorithm is used to calculate the amount of water flowing through each grid cell. Finally, the watershed boundaries are delineated using algorithms that trace the flow path of water from each pour point to the ridges separating the watersheds.

The delineation of a watershed within a study area is a critical step in hydrological analysis. To accomplish this task, various datasets and software tools are utilized. The MOLA-DEM data, which provides a digital elevation model of the Martian surface, is used in this project for watershed delineation within the study area. The data is loaded into ArcGIS software (version 10.8), with projected coordinate system Equirectangular Mars, for further processing using the WhiteboxTools. This open-source toolset, initiated in 2017, contains numerous functions for hydrological analysis. One of the primary functions used in this project is the "FlowAccumulationFullWorkflow," which can resolve all of the depressions in a DEM. It outputs a breached DEM, an aspect-aligned non-divergent flow pointer, and a flow accumulation raster. To run the watershed function from the same toolset, an input pour points file (outlet) is necessary. The combined use of these datasets and tools provides a good approach for watershed delineation, however, manual retracing to fix the anomalies of the output raster is required.

In order to accurately determine the pour points for the watershed delineation process, high-resolution CTX mosaic images are utilized. These images provide a detailed view of the Martian surface within the study area, allowing for a more precise identification of the best locations for pour points. The pour points are then selected based on careful analysis of the CTX mosaic images in conjunction with the flow accumulation raster and DEM raster. By using these datasets together, it is possible to identify the areas where water is most likely to flow, ensuring that the pour points are placed in the most reasonable locations possible.

Table 1 in the appendices provides precise information on the exact locations of the selected pour points in projected coordinate systems (Equirectangular_Mars) and geographic coordinate systems (GCS_Mars), allowing for easy reference during the analysis process. Overall, the careful selection and precise determination of pour points is crucial to the accurate and effective delineation of watersheds within the study area.

With all of the required inputs ready, the next step is to apply the "watershed" function, which is a crucial tool for the automatic delineation of watersheds within the study area. The pointer file from the previous step and the pour points shapefile are the two inputs needed for this function to run efficiently. By using this function, the tool will be able to create a representation of the watershed for the areas that are emptying into the selected pour points or outlets with the same resolution as the original DEM. This process will be performed automatically, which means that the software will use algorithms to identify the drainage areas for each outlet point, and the resulting watershed raster will be generated as output. The raster will provide a visual representation of the boundaries of flow paths and accumulation of water.

To improve the accuracy of the final output of the watershed delineation, a trial-and-error approach was employed by running the watershed function multiple times. The locations of the pour points were slightly modified with each run to see if there were any significant changes in the resulting watershed boundaries. The purpose of this iterative process was to find the best possible locations for the pour points that would result in the most accurate watershed boundaries. By making slight modifications to the pour point locations and re-running the watershed function, it is applicable to identify any areas where the boundary was not well defined or where it did not match the expected topography. Once satisfactory accuracy of the delineated watersheds is obtained, the final retracing and fixing of the watershed boundaries is performed to produce the final output.

After the completion of watershed delineation, the final step involves retracing and fixing the watershed boundaries manually to ensure accuracy. This step is critical in generating an accurate and reliable representation of the watersheds in the study area. It is recommended to utilize the CTX mosaic images and the MOLA-DEM to ensure that the boundaries are aligned with the surface geology and topology. The polygon shape file generated after this step can be used for further analysis, such as calculating the descriptive statistics for various hydrological proxies, including valley width, incision depth, subbasin area, and eroded material. These statistics can help to draw more robust conclusions about the history of water on Mars. Additionally, by comparing these statistics across different subbasins, it is possible to identify which subbasins have contributed more significantly to the overall outflow and gain a better understanding of the Martian hydrological system.

4.3.2 Valley network delineation

Valley network delineation is a crucial process that involves identifying and mapping the channels of water flow present in a given study area. A plethora of techniques and tools, such as remote sensing data, topographic maps, and field observations, are often employed in this process. However, the current project presents unique challenges, with limited availability of field observation measurements and a lack of high-resolution data (<5 meters per pixel). In such situations, digital elevation models (DEMs) offer a reliable approach to valley network delineation. These models provide a comprehensive, three-dimensional representation of the Martian surface, enabling the identification and mapping of valleys and channels within the area of interest.

Valley network delineation through DEMs can be carried out using various algorithms, each with its own unique features. One of the widely used methods is the flow accumulation algorithm, which calculates the amount of water that would pass through each pixel based on the surrounding terrain's slope and elevation. This method is effective in identifying the main channels of water flow in the landscape and the smaller tributaries that feed into them. However, the reliability and computational efficiency of this approach depend significantly on the resolution of the DEM data used. In the current project, this poses a significant challenge as the available MOLA-DEM data has a low resolution of 463 meters per pixel, limiting the reliability of the results obtained from the flow accumulation algorithm. Despite these challenges, it is still possible to use the available data to obtain valuable insights into the valley network's distribution and morphology, although caution must be taken to account for the lower resolution.

Thus, the utilization of high-resolution images from CTX mosaic (5 meters per pixel) plays a crucial role in the success of this project. These images offer the most superior quality representation of the Martian surface, making them an indispensable tool for valley delineation. With their exceptional level of detail, CTX mosaic images provide a comprehensive view of the morphology of river valleys, as depicted in figure 9. By incorporating these images into the project, we can gain valuable insights into the intricacies of the Martian landscape and achieve a more accurate valley delineation within the study area.

Figure 4.4 provides a detailed view of the study area, specifically focusing on the CTX mosaic images near the outlet of the valley, which empties into the lowland of Mars. This section of the study area is pointed by a blue arrow, indicating the clear depiction of the valley in this region. Furthermore, the green line demarcates the boundary of the area of interest.

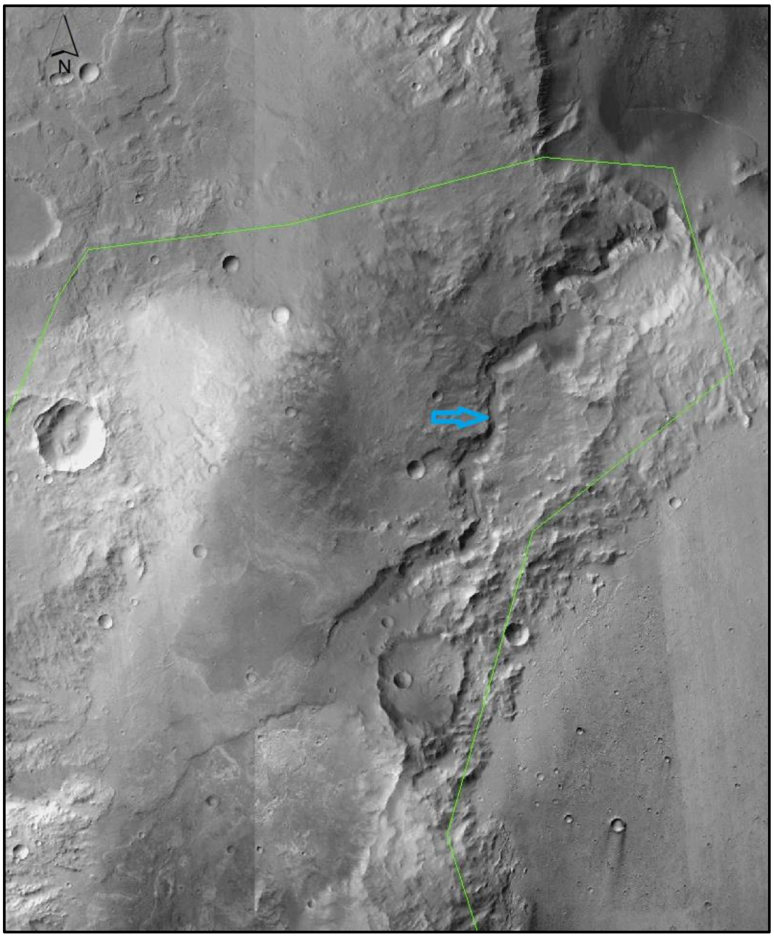

Figure 4.4: CTX mosaic image that show clear details of part of the valley network within the area of interest (The Murray Lab - A Global CTX Mosaic of Mars, 2018)

Now, the delineation of valley networks on the Martian surface within the area of interest requires the utilization of the MOLA-DEM data loaded on ArcGIS, followed by further processes. The output of the "FlowAccumulationFullWorkflow" includes a flow accumulation raster that enables the measurement of the flow of water through each pixel. However, in some areas, this model may produce weak results due to the course resolution of the MOLA-DEM. To address this limitation, the most updated valley network from the database of is selected and projected onto the study area (Alemanno et al., 2018). The process of retracing the main valley is then initiated, utilizing the CTX mosaic images, along with THEMIS-IR and HiRISE imagery. This approach allows obtaining a more precise and accurate delineation of the valley network.

Prior to manually retracing, it is crucial to adjust the representation of all available data. This process involves altering the transparency or contrast of the MOLA-DEM and CTX mosaic, as well as reclassifying the flow accumulation raster to only show pixel values over 400. This is necessary to mitigate any issues that may arise from the complex details within the raster, which can make it challenging to fix the primary valley network. By utilizing the most up-to-date database of valley networks on Mars, the primary valley within the area of interest can be accurately traced. Additionally, if the data suggests that there was past hydrological connectivity of separate valleys disrupted by impacts, or if the flow followed a different course, these discrepancies should be addressed during the manual retracing process.

Finially, the hydrogeological proxies were estimated by utilizing CTX stereo DEM data and running a hydraulic model using HEC-RAS software. For the hydraulic model to produce accurate results, a high-resolution DEM or terrain is crucial. Therefore, MOLA-DEM cannot be used in this process. Instead, CTX stereo DEM can be utilized after some data processing, such as resampling and terrain creation. The primary objective of the model is to obtain a profile of the valley outlet that corresponds to the available CTX stereo DEM data. This profile can reveal many critical and useful proxies, such as the maximum volume of the outlet channel, the maximum discharge, top width, flow area, slope, water surface elevation, velocity of the channel, and complete profiles of several cross sections. These proxies can provide insights into the causes of valleys' formation during the specified period on Mars and their relative contribution to the overall outflow. Thus, the hydraulic model is a valuable tool for investigating the hydrogeological characteristics of the Martian valley network.

To enhance our understanding of the hydrological processes on Mars, it is essential to develop a fully developed hydraulic model for the entire valley network within the study area. This should be the upcoming steps for this project as further research. This model is limited by the availability of appropriate data which provide valuable insights into the maximum discharge of the valley network. Such a model can also improve our understanding of the hydrological processes that occur within the study area and on Mars generally.

5 Results

This chapter presents the comprehensive outputs of the algorithm utilized for the delineation of both the watershed and valley network within the study area on the surface of Mars. The section provides a summary of all the outputs that were obtained from the algorithm-assisted mapping campaign conducted with the help of the collected datasets, including MOLA-DEM, CTX mosaic, CTX stereo, HiRISE, THEMIS-IR, and a database of the valley network on the Martian surface.

Firstly, the results from the watershed (subbasins) delineation are presented based on a semi-automatic algorithm. The outcomes consist of detailed descriptions of these watersheds in the form of comparisons and statistics. Secondly, the findings from mapping the valley network aim to enhance the quality of the database of Martian surface valley networks. The outputs include updated maps of the valley network and the determination of hydrological proxies, such as valley width, incision depth, and slope. Finally, a comparison of these proxies is conducted to reveal relatively higher or lower contributions to the overall outflow, providing further insight into the Martian surface hydrology. Through these results, this study contributes to a better understanding of the Martian landscape and provides valuable information for future research in this field.

5.1 Watershed mapping campaign

The results of the mapping campaign of watersheds in the study area were carried out through a multi-step process involving both automatic and manual methods. The MOLA-DEM and CTX mosaic datasets were used to delineate subbasins, and the "watershed" function from the Whitebox toolset was utilized to generate watersheds automatically. To ensure the accuracy of the results, pour points identified on the flow accumulation model were saved in a points shapefile using ArcMap. However, the accuracy of the automatic results was improved by cross-referencing with high-resolution images from the CTX mosaic. By aligning the boundaries of watersheds to CTX images, a more precise mapping was achieved. This new mapping campaign marks a significant advancement in our understanding of the hydrology and geology of the planet.

The findings of the study suggest that the implementation of a new algorithm-assisted mapping campaign has led to a substantial improvement in the accuracy of watersheds delineation in the area of interest especially near the boundaries. based on analysing the results raster of the watershed function, it was observed that there were several mismatches at the boundaries which required fixing. This was attributed to the significant difference in resolution between the MOLA-DEM dataset (463 meter/pixel) and the high-resolution CTX mosaic images (up to 5 meter/pixel). Due to this mismatch, the boundaries of the watershed raster did not correspond to the geomorphological features of the Martian surface. However, the use of CTX images allowed for a clear tracing and delineation of these features. The higher resolution of the CTX images enabled the identification of additional details that were not discernible in the MOLA-DEM data. This led to a more accurate and refined mapping of the watersheds.

In Figure 5.1, the delineated watersheds are displayed in various colours utilizing the WhiteBox toolset, with the CTX mosaic serving as the base map to demonstrate the consistency of the output with the geomorphological features of Mars. The study area contains five watersheds that exhibit potential valley networks, which have garnered further analysis. However, one crater located in the eastern part of the study area is not included in any watershed, and the southernmost subbasin is not entirely within the area of interest, with the crater portion falling outside it. This information is crucial in understanding the distribution of water and potential hydrological activity in the study area. The use of the CTX mosaic as the base map enables the identification of the morphological features of the Martian surface and provides a valuable context for the delineated watersheds.

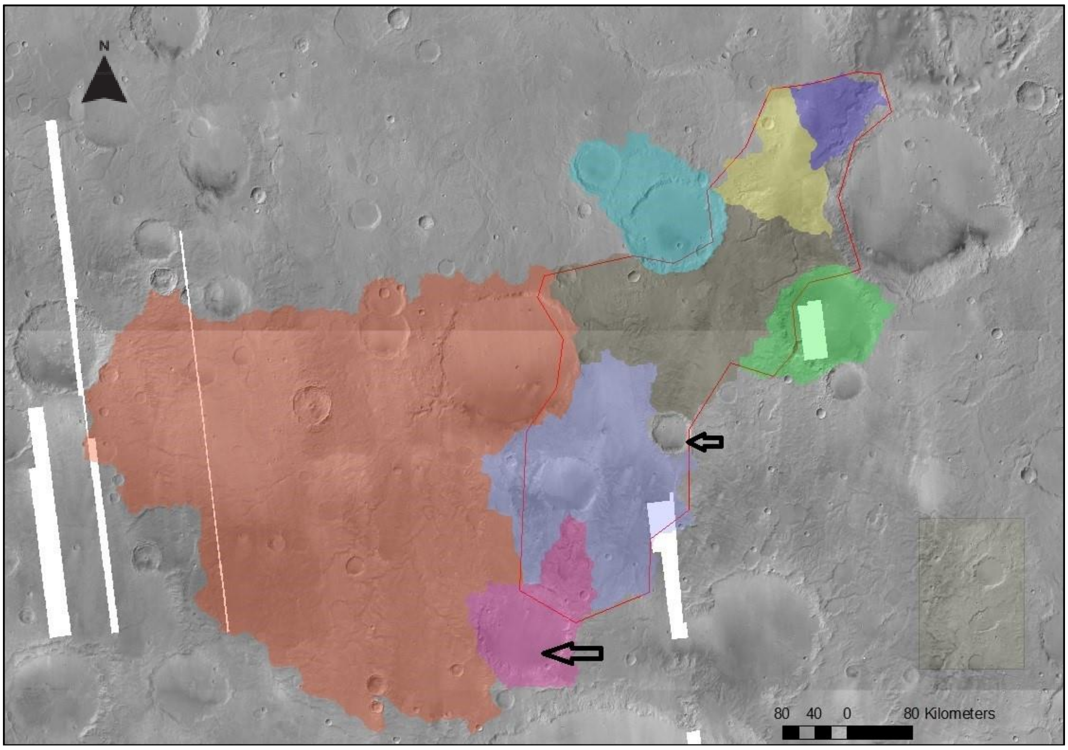

Figure 5.1: The delineated watersheds within the area of interest in various colours produced by the WhiteBox toolset. And the CTX mosaic as base map.

To accurately delineate watersheds, it is essential to identify the optimal pour points. This involves a meticulous process of analysing the flow accumulation model and the geomorphological features obtained from CTX images. However, this task can be challenging, particularly in areas where the primary channel of the flow accumulation model does not align with the delineated valley network. Despite these difficulties, the pour point selection is crucial for obtaining accurate results. In the forthcoming sections, we will elaborate on the valley network findings. To provide a visual representation of our best estimates, we have included Figure 5.2, showcasing the optimal pour points.

In order to create an accurate delineation of the watersheds, it is necessary to perform manual retracing and fixing of the watershed raster. This process produces a new watershed polygon shape file that matches the geomorphological features of Mars, providing refined borders for the watersheds. The manual tracing is a crucial step in the analysis, as it enables further investigation into the watersheds, such as determining their respective areas within the area of interest. Although this step can be time-consuming, it is an essential aspect of enhancing our understanding of the hydrology of Mars. It is worth noting that this task is focused on the watersheds within the study area, as they possess the potential for a valley network to flow.

The final output of the watershed's mapping campaign is presented in Figure 5.2, with each watershed represented by a different colour, varying in size. The smallest watershed, located near the valley outlets, covers an area of approximately 2250 km2. This can be attributed to the area's northern region having the highest slope values, as demonstrated in Figure 4.3(B). Consequently, the changes in elevation within this region are steeper than in other areas. The largest watershed, covering an area of almost 12940 km2, is located in the southern part of the area of interest. However, despite its size, this watershed lacks any apparent geomorphological features that indicate the potential for a large valley network. This observation is consistent with the available Martian database of valley networks and datasets, such as CTX and HiRise images. The middle watershed, covering an area of over 12500 km2, is the most eroded surface, revealing a dense valley network flowing within it. Additionally, most of the pour points are situated near the outlets of large craters, as these craters are an optional source of water for the valley network.

The valley networks depicted in the figure are a segment of the Martian surface valley network identified by Alemanno in 2018. The purpose of including this network is twofold: firstly, it aids in elucidating the characteristics of the delineated watersheds, and secondly, it highlights the constraints inherent in selecting the pour point locations.

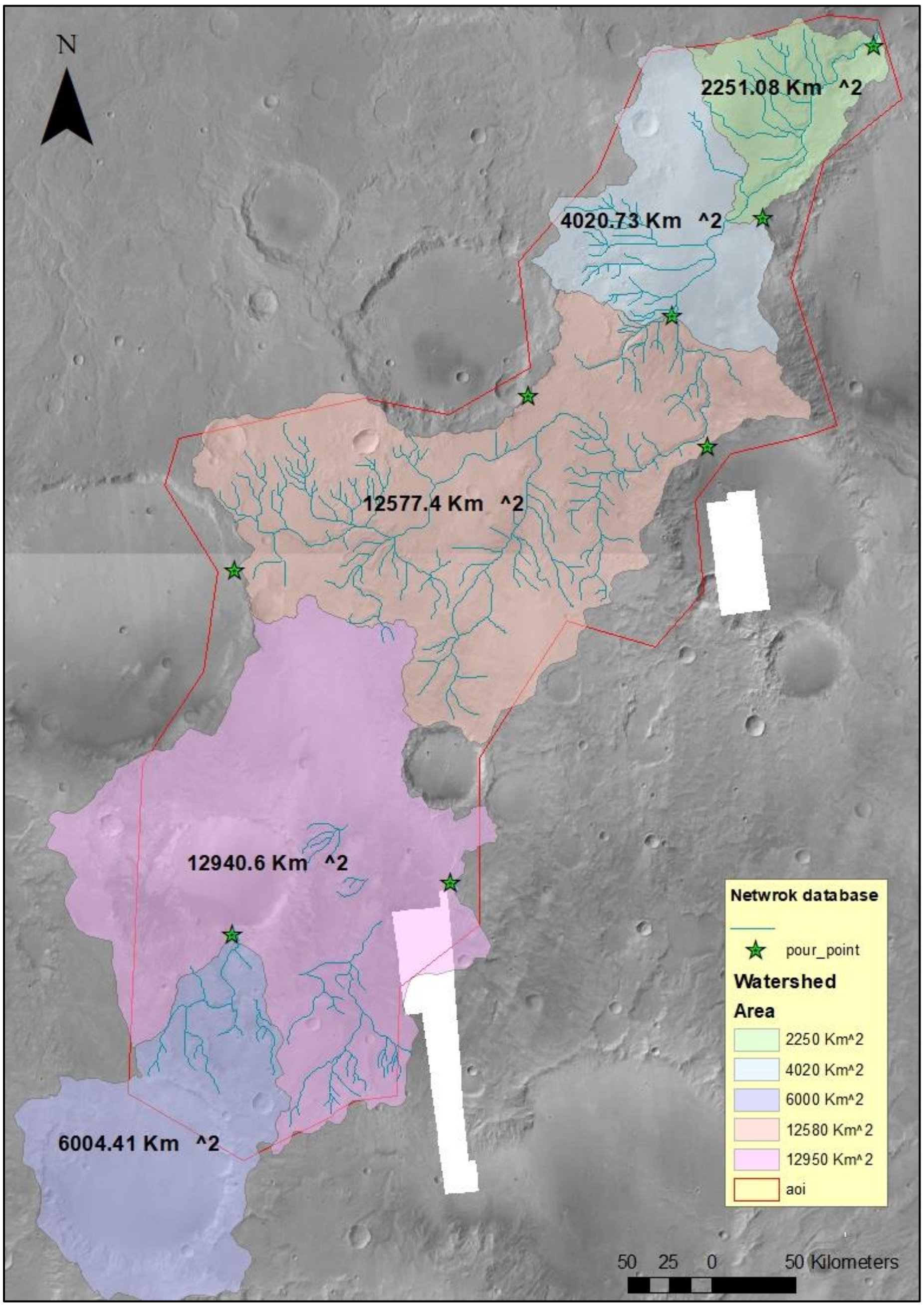

Figure 5.2: Final output of the watershed's mapping campaign, with pour points location and Martian valley network database by by Alemanno in 2018.

Figure 5.3 depicts the length of the valley network, by Alemanno 2018, within each watershed of the study area. Using the same colour scheme as the previous map, the third watershed has the longest valley network, measuring 1722.1 km from the Martian valley dataset. Conversely, the fifth watershed has the smallest valley network, measuring approximately 206.5 km in length. Moreover, the graph shows the percentage of each valley to the total length of the valley, with each column representing a specific watershed. The third watershed, for instance, contains roughly

56.1% of the delineated valley network from the Alemanno database. Conversely, the first watershed, located near the outlet of the entire valley network, contributes to approximately 10.4% of the total valleys within the study area from the same Martian surface valleys database. It is noteworthy that the total length of the valley network from the database within the study area is 3070.5 km. However, the type of valley, whether main channel or tributaries, is not defined in their database. These findings are crucial when comparing them with the newly delineated valley network produced by the new mapping campaigns.

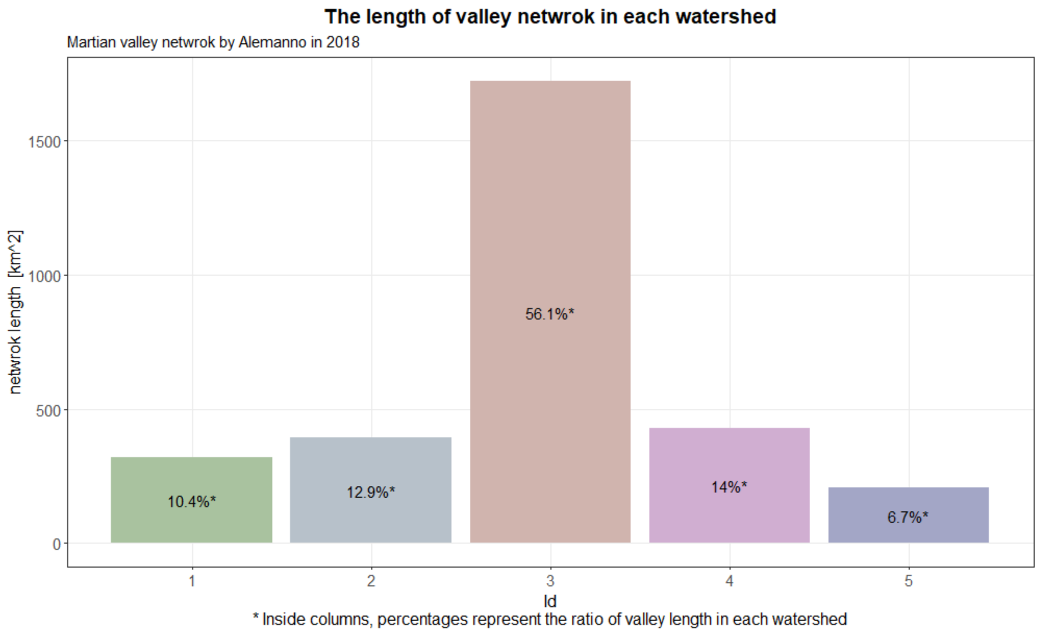

Figure 5.3: the length of the valley network database within each watershed of the study area; colour coded with the same colour of watershed's mapping campaign.

In Figure 5.4, the boxplot provides a visual representation of the elevation variability across the 5 watersheds in the study area. The colour-coding distinguishes each watershed on the map above, and it shows that the mean elevation of watersheds decreases from watershed 5 to 1 in the direction of the flowing water. This decreasing trend is attributed to the shift from highland in the south of the study area towards the lowland near the outlet of the valley network. The mean elevation of the watersheds varies from 2250 m high in watershed 5 to 400 m high in watershed 1. Watershed 4 has the narrowest range of elevation, which explains the lack of various geomorphological features in this area. This observation is consistent with the Mars valley database, which indicates that this area has the least possibility of valley network flowing. The first watershed has the largest elevation range, from almost -1800 m up to 1100 m. The data points that are circled in red are located along the valley outlet, which can be clearly identified through high-resolution CTX mosaic images. These findings provide insight into the topography and geomorphological features of the study area and are important for further analysis and interpretation of the hydrology of Mars.

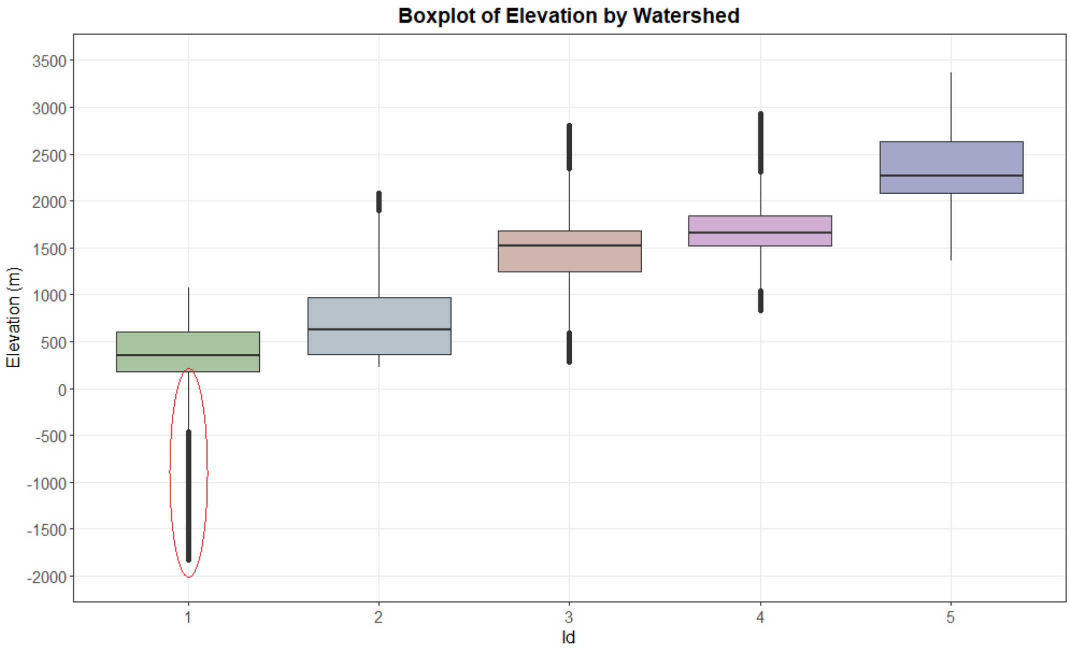

Figure 5.4: Boxplot of elevation by watershed; with the same colour of watershed's mapping campaign.

In Figure 5.5 the boxplot provides a clear visualization of the variation of slope across the 5 watersheds. The use of colour coding for each watershed allows for easy identification on the corresponding map above. The mean slope for each watershed ranges between 1.5 to 2.5 degrees, with the steepest slopes found within the first watershed near the outlet of the valley. The continuous erosion caused by the flowing water has created a steeper surface in this area, resulting in a wide range of slope values from 0 to 8.5 degrees, the minimum and maximum slope, respectively.

These findings are consistent with the outputs of elevation across the watersheds as the first watershed has the highest range and lowest points of elevation. On the other hand, watersheds 2 and 3 lack significant craters, yet they have higher slope values compared to watershed 4, which has a narrow range of slope values. This suggests that the lack of significant geomorphological features does not necessarily correlate with lower slope values. Overall, the slope analysis provides valuable insights into the topography of each watershed, which can be used for further analysis and understanding of the Martian landscape.

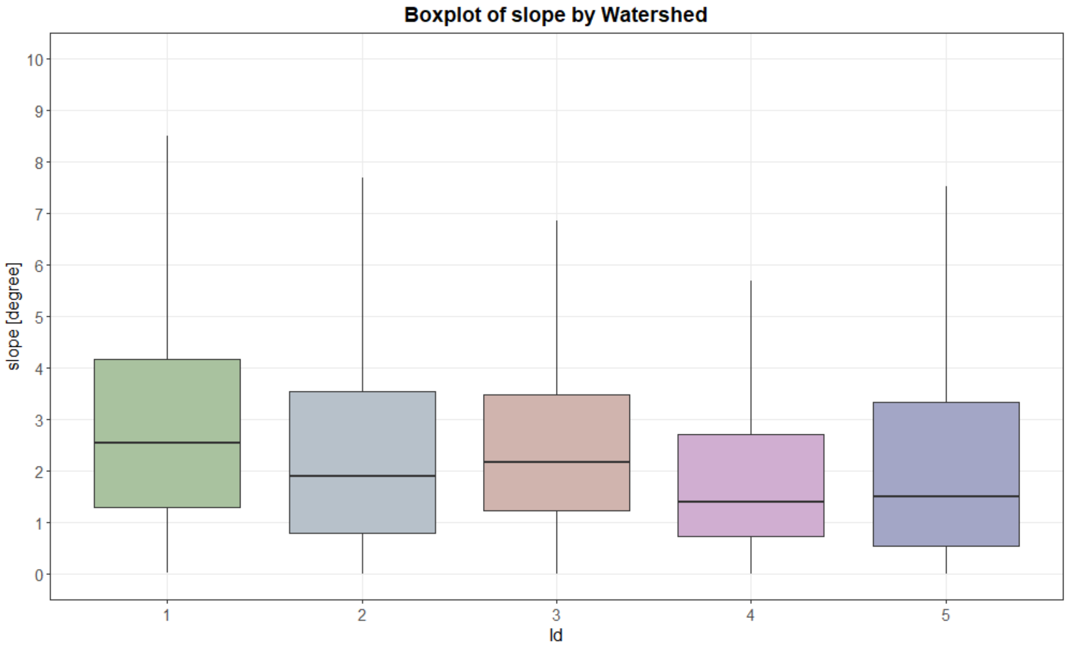

Figure 5.5: Boxplot of slope by watershed; with the same colour of watershed's mapping campaign.

By drawing comparisons between the delineated watersheds and the established Martian surface valley network, we can gain a deeper understanding of the hydrological processes at play on Mars. Furthermore, the limitations of the pour point selection are illuminated by analyzing how the network interacts with the delineated watersheds. By using this approach, it could interpret the results of the watersheds mapping campaign, improving our understanding of Martian hydrology. Such comparison would help improve our understanding of the Martian surface's geomorphology, providing insights into its hydrological processes.

5.2 valley mapping campaigns

The mapping campaign for Martian valley networks involved the use of a flow accumulation model and the latest database of Martian valleys. However, to ensure the accuracy of the results, the valley networks were corrected using high-resolution images from the CTX mosaic. By matching the valley networks to these detailed images, it is possible to refine their mapping and produce more accurate results. The new mapping campaign for networks represents a significant step forward in our understanding of the planet's hydrology and geology.

The study shows that the application of a new algorithm-assisted mapping campaign has significantly improved the accuracy of the Martian valley network delineation. Compared to the flow accumulation model that relies solely on elevation data from MOLA-DEM with a coarse resolution (463 meters per pixel), the new approach utilizes high-resolution images of CTX mosaic to trace and correct the model, resulting in a higher number of accurately identified river valleys.

The new algorithm-assisted mapping campaign offers several benefits over the traditional flow accumulation model. It can help to identify and correct inconsistencies in the flow accumulation model, resulting in a more accurate representation of the Martian valley network. This approach can also provide a more detailed and comprehensive understanding of the hydrological processes on Mars. In addition, the new delineated valley network is more consistent with the recent database of Martian surface valley network by Alemanno in 2018. These findings provide further support for the use of high-resolution images in improving the accuracy and reliability of Martian hydrological studies.

Figure 5.6 presents a map illustrating the results of flow accumulation analysis based on MOLA-DEM data, obtained using the "FlowAccumulationFullWorkflow" function in WhiteBox toolset. To improve the clarity of the model, the map has been divided into two main types of valleys, namely the main channel, represented in white, and tributaries, represented in black. The map excludes low values (< 500), which can be considered impurities. The area of interest is delineated with a red line.

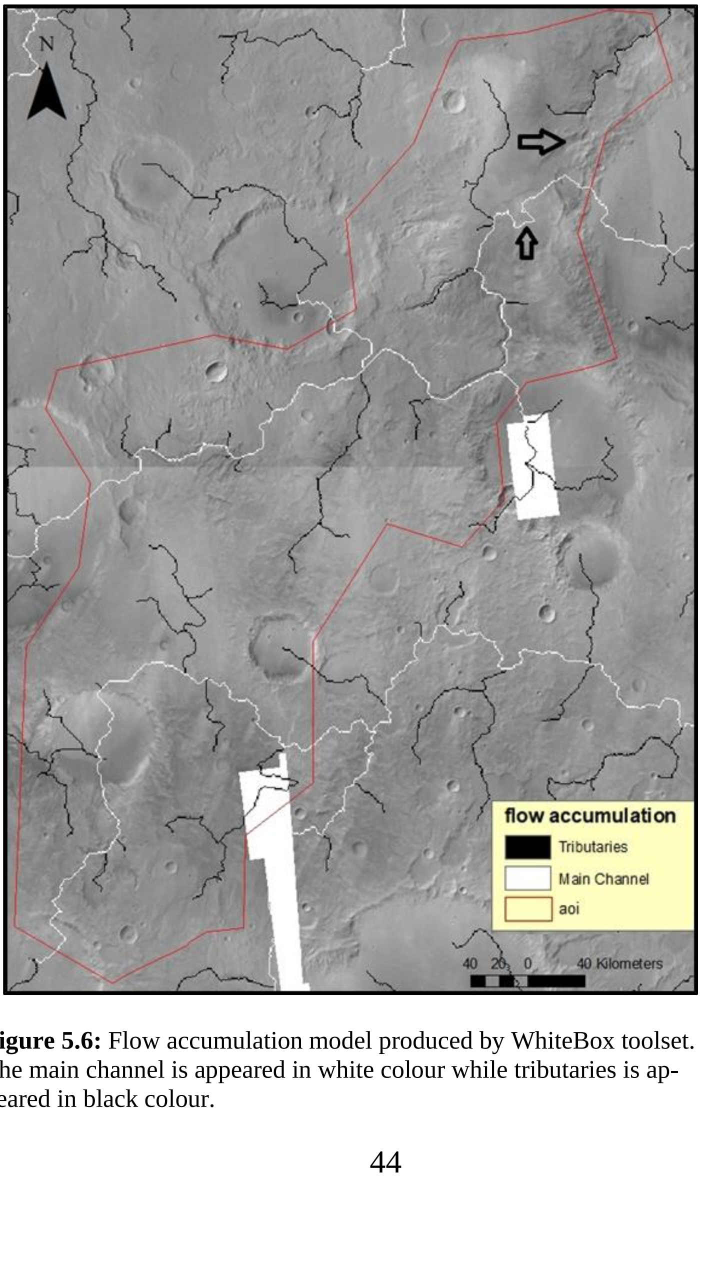

Figure 5.6: Flow accumulation model produced by WhiteBox toolset. The main channel is appeared in white colour while tributaries is appeared in black colour.

Although the model provides an accurate representation of the valley network in some areas, it appears to mismatch with high-resolution images of CTX mosaic in some locations. Figure 5.6 highlights some of these inconsistencies with black arrows. Despite these limitations, the model still offers valuable insights into the flow accumulation patterns in the area of study.

Despite the limitations mentioned earlier, the accurate determination of the flow accumulation patterns is essential for understanding the Martian hydrology and the history of water on Mars. One potential solution to address the inconsistencies in the flow accumulation model is the use of high-resolution elevation model data.

Currently, a new algorithm has been developed that involves tracing the model and correcting it using high-resolution images of CTX mosaic, which is a promising approach to overcome these issues, particularly in areas with extensive interest and availability of images. This approach can help improve the accuracy and reliability of the flow accumulation models, providing a more comprehensive understanding of the hydrological processes on Mars.

It is worth noting that flow accumulation models remain critical for providing valuable information on the paths and direction of surface running water on Mars. These models can help researchers identify potential locations for water resources and understand how water flows through different channels and valleys, contributing to our overall understanding of Martian geology and planetary processes.

The updated valley network presented in figure 5.7 is a result of the new algorithm-assisted mapping campaign conducted within the study area. It represents a significant improvement over the earlier database of Martian surface valleys, which lacked detailed information about the different types of valleys present in the area. The new network shows good connectivity from the south part of the study area to the north at the main outlet of the valley to the lowlands. The main channels are presented in cyan while the tributaries are presented in red as well as the study area are framed with yellow line.

One notable feature of the updated valley network is its consistency with the flow accumulation model presented in figure 5.6. This indicates that the new algorithm-assisted mapping campaign has produced accurate results that align with existing models of water flow on Mars. However, some parts of the valley were delineated according to the CTX mosaic images which were unconnected in the flow accumulation model due to the coarse resolution of MOLA-DEM. This suggests that a combination of high-resolution imagery and detailed topographic models are needed to fully understand the hydrological processes on Mars.

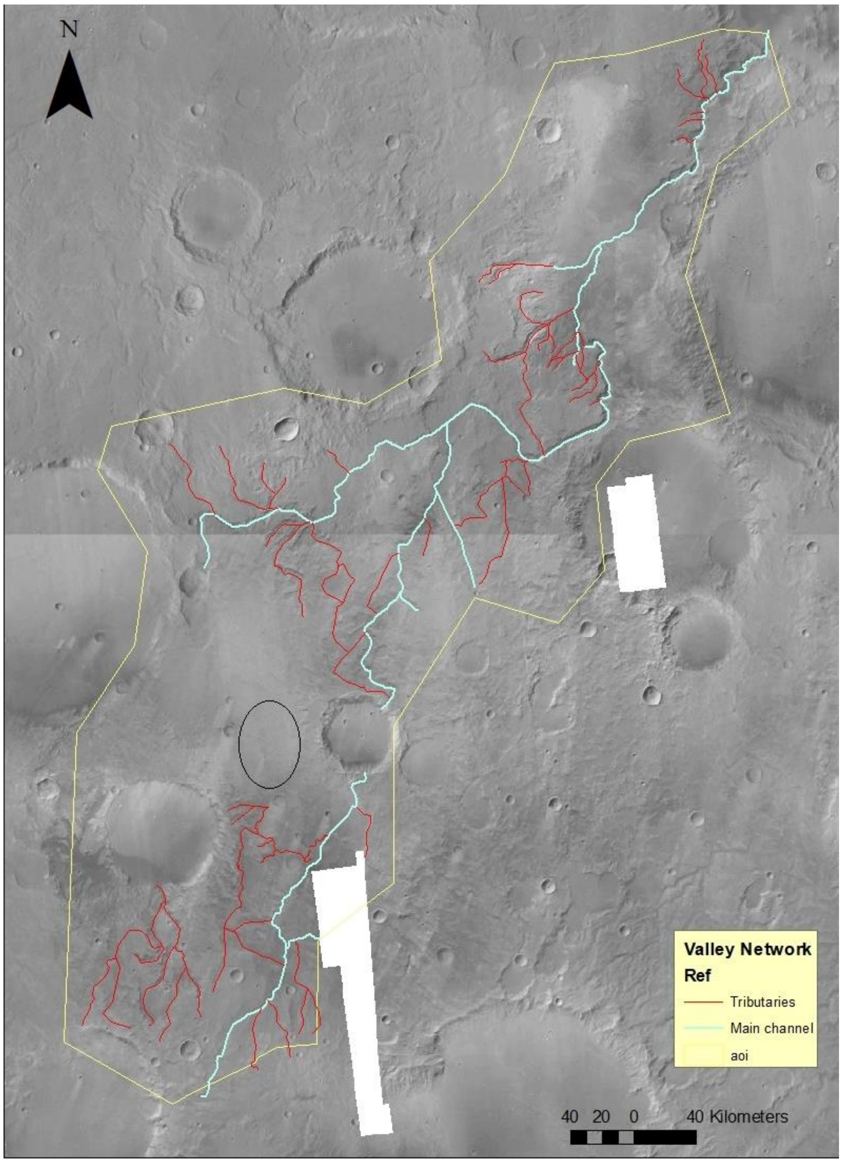

Figure 5.7: Updated valley network as a result of the new algorithm-assisted mapping campaign conducted within the study area. The main channel is appeared in cyan colour while tributaries is appeared in red colour.

Despite the general agreement between the flow accumulation model and the updated valley network, there are some differences that are worth noting. For example, the flow accumulation model suggests that water flows from a big crater in the fourth watershed to the eastern land outside the study area. However, this valley is not delineated in the new network due to the lack of evidence of flowing water in this area according to CTX mosaic images which illustrated by black circle in figure 5.7. This is consistent with the earlier database of Mars valleys and highlights the importance of using multiple sources of data to map the surface of Mars accurately.

The updated valley network has been classified into two types, namely the main channel and tributaries, figure 5.7. However, the main focus of the project is on the main channels since they are expected to be more visible in the CTX mosaic images. While the CTX mosaic provides a detailed information of the location and distribution of valleys, the HiRISE images, which have higher resolution, enable the identification of smaller and narrower valleys. Consequently, the compression of the updated valley network and the earlier valley database of Mars should mainly concentrate on the main channels. It should be noted that the available database of Mars is not classified, but it is still essential to focus on the main channels as they are likely to be the most significant contributors to the hydrological cycle of the planet.

The length of the updated valley network, as presented in Figure 5.8, provides important insights into the distribution of valleys within the study area. It is interesting to note that the third watershed has the longest valley network with a length of 1056.3 km, which is almost half of the total delineated valley network. This watershed also has the highest percentage of the main channel with 57.8% flowing in this area, indicating that this watershed is crucial to the overall water flow of the study area. The length of the valley network in the fourth watershed is 486.4 km, which is the second longest. On the other hand, the second watershed has the smallest valley network with only 112.9 km long, representing only 5.5% of the total valleys. However, almost half of the valleys in this watershed are main channels with a length of 60.2 km, indicating the importance of this area for water flow. It is noteworthy that the fifth watershed has 226.5 km of valleys, accounting for 11% of the delineated network. However, none of these valleys are main channels, implying that this watershed may not contribute significantly to the overall water flow. The cyan colour columns in the figure represent the main channels within each watershed, providing an easy visual comparison of the distribution of the main channels across the study area. Overall, the length of the valley network provides valuable information for further analysis of the water flow and its potential impact on the geomorphology of the study area.

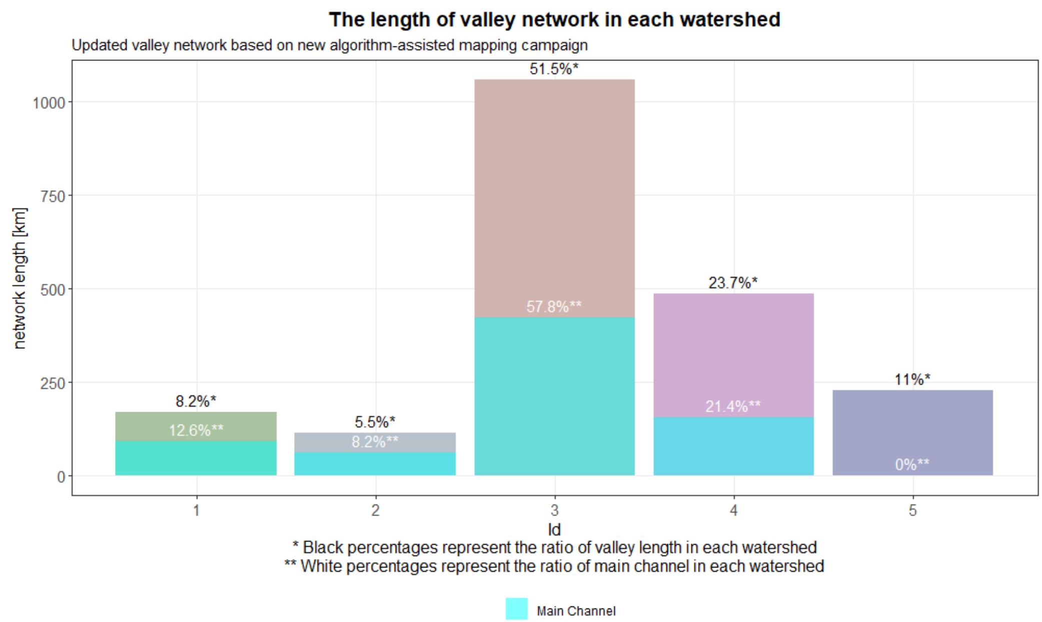

Figure 5.8: The length of the updated valley network within each watershed of the study area; colour coded with the same colour of watershed's mapping campaign. The cyan represent the main channel lengths.

Table 5.1 provides a comprehensive summary of the updated valley network length for the study area. It shows the total length of the updated valley network, which is 2050.8 km, while the total length of the valley database for Mars is 3070.5 km. The difference in the total length of the updated valley network and the Mars database can be attributed to the many tributaries in the Mars database that contribute to the overall length. However, it is important to note that the main channel in both valley networks is almost the same length. The updated valley network has a total length of main channels which is approximately 730.9 km, which represents almost 35.6% of the total valley network. In contrast, the length of the study area is only 413.2 km. This implies that the valley network is much more extensive than the study area itself. Furthermore, the tributaries represent a significant portion of the total valley network, accounting for about 64% with a total length of 1320 km. Overall, Table 5.1 provides a comprehensive overview of the updated valley network length, highlighting the significant contribution of the tributaries to the overall length of the valley network.

Table 5.1: A comprehensive summary of the updated valley network length for the study area.

WS	Area	Valley Database	Updated Network	Main channel	Tributaries	Main channel	Tributaries
Id	[km2]	Length [km]	Length [km]	Length [km]	Length [km]	%	%
1	2251.1	318.9	168.6	91.8	76.8	54.5	45.5
2	4020.7	394.7	113.0	60.2	52.7	53.3	46.7
3	12577.4	1722.1	1056.3	422.8	633.5	40.0	60.0
4	12940.6	428.4	486.4	156.1	330.4	32.1	67.9
5	6004.4	206.4	226.5	0.0	226.5	0.0	100.0

Figure 5.9 provides two boxplots that describe the slopes and elevations of the valley network by type of valley. The cyan colour represents the main channel while the red colour represents the tributaries. For the slopes in A), the average slope in the main channel is ≈ 3.12 degrees, while the average slope in tributaries is ≈ 2.83 degrees. It is interesting to note that the range of slopes in the main channel is much higher than that of the tributaries. In some areas, the slope of the main channel can be as high as 19 degrees. This variation in slopes could be attributed to the fact that the main channel has a steeper slope to facilitate water flow. On the other hand, the tributaries have a gentler slope as they are mainly responsible for contributing water to the main channel.

For the elevations in B), the average elevation of the main channel is ≈ 1082 meters, while the average elevation of the tributaries is ≈ 1498 meters. This difference in average values is expected and can be explained from a hydrological perspective. The range of elevations in the main channel (-2259 meters to 2882 meters) is much higher than that of the tributaries (-231 meters to 2678 meters). This disparity in the range of elevations could be explained by the fact that the main channel flows through all five watersheds in the study area. As such, the valley passes through the highland before reaching the outlet near the lowlands. In contrast, more tributaries are delineated in the south of the study area, which is closer to the highland. The number of tributaries decreases in the first and second watersheds, which are the closest to the lowlands.

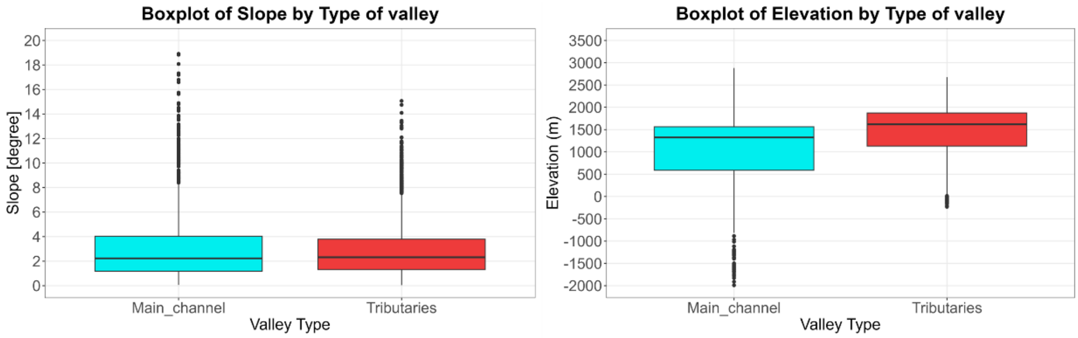

Figure 5.9: Two boxplots is categorized by valley type. A) represents boxplot of slope while B) represents boxplot of elevation. The colours are the same as updated valley network categories.

In order to accurately model the hydrology of the Mars valley network, it is essential to have access to high resolution data. Fortunately, a high-resolution digital elevation model (DEM) is available for the outlet area (figure 5.10 B), which was generated by processing a CTX stereo on the MarsSI platform. This high-resolution DEM has a resolution of 12 by 12 meters, which is considerably more detailed than the lower resolution datasets previously used. The increased resolution of this data allows for a more accurate representation of the cross sections of the valley network and provides a wealth of valuable hydrological information. This includes detailed information about the valley's shape, size, and the gradient of the terrain, all of which are critical factors in understanding the hydrological processes. By utilizing this high-resolution DEM data, we can obtain a much more robust hydrological proxy of the Mars valley network, which will allow for more accurate modeling and analysis of the hydrology of this important Martian landscape.

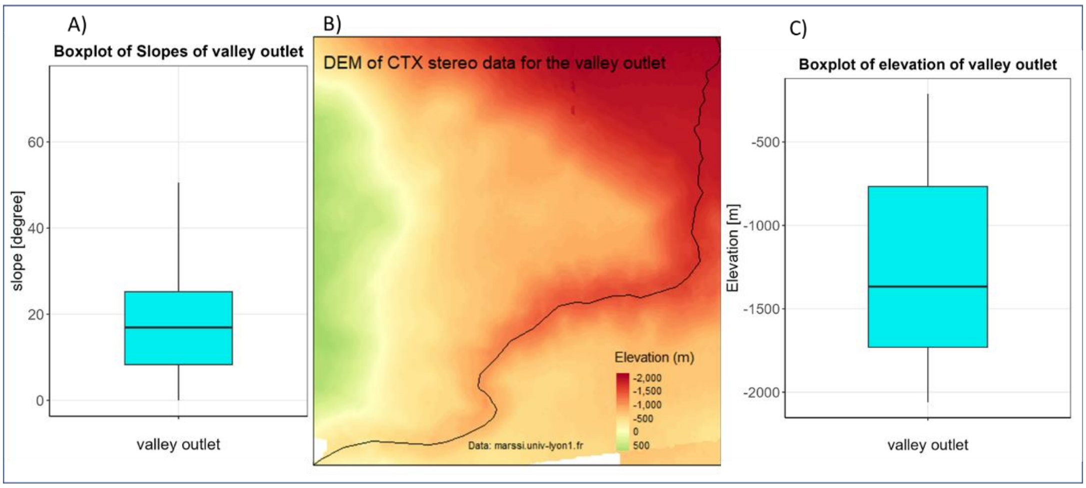

Figure 5.10: Detailed analysis of the valley's outlet, including A) a boxplot of slopes in the outlet of the valley, B) a map of the area at the outlet of the using CTX stereo DEM as base map, and C) a boxplot of elevation of the outlet valley.

The hydrological characteristics of the outlet area of the valley network are critical for understanding the behavior of the Martian surface water. Therefore, it is important to validate the results obtained from the new algorithm-assisted mapping campaign through a high-resolution DEM. Figure 5.10 presents a more detailed analysis of the outlet area of the valley network, including A) a boxplot of slopes in the outlet of the valley, B) a map of the area at the outlet of the valley which is the same as the blue star in figure 4.1, and C) a boxplot of elevation of the outlet valley. From B), the CTX stereo reveals elevations that match the valley outlet delineated from CTX mosaic, providing further evidence of the accuracy of the new algorithm.

A) The boxplot of slopes shows that the median slopes in the outlet area are much higher than the general median slope of the main channel through the whole valley. This indicates that the surface of Mars is very steep towards the lowland near the outlet of the valley, which may lead to increased erosion and sediment transport.

B) The map of the outlet area of the valley network shows that the outlet is located in a region low elevation, with main channel that drain towards the lowlands. This suggests that the outlet area is a critical location for the transport and deposition of sediments, and the formation of new channels.

C) The boxplot of elevation shows that the median elevation of the outlet valley is below -1300 m, which is well below the average elevation of the main channel by 2400 meters. Furthermore, the highest point of the valley outlet is below – 200 meters, and the deepest point is below – 2000 meters. This suggests that the outlet area is a region of very low relief and is likely to be affected by significant amounts of subsurface water flow.

Overall, the analysis of the outlet area of the valley network using the high-resolution DEM provides valuable insights into the hydrological behavior of the Martian surface water. It confirms the accuracy of the new algorithm-assisted mapping campaign and highlights the importance of further research on the outlet area to understand the dynamics of sediment transport and channel formation.

In Figure 5.11, the terrain profile of the valley outlet using CTX stereo DEM, which provides detailed information on the elevation changes over a distance of more than 25 km. The profile shows a nearly linear slope of approximately -0.07, indicating a gradual descent of the valley floor toward the lowlands. This slope may indicate a stable, long-term erosion process that is consistent with the hydrological processes that have shaped this Martian landscape. Additionally, the profile reveals several peaks and troughs that may correspond to individual tributaries or other geological features that have contributed to the formation of the valley network. The detailed terrain information provided by the CTX stereo DEM allows for a more comprehensive understanding of the valley outlet and its surrounding landscape, providing insights into hydrological processes that have shaped the Martian surface over time.

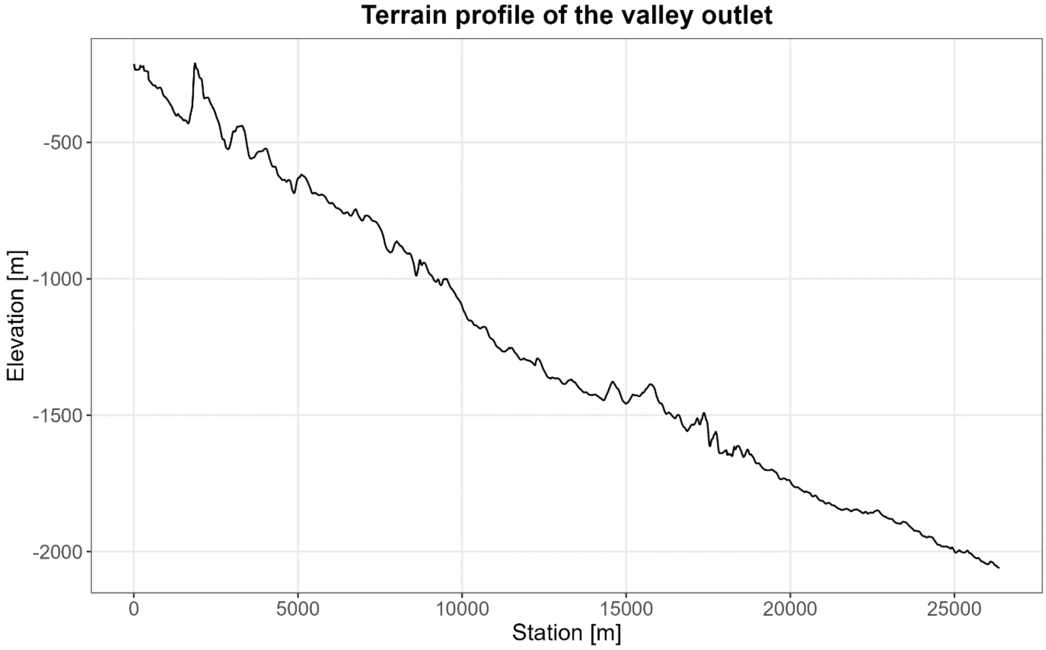

Figure 5.11: Terrain profile of the valley outlet using CTX stereo DEM.

Figure 5.12 presents several cross-sections extracted from the valley outlet using the high-resolution CTX stereo DEM. Panel A shows the first cross-section with a deepest point of -380 m, panel B shows the cross-section at a distance of 12 km from the start point, with a deepest point of -1200 m, while panel C displays the last cross-section of the valley outlet with the deepest point of -1700 m. All three cross-sections exhibit non-uniform geometries, with a trapezoidal shape approximating the closest geometric shape. However, for cross-sections with very steep riverbank lines, a triangular shape may be more appropriate, with a side slope ratio of 1:2. These cross-sections offer valuable information on the variation of the valley's depth along its length, which can inform further analysis and modelling of the valley's hydrological properties.

Finally, the channel top widths exhibit variability along the cross sections for the outlets and are also subject to fluctuations with varying discharge. In certain cross sections, the widths range between 0.5 km for flow rates of 1×10^6 m^3 s^{-1} to more than 3 km for large flow rates of 5×10^7 m^3 s^{-1}. At the outlet area, the volume of the channel varies between 3×10^7 m^3 and 7×10^7 m^3. However, given that the modeled area is significantly smaller than the total length of the valley, the expected volume of the valley network is significantly higher (by a factor of < 25) than the modeled volume. With a rough estimation, the maximum discharge of the valley network is expected to range from 1×10^9 m^3 s^{-1} to 2×10^7 m^3 s^{-1}. Nevertheless, to obtain a more accurate volume calculation, a robust hydraulic model for the entire valley network, based on high-resolution DEM data, is necessary.

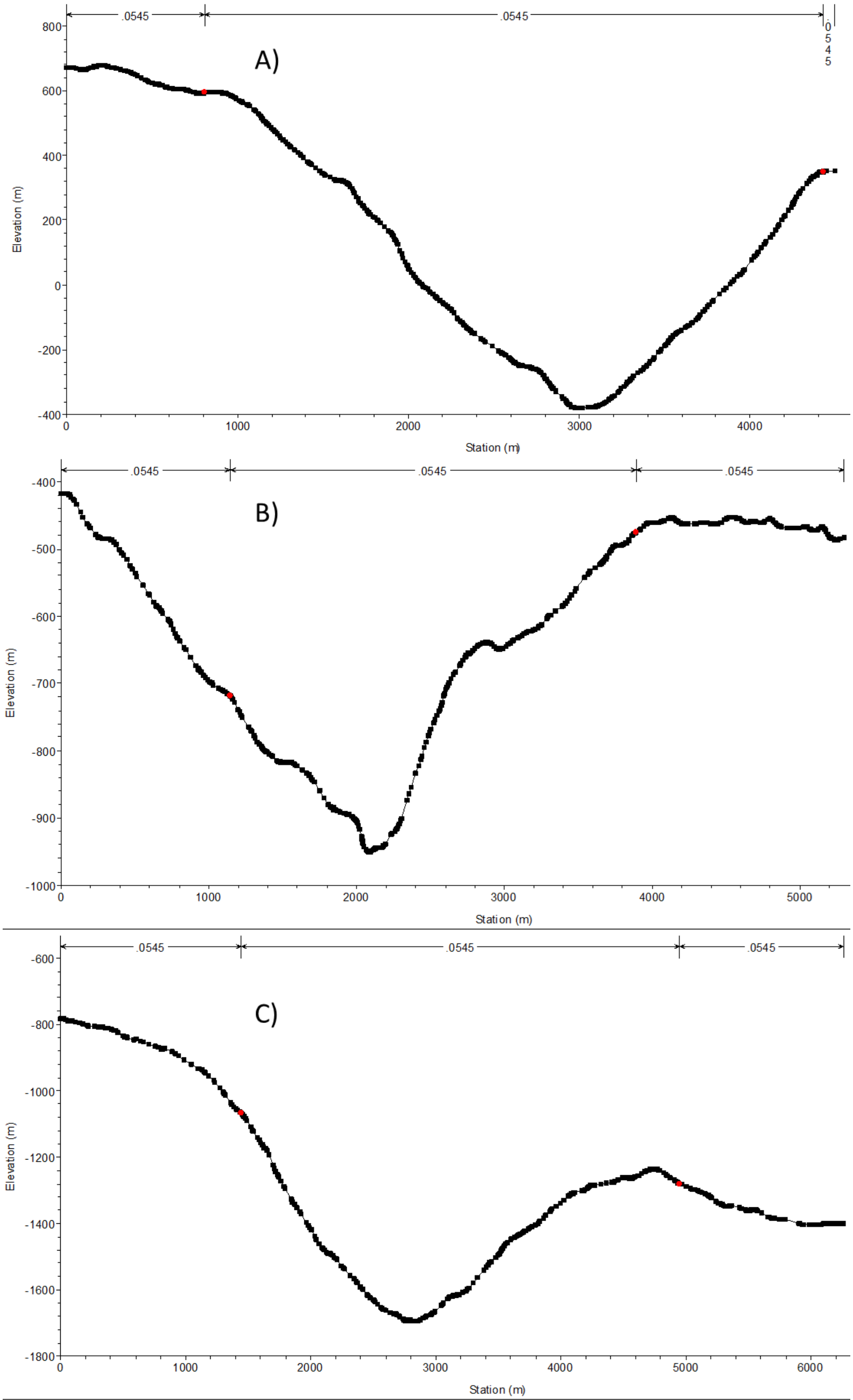

Figure 5.12: Several cross-sections extracted from the valley outlet using the high-resolution CTX stereo DEM by HEC-RAS software. A) first cross-section downstream, B) a cross-section in the middle of the valley outlet, C) last cross-section of the valley outlet.

6 Discussion

This section aims to interpret and analyse the results obtained from the previous section in the context of the research question, which is to understand and model the hydrological processes on Mars as well as the water history on Mars. In this section, the reliability of the available datasets is assessed, and the use of the new algorithm-assisted mapping campaign to delineate both watersheds and valley networks is evaluated.

One of the main advantages of the new algorithm-assisted mapping campaign is the enhancement of the connectivity of the main channel of valley networks, which leads to more precise watershed borders. This improvement is significant for modelling the hydrological processes on Martian surface. However, the main drawback of this campaign is the time required for valley delineation and watershed border identification. The time-consuming process may limit the applicability of this campaign in other studies.

In addition, the resolution of the available data is a limitation that affects the quality of the final outputs of watersheds and valley networks. Although the improvements made to the current datasets of Martian valley networks are significant, there is still a need for higher resolution data to enhance the quality of the results. Nonetheless, the new algorithm-assisted mapping campaign has provided a valuable tool to investigate the hydrological processes on Martian surface.

Overall, the discussion section provides an in-depth analysis of the results obtained in this study and their implications for the field of Martian hydrology. It highlights the strengths and limitations of the current datasets and presents future research directions that can contribute to our understanding of the hydrological processes on Mars.

6.1 Delineated watershed

The results of the mapping campaign of watersheds in the study area mark a significant advancement in understanding of the hydrology and geology of the within the area of interest. The implementation of the new algorithm-assisted mapping campaign has improved the accuracy of watersheds delineation, especially near the boundaries. Although the automatic results generated by the "watershed" function from the Whitebox toolset were generally accurate, cross-referencing with high-resolution images from the CTX mosaic was required to ensure their reliability. The use of CTX images allowed for a clear tracing and delineation of geomorphological features that were not discernible in the MOLA-DEM data. However, the significant difference in resolution between the two datasets caused some mismatches at the boundaries of the watershed raster. Based on analysing the results raster of the watershed function, it was observed that several mismatches required fixing. Nevertheless, the higher resolution of the CTX images enabled the identification of additional details, leading to a more accurate and refined mapping of the watersheds. These findings demonstrate the potential of the new algorithm-assisted mapping campaign for enhancing our ability to model past hydrological processes on the Martian surface.

The application of digital elevation models, such as CTX stereo, will greatly improve the automatic mapping of watersheds through the "watershed" function. The boundaries of the output raster are more likely to match the geomorphological features and characteristics of the Martian surface, reducing the time and effort required to fix the output raster according to high-resolution images. However, to achieve even better delineation, HiRISE stereo pair DEM could be utilized. Despite their limitations in covering the Martian surface, these data offer improved accuracy in pour point detection in the flow accumulation model produced by the "FlowAccumulationFullWorkflow" function from WhiteBox toolset. By matching the observed valley network on the high-resolution images of CTX mosaic or HiRISE, the optimal location of pour points can be identified, enhancing the credibility of the algorithm-assisted mapping campaign for further hydrological models.

In analysing the delineated watersheds in the study area, a clear pattern emerges that highlights the important role of water in the evolution of Mars. By examining the ranges of slopes and elevations in each watershed, we can observe the impact of flowing water and the density of valley networks on the surrounding landscape. As demonstrated in Figure 5.2, the fourth watershed lacks any geomorphological evidence for surface runoff, which leads to a narrow range of elevations and slopes in Figures 5.4 and 5.5. In contrast, other watersheds, particularly the third, display clear evidence of surface runoff in the CTX images, which is reflected in their broader ranges of slopes and elevations. This finding is consistent with the conclusions of a previous study on the Tyrrhena Terra region of Mars, which found that surface runoff derived from rainfall or snowmelt was the dominant erosional process, with most activity occurring during the Noachian period (Mest et al., 2010). Indeed, this is the same geological unit for our study area, as depicted in Figure 4.1. These results suggest that water played a crucial role in shaping the Martian landscape over time and that the new algorithm-assisted mapping campaign has provided us with a more accurate understanding of this process.

6.2 Delineated valley network

The mapping of Martian valley networks is an important aspect of understanding the planet's hydrology and geology. The traditional flow accumulation model that solely relies on elevation data from MOLA-DEM with a coarse resolution has been supplemented with a new algorithm-assisted mapping campaign that utilizes high-resolution images of CTX mosaic. The study shows that the application of this new approach has significantly improved the accuracy of the Martian valley network delineation.

The updated valley network presented in Figure 5.7 offers significant improvements over earlier Martian surface valley databases. The study aimed to enhance the understanding of the hydraulic connectivity of Martian valley networks and classify the network into two categories based on hydrological proxies. The updated network shows good connectivity from south to north, providing valuable insights into valley formation and the hydrological processes on Mars. This new methodology of algorithm-assisted mapping campaign allows for better hydrological applications.

To explain, the use of high-resolution images has allowed for the identification and correction of inconsistencies in the flow accumulation model, resulting in a more accurate representation of the Martian valley network. Moreover, the new delineated valley network shows more consistency with geomorphological feature of valleys observed on CTX mosaic images than the recent database of Martian surface valley network by Alemanno in 2018. These findings not only offer several benefits over the traditional flow accumulation model but also provide further support for the use of high-resolution images in improving the accuracy and reliability of Martian hydrological studies.

In this study, we compared the updated valley network generated in this project with the recent database of Martian valleys. The results showed that both the datasets have quite similar density distribution, although the total length of valleys was 33% higher in the Martian database. Interestingly, the lengths of the valley network in the third watershed were found to be the highest in both datasets, whereas the fifth watershed had no main channels in both datasets. Figure 5.3 and 5.8 demonstrate that the updated valley network has significantly improved valley delineation in the fourth watershed, especially in identifying the main channel that empties into the crater. By analysing the findings of table 5.1, we found that 36% of the total length of the valley network in the study area was made up of main channels, while the remaining 64% were tributaries. However, we cannot make a similar comparison with the Martian dataset due to unclassified data. Nevertheless, by overlaying the two valley networks, we observed that the percentage of tributaries in the Martian dataset is much higher than in the updated valley network. Additionally, these tributaries are the primary reason for the difference in the total length of the valley network in both datasets. Overall, these comparisons provide valuable insights into the similarities and differences between the updated valley network and the Martian dataset, which can be used to further refine our understanding of the Martian hydrological system.

To further illustrate the importance of high-resolution datasets in algorithm-assisted mapping campaigns, we compare between the MOLA-DEM and CTX stereo pair. As shown in Figure 6.1, the DEM of an area near the outlet of the study area and valley outlet with a distance of 26.5 km reveals a significant difference between the two models. The MOLA-DEM has a resolution of 463 meters per pixel while the CTX stereo pair has a much finer resolution of 12 meters per pixel. The high-resolution CTX stereo pair allows for better identification of the valley network, which is crucial for further hydraulic modelling. The cross sections in Figure 5.12 highlight the importance of the high-resolution DEM as the bottom width of the valley outlet, where the widest section of the valley network is expected to be, is less than 400 meters, which is smaller than the resolution of the MOLA dataset. That is why, the CTX mosaic images with a resolution of 5 meters per pixel enable more accurate tracing of the valley network. However, even more accurate models can be obtained when the HiRISE stereo pair dataset is available in the study area. Unfortunately, this dataset is currently under development and only covers small areas of the Mars surface. Therefore, it is clear that high-resolution datasets are essential for accurate mapping and understanding of the Martian landscape

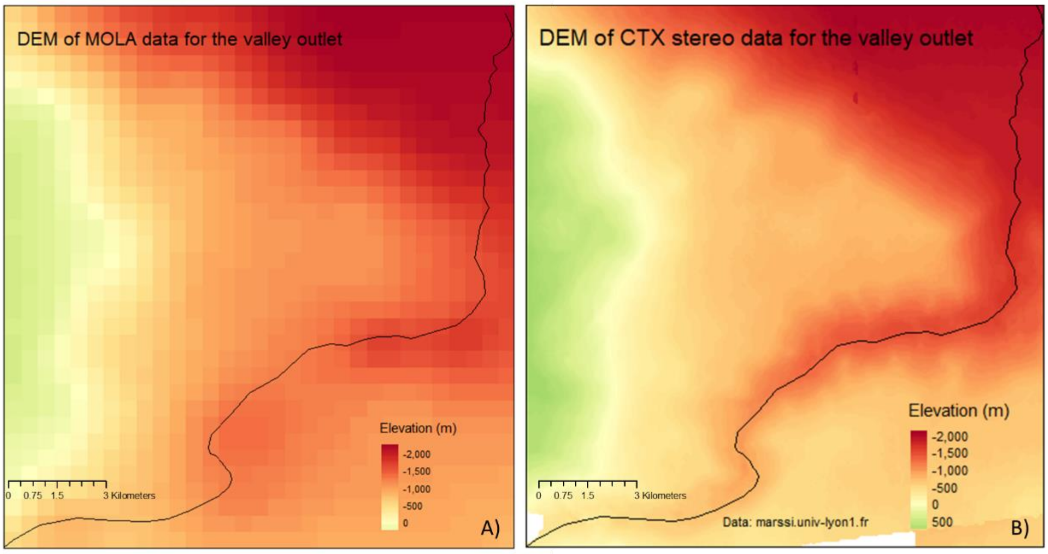

Figure 6.1: The DEM of an area near the outlet of the study area. A) MOLA-DEM of the valley outlet's area. B) CTX Stereo DEM of the valley outlet's area.

The trapezoidal and triangular cross sections of the modelled valleys provide strong evidence for the hypothesis that the valleys on Mars were formed due to flowing water. The presence of water on Mars in the past is supported by various studies, including those that suggest volcanic activity on Mars caused a greenhouse effect that increased temperatures during the Noachian Era (Bouley et al., 2016; Grotzinger et al., 2014). These findings are consistent with the existence of fluvial systems on Mars, such as the valley network observed in this study, and are supported by the work of other scientists (Erkeling et al., 2010; Gulick & Baker, 1990). On the other hand, it is important to note that some researchers have proposed alternative hypotheses for the formation of valleys on Mars, such as through the melting of ground ice rather than the flow of liquid water (Fastook & Head, 2015). While this study supports the flowing water hypothesis, further research and analysis are necessary to fully understand the complex processes that shaped the Martian surface.

Valley formation on our study area on Mars is most likely caused by the erosion of surface materials by flowing water, as supported by previous studies (Carr, 2012). The fact that the valleys are found in ancient terrains, Noachian, further strengthens this hypothesis. In addition, the results of the PCA analysis revealed that 35% of the valleys are best explained with fluvial erosion while 5.7% best explained with sapping erosion (Grau Galofre et al., 2020). However, the presence of numerous impact craters within the study area suggests that impact cratering may have also contributed to valley formation. This is supported by the steep slopes found in the watersheds inside the craters and the findings of (Brakenridge et al., 1985) that the force of the impact can cause the ground to crack and collapse, forming valleys and channels that radiate out from the crater.

Furthermore, the lengths and widths of the delineated valley network, as well as the V-shaped cross section, provide further evidence for the hypothesis that water erosion formed valleys on Mars as a sign of past water activity (Penido et al., 2013). It's important to note that the formation of valleys on Mars might have been a result of a combination of processes, such as erosion due to flowing water, tectonics, and impact cratering. The complex geological history of Mars makes it challenging to define a single process responsible for valley formation, but the findings from this study contribute to our understanding of the Martian surface and its evolution.

Finally, the estimation of flow rate from the results is prone to various sources of errors. Firstly, the modeled area of the valley network constitutes only 1.3% of the total delineated valleys and 3.5% of the main channel valley. Consequently, assuming the behavior of the valley upstream to be similar to the modeled area could lead to incorrect estimations of the total volume of the valley and the maximum discharge. However, the use of CTX stereo DEM data for the entire valley when available can help to address this issue. Furthermore, the minimum formation timescales of Martian valley networks range from 10^5 to 10^7 years, with some valley networks forming in as little as 200 to 5000 years (Hoke et al., 2011). This makes the estimation of the actual flow rate that flows in this network difficult to be accurately estimated using just DEM data or high-resolution images. Consequently, further research could be conducted in this area to determine the age of the valley network, which could then be incorporated to estimate the actual flow rate and maximum discharge more accurately.

6.3 Limitation and further research

The process of studying Mars' geomorphology is challenging due to the limited availability of various datasets. Field measurement and data collection is not feasible, and so remote sensing techniques and data analysis are necessary. This study focused on a limited area and used datasets with varying resolutions to model the valley network and watershed boundaries.

One of the primary limitations of this study is the limited availability of high-resolution datasets. While some areas have high-resolution digital elevation models, such as the HiRISE stereo pair with spatial resolutions up to 0.5 meters per pixel, the majority of Mars has resolutions of up to 200 meters per pixel. Even if higher resolution datasets were available for the study area, such as the CTX stereo with up to 5 meters per pixel, processing and georeferencing take time. Additionally, although the CTX mosaic provides high-quality images of the Martian surface, higher spatial resolution images such as HiRISE can provide more details in delineating tributaries that do not appear on the CTX mosaic.

Another challenge is the time required to trace the watershed boundaries and valley database accurately. It requires a trained eye to differentiate between the various geomorphological features of the Martian surface, and it is a time-consuming process. Moreover, dealing with large datasets requires powerful processing systems and adequate storage, especially when the region of interest is relatively large.

Furthermore, the limitations of this study extend to the scope of the project. The study focused on a limited area, and the results cannot be generalized to the entire Martian surface. The conclusions drawn from this study are specific to the area of interest, and the results may not be applicable to other regions on Mars. Thus, future studies must consider the limitations of this study and expand the scope of their projects to obtain more representative results.

However, despite these limitations, further research can be conducted to test the new algorithm-assisted mapping campaign in different regions on Mars as well as to estimate the contributions to the overall outflow of this area of interest. Firstly, this new algorithm-assisted mapping campaign should be tested in different regions on Mars to determine its applicability and effectiveness in other areas. Moreover, future research could estimate the contributions to the overall outflow of this area of interest, which could provide insights into the hydrological processes on Mars. This project could also be considered as the next step toward the Global Map of Martian Fluvial Systems done by the Alemanno group, partially using more recent data such as CTX stereo in conducting hydraulic modelling.

By using hydraulic modelling combined with geomorphological modelling, a better understanding of the hydrological processes on Mars could be achieved. It is also recommended to perform further analyses of the correlation between the valleys' maximum ages and their eroded volume, and to compare their data set with other data sets of the surface of Mars to better understand the origin and potential habitability of the planet. As this valley network was formed many years ago by flowing water on several periods, further research can help to shed light on the history of water on Mars. This will reveal relatively higher/lower contribution to the overall outflows.

In addition, the Terra Cimmeria region is particularly interesting for further research due to the high values of dissection density found in the northern Terra Cimmeria. The pattern of dissection in this area can be interpreted in terms of climate controlling factors (Luo & Stepinski, 2009), so more area should be mapped to reveal the truth of the density of valley networks on Mars and its water history.

Finally, recent analysis techniques, such as discordance analysis, should be applied to examine the effects of spatial scale. This will help to understand the relationship between the orientation of valleys on Mars and the surface slope direction at different spatial scales. In summary, this project provides a foundation for future research into Mars' fluvial systems, and there are many opportunities for further investigation that could deepen our understanding of the planet's geology, hydrology, and potential habitability.

7 Conclusion

In conclusion, the study of Martian hydrology and the role of water in its evolution remains a critical area of research for scientists. As, it is always suspected to influenced by the new datasets and discoveries. This thesis has contributed to the field by updating and improving the mapping of the valley network and watershed in the study area, providing valuable insights into the history of water on Mars and its potential impact on the Martian surface geomorphology.

The improved accuracy and reliability of the mapping campaign and updated valley network will certainly contribute to further advancements in Martian hydrology studies. The inclusion of both main channels and tributaries in the updated valley network provides a more comprehensive picture of the valley network, and the use of high-resolution imagery (CTX mosaic) and digital elevation models (MOLA-DEM) has led to a more accurate delineation of the valleys. However, it is important to acknowledge the limitations of this study, including the limited availability of high-resolution datasets (HiRISE stereo pair) and the time required for accurate tracing. Not to mention, the Manual delineation need an eye of expert and always will be suspected to different perspective.

Moving forward, further research is needed to fully understand the processes driving water flow on Mars, and new algorithm-assisted mapping campaigns will continue to play a critical role in advancing our understanding of Mars planet. The study provides insights into the geologic and climatic conditions of watershed formation on Mars, and the findings could help improve our ability to model past hydrological processes. Especially with the fact growing datasets and efforts to make them available for scientists, these robust models are a matter of time. By using the hydrological proxies which obtained from modelling modeling combined with the valley's age analysis, it is possible to reveal relatively higher/lower contributions to the overall outflow.

To further advance the field, future research could involve a comparison between the updated valley network and databases of Martian surface valleys, which would help improve our understanding of the Martian surface's geomorphology and sue these databases for validation. Additionally, the study could be expanded to other regions on Mars, and more advanced techniques could be developed to better analyse the complex processes driving water flow on the planet.

In summary, this thesis has contributed to our understanding of Martian hydrology and the history of water on the planet, but there is still much to be explored and discovered. With continued advancements in technology and data collection, we can expect to gain even deeper insights into the processes driving water flow on Mars and the potential for life on other planets.

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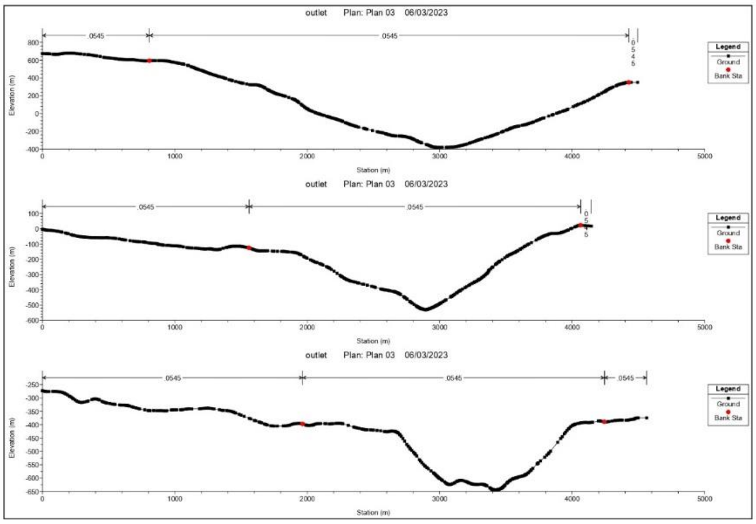
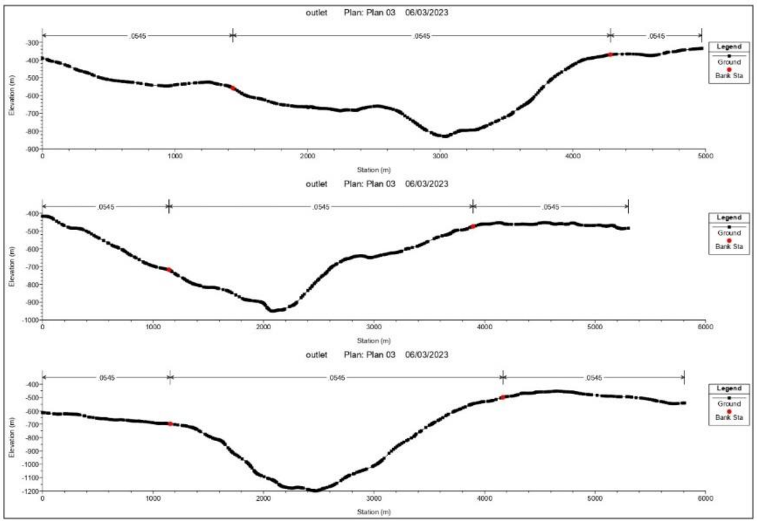
List of Abbreviations

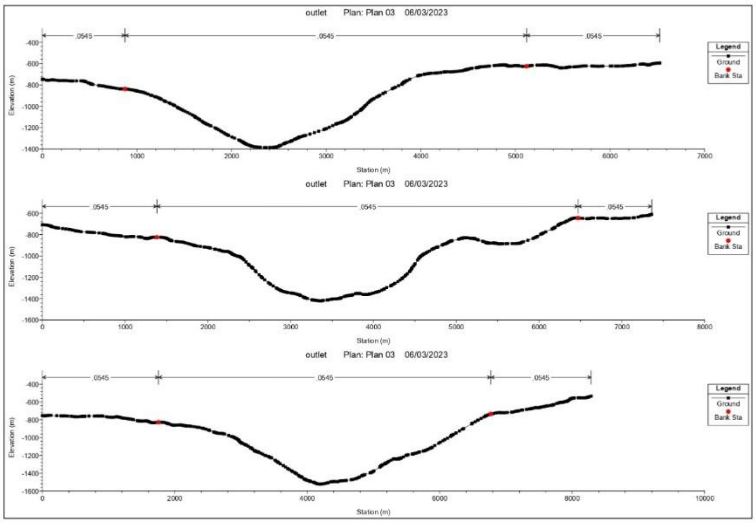
VN	Valley network
NASA	National Aeronautics and Space Administration
UV	Ultraviolet
MOC	Mars Orbiter Camera
MOLA	Mars Orbiter Laser Altimeter
DEM	Digital elevation model
MER	Mars Exploration Rovers
HiRISE	High-Resolution Imaging Science Experiment
THEMIS	Thermal Emission Imaging System
IR	Infrared
CTX	Context Camera
MRO	Mars Reconnaissance Orbiter
LNIH	Late Noachian Icy Highlands
SVNs	synthetic valley networks
PCA	principal component analysis
MCD	Mars Climate Database
GIS	Geographic Information System
USGS	United States Geological Survey
mNh	Middle Noachian highland unit
eNh	Early Noachian highland
HNt	Hesperian and Noachian transition
LNh	Late Noachian highland unit

Appendix

- **Valley outlet's cross sections; all simulated sections by HEC-RAS.**







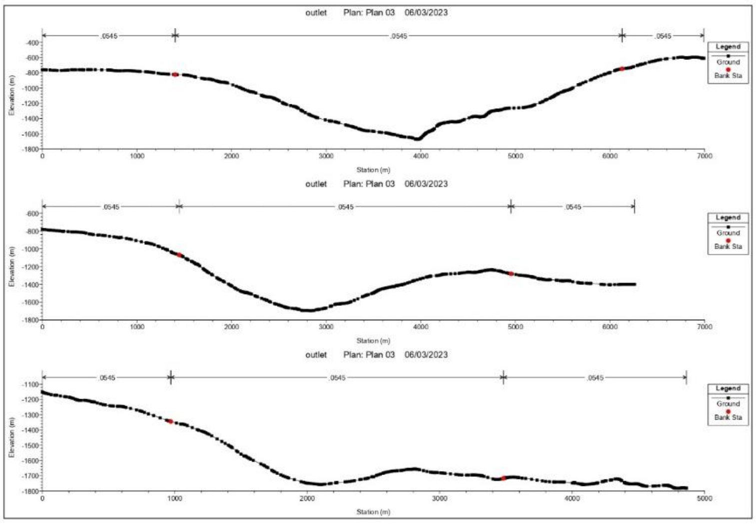


Figure 1: Valley outlet's cross sections; all simulated sections.

- **Table of all pour points used for watershed function.**

Table 1: The exact locations of pour points in projected coordinate system.

FID	Y	X
0	-312807	7874420
1	-398785	7810320
2	-440141	7821440
3	-479558	7671560
4	-594895	7670890
5	-367461	7839190
6	-423983	7764540
7	-578635	7740110