Chapter

Prediction of the Transported Soil Volume by the Presence of Water in the Vicinity of Ma'adim Vallis (Mars)

Emilio Ramírez-Juidías

Abstract

Ma'adim Vallis is a channel that ends at the Gusev Crater. In general terms, the length of the channel is about 700 km while its width can reach 20 km and its depth 2 km. Currently, the images obtained from the area allow to visualize a landscape of abundant gullies with important signs of water erosion. In order to predict the volume of transported soil by the presence of water in the vicinity of Ma'adim Vallis, as well as to generate a rainfall model applicable to the red planet, a total of 16 cross-sectional profiles were made along the main canyon, ensuring that all were equidistant from each other depending on the orographic characteristics of the study area. Once the volume of transported soil was obtained, a novel model capable of predicting the rainfall concentration index (RCI) necessary to produce a certain water erosion on the Mars surface was obtained. This model is applicable to other rocky planets as a result of its simplicity.

Keywords: DEM, advanced remote sensing, rainfall model in Mars, big data analysis

1. Introduction

Currently, it is believed that the gravitational accretion process, of material from the protoplanetary disk that orbited the Sun, was the reason by creating Mars about 4.6 billion years ago [1, 2]. At that time, the solar wind accumulated the elements with a lower boiling point on the outermost rocky planet, which explains why the red planet has a higher concentration of Cl, P and S than Earth [3]. Regarding its initial orbit, there are studies [4] that support the theory that its formation occurred in the asteroid belt, taking place around 120 million years later, a migration towards its current position. The presence of liquid water on the surface would gradually disappear as a result of the existence of a tenuous atmosphere and an intense solar wind [5].

In another vein, about 4 billion years ago, during the late heavy bombardment (LHB), most of the impact basins were created on planets' surface [6], which it given rise to the dichotomy between both Northern and Southern hemispheres of the red planet [7].

With regard to Martian geology, it is very important to bear in mind that the record of its evolution is preserved in the rocks and sediments existing on the surface of the red planet. In this sense, and according to [8], minerals can fingerprint many processes that build the Martian rock record. For this reason, and with the purpose of knowing the composition of this planet, infrared spectroscopy instruments have been used in order to make a series of mineralogical maps from orbiters or rovers currently existing on the surface.

As is well known, the surface of Mars is made up of ferric oxides and oxyhydroxides, giving its surface its characteristic red color. However, under the dust layer there is a basaltic crust, which bears some similarity to the terrestrial, more specifically to the oceanic. In relation to the above, it must be emphasized that the early Martian crust, formed during the first billion years, preserves a rich chemical record of multiple and diverse hydrated environments. Nevertheless, the more recent crust exhibits a less frequent and less intense interaction between itself and water [8]. This fact can reinforce the theory of the continuous drying of the planet and, therefore, the presence of high concentrations of salts on the surface.

Regarding its atmosphere, Mars is composed mainly of carbon dioxide (95.7% CO_2, 2.1% Ar, 2% N_2, traces of O_2, CO, water and CH_4 among other gases [9]). The mean atmospheric pressure on its surface is 6 mbar, about 0.6% of the mean sea level pressure on Earth. It ranges from a low of 0.30 mbar at the peak of Mount Olympus to more than 11.55 mbar in the depths in Hellas Planitia. Another interesting fact is that the mass of the Martian atmosphere (about 25×10^{15} kg) is about 200 times less than the Earth's (about 5148×10^{15} kg).

According to [10], Mars has important similarities to Earth, such as the presence of polar caps, the existence of seasonal changes, and the presence of observable weather patterns. While the climate of Mars has similarities to that of Earth, including periodic glaciations, there are also important differences, such as much lower thermal inertia. Although there has been a notable increase in sublimation in the polar regions, in recent decades there has been a decrease in global temperature, probably due to the same cyclical phenomenon that exists on Earth and, thanks to which, the climate change makes possible, every thousands of years, the appearance of a thermal variation with great repercussions on the entire planet. The fact of being further from the Sun than the Earth, as well as the existence of a tenuous atmosphere that retains little heat, causes the average surface temperature to be about −55°C, with superficial thermal variations from 27°C in summer, in the equator, down to −143°C in the polar caps [11]. It is convenient to emphasize dust storms (wind speed of around 200 km/h) caused by the difference in energy that the planet receives at aphelion and perihelion. Since they occur on a global scale, they cause a decrease in maximum temperatures (due to the decrease in energy from the Sun), and an increase in minimum temperatures.

In general, and with regard to the orography of the planet, [5] specifies that the existing channels, as well as the gullies and the runoff processes associated with them, suggest the presence of liquid water on the surface in the past. Furthermore, taking into account that the atmospheric pressure in the Martian past was ostensibly higher than the current one, and according to [12], raindrops with enough size could be formed to give rise to orographic incidents on the surface.

Regarding the erosion processes, reference [5] obtained a series of predictive algorithms of soil transported volume valid on Mars surface. Other studies [13] specifies that levitation forces enhance the downslope transport on Mars, even though there is evidence that in the past, in the period in which the atmospheric density was such that it allowed the existence of water in a liquid state on its surface, the loss of soil due to sedimentary transport in watercourses was the force that it modeled the morphology of the Martian surface. In relation to the above, it is necessary to bear in mind the work of reference [14], since one way of being able to study the climatic conditions of Mars (when liquid water existed on the surface) is by observing the value of the angle formed by the valleys network ramifications on Mars. This consideration is due to the fact that, over the years, the angle that these ramifications have usually remains unchanged.

Although numerous studies have been carried out on Mars to date, none of them have obtained the transported soil volume using cross sections methodology. In the same way, no scientific work has inferred an algorithm capable of obtaining a novel model that can predict the rainfall concentration index (RCI) necessary to produce a certain water erosion on the Mars surface. For this reason, this work pretends to be a reference in future studies because this chapter's novel model may be applicable for rocky planets.

2. Study area

Located in the southern hemisphere (**Figure 1**), Ma'adim Vallis (21,98° S; 177,5° E in planetocentric coordinates) is a channel that ends at the Gusev Crater (14,44° S;

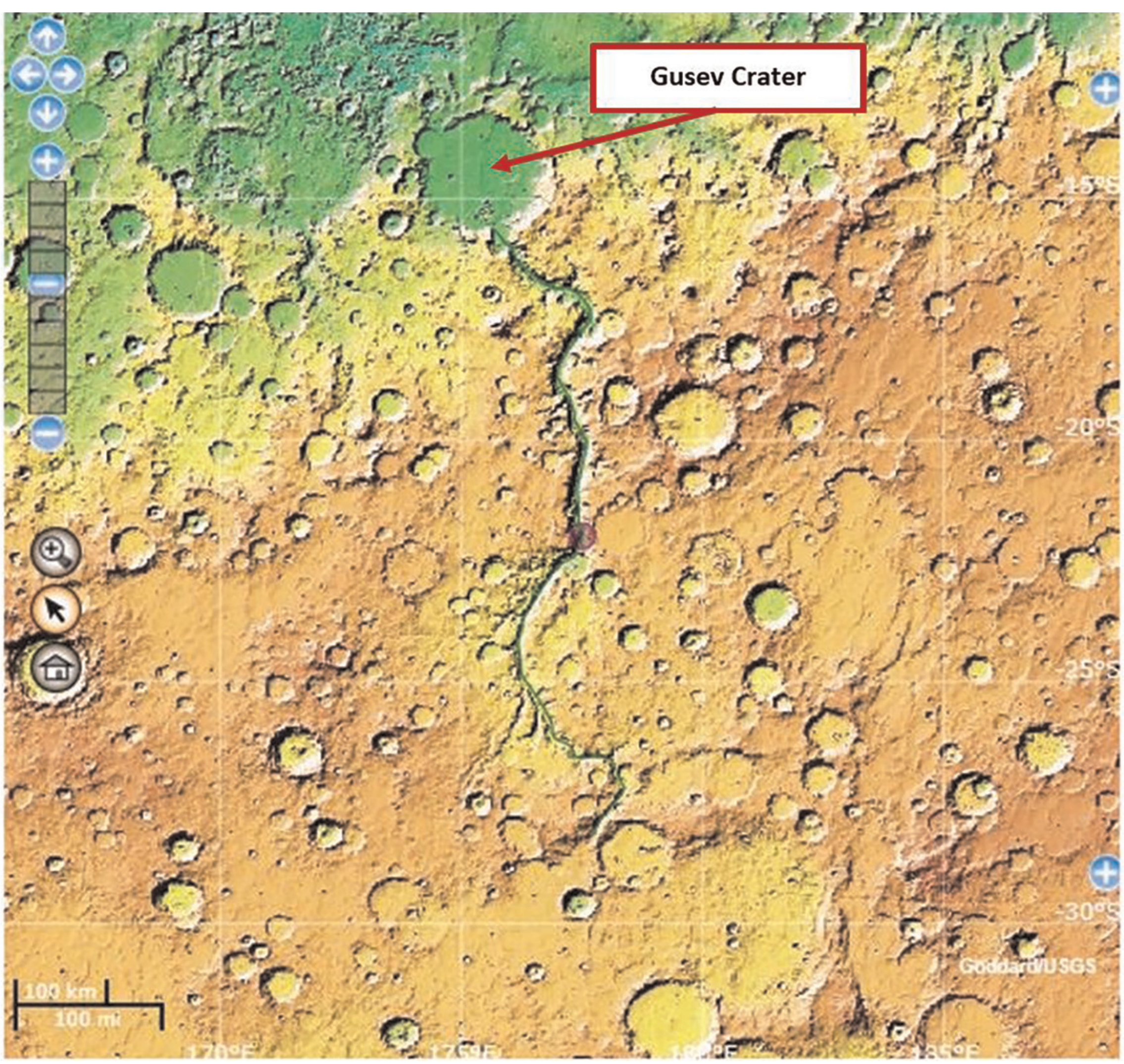


Figure 1.
Location of the study area.

175,29° E also in planetocentric coordinates). In general terms, the length of the channel is about 700 km while its width can reach 20 km and its depth 2 km.

Several studies [15, 16] suggest that Ma'adin Vallis originated as a result of the overflow of a lake located in the Eridania basin. As a result of this event, Ma'adim Vallis has a peculiar topography (**Figure 2**) characterized by a network of channels of variable width (8–25 km), as well as a system consisting of step terraces and several inner channels that flow into the main one.

According to [15], Ma'adim Vallis enters Gusev crater through an opening in its southern edge, and a separate crevasse opens northwestward toward the northern lowlands, suggesting past flow into Gusev crater. It should be noted that the divides of Gusev crater and the Eridania basin are only partially incised, so volumetrically reduced central basins still exist. However, the northern divide of the intermediate basin was downcut to below its floor level, opening the basin completely for through-flowing drainage [16].

On the other hand, and considering the longitudinal profile of Ma'adim Vallis (**Figure 3**), it can be divided into three different areas. The first one, descends from the beginning (445 m high) to the first 324.48 km (−796 m high) with an average slope of 0.38%. This is followed by a 0.17% slope area in 193,820 km, where the elevation difference is 332 m. The last part, with a slope of around 0.21%, has a length of 198.18 km, being the mouth towards the Gusev crater.

In relation to the above, it is necessary to specify that both at the beginning and at the end of the longitudinal profile considered in the present work, the width of the main channel is practically constant, being much greater in the central part, which corresponds to the area of less slope. This fact may be due to the fact that, logically, in the steepest areas, water erosion wears down the channel in depth, while in those with a lower slope value, the erosion occurs mainly in the width of the channel.

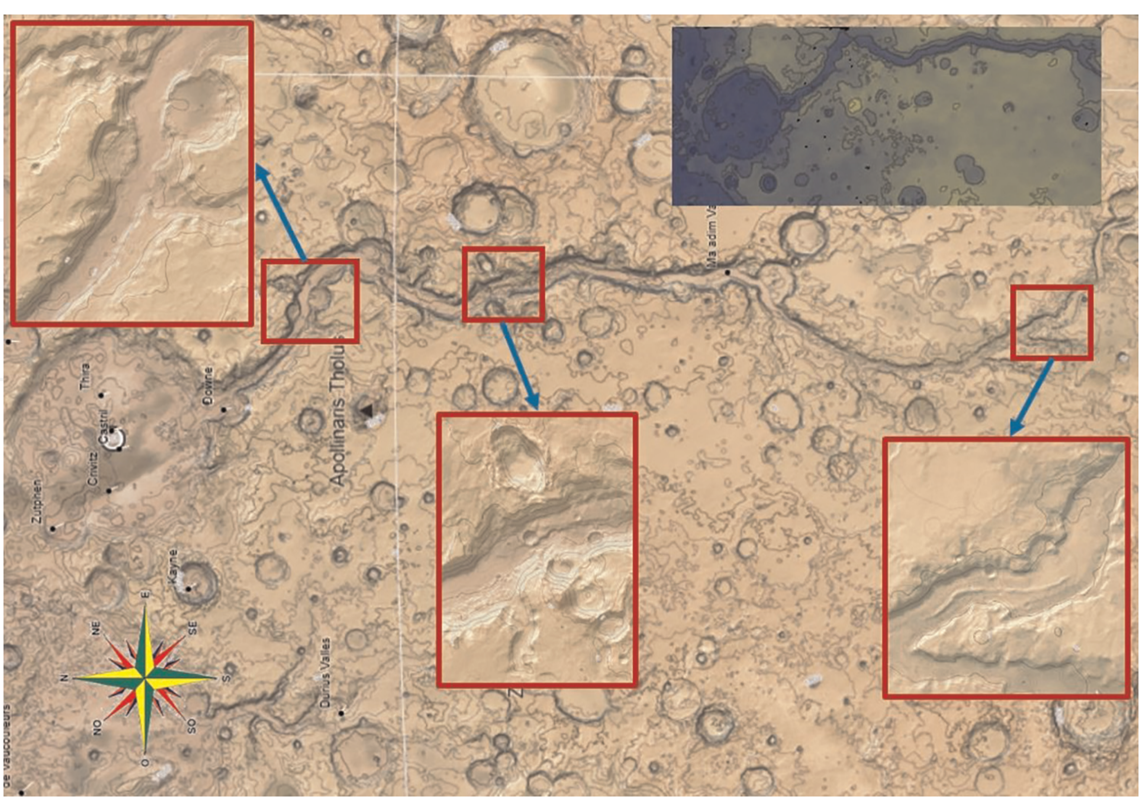


Figure 2.
Topography of Ma'adim Vallis.

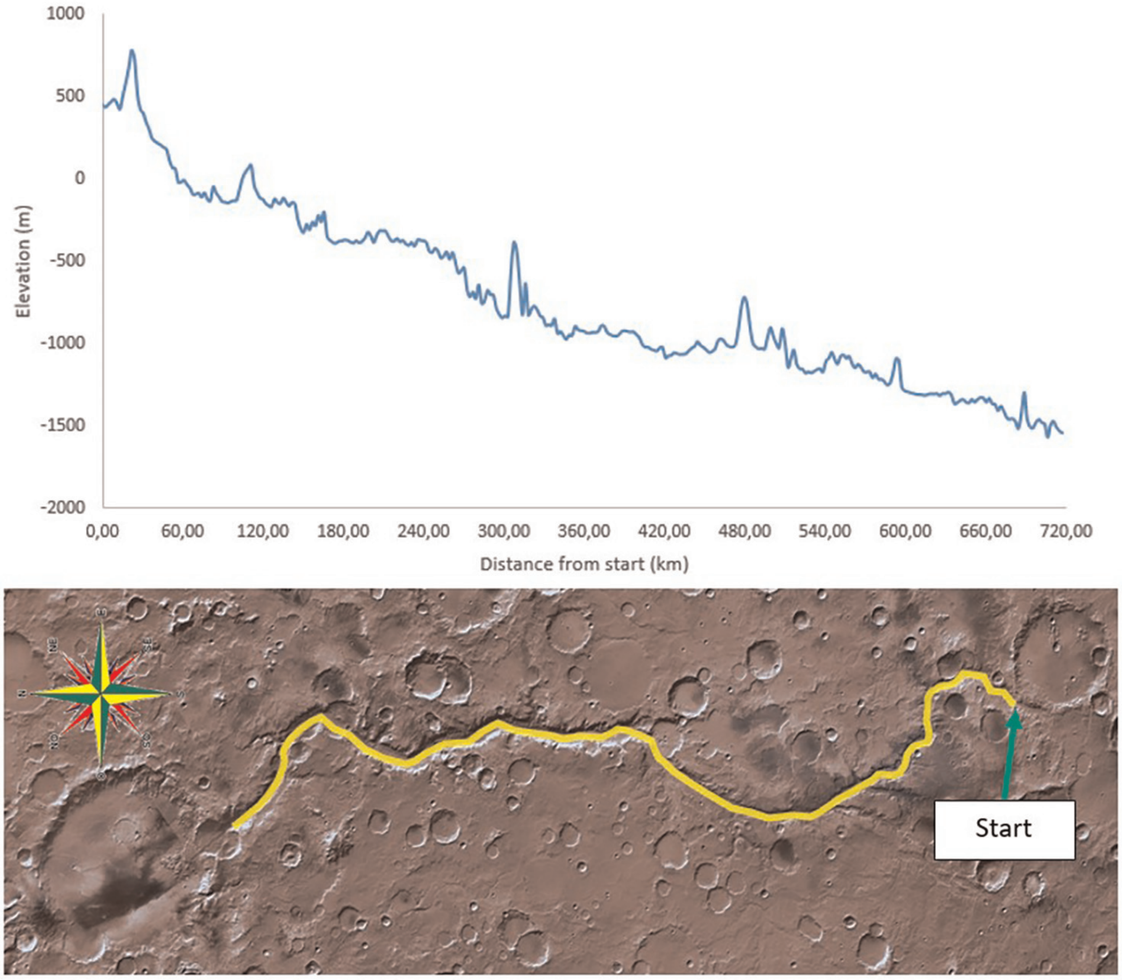


Figure 3.
Longitudinal profile of study area.

As is evident, the causes of water erosion are varied (rainfall, continuous flow of water "river erosion", existence of tides and associated waves, or even occasional dripping on the ground), although the water erosion produced by subsurface runoff should not be forgotten.

Based on the characteristics of the study area, as well as those corresponding to areas of Earth with evidence of water erosion, it is clear that Ma'adim Vallis has been shaped by water.

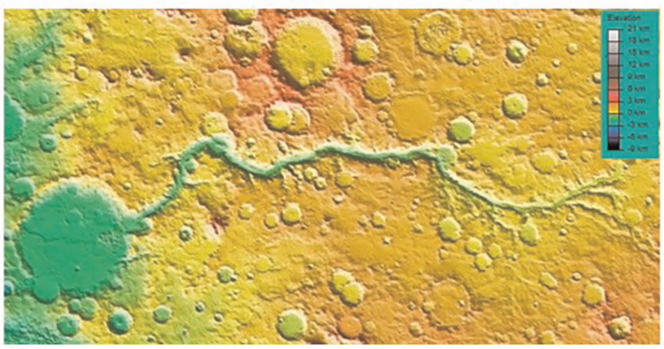
Perhaps, this is one of the reasons why Ma'adim Vallis is one of the most important areas of Mars, which shows that in the past there was a predominant constant hydrological cycle on the planet, and therefore, more favorable conditions for the existence of life.

3. Materials and methods

For the development of this work, a total of 16 cross-sectional profiles were selected, equidistant among themselves, along the main channel of the study area (**Figures 4** and **5**).

In order to obtain the amount of soil lost (eroded), over time, until giving rise to the gully system that predominates in Ma'adim Vallis, it was proceeded to measure, in

Cross-section profile	Top edge width (km)	Base width (km)	Depth (km)
1	11,410	2,992	0,677
2	9,342	2,215	0,710
3	12,042	3,078	0,545
4	15,820	1,356	0,550
5	15,077	5,786	0,590
6	12,139	2,388	0,607
7	10,540	3,260	0,651
8	*27,185*	*11,273*	*1,393*
9	*35,925*	*20,118*	*0,649*
10	18,865	9,894	1,657
11	18,056	6,216	1,731
12	18,615	4,875	1,820
13	18,409	7,699	1,648
14	17,850	9,135	1,390
15	25,193	8,541	1,632
16	*30,510*	*1,695*	*1,828*
Mean ==>	18,561	6,283	1,130
	Gully length ==>	771	km



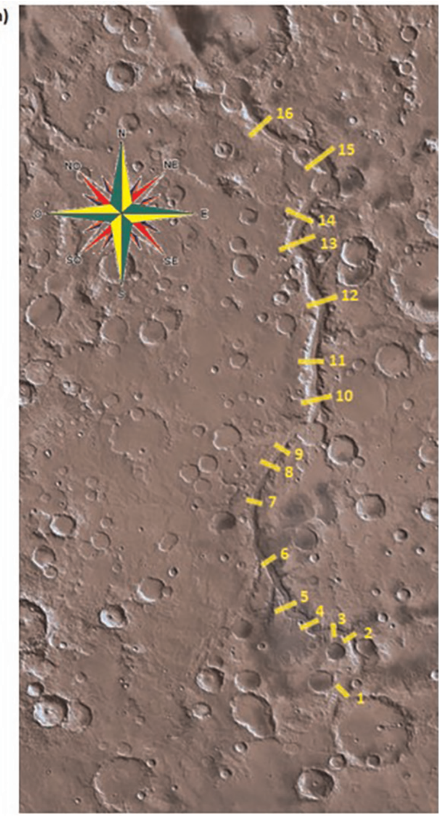


Figure 4.
Location of cross-section profiles, and data, in the study area.

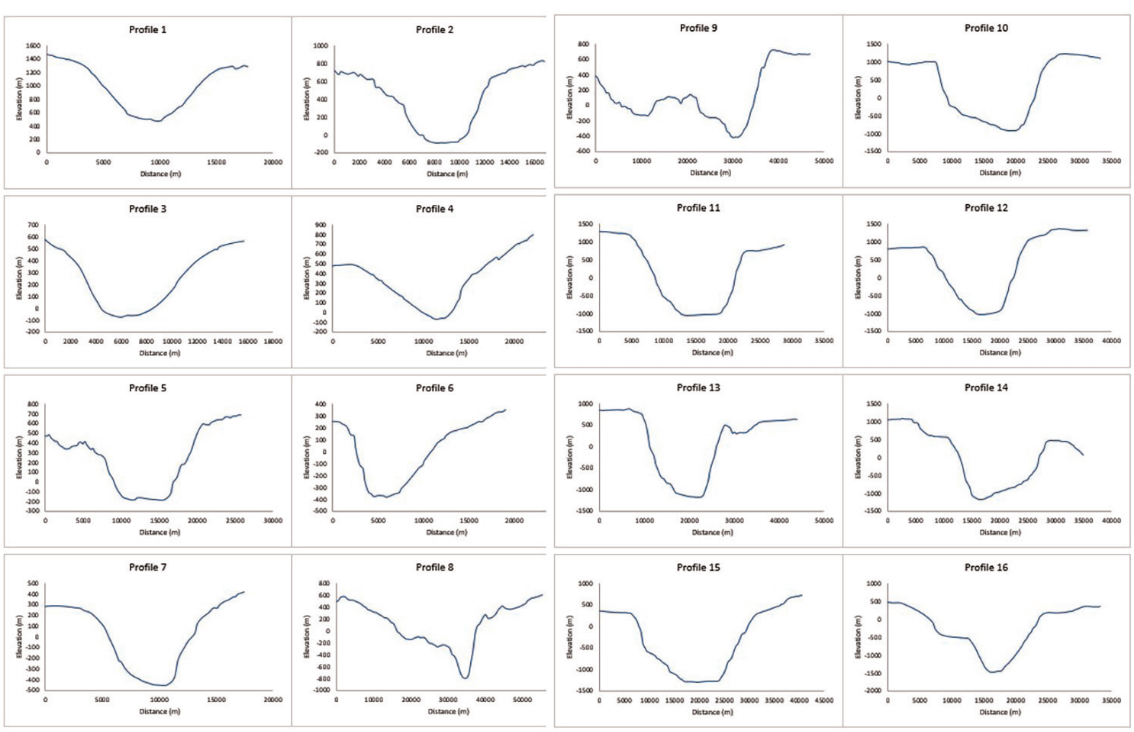


Figure 5.
Cross-section profiles.

each transverse profile, both the upper width "U_w" (in km) and the base width "B_w" (in km) of the gully, as well as its depth "D" (in km). Subsequently, the mean values of the three mentioned variables were calculated, thanks to which, and by applying

Eq. (1) in order to always be on the side of safety, it was possible to obtain the soil lost volume (V) in the study area. Logically, the channel, or gully, length "L" (in km) will be necessary.

$$V\ \left(\mathrm{km}^3\right) = \left[(U_\mathrm{w} + B_\mathrm{w}) \cdot D\right] \cdot L\ (\mathrm{km}) \tag{1}$$

In a later phase, the data from MOLA was downloaded (the soil lost volume was also determined by using of Topocal 2022-v9.0.811 software) and, after an exhaustive analysis, the contributing watershed area corresponding to the study area was determined. This was necessary to convert the soil lost volume to an equivalent per km^2.

In another vein, a model capable of predicting the RCI through [17] was developed (Eq. 2) taking into account the similar behavior that liquid water has on the surface both on Earth and on Mars.

$$\mathrm{RCI} = e^{\frac{1.56 + \log\left(\frac{Q'_\mathrm{s}}{t'}\right) - 0.46 \cdot \log(H) \cdot \tan(S)}{2.65}} \tag{2}$$

where:

Q'_s = relationship between the existing sediments mass (in g) and the contributing watershed area (in m^2) in Ma'adim Vallis.

t' = time required, in Martian years, to generate the sediment mass existing in the study area. It is necessary to specify that $t' = 1.882 \times t$, where "t" is the Earth elapsed time in years.

H = it is the average elevation (in m), taking as 0 the lowest elevation of the longitudinal profile corresponding to the gully base.

S = it is the average slope of the contributing watershed (in °).

Finally, in order to adequately reference this work, an exhaustive bibliographic review was carried out.

4. Results and discussion

The soil loss, and its consequent degradation, can occur in many ways. In general, after a degradation process, the soil becomes thin and stony, giving rise to severe impacts for the surrounding environment, such as those specified below:

- Increase in bulk density, as well as crusting of the upper soil layer.

- Reduction of the upper layer thickness of the soil, in addition to the exhumation of the subsoil as a result of long periods of continuous erosion.

- As a result of the fact that Ma'adim Vallis is located in the tropical zone (orange area "zone D") of Mars (**Figure 6**), it must be taken into account that an increase in the acidity of the soil may occur due to a selective elimination of calcium cations in the exchange complex. This fact affects the availability of other chemical elements, giving rise to the fixation of phosphorus and producing free aluminum, which ultimately causes severe toxic effects in the soil.

- Reduction of the soil microbial population, as well as its microflora, which affects nitrification processes.

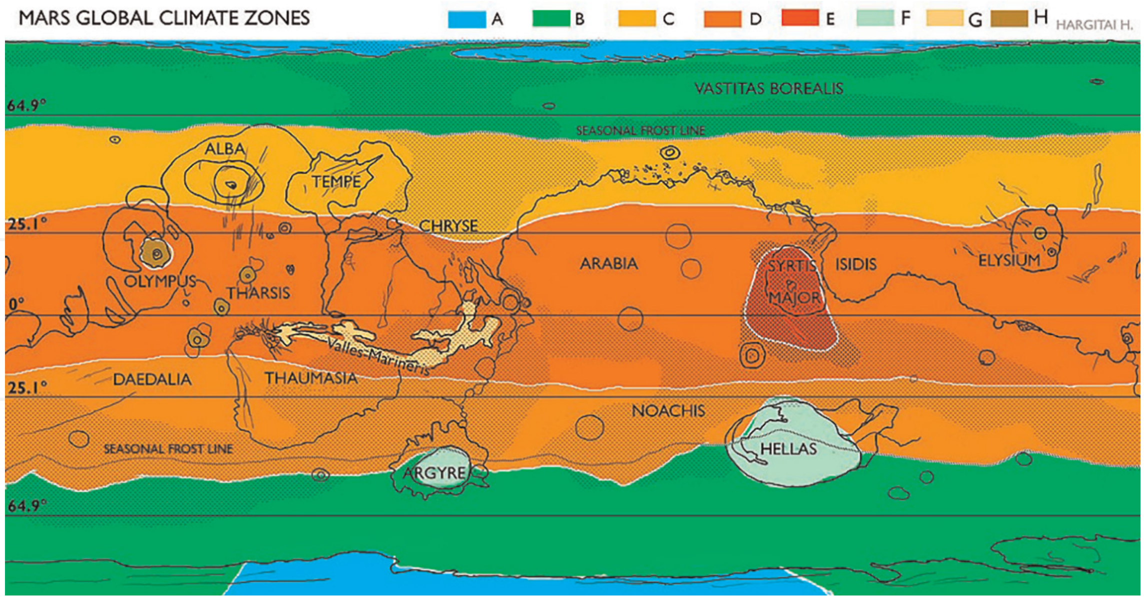


Figure 6.
Mars global climate zones [18], based on temperature, modified by topography, albedo, actual solar radiation. A = glacial (permanent ice cap); B = polar (covered by frost during the winter which sublimates during the summer); C = north (mild) transitional (C_a) and C south (extreme) transitional (C_b); D = tropical; E = low albedo tropical; F = subpolar lowland (basins); G = tropical lowland (chasmata); H = subtropical highland (mountain).

It is evident, after analyzing the shape and dimensions of the cross-section profiles made in the study area, that the main channel has the typical shape of a gully. In a broad sense, a gully is a deep depression, channel or ravine, very active for the natural drainage of a liquid fluid that flows through the surface. Although gullies can be continuous and discontinuous, it should be taken into account that the last one appears when the gully bed has a lower slope level than the general slope of the surrounding terrain.

On the other hand, it is also known that, in a gully, runoff is channeled into trenches that deepen over time to form a marked front (head) with very steep faces (walls). The gullies extend and deepen in an upward direction due to cascading erosion and progressive collapses of their upper parts. Similarly, gully slopes can collapse due to seepage of water, as well as undermining the flow of water within the gully.

With regard to the Earth (**Figure 7**), it should be noted that gullies tend to form where the slopes are long and there has been a logical loss of vegetation. This fact has as a consequence an increase in surface runoff. In particular, they tend to be dominant in areas where the soil is composed of deep silty or clay materials, in soils with unstable clays (as in the case of sodium soils), under bare rocky surfaces and on very steep slopes subject to water infiltration and earthmoving.

In another vein, and in relation to the cross-sectional profiles obtained, **Table 1** shows the area of each one of them. As can be seen, from cross-section profile number 8 (km 347 from start in **Figure 8**), inclusive, there is a significant increase in the surface of the gully, perhaps due to the contribution made by an effluent or another contributing watershed, such as [19] specifies.

Regarding the volume of soil lost (Eq. 1) in the study area, it should be noted that a result of 10,817.812 km^3 has been obtained. If this result is compared with that obtained by [19–21] (**Table 2**), it can be seen that the methodology used affects the calculation of the volume, so much so that, if Eq. (3) would have been used

DOI: http://dx.doi.org/10.5772/intechopen.102985

Figure 7.
Gullies of Cerro Negro (Castilla La Mancha, Spain).

Profile no.	Top edge width (km)	Base width (km)	Depth (km)	Area (km^2)
1	11.410	2.992	0.677	4.87
2	9.342	2.215	0.710	4.10
3	12.042	3.078	0.545	4.12
4	15.820	1.356	0.550	4.72
5	15.077	5.786	0.590	6.15
6	12.139	2.388	0.607	4.41
7	10.540	3.260	0.651	4.49
8	27.185	11.273	1.393	26.78
9	35.925	20.118	0.649	18.17
10	18.865	9.894	1.657	23.83
11	18.056	6.216	1.731	21.01
12	18.615	4.875	1.820	21.37
13	18.409	7.699	1.648	21.51
14	17.850	9.135	1.390	18.75
15	25.193	8.541	1.632	27.52
16	30.510	1.695	1.828	29.44

Table 1.
Area in each cross-sectional profiles.

(**Figure 9**), the soil lost volume, in the present work, would have been 11,553.29 km^3. Calculation of this volume using the Topocal 2022-v9.0.811 software resulted in 12,700 km^3.

$$V\left(\text{km}^3\right) = \frac{d}{6}\left(A_1 + 4 \times A_{\text{m}} + A_2\right) \tag{3}$$

Regarding the RCI shown in Eq. (2), each of its variables has been obtained as follows:

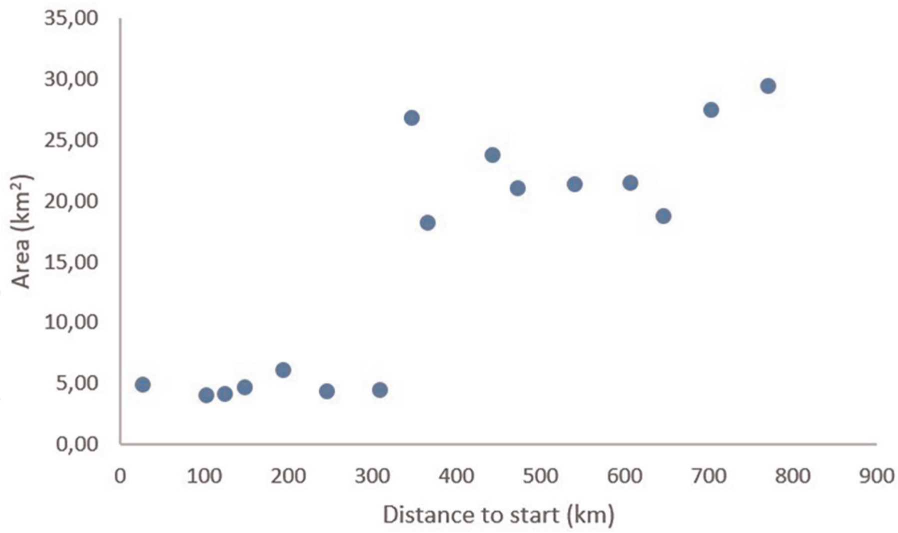


Figure 8.
Relationship between the area of each cross-section profile and its distance to start.

Author or work	Methodology	V (km^3)
Cabrol et al. (1996) [19]	Geometric model	13,900
Goldspiel and Squyres (1991) [20]	Contributing watersheds	13,000
Irwin III et al. (2002) [21]	Sedimentary transport	15,100
This work	Eq. (1)	10,817.812
This work	Prismatoid equation (Eq. 3)	11,553.29
This work	Topocal 2022-v9.0.811	12,700

Table 2.
Soil lost volume in Ma'adim Vallis by different methodologies.

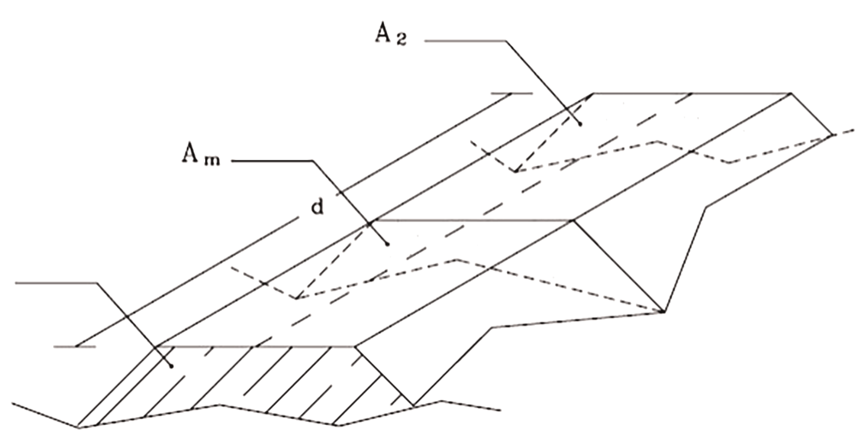


Figure 9.
Sketch to obtain the volume by the prismatoid equation. A_m *is the mean cross-section area between* A_1 *and* A_2.

The Q'_s value, dependent on the mass ("m" in g) of soil lost and of the contributing watershed area ("A" in m^2). According to [22], the average density of soil on Mars is 2.58 g/cm^3. Taking into account, as soil lost volume, for having been calculated according to the MOLA data, that corresponding to that obtained through Topocal 2022-v9.0.811, that is, 12,700 km^3, the soil mass amounts to the value of:

$$m = 12700\ \text{km}^3 \times 2.58\,\frac{\text{g}}{\text{cm}^3} \times \frac{10^{15}\ \text{cm}^3}{1\ \text{km}^3} = 3.28 \times 10^{19}\ \text{g} \tag{4}$$

According to [16], the contributing watershed area is 208,500 km^2 (2.085 10^{11} m^2), so the Q'_s value is:

$$Q'_s = \frac{3.28 \times 10^{19}\ \text{g}}{2.085 \times 10^{11}\ \text{m}^2} = 1.57 \times 10^8\,\frac{\text{g}}{\text{m}^2} \tag{5}$$

If the soil lost volume is converted to an equivalent per km^2, it is obtained (12,700 km^3/208,500 km^2) 0.0609 km^3/km^2.

In order to obtain the average elevation ("H" in m) of the study area, data shown in **Figure 3** were taken into account. It should be noted that the average elevation does not refer to that calculated with respect to level 0, since, in this case, the result varies depending on the absolute elevation at which the study area is located, which does not would make sense. For this reason, the average elevation is obtained taking into account that level 0 is the lower level of Ma'adim Vallis, so H will be the average elevation at said level, that is, 2 km (431 m − 1569 m).

In order to infer the average slope ("S" in °) of the contributing watershed, and knowing that the gully length is 771 km, it will only be necessary to perform the following calculation:

$$S = \tan^{-1}\left(\frac{2\ \text{km}}{771\ \text{km}}\right) = 0.149^\circ \tag{6}$$

Finally, substituting all the numerical values in Eq. (2), the following valid expression for Ma'adim Vallis is obtained:

$$\text{RCI} = e^{\frac{1.56 + \log\left(\frac{1.57\times 10^8}{t'}\right) - 0.46\times\log(2000)\times\tan(0.149)}{2.65}} = e^{\frac{1.556 + \log\left(\frac{1.57\times 10^8}{t'}\right)}{2.65}} \tag{7}$$

It is necessary to emphasize that the developed model has been calculated taking into account the runoff of liquid water due to rainfall in the form of rain that, in the past, would have occurred on Mars. In addition, as is well known, on the red planet the sublimation of groundwater, in low pressure atmospheric conditions, can cause a landslide analogous to that produced by runoff of liquid water flowing on the surface, a phenomenon that should be taken into account in future studies in order to be able to obtain all the causes that can affect the soil loss on Mars.

5. Conclusions

In present work, the RCI has been obtained assuming that, exclusively, similarly to what happens on Earth, the soil loss on surface is caused mainly by the action of runoff water that circulates down slope.

It is evident that the collected data to date, in relation to the relationship between erosion and rainfall, are insufficient to be able to reach a reliable conclusion. However, a possible more global development, of the presented RCI, valid for all planets, may be important when deciding the fate of future missions to Mars, especially with regard to the study of the action of water on Martian landscape.

Studies on this field have been carried out on Earth, which is why it will be necessary to start from these in order to develop algorithms, or mathematical models, capable of predicting, or calculating, the action of water globally (interaction between soil, possible existence of organisms on the surface and atmosphere).

For this reason, it is evident that future missions to Mars must be developed under the supervision of a multidisciplinary team of experts in all areas of knowledge, that is, biologists, physicists, chemists, astrophysicists, geologists, computer scientists, aerospace engineers and agronomical engineers among others.

Acknowledgements

This work has been possible thanks to the use of equipment from the University of Seville, as well as the Technology-Based Company RS3 Remote Sensing SL.

Conflict of interest

The author declares no conflict of interest.

Author details

Emilio Ramírez-Juidías
Graphic Engineering Department, University of Seville, Seville, Spain

*Address all correspondence to: erjuidias@us.es

References

[1] Manske L, Marchi S, Plesa A-C, Wünnemann K. Impact melting upon basin formation on early Mars. Icarus. 2021;**357**:114128. DOI: 10.1016/j.icarus.2020.114128

[2] Barnes JJ, McCubbin FM, Santos AR, Day JMD, Boyce JW, Schwenzer SP, et al. Multiple early-formed water reservoirs in the interior of Mars. Nature Geoscience. 2020;**13**:260-264. DOI: 10.1038/s41561-020-0552-y

[3] Lammer H, Scherf M, Kurokawa H, Ueno Y, Burger C, Maindl T, et al. Loss and fractionation of noble gas isotopes and moderately volatile elements from planetary embryos and early Venus, Earth and Mars. Space Science Reviews. 2020;**216**(4):1-65. DOI: 10.1007/s11214-020-00701-x

[4] Brasser R, Mojzsis SJ, Matsumura S, Ida S. The cool and distant formation of Mars. Earth and Planetary Science Letters. 2017;**468**:85-93. DOI: 10.1016/j.epsl.2017.04.005

[5] Ramírez-Juidías E, Villavicencio-Valero K, Borja A. Sedimentation and proposed algorithms to detect the possible existence of vegetation and humidity in the landing area of the Mars Exploration Rover-B (Opportunity). In: Bevelacqua J, editor. Solar System Planets and Exoplanets. London, UK: IntechOpen; 2021. pp. 77-95. DOI: 10.5772/intechopen.97628

[6] Mojzsis SJ, Brasser R, Kelly NM, Abramov O, Werner SC. Onset of gigant planet migration before 4480 million years ago. The Astronomical Journal. 2019;**881**(44):1-13. DOI: 10.3847/1538-4357/ab2c03

[7] Andrews-Hanna JC, Zuber MT, Banerdt WB. The Borealis basin and the origin of the martian crustal dichotomy. Nature. 2008;**453**:1212-1215. DOI: 10.1038/nature07011

[8] Ehlmann BL, Edwards CS. Mineralogy of the Martian surface. Annual Review of Earth and Planetary Sciences. 2014;**42**:291-315. DOI: 10.1146/annurev-earth-060313-055024

[9] Livengood TA, Kostiuk T, Hewagama T, Smith RL, Fast KE, Annen JN, et al. Evidence for diurnally varying enrichment of heavy oxygen in Mars atmosphere. Icarus. 2020;**335**:113387. DOI: 10.1016/j.icarus.2019.113387

[10] Kass DM, Schofield JT, Kleinböhl A, McCleese DJ, Heavens NG. Mars climate sounder observation of Mars' 2018 global dust storm. Geophysical Research Letters. 2020;**47**(23):1-9. DOI: 10.1029/2019GL083931

[11] Hockey T, Bartlett J, Boice D. Rusty Mars. In: Hockey T, Bartlett JL, Boice DC, editors. Solar System. Boca Raton: CRC Press (Taylor & Francis Group); 2021. pp. 101-114. DOI: 10.1201/9781003197553

[12] Craddock RA, Lorenz RD. The changing nature of rainfall during the early history of Mars. Icarus. 2017;**293**:172-179. DOI: 10.1016/j.icarus.2017.04.013

[13] Raack J, Conway SJ, Herny C, Balme MR, Carpy S, Patel MR. Water induced sediment levitation enhances downslope transport on Mars. Nature Communications. 2017;**8**:1151. DOI: 10.1038/s41467-017-01213-z

[14] Seybold H.J., Kite E., Kirchner J.W. The Role of Surface Water in the Geometry of Mars' Valley Networks and Its Climatic Implications [Internet]. 2017. Available from: https://arxiv.org/abs/1709.09834v1 [Accessed: 01-12-2021]

[15] Leverington DW. Incision of Ma'adim Vallis (Mars) by dry volcanic magafloods effused from multiple highland source. Planetary and Space Science. 2020;**191**:105021. DOI: 10.1016/j.pss.2020.105021

[16] Irwin RP III, Howard AD, Maxwell TA. Geomorphology of Ma'adim Vallis, Mars, and associated paleolake basins. Journal of Geophysical Research. 2004;**109**(E12):1-33. DOI: 10.1029/2004JE002287

[17] Fournier F. Climat et erosion: La relation entre l'érosion du sol par l'eau et les precipitations atmosphériques. 1re éd. Paris: Presses Universitaires de France; 1960. p. 206. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/2021-11/010080384.pdf

[18] Hargitai H. Mars Climate Zone Maps Based on TES Data [Internet]. 2009. Available from: http://planetologia.elte.hu/mcdd/climatemaps.html [Accessed: 15-12-2021]

[19] Cabrol NA, Grin EA, Dawidowicz G. Ma'adim vallis revisited through new topographic data evidence for an ancient intravalley lake. Icarus. 1996; **123**:269-283. DOI: 10.1006/icar.1996.0157

[20] Goldspiel JM, Squyres SW. Ancient aqueous sedimentation on Mars. Icarus. 1991;**89**(2):392-410. DOI: 10.1016/0019-1035(91)90186-W

[21] Irwin RP III, Maxwell TA, Howard AD, Craddock RA, Leverington DW. A large paleolake basin at the head of Ma'adim Vallis. Mars. Science. 2002;**296**:2209-2212. DOI: 10.1126/science.1071143

[22] Goossens S, Sabaka TJ, Genova A, Mazarico E, Nicholas JB, Neumann GA. Evidence for a low bulk crustal density for Mars from gravity and topography. Geophysical Research Letters. 2017; **44**(15):7686-7694. DOI: 10.1002/2017GL074172